Waste Collection Based on Real-Time Information

The case of ERSUC

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Abstract

The constant increase of competitive environment throughout the years has led companies to require improvements on its processes´ efficiencies, in order to maintain their position in the market. In waste management companies, the waste collection process is one of the core operations and contains a substantial weight on the overall costs. In the past, inefficiencies in the operation would be extremely difficult to overcome due to its complex nature, however, advances in technology developed throughout the years created new approaches to deal with such concern. More specifically, the implementation of information and communication technologies (ICTs) in waste collection operations to deal with specific constraints permits an increase in the benefits and a decrease in costs.

In this context, ERSUC, a waste management company responsible for collecting nearly 300 000 tons of solid waste in the Portuguese districts of Aveiro and Coimbra, intends to improve its operations regarding the selective collection, while reducing the associated costs.

To achieve the company´s goals, this dissertation aims to obtain alternative scenarios for the waste collection operation in order to mitigate the major limitations their current operation contains, which are the route frequency and route sequence. Two scenarios will be proposed. The first will attempt to optimize the route frequency of the current operation of the company, while the second will attempt to optimize the route sequence by developing dynamic routes that maximize the quantity collected while minimizing the distance travelled.

Keywords: vehicle routes, waste collection systems, information and communication technologies, real-time information

Resumo

O constante crescimento ao longo dos anos do ambiente competitivo levou a que as empresas necessitassem melhorar a eficiência dos seus processos, de maneira a manter a sua posição líder no mercado. Nas empresas de gestão de resíduos, o processo de recolha de resíduos é uma das principais operações, e contém um peso considerável nos custos totais da empresa. Antigamente, as ineficiências nas operações eram bastante difíceis de superar devido à sua natureza complexa, no entanto, avanços na tecnologia criaram novas abordagens para lidar com tais complicações. Mais especificamente, a implementação de tecnologias de informação e comunicação (ICTs) nas operações de recolha de resíduos para lidar com limitações específicas permitem um aumento no benefício e uma descida de custos.

Neste contexto, a ERSUC, uma empresa de gestão de resíduos responsável de recolher cerca de 300 000 toneladas de resíduos sólidos nos distritos de Aveiro e Coimbra, pretende melhorar a operação de recolha de resíduos seletiva, ao mesmo tempo que reduz os custos associados.

De maneira a atingir os objetivos da empresa, o objetivo desta tese serve para obter cenários alternativos para a operação de recolha de resíduos de maneira a mitigar as maiores limitações da operação atual, que são a frequência e a sequência das rotas. Dois cenários serão propostos. O primeiro cenário tenta otimizar a frequência das rotas da operação atual de recolha de resíduos. O segundo tenta otimizar a sequência da rota desenvolvendo rotas dinâmicas que maximizem a quantidade de resíduos recolhida enquanto minimizam a distancia percorrida.

Keywords: vehicle routes, waste collection systems, information and communication technologies, real-time information

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List of Abreviations

AMD – Adaptive Memory Procedure

APA – *Agência Portuguesa do Ambiente*

EGF – *Empresa Geral do Fomento*

EPR – Enterprise Producer Responsibility

ERSUC – Empresa de Resíduos Sólidos Urbanos do Litoral Centro

GAMS – General Algebraic Model System

GPS – Global Positioning System

GPRS – General Packet Radio Service

GSM – Global System for Mobile Modification

ICTs – Information and Communication Technologies

MCARP-LML – Mixed Capacitated Arc with Limited Multiple Landfills

MP-MDVRP – Multi-product, Multi-depot Vehicle Routing Problem

MBT – Mechanical Biological Treatment Units

OP – Orienteering Problem

PCTSP – Prize Collecting Travelling Salesman Problem

PDA – Personal Digital Assistant

PERSU – *Plano Estratégico para Resíduos Sólidos Urbanos*

PTP – Profitable Tour Problem

PVRP – Periodic Vehicle Routing Problem

RDF - Refused Derived Fuel

SMAUT – Sistemas Municipais Autarquias Aderentes

SPV – *Sociedade Ponto Verde*

SW – Solid Waste

SWM – Solid Waste Management

TOP – Team Orienteering Problem

TSP – Travelling Salesman Problem

VRPPs – Vehicle Routing Problem with Profits

VRPTW – Vehicle Routing Problem with Time Windows

1. Introduction

1.1 Context and Motivation

Nowadays companies face very competitive environments that puts them through daily challenges, and in order for them to progress, all the inefficiencies presented in their processes must be eliminated.

One of the urges for development is associated to inefficiencies in waste collection operations that companies responsible to collect and treat the waste face daily. This inefficiency is often related to the high uncertainty presented in the waste bins´ fill-levels when planning the collection routes and is directly caused by ceaseless population growth and continuous consume pattern modifications throughout the years. All of these factors debilitate the company´s performance, where routes planned often leads to waste vehicles travelling hundreds of kilometers only to collect small amounts of waste.

Therefore, to increase efficiency, the uncertainty must be reduced or even eliminated, if possible. One way to achieve this is through the use of Information and Communication Technologies (ICTs), which has seen extreme expansion in the last years. Volumetric sensors can be placed inside waste bins and send immediate information about any modifications that occur to the fill-level.

However, using ICTs by itself is not enough for increasing the operation´s efficiency: there is also the need for a proper optimization models that can use the sensor´s data, and propose efficient waste collection routes. The definition of waste collection routes using bins´ fill-levels information transmitted by sensors is known in the literature as the Smart Waste Collection Problem (Ramos et al, 2018), and is a variant of the well-known Vehicle Routing Problems (VRP). In an ideal setting, the real-time information regarding the fill-level is given by volumetric sensors placed inside the bins. However, such setting is not possible in this case study since sensors are not available. Thus, in this case, the information registered by the waste collection vehicle drivers will be used as the "sensors readings", to simulate a scenario where that information is known a priori, i.e., before a route is performed.

This work will have special focus on a company named ERSUC, currently in charge of the waste management in Coimbra and Aveiro, Portuguese areas that cover around 6700 km^2 of territory. The company suffers nowadays several issues in its waste collection planning procedures, mainly provoked by the uncertainties in the container´s fill-level. Therefore, alternative approaches will be considered in order to optimize the mitigations presented in the company´s current waste collection operations.

1.2 Objectives

The overall objective of this dissertation is to improve the waste collection operation of ERSUC through route optimization and to assess the benefits of having access to real-time information provided by ICTs in the collection operation. More specifically, the objectives are:

- Analyze the data regarding the company´s current waste collection routes
- Develop and adapt an optimization models to apply in the case study, with the required data and assumptions
- Implement the models to each scenario
- Analyse the results for each scenario and compare with the current operation of the company

1.3 Methodology

The methodology implemented for this thesis is divided in six steps, as follows:

1. **Problem description**: The first step will be to analyze the current waste collection operations of ERSUC. Therefore, a company characterization was made with data sent by the company and interviews with its executive administrator and responsible technician. Additionally, to identify the operations limitations, some interviews were also conducted to some drivers, and to perceive in-loco the difficulties the drivers´ experience when performing collection routes, a driver was escorted during the execution of a plastic route performed in the district of Soure.

2. **Literature review**: The next step will be to research models and methods that have been employed throughout the years for solid waste management. Therefore, scientific databases such as Science Direct, Google Academic and Web of Science were used together with key-words like: waste management systems, vehicle routing problem, information and communication technologies and real-time information.

3. **Data Collection and Treatment:** The third step is to collect data regarding the current waste collection operation of the company, and afterwards, treating it in order to analyze the different proposed scenarios. It was decided to analyse two districts in depth – Soure and Condeixa.

4. **Models:** The fourth step is to describe and analyze the proposed models for the alternative scenarios.

5. **Test and Model Validation:** The fifth step is to verify the model and its practical applicability.

6. **Result Analysis:** The last step is to analyse the results of the alternative scenarios and compare them to current waste collection operation.

1.4 Structure of the Dissertation

The dissertation is structured according to the following chapters:

The first chapter consists in a contextualization of the dissertation, approaching the problems occurring in the waste management companies. Moreover, the objectives and methodology of the dissertation will be presented.

The second chapter describes how packaging waste is managed in Portugal and then focuses on one of the companies responsible for packaging waste collection in Portugal, ERSUC. The company´s infrastructure, waste collection vehicles and routes will be analyzed. Afterwards, all the limitations regarding route planning and performance will be mentioned and alternative scenarios will be mentioned in order to eliminate these constraints.

The third chapter is an extensive analysis to the existing literature. Firstly, the solid waste management is analyzed with special focus in logistics issues. Secondly, information and communication technologies are presented together with its advantages of implementation in the solid waste management. Thirdly, vehicle routing problems and its numerous variations are analyzed, together with the existing applications in the solid waste management. Lastly, one of the vehicle routing problems, the vehicle routing problems with profits, will be thoroughly described together with the additional recent applications in the waste management field.

The fourth chapter is the presentation of the models used and its mathematical formulations described.

The fifth chapter describes the methods used to treat the data implemented into the models described in the fourth chapter. Since the data given is not complete, all the adaptations and assumptions required will also be described.

The sixth chapter exhibits the results of the models applied to the case study, and comparison of the different outcomes.

The seventh chapter describes the main conclusions of the dissertation and considerations for future studies.

2. Problem Description

2.1 Packaging Waste Management in Portugal

Constant growth of consumption and inadequate treatment were two factors that made packaging waste being considered a major concern for most developed countries. The first factor was developed by socio-economic features such as income increase and changes in people´s lifestyle and consumption patterns, especially during the 90´s (Tencati et al, 2016). The poor treatment was the outcome of depositing packaging waste in landfills instead of re-using it (Buclet & Goddard, 2001, Simões & Marques, 2009, EU, 2014).

Therefore, throughout the years the EU introduced several Directives to promote sustainability and a better management of the waste stream. The Directive on Packaging and Packaging Waste, or PPW Directive (94/62/EC) was, perhaps, the one with higher impact in industry and in waste management operators. The Directive states that all countries, by the end of 2001, should recover 50% of all packaging waste and recycled 25%, and was then updated to the Directive 2004/12/EC. More recently, the Waste Framework Directive (2008/98/EC) further stressed the importance of resource efficiency, imposing a packaging waste recovery of 60% for all EU countries, and also a recycling rate up to 60%, depending on the raw material (Cruz et al, 2012, Cruz et al, 2014, Tencati et al, 2016).

Although these targets were set for all members in the EU, the model implemented for achieving them differ from country to country. In Portugal, the model used is established in the *"Plano Estratégico para Resíduos Urbanos"*, PERSU 2020 (in English: Strategic Plan for Urban Waste). This plan, created in 2014 and lasting until 2020, sets the target of recycling 70% of all the packaging waste produced in Portugal (PERSU2020, 2014). One of the entities responsible for developing this plan, and currently in charge of implementing and monitoring it, is the *Agência Portuguesa do Ambiente*, APA (in English, Portuguese environmental agency) (APA, 2018).

Furthermore, the national law follows the Extended Producer Responsibility (ERP) principle (Pires et al, 2015). According to the OECD (2001), the ERP is "an environmental policy approach in which a producer´s responsibility for a product is extended to the post-consumer stage of a product´s life cycle". The objective is to change the responsibility upstream, to the producer, in order to increase its environmental concern (Forslind, 2009). So, companies had to choose one of two options: developing their own waste management system (that needed to be approved by the National Waste Authority), or transfer this responsibility to another entity, licensed by APA, in exchange for a fee whenever they placed packaged products in the market (Cruz et al, 2014).

This way, the *Sociedade Ponto Verde*, SPV (in English, Green Dot Society) was born. It is a private, non-profit organization, responsible for the management of most of the national reusable and non-reusable packaging waste. SPV responsibility concerning collection and recovery of packaging waste is operationalized through contracts with districts, multi-municipals or intermunicipal, distributed across Portugal, in exchange for a percentage of the fee SPV receives from the companies. Multi-municipals are a partnership between a district and the *Empresa Geral do Fomento*, EGF (in English, General Development Company). Intermunicipal, however, is an institutionalized public and private partnership. After the collection and treatment of the packaging waste, the SPV then sells it to recyclers. (Cruz et al, 2012)

As demonstrated in Figure 1, the packaging waste framework operates in cycles. Once the waste is sold to recyclers, it passes through a lot of different processes to be transformed into a product – thus retaining value –. The product is then sold, used, and deposited in ecopoints. Ecopoints are a set of three different containers, divided according to the waste deposited inside, which can be glass, paper/cardboard or plastic/metal. Finally, the districts, multi-districts and inter-municipal, responsible to collect and treat waste, develop waste collection routes to visit the ecopoints, and cycle starts over.

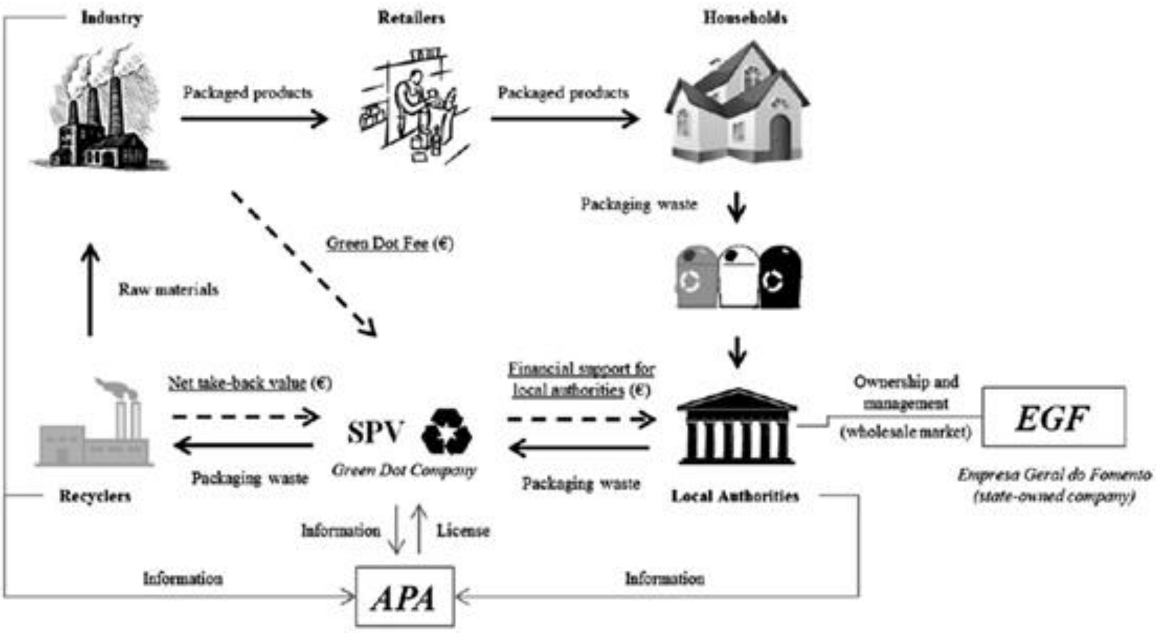

Figure 1: Packaging Waste Framework in Portugal (Source: Cruz et al, 2012)

Currently there are 23 companies responsible for packaging waste collection and treatment in Portugal. One of them is ERSUC, a company responsible for the collection of packaging waste in 36 districts, covering an area of 6700 km^2 across the coaster central of Portugal. The next section will further describe the company and its operations.

2.2 ERSUC

ERSUC – *Resíduos Sólidos do Centro, S.A.*, is a multi-municipal company responsible for the treatment of 300 000 tons of solid waste per year, covering a Portuguese area of 6700 Km^2, and serving almost a million citizens in Portugal.

The company was created in 1993, and in 1996 the decree law nº 166/96 assigned ERSUC to manage the coaster central area of Portugal. In 2014, this decree law was altered to the decree law 102/2014, allowing ERSUC to continue to manage the area until 2034.

The company sells 4 different products, that represent its major source of income:

- Electric Energy: Usually produced in sealed landfills or in centrals, it is categorized according to the material used to produce it: when the raw materials are urban solid waste, then it is biogas. However, if it is made with a specific organic fraction, an outcome of several treatments made to the solid waste, then it is biologic digestion. The energy is then sold to the *Rede Eletrica Nacional* (in English, National electric network).
- Fertilizers: Obtained in specific centrals that treat urban solid waste, located in Aveiro and in Coimbra. Due to its specific proprieties, these fertilizers are usually used in agricultural processes.
- Refused Derived Fuel, RDF: This fuel is a result of a flow with high calorific potential, coming from waste treatment centrals when processing the urban solid waste. This flow is then treated and used as a substitute of fossil fuels in industries.
- Recycled Materials: Obtained from a sorting operation made to the waste collected from the ecopoints. These materials are sold to SPV, and afterwards transferred to recyclers.

The area where ERSUC operates is divided in 36 districts, covering all the area of the districts of Coimbra and Aveiro, and representing about 7.6% of the total area of Portugal, as seen in Figure 2.

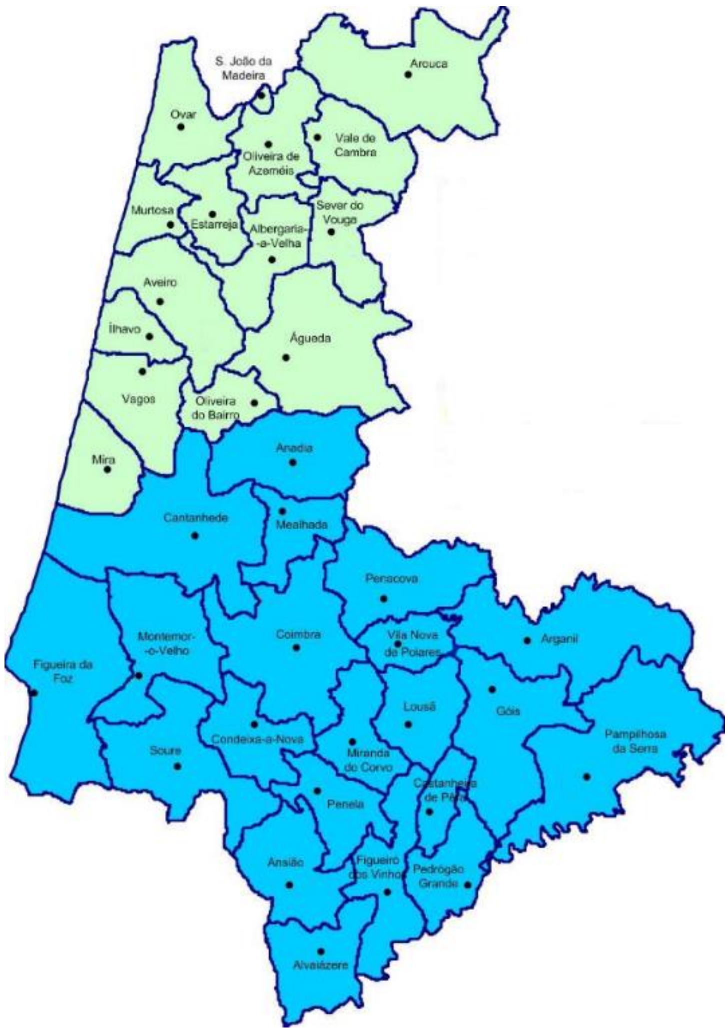

Figure 2:Area covered by ERSUC (Souce: ERSUC, 2018)

Regarding ERSUC´s operations, it is only responsible to collect waste that was previously separated by the citizens before its disposal, named selective waste. There can be distinguished two types of operations regarding selective collection: Door-to-door and drop-off. In door-to door operations, the company sends canvassing vehicles to specific areas located inside cities that possess abundant small commerce, for waste collection. This waste must be packed in 3 special bags that were distributed beforehand by commercial establishments: blue bags for paper/cardboard, yellow for plastic/metal packages and green for glass packages. This initiative can increase the quantity of selective waste recycled, despite the superior associative costs. Drop-off operations consists on sending waste vehicles to collect paper/card, plastic/metal and glass packages from waste containers spread over the company´s area of operation. This operation as well as the characterization of the containers will be explained further ahead.

In addition, waste that does not suffer this separation process is called undifferentiated waste, and its collection is performed by the districts. The waste is then transferred into specific infrastructures located inside ERSUC´s depots for treatment. All the different types of infrastructures will be described in the next section.

2.2.1 Infrastructures

The company´s infrastructure is presented in table 1.

Table 1: ERSUC´s type of infrastructure, quantity and location

Type of Infrastructure	Quantity	Location
Mechanical and Biological Treatment	2	Aveiro and Coimbra
Sorting Stations	2	Aveiro and Coimbra
Landfill	2	Aveiro and Coimbra
Water and Leach Treatment	2	Aveiro and Coimbra
Organic Valorization	2	Aveiro and Coimbra
Energetic Valorization	3	Aveiro, Coimbra, Figueira da Foz
Transfer Station	7	Ansião, Estarreja, Figueira da Foz, Góis, Ossela, Pampilhosa da Serra and Sever do Souga
Ecocenter	9	Ansião, Aveiro, Coimbra Estarreja, Figueira da Foz, Góis, Ossela, Pampilhosa da Serra and Sever do Souga

Each type of infrastructure has a specific purpose and all of them intend to maximize the amount of resources extracted from waste, whether it is undifferentiated or selective.

- <u>Mechanical and Biological treatment plants (MBT)</u> are industrial units where undifferentiated waste is treated in two major sequential processes: mechanical and biological. In the mechanical treatment the waste is separated into four different flows: organic matter, recyclable waste, RDF and refuse. In the biological treatment, the organic matter obtained from the mechanical treatment is transformed into fertilizing through specific treatments. Concerning the rest of the flows, they will be explained together with the other infrastructures.
- <u>Sorting stations</u> are specific locations where two of the three types of selective waste, paper/cardboard and plastic/metal, will suffer several operations for contaminants extraction. Once both types are contamination-free, they will be stored in warehouses. The other selective waste flow – glass – has a very low contaminant percentage, thus, it is only stored in warehouses.

- Landfills are locations where the refuse waste – waste that cannot be re-utilized – is eliminated. Due to environmental concerns, the refuse is carefully stored in containment cells, releasing water and biogas in the process.
- Water and Leach treatment units eliminate the contaminants from the water that exits from the biological treatments made to organic matter, and from the containment cells. Once contaminated-free, the water is used in the biological treatment.
- Organic Valorization units transform the RDF produced in the MBT´s mechanical treatment, into consumable fuel prepared according to specific industry requirements.
- Energetic Valorization units retain the biogas that exits the containment cells located in landfills, and transforms it into consumable energy.
- Transfer stations are specific areas where undifferentiated waste produced in areas located far away from the depots of Aveiro and Coimbra are deposited. Inside, the waste is properly prepared for transportation, and is transported in high capacity vehicles into the depots. These operations make the waste collection of the most distant districts more economically viable.
- Ecocenters are specific areas for selective waste disposal that have dimensions greater than the ones of selective waste containers.

2.2.2 Ecopoints

As mentioned, ecopoints are a set of three bins, differentiated by a specific color, that allows the disposal of the selective waste. Thus, one of the three bins is green and is designated for glass disposal, another blue for paper and cardboard, and the other yellow, for plastic and metal. This 3-container set is placed among specific locations where ERSUC sees potential demand for each bin. However, the company can choose to place single selective waste bins, instead of ecopoints, whenever the demand does not exist for all the three types. The total number of containers are 13625, 5324 of them green, 4166 blue and 4135 yellow.

Figure 6 indicates the number of ecopoints and single bins presented in each district.

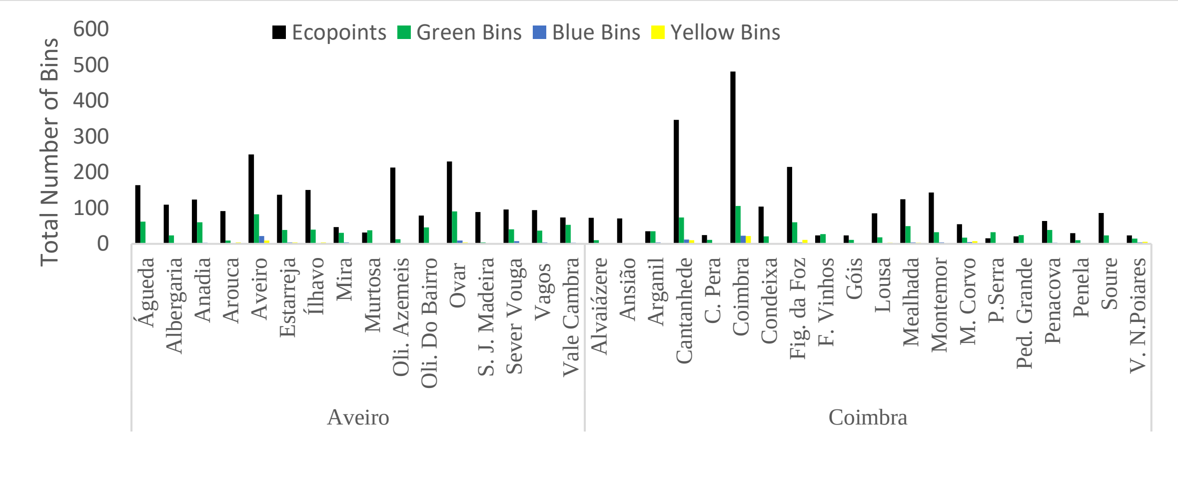

Figure 3:Number of ecopoints, green, blue and yellow bins in each district

As can be seen in Figure 3, the districts with the highest number of waste bins are Coimbra, Cantanhede and Aveiro, representing approximately 27% of all ERSUC´s waste bins. On the contrary, Mira, Murtosa, Arganil, Castanheira da Pera, Figueiró dos Vinhos, Gois, Pampilhosa da Serra, Penela and Vila Nova de Poiares only represent a 6% of ERSUC´s total bins. This discrepancy is due to differences in populational density (for example, Coimbra has 449 habitants per km^2, while Gois has 11.3 habitants per km^2) and area covered (Cantanhede covers almost 400 km^2 while Murtosa only 74 km^2). Additionally, it can be noticed that the number of green bins out scales the number of blue and yellow bins. Such is due to, firstly, because there were already some collection operations performed by districts. Therefore, a number of green bins were previously placed before ERSUC was in charge. Secondly, since recycling glass was a habit, especially in rural zones, green bins were even more reinforced by the company.

Figure 4 shows the geographical distribution of waste bins throughout the area covered by ERSUC

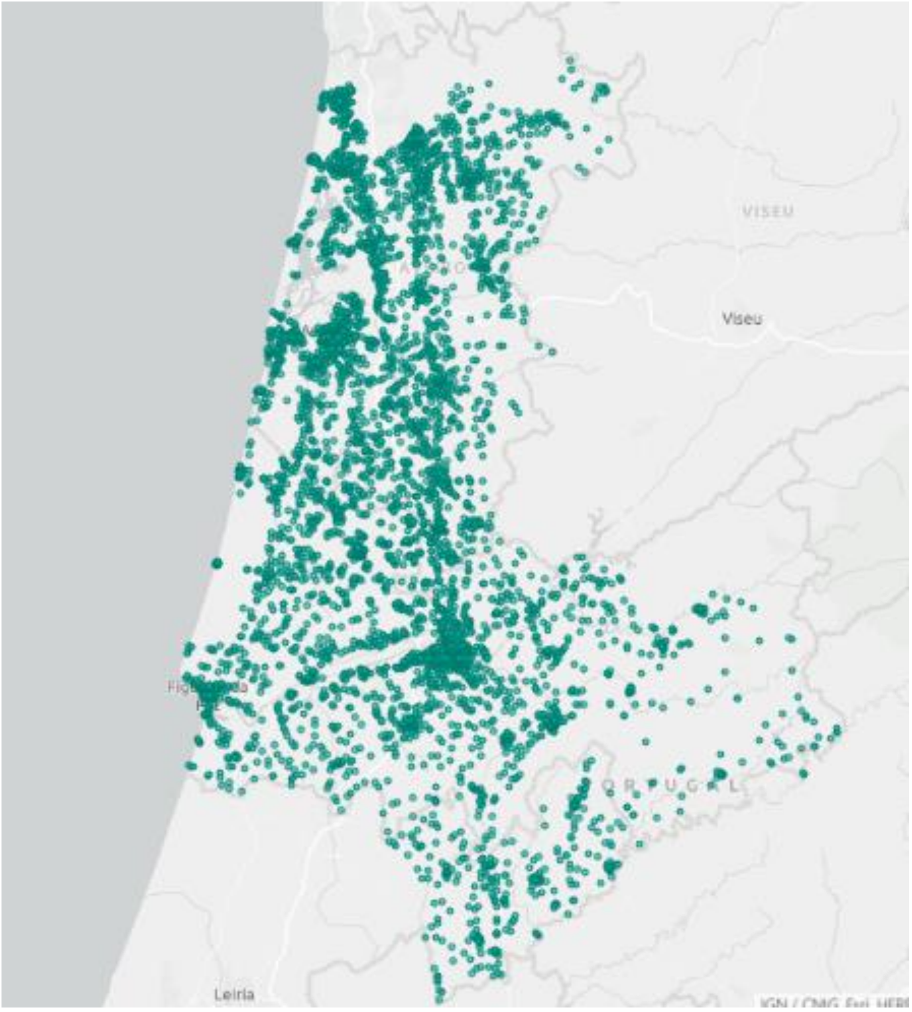

Figure 4:Waste bins location throughout ERSUC´s area of operations

2.2.3 Waste Collection Vehicles

ERSUC currently owns 30 selective waste collection vehicles, 16 of them are based in Aveiro and the rest in Coimbra. Table 2 specifies the vehicle´s characteristics in Aveiro. Appendix 1 contains the vehicle´s characteristics in Coimbra for further interest.

Table 2: Brand, acquisition year, typology, registered tare, weight capacity and volume capacity of waste collection vehicles

District	Brand	Acquisition Year	Typology	Registered Tare (kg)	Weight Capacity (kg)	Volume Capacity (m3)
Aveiro	Volvo	1999	Cargo net	11360	7640	28
	Volvo	1999	Cargo net	11360	7640	28
	Volvo	1999	Cargo net	11360	7640	28
	Volvo	2002	Electric System	11700	7300	28
	Volvo	2002	Electric System	11920	7080	28
	Volvo	2002	Electric System	11840	7160	28
	Volvo	2002	Electric System	11780	7220	28
	Volvo	2002	Electric System	11940	7060	28
	Volvo	2002	Electric System	11780	7220	28
	Scania	2009	Cargo net	11280	7720	28
	Scania	2009	Cargo net	11220	7780	28
	Scania	2009	Compactor	14140	4860	22
	Scania	2009	Compactor	13980	5020	22
	Scania	2010	Compactor	14120	4880	22
	Scania	2010	Compactor	13980	5020	22
	Scania	2010	Cargo net	11320	7680	28

There are three different typologies of vehicles that can be identified in the table 2: vehicles with cargo net, electric system or compactor. Both the cargo net and the electric system cover the top of the vehicle and its purpose is to avoid spreading any waste during the collection operation. However, the difference between them is that the electric system is easier to handle than the cargo net, which requires a manual process. The compactor is used to allow a better use of space inside the vehicle, by increasing the density of the materials deposited in it. Vehicles with compactors do not collect glass since this material does not require such process. Furthermore, this system occupies space inside the vehicles, which decreases the vehicle´s volume capacity: thus, all vehicles with compactors only tolerate waste until 22 m^3 of volume, instead of 28 m^3.

The fuel consumption of the vehicles ranges between 37 l/100km and 48 l/100km.

2.2.4 Routes

ERSUC has 262 pre-defined routes for selective collection that are delimitated by districts, 108 routes to collect glass and 77 to collect paper and plastic respectively. Additionally, all routes are closed, meaning that the vehicles start and end their route at the same depot (Aveiro or Coimbra).

The information in table 3 indicates the route´s frequency for each material during the full year of 2017.

Table 3:Average, maximum, minimum number and standard deviation of route frequency

	Frequency			
Material	**Average**	**Max**	**Min**	**Stand Dev**
Glass	18	26	13	2
Paper	5	8	2	1
Plastic	6	15	3	2

The frequency indicates the time interval between routes for each type of material. The highest average number belongs to the glass collection routes, with a time interval of 18 days. Paper is collected with an average time interval of 5 days and plastic with 6 days. Glass routes also hold the maximum time interval of days, 26, whereas the minimum interval belong to paper, with a 2-day interval.

Table 4: Average, maximum, minimum and standard deviation of the number of bins per route

	Number of bins			
Material	**Average**	**Max**	**Min**	**Stand Dev**
Glass	48	74	29	41
Paper	47	68	16	38
Plastic	46	69	12	41

Regarding the number of bins collected in the routes, presented in table 4, the numbers are quite similar for all three materials, in 2017. However, the standard deviation attains substantial values. Such happens because of the difference between the number of bins located in each district, as shown in chapter 2.4, and by the fact that each route is defined within each district´s boundaries. This discrepancy also explains the vast differences between the maximum number of bins collected in a route, and the minimum, for each material.

Table 5: Average, maximum, minimum and standard deviation of the amount of waste collected per route

	Waste collected (kg)			
Material	**Average**	**Max**	**Min**	**Stand Dev**
Glass	5991	7700	1854	1193
Paper	1173	1932	728	1854
Plastic	1091	1563	676	728

Table 5 indicates the quantity of selective waste collected per route during 2017. The average quantity of glass collected, 5991kg, is far superior to both paper and plastic, that present values of 1173kg and 1091kg. Glass additionally was the maximum quantity collected in a route, nearly achieving the maximum weight capacity that the vehicle with the maximum hold value, which is 7780kg from the 2009 Scania with cargo net. The reason is due to the differences in the density of the materials, where glass´ density is 244kg/m^3, while paper is 40kg/m^3 and plastic 30kg/m^3. The route with the minimum amount of waste collected belongs to plastic with a mere value of 676kg.

Table 6: Average, maximum, minimum and standard deviation of the distance travelled per route

	Distance Travelled (km)			
Material	**Average**	**Max**	**Min**	**Stand Dev**
Glass	122	263	64	7
Paper	125	242	58	9
Plastic	122	263	64	7

Information about the distance travelled by the vehicles while performing the routes in 2017 is displayed in table 6. The highest average route distance travelled is 125 kilometers to collect plastic. Additionally, collection routes for plastic and paper have an average distance of 122 kilometers. Furthermore, the maximum distance in a route goes to the collection of glass and plastic, with 263 kilometers, and the minimum distance was to perform a paper route, with 58 kilometers.

Nonetheless, what really stands out is the difference between the maximum and minimum distances the routes have among all three materials - in the best-case scenario, this difference is 184 kilometers. This happens because districts that are located far away from the depots require a substantial amount of kilometers travelled just to visit the first container of a route and a substantial amount to return to the depot once the last container has been visited.

Concerning the duration of the routes, the ones performed nearby the depot can last around 2,5 hours, value that increases along with the distance between the set of bins to collect and the depot, and the number of total bins to collect, until a maximum time of 6 hours 40 minutes. The routes can be executed from Monday to Saturday, in two different shifts:

- **Shift 1**: Starts at 6 a.m. and finishes around 12 a.m.
- **Shift 2**: Starts at 2 p.m. and finishes around 8 p.m.

2.2.5 Description of the collection operation

The collection operation is a standardized process applied to all routes, covering the 36 districts where ERSUC can operate. Figure 5 below demonstrates the process flow diagram of the operation.

The operation begins with the person in charge deciding which route to perform, the required vehicle and its driver. All routes were previously established, are performed periodically, and are static - there is no possible modification, no matter the fill-level of the waste bins. Additionally, the vehicle used differs if the collection is for paper and plastic, where a compactor is required, or if it is for glass collection, where it is not.

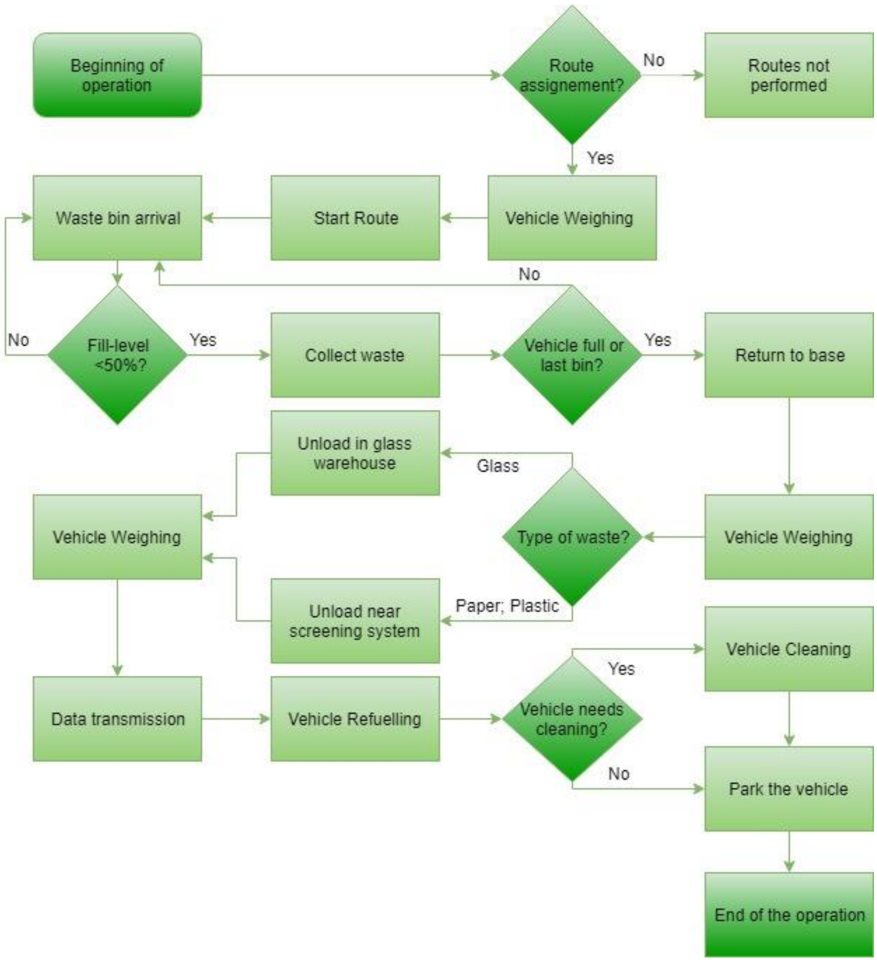

Figure 5:Flow diagram of the collection operation in ERSUC

The vehicle´s initial weight is recorded, and the route starts. Upon arrival to the first bin, the driver steps out of the vehicle and checks the fill-level of all the containers (if the route is to collect glass, for example, the fill-level of paper and plastic bins are also assessed). If the container that belongs to the route has a fill-level equal or higher than 50%, then the driver equips the cradle to the container and extracts the waste. However, if the fill-level is lower than 50%, waste is not extracted to save time. In most routes, saving time is important to avoid the need to return to depot without visiting all containers, since most of the routes cover a substantial number of containers, and the shift only lasts a maximum of 6 hours 40 minutes. Before moving to the next container, the driver registers the fill-levels of all the bins checked in a Personal Digital Assistant (PDA).

Once the vehicle is full or the route completed, the driver returns to the depot, where the vehicle is weighted once more. If the waste collected is paper or plastic, then it is unloaded into a screening system. However, if it is glass, due to its low percentage on contaminants, it is unloaded in a glass storage.

Then, due to problems in the system, the vehicle´s weight is checked once more, it is compared to the initial value (taken before the vehicle left the depot), and it is refueled. Afterwards, the driver registers information into the PDA, such as the amount of waste collected, the amount of fuel needed to refill the vehicle, and the total distance travelled. This information together with the fill-level percentage of each container is transmitted into an informatic system. Finally, the vehicle is cleaned only if it needs to, and parked.

2.2.6 Limitations of the Operation

The company suffers from some limitations in the collection operation preventing them from achieving maximum efficiency. The purpose of this thesis is to identify them and study alternatives to mitigate or, if possible, eliminate these concerns. The identified limitations are:

i. **Extensive covered area**

As mentioned before, the company´s area of operation covers 36 districts, which represents 7% of the Portuguese territory. Therefore, the drivers that are assigned to routes located far away from the depots must travel a substantial number of kilometers only to arrive at the first bin. This activity results in fuel expenses and time wasted without even having collected any waste.

For a reader´s better understanding, to perform the glass collection route in Pampilhosa da Serra, the vehicle must depart from the depot in Coimbra and travels 90 kilometers just to arrive at the first container.

ii. **Geographic position of the ecopoints**

The entities responsible for the location of the containers are the districts, whose main concern is only focused in necessities of the final consumer, who deposits the waste. Therefore, the containers located in narrow streets, one-way streets, urban areas with constant traffic or rural areas with difficult access make the waste collection process more troublesome since the time required to collect the waste from the bin increases.

iii. Working hours

The maximum amount of working time for drivers is 6 hours and 40 minutes, thus, all the routes must be performed within this time period. However, due to the huge amount of containers to collect per route, their poor geographic location and the extensive area that often needs to be travelled, the drivers are in a constant hurry to attempt visiting all the bins. Therefore, when the driver does not visit some of the containers, the waste overflows and it is only collected the next time the route is performed.

iv. Sequence of the containers visited in the routes

The first routes developed contained a set of bins that were located in a specific area. Yet, as the years passed, several containers were added or removed, and the routes have not been correctly adapted to these modifications. This situation results in routes that not only cover one area, but also parts of others, increasing the distance a driver has to travel to do the route.

v. Frequency of the routes

Route frequency suffers the same problem as the limitation mentioned before: it has not been adapted properly to any changes, which in this case, are the result of modifications in consumption patterns and in the total quantity of containers. Therefore, waste collection routes still have static frequency that is based on ancient data regarding the fill-level of each container.

vi. Amount of waste collected in the routes

Table 7 indicates the fill-level percentages of the containers registered during the collection operations made throughout the year 2017.

Table 7: Percentage of the container according to their fill-levels registered in the waste collection operation

Fill level percentages of collected bins					
<25%	**25%**	**50%**	**75%**	**>75%**	**Total**
7.6	39.15	27.3	21,65	4.3	100

Only 4.3% of the containers were visited with a fill-level over 75% and the majority of the containers (66%) are visited with a fill-level between 25% and 50%.

Considering the extensive area of ERSUC, this information means that vehicles travel hundreds of kilometers to collect very few amounts of waste. Economically speaking, this represents a huge amount of costs associated to the actual benefit that is being withdrawal.

2.2.7 Proposal of alternative scenarios

Given the limitations observed in the current operation of ERSUC, the ones that have the most impact on the operation´s efficiency are the frequency, sequence of the containers visited, and the amount of waste collected in the routes. Therefore, a set of scenarios will be proposed, for its elimination.

Scenario 1: Frequency optimization

The first scenario will propose new route´s frequencies using the historical data from the company. It can be considered an intermediate approach, since only the frequency of the routes will be optimized. The amount of waste collected will still prevail as a concern.

Scenario 2: Route optimization with sensors

The second scenario will assume that the information on the container´s fill-levels will be known at the beginning of each day and use it to propose new collection routes. Therefore, uncertainty regarding the container´s fill-levels will be eliminated. In addition, since these new developed routes intend to optimally reduce the costs while increase the amount of waste collected, it will be defined for each route the visiting sequence of the containers. Moreover, the routes will only be performed whenever a real necessity is presented, and not according to a stipulated frequency.

2.3 Problem Description´s Conclusions

ERSUC has a set of infrastructures located in the districts of Aveiro and Coimbra. Regarding its collection operation, the company has 30 vehicles, 16 located in Aveiro, and 14 in Coimbra.

The vehicles collect waste from the waste containers placed along the 36 districts covered by ERSUC´s area of operation. The bins are divided according to the type of waste: from the 13625 bins, 5324 are for glass disposal, 4166 for paper/cardboard and 4135 for plastic/metal.

Furthermore, ERSUC has 262 static routes for waste collection, 108 for glass and 77 for paper/cardboard and plastic/metal, respectively. In terms of average frequency, routes for glass collection present the highest value, with an 18-day interval between each route. Additionally, the values regarding the number of bins collected are almost the same for each, however, the standard deviation stands out due to the substantial discrepancy between the number of bins each route can have. Moreover, the fill-level percentage of the containers registers values under 50% in almost 74% of the containers.

Once the operation analysis was concluded, its constraints were identified. Among all, the sequence of the containers visited, the frequency of the routes and the unknown amount of waste contained inside bins are considered the ones with higher impact. Nevertheless, the extensive area of operation, geographic position of the ecopoints and the maximum amount of available work hours are limitations that must also be taken into account when attempting to develop alternative scenarios.

Therefore, to mitigate these limitations, two alternative scenarios were proposed to be further studied: the first scenario will propose new route´s frequency with the historical data presented by the company. It can be considered an intermediate solution, since it does not solve two of the three critical limitations, which are the visiting sequence and the uncertainty regarding the container´s fill-level.

The second scenario will attempt to optimize collection routes through real-time information regarding container´s fill-levels. Therefore, all the critical limitations can be eliminated and maximum benefits while costs diminished can be achievable.

3. Literature Review

3.1 Solid Waste Management

Solid waste (SW) is any solid or semi-solid material that no longer presents value or use to an entity responsible for its production, transformation or consumption (OECD, 2001). According to its production location, it can be divided in 3 categories: municipal waste (waste produced by households, commerce, institutes, construction and demolition companies and municipal services), industrial waste and agricultural waste. Solid waste management (SWM), however, can be defined as plans and plants built for the disposal of waste, through recycling, reuse, composting and incineration. Therefore, SWM deals with the waste from its source generation until its disposal, including all necessary operations and waste transformation (Badran & Haggar, 2006).

Since the last decade of the 20th century, EU regulations have been created to develop an efficient SWM. These regulations state, for example, requirements for the development of a specific network design, allowing member states to be self-sufficient regarding waste recovery, and establishing a minimum percentage for the reuse and recycle of the total waste production (EU, 2012). The objective is to confront global concerns like the enormous global waste production (according to Hoornweg (2012), waste generation in 2010 was approximately 1.3 billion tons) and resource scarcity (Pires, 2010: Jouhara, 2017).

One of the literature focus is directed to the SWM´s waste collection operations, since it was proved that its associated costs can represent 80-90% of the SWM´s budget in low income countries, and 50-80% in middle income countries (Das et al, 2015). Thus, any method that brings down this cost can produce a huge impact on the total WM´s budget.

According to Bing et al (2016), the main issues when planning an efficient SWM´s logistic operation can be divided in:

- Deciding what type of waste container to use: curbside or drop-off container. The most popular collection sites are the traditional curbsides, such as thrash cans or plastic bins. The drop-off are specific central collection points filled with waste brought by the community. This decision must be made according to what type of collection site can provide the biggest amount and quality (i.e. lower percentage of contaminants) of waste.
- Deciding what type of waste collection vehicles to use: Usually, rear loaded vehicles are used in curbside systems, while top loaded vehicles are used in drop-off systems. Additionally, vehicles can have pressing functions for increasing capacity, and also multi-compartments for collecting more than one type of waste.

- Deciding which organization will be collecting the waste: Oftentimes, the organizations selected are the districts, responsible for the waste collection in each correspondent area. In Portugal, however, municipal waste collection companies, called SMAUTs, can be multi-municipal, inter-municipal, or private organizations oftentimes. Moreover, these organizations also have to determine the routes for the waste collection vehicles, and the frequency of collection, which can be a serious challenge due to its complex nature.

There are numerous approaches concerning the determination and optimization of vehicle routes and collection frequency. Mathematical programming is often used, and some even include ICTs (Information and communication technologies) for an improved decision support system. The next chapter will describe the ICTs employed in waste collection, followed by a chapter dedicated to vehicle routing problems.

3.2 Application of ICTs in SWM

Information and communication technologies (ICTs) can be described as the set of technologies that aid in capturing, processing and communicating information. ICTs provide instant access to information from remote locations, at a very low cost, while having the capability of analyzing huge amounts of data. Thus, ICTs can be solution to many limitations of SWM systems, like deciding the site selection, lack of collection monitoring, improved intelligent recycling and the reduction of waste disposal (Hannan et al, 2015).

According to Melaré et al (2016), the main SWM areas where ICTs can have a positive impact are: management of collection, route and transport: management of monitoring containers: Recycling of solid residues: public administration and sustainable development: forecasting and planning methods: and determination of waste disposal sites. Since, as mentioned, SWM logistics' present the biggest costs, and its optimization can be considered a challenge, its ICTs application will be the central focus.

The more frequently employed ICT in SWM logistics´ is geographical information system (GIS), defined as software information system that provides the ability to collect, manage, integrate, manipulate, analyze and display geographically referenced data in a form of digital map. In most cases, GIS is combined with geographical positioning system (GPS), which is a global navigation and localization system based on the position of numerous satellites and ground stations that provide accurate orbital and time information. These ICTs give support for the design of waste collection routes and monitoring waste collection vehicles (Hannan et al, 2015: Melaré et al, 2016).

Other employed ICT is the radio frequency identification (RFID), based on radio waves for automatic identification or tracking of objects. An RFID system consists on 3 components: an RFID tag, that is placed in the object (for example a container or vehicle) and has a unique serial number for recognition: an RFID reader that can scan the tag and access the information in it: and a host (usually a computer) that displays the information provided by the tag. RFID provides the ability of monitoring the waste collection vehicles when they reach the containers, and reduces the driver´s responsibility through the automation of some manual processes. (Hannan et al, 2015)

Furthermore, some ICTs can be used for container quantity and quality estimations. Thus, a detailed report of the container´s weight, capacity, temperature, humidity, pressure and waste type can be identified, to support decisions like which set of containers should the vehicles empty. Such can be achieved with the application of sensors and image processing. The first one can be stated as devices that perceive and measure numerous features that define an object. These features are then converted into signals and transmitted to a device that can read and display the information. The second can be defined as the set of activities that capture, store, manipulate and display images. The image data can be captured through different devices, such as cameras, scanners or video surveillance (Hannan et al, 2015)

Lastly, data communication ICTs can also be employed for transferring data from containers or vehicles, to central servers, for information analysis. The most used ICT are the global system for mobile communication (GSM), and the general packet radio service (GPRS), defined as networks for wireless transition of information, however, GPRS can be considered an upgrade of GSM, since it can transfer higher quantity and quality data.

All these ICTs present good performance when used separately, however, if used together, unlock their true potential through a full control on the time spent by each vehicle and planned routes according to roads, containers and recycling treatment plants (Melaré et al, 2016). In the next chapter some of the mathematical approaches that are used in SWM´s logistics will be mentioned.

3.3 Vehicle Routing Problem (VRP)

The Vehicle Routing Problem (VRP) can be stated as the design of the least-cost delivery or collection routes from one depot to multiple customers located at a specific geographic area, in such way that one customer is visited only once by one vehicle and all routes start and end at the depot (Laporte, 1992). Its roots come from the Travelling Salesman Problem (TSP) (Dantzig et al, 1954), only considering the optimization of one vehicle route (instead of multiple) to supply all customers.

The VRP approach has been very successful when reducing costs associated to logistics, so, throughout the years, many computational algorithms were developed to solve it. These can be classified into exact, heuristic and metaheuristic: Exact algorithms find optimal solutions to the problem: however, they can only be applied when there is a limited number of vehicles and customers, otherwise the solution can take too long to obtain, or, when found, it may not be feasible. The most popular exact algorithms are the branch-and-bound and branch-and-cut, that consist on finding the optimal solution in a set of candidate solutions using estimated lower and upper bounds to achieve the optimal solution (Cordeau, et al, 2007).

Heuristic algorithms are applied in more complex VRP´s, presenting feasible solutions without requiring a lot of computational time. Two examples are the savings algorithm (Clarke & Wright, 1964) and the sweep algorithm (Gillet & Miller, 1974). The first one, starts from an empty solution and iteratively builds routes by inserting one customer in each, until there are no customers left. Then, it calculates the estimate cost reduction obtained by serving two customers in one route instead of only one. If it exists, then this route replaces the previous two. The process continues, and more customers are grouped in routes that have customers already on it, until the algorithm maximizes the cost reduction. The second heuristic starts with assigning one vehicle to a random customer, then, it groups more customers into the vehicle route according to their polar angle with respect to the depot and the initial customer. When the route is full, the algorithm creates another empty route, and starts again, until all customers are assigned to a vehicle.

Metaheuristics algorithms also find feasible solutions to the problem and do not require high computational times, however, they do not have the inconvenience of obtaining local optimum solutions, that is, an optimal solution found only between a set of feasible solutions, and not all of them, like heuristics sometimes reaches. An example of metaheuristic algorithm is Tabu search, that starts with an initial solution, and proceeds to perform a local search exploring the solution space to find a better solution in the neighborhood. If it finds one, the new solution is inserted in a memory, called tabu list, and the algorithm continues the local search without performing any iteration that allowed it to find the new solution (Glover, 1974). Other examples of metaheuristics are the ant colony optimization, based on the behavior presented in ants once they find food, and simulated annealing, based on a metallurgic process (Cordeau et al, 2007).

3.3.1. Applications of VRP in SWM

The first VRP-based application to municipal solid waste was done by Beltrami & Bodin, (1974), introducing one of the VRP variants, the Periodic Vehicle Routing Problem (PVRP). The PVRP differs from the VRP because it assumes a different frequency of visit from customer to customer (for example, some are visited on a daily basis, and others, weekly). Since then, numerous applications are stated in literature and some will be mentioned.

Kim (2006) addressed a VRP variant that considers that each customer has a specific time window [x, y], to be visited, called Vehicle Routing Problem with Time Windows (VRPTW). In the VRPTW vehicles can arrive earlier than hour x in the day, and wait until the customer is available, but can never arrive after hour y. The VRPTW was employed to a real-life case with multiple disposal sites and collection vehicles so route compactness (vehicles routes with a smaller number of crossovers among them) could be increased and workload could be equal between all vehicle drivers. The author also considered driver´s breaks to lunch during a 3hour time period.

Benjamin & Beasley, 2010, also considered a VRPTW model to solve a problem with multiple waste disposal facilities, and multiple vehicles for waste collection. The vehicles leave the depot and collect waste until they get full and must be emptied in the nearest facility. Then, they continue their pre-determined routes until all waste is collected and must return to the depot empty at the end of the day. The algorithm employed is a heuristic that clusters a customer to its neighbors with similar time windows and attempts to create a vehicle route taking into consideration its capacity. Rodrigues & Ferreira (2013) also tried to solve the same type of problem in Monção, Portugal, with the difference that the numerous disposal facilities all over Monção have different capacities, and some are so small that is only permitted a limited number of times the disposal of the waste contained in a vehicle. The authors considered this problem as a Mixed Capacitated Arc Routing Problem with Limited Multi-Landfills (MCARP-LML), a VRP variant that assumes constraints in the waste collection vehicles capacity, one-way roads, and multiple depots with limited capacities for waste disposal. According to the authors, this last factor increases the level of complexity of the problem since in some cases the vehicles wishing to dispose the waste in the nearest disposal site cannot do it if they have already emptied in that site the number of times they were allowed.

Ramos et al (2014) considered a VRP variant to solve a problem for selective packaging waste collection with multiple types of waste, vehicles and disposal facilities. In this problem, three different types of specific waste bins are scattered around a given area, and routes are designed to collect waste from only one type of bin and transfer it to disposal facilities. The model used to approach the problem was the multi-product, multi-depot vehicle routing problem (MP-MDVRP), with focus on economic and environmental factors. The results show a decrease in the total distance travelled and in the CO_2 emissions produced by the vehicles.

Nevertheless, Lee et al (2016) developed a mathematical model for scenario analysis regarding all waste management in Hong Kong, since efficient measures have not been applied yet in the city. Moreover, Simonetto & Borenstein (2007) modelled and implemented a decision support software system named SCOLDSS using integer linear programming to solid waste management in Porto Alegre, Brazil, to determine the vehicle routes, the amount of each type of solid waste to be sent to each sorting facility, increase the city´s recycle rate, decrease the quantity of waste sent to landfills and avoid waste of labor force.

All the mentioned applications suppose that some information about the quantity of waste in each bin is deterministic, and routes were designed according to that assumption. However, Nuortio, (2006) mentioned that this information is stochastic, rather than deterministic, and depends of numerous factors such as number of habitants in a region or time of the year. This means that some routes can cause wastage of resources if the vehicle travels to a set of empty bins, thus collecting few or no waste, or some bins can already be completely full before the scheduled day for waste collection. Such issue, together with others like the lack of vehicle control and a geographical digital map, can produce serious impacts in the final design of the vehicles 'routes. Therefore, the implementation of the ICTs allows real-time information of bin status and truck position to minimize the number of vehicles, save travel distance, reduce fuel consumption, labor cost and operation time (Hannan et al, 2018).

Although the literature for applications of ICTs in waste management is scarce, some examples will be quoted above. One of the first applications regarding the importance of considering real-time information was mentioned by Johansson (2006) that evaluated three different scenarios in Malmoe, Sweden. The first scenario considered static scheduling and routing, where routes were fixed, and data was assumed to be known: the second scenario presented dynamic scheduling and routing, where information was stochastic and the collection of the containers happened only when they were full: and the third scenario with dynamic scheduling and routing, where the collection of the containers happened when they were almost full. The author proved that in order to optimize the vehicle routes, the information must be considered stochastic.

Three years later, Vicentini et al (2009) performed a route optimization in a companies' waste collection operations considering information such as overall cost, weight of waste and road distance and its condition, using sensors on waste containers. An ultrasonic distance sensor was placed at the top and reported the shape, area and height of the materials placed in the container, and when the container was full, the sensors sent the data to a central base with a signal warning the need empty the container.

Faccio et al (2011) performed an optimization of the waste collection routes of a city in Italy, with homogeneous and variable fleet size and a single depot, applying volumetric sensors to identify the bins filling, RFID tags for identification of the bins and trucks, and GPS for monitoring the vehicle´s position. In this model, during a developed route, every time a bin is emptied the RFID tag in the bin communicates to the vehicle its identification number and waste type that it contained. Then, the vehicle communicates to an operations center the weight of loaded waste contained in the bin, the bin identification and its available capacity, if it still has one. The operation center receives the information, processes it, and if the vehicle still has capacity, sends information regarding the next bins the vehicle must visit, according to the route model.

Longhi et al (2012) created a sensor-based model with data from the bins filling to improve the on-site handling and transfer optimization in waste management. Each sensor transfers data to a server and the server decides the shortest path for the waste collecting vehicle using has decision parameters the quantity of waste in each bin and the vehicles´ estimated capacity. In the same year, Anghinolfi et al (2012) designed a set of routes to be applied in the waste management in the city Cogoleto, Italy, where everyday routes are planned according to the quantity of waste in each bin and the quantity of waste collected during the day, provided by the information given by sensors and RFID tags placed in the bins and trucks respectively.

More recently, Gutierrez et al (2015) analyzed the potential benefits of setting volumetric sensors in bins located in Copenhagen, Denmark, for continuous knowledge of waste volume information inside the bins. The results indicate that the efficiency improvement created by the volumetric sensors drastically reduce the percentage of bins with waste overflow in the city.

According to Ramos et al (2018), the route design with application of volumetric sensors in containers to obtain their fill rate cannot be made through classical VRP, since decisions about what containers to visit must be made depending on its "attractiveness" (i.e. their fill-level). Therefore, the authors built an innovative mathematical approach supported with Vehicle Routing Problem with Profits (VRPPs) that finds the set of containers to be visited each day and which visit sequence that maximizes profit while satisfying the capacity of the vehicle, the route´s length and the bin´s capacity. The profit is the result of the difference between the revenues obtained from selling the waste collected to recycling entities minus the transportations costs of extracting it from the containers.

Due to this work, a more extensive approach to VRPPs will be made in the next section

3.4 Vehicle Routing Problem with Profits (VRPPs)

Vehicle Routing Problem with Profits (VRPPs) is a variation of the classical VRP where logistics costs and customer profit are taken into account when defining the routes. Therefore, two decisions must be taken: determine which set of customers to visit and design vehicle routes to visit each selected customer. The customer´s attractiveness depends on its potential profit associated and how far it is from the vehicle. In this problem each vehicle starts and ends in a depot, one or more vehicles are available to perform the routes, and there cannot be multiple visits to one specific customer during a vehicle´s route. The main constraints associated to VRPPs can be a time limit related to the duration of the route or a maximum total profit to be collected by the vehicles, established *a priori* (Archetti et al, 2013).

The main applications for VRPPs are: recruiting athletes from high schools (Butt & Cavalier, 1994), design tourist trips to maximize the value of the visited attractions in certain a period (Vansteenwegen & Oudheusden, 2007) or reverse logistics in a firm that aims to collect used products from clients (Aras et al, 2011)

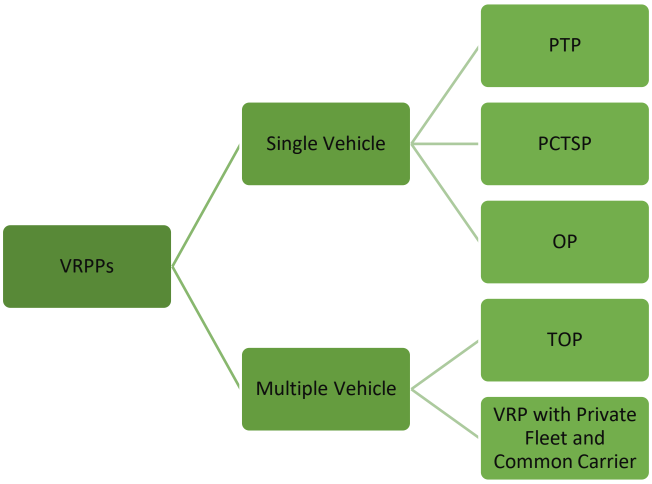

Figure 6:VRPPs categories

Due to the different applications of the VRPPs, multiple variations have been identified according to different scenarios (see Figure 6). These can be divided by single or multiple vehicle, since there is a major difference between solving a problem with a single route (associated to one vehicle) or numerous routes (each route associated to one vehicle). Regarding single vehicle VRPPs, the main subdivisions are: Profitable Tour Problem (PTP), Prize Collecting Travelling Salesman Problem (PCTSP) and Orienteering Problem (OP) (Archetti et al, 2013).

The PTP is the problem of designing a route that maximizes the difference between the total revenue and the total travelling cost, without imposing any additional constraint (Archetti et al, 2013). Due to its simple structure, neither exact or heuristic algorithms were specifically proposed for this problem, with an exception made by Dell´Amico et al (1995), who proposed a Lagrangian relaxation (method that turns complex problems into more simple ones) in a problem with up to 500 customers.

The PCTSP is the problem of obtaining a route that minimizes the total travelling cost with the constraint of collecting a profit that is specified *a priori*. Fischetti & Toth (1998), developed an exact approach to solve instances with up to 200 customers based on obtaining lower bounds using problem relaxations and then applying it to a Branch-and-bound algorithm. Additionally, a heuristic was created by Dell´Amico et all (1998), that starts from a lower bound and attempts to create a feasible solution, solving instances with up to 500 customers.

The OP is the problem whose objective function is the maximization of the total profit, constrained by a maximum duration and vehicle capacity. Chao et al (1996) defined the OP as a variant of the TSP. The authors presented an example where a salesman wanted to visit a set of cities, but since the time was limited, not all could be visited, so a selection of which cities to visit was made according to their potential profit. Golden et al (1987), pointed out that exact solution approaches would be very time consuming, so heuristics would be the go to whenever practical applications with multiple customers of the OP exist. However, Laporte & Martello (1990), created an exact algorithm based on branch-and-bound, but could only solve instances with less than 20 customers. Furthermore, Gendreau et al (1998a), mentioned the difficulty of finding acceptable heuristic algorithms for the OP. The authors stated that the profit of a customer and the time to reach it present no correlation, which makes the selection of the customers very complicated. Nevertheless, there are many heuristic algorithms that can provide feasible solution. Tsilligirides (1984) was one the first to create a heuristic approach to the salesman example mentioned above, proposing stochastic and deterministic algorithms (S-Algorithm and D-Algorithm respectively). The first one generates routes according to the customer´s profit and its distance, and selects the best one, whereas the second algorithm is based on a center-of-gravity heuristic where routes are created by inserting customers and are improved afterwards, then, a new path is obtained by ranking the customers according to their profits and distance to the center of gravity from previous routes. More recently, Campos et al (2013) proposed a heuristic based on the Greedy Randomized Adapted Search Procedure, that showed good computational results and quality solutions.

Multiple vehicle VRPPs are substantially more difficult to solve than single vehicle VRPPs, since the design will now be for multiple routes, instead of only route. Multiple vehicle VRPPs can subdivided in: The VRP with Private Fleet and Common Vehicle, and Team Orienteering Problem (TOP).

VRP with Private Fleet and Common Vehicle is applied when the objective is the minimization of the total cost, and decisions must be made regarding which customers will be served by the company´s private fleet, which will be served by an outsourcing logistics company (usually smaller than previous one) due to capacity constraints presented in the private fleet, and which customers will not be serviced due to negative profit. An example of an important application is in the context of Small Package Shipping (SPS) where in most cases customers are distributed in various areas. Large SPS companies outsource last-mile deliveries to small regional suppliers (subcontractors) when the areas to be serviced have very few customers and are far away (Archetti et al, 2013). VRP with Private Fleet and Common Vehicle was first introduced by Chu, (2005) considering a single depot with outsourcing options. The author proposed a simple heuristic based on a modified savings algorithm. Li & Lu (2014) applied VRP with Private Fleet and Common Vehicle to a logistics company with full truck loads and solved it with a modified savings and sweep heuristic combined.

The TOP is the problem of finding a set of routes, one per vehicle, that maximize the total profit given by a group of customers while satisfying a maximum time limit constraint. Its only difference to OP is that it considers multiple vehicles instead of only one. The first approach in this area was made by Butt and Cavalier (1994), naming it Multiple Tour Maximum Collection Problem, regarding the visit of a college to several schools for recruiting American football athletes.

Throughout the years TOP has been studied numerous times by different authors due to its many practical applications in companies' logistics areas. Therefore, different approaches to solve it were created. For starters, some exact algorithms were developed to find optimal solutions for TOP problems. However, considering TOP´s high complexity, few attempts had success. One example for exact algorithm was proposed by Boussier, et al (2007) by means of employing a Branch-and-Price algorithm, requiring less than 2 hours to solve instances with up 100 customers from the chosen set of customers. Moreover, metaheuristic approaches are widely used to produce feasible solutions in smaller computational times. Tang & Miller-Hooks (2005) developed a tabu search heuristic combined with an Adaptive Memory Procedure (AMP) that alternates between small and large neighborhoods during the search for a new best solution, outperforming all previous studies. Archetti et al (2006), proposed two tabu searches differing on exploring (or not) admissible solutions during the search for new best solutions, finding even better feasible solutions in each than the previous mentioned authors.

3.5 Literature Review´s Conclusions

In this chapter, a literature review was performed regarding SWM, vehicle routing problems and ICTs with applications in the SWM.

The model developed by Ramos et al (2014) was applied to a case study which can be considered similar to the case study of this thesis. The mathematical algorithm uses a VRP variant to optimize waste collection routes of a company using its historical data, and its results were satisfactory.

Additionally, recent advances in technology can allow an accurate real-time information display about the fill-levels of the waste containers. Such information, conjugated with a mathematical algorithm, has proven to potentially increase the efficiency of the operation. The major applications in waste management reported attempt to develop routes to collect the waste from the containers whose fill-level exceeds a previously established value.

However, the operation´s efficiency is still not completely optimized since the models used do not take maximum advantage of the real-time information given by the ICTs. Only recently Ramos et al (2018) developed a model that considers a different approach, through conjugation of VRPPs with real-time information: containers will be visited according not only to its fill-level, but to its “attractiveness”, in other words, the potential profit they contain, and its results have proven to take the operation´s efficiency up a notch.

Thus, if we take into consideration the critical limitations of ERSUC´s waste collection operation, which are the visiting sequence of the containers, route´s frequency and thee unknown amount of waste inside containers, then this model is the perfect fit to eliminate all of them. In one hand the limitations like visiting sequence and the frequency of routes will be dealt by using mathematical algorithm that focuses in maximizing the amount of benefits withdrawing from the routes while minimizing the associative costs of route performance will. On the other hand, the real-time information provided by volume sensors used in the model will eliminate any uncertainty regarding waste container´s fill-levels.

4. Models

4.1 Introduction

In chapter 2 the major limitations that impacted the efficiency of the waste collection operation were presented. Given the literature review (chapter 3), two solution approaches to mitigate such limitations will be implemented. In this chapter, those approaches will be described along with their required adaptations, in order to fit in with information given by the company.

The first approach that will be presented below is the Frequency Optimization approach. As mentioned before, ERSUC defines the route´s time interval using outdated data that does not contemplate the consumer pattern changes that occurred throughout the years. Thus, this approach attempts to eliminate one of the limitations of the operation – the route frequency – by calculating the optimum value that allows to collect the waste inside the bins while never surpassing the vehicle´s maximum capacity.

The second approach is the one proposed by Ramos et al (2018) to solve the Smart Waste Collection Routing Problem (SWCRP). In this approach, information about the fill level of each bin is received every day, and when, in a given day, at least one bin is expected to overflow, a VRPP model is solved for that day. The VRPP model defines the bins to be visited and the visiting sequence (the routes) that maximize the amount of waste collected while minimizing the distance travelled. This way, route frequency is also optimized.

4.2 Frequency Optimization

The Frequency Optimization approach is a heuristic that uses the company´s data regarding the routes performed during the year of 2017. More specifically, for each route, it uses:

- Dates of each performed route
- The amount of waste collected in each performed route, in kg:
- Maximum quantity that the vehicle can transport, in kg.

The heuristic then calculates the optimum frequency for each route iterations, while assuring that the quantity collected never surpasses the vehicle´s capacity limit. Such iterations permit finding an overall frequency, for each route, that reduces the total distance travelled in a year.

The heuristic is illustrated in figure 7.

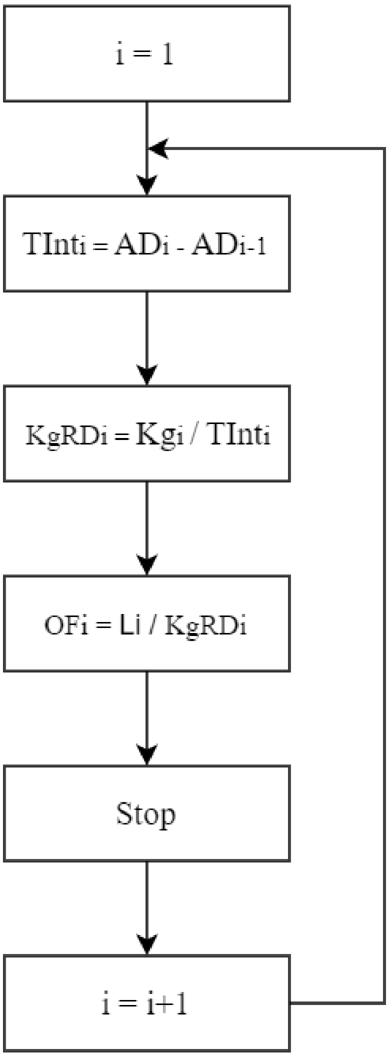

Figure 7:Flow chart of the frequency optimization model

As mentioned before, this heuristic is applied for each collection route and acts on each recorded time it was performed (*i*). Therefore, the first step is to calculate the time interval between routes ($Tint_i$). This time interval is calculated by subtracting the dates of route *i* (AD_i) and the previous one (AD_{i-1}). As an illustrative example of this step, Table 8 shows the routes performed in October 2017 of one of the routes in Soure, that collects paper/cardboard, and their time intervals ($Tint_i$):

Table 8: Time interval calculation for route Soure 1 paper/cardboard

Date	Waste Collected (kg)	$Tint_i$ (days)
28/10/2017	840	4
24/10/2017	1820	8
16/10/2017	860	6
10/10/2017	660	5
05/10/2017	1800	-

As shown in table 8, the time interval between the first and second routes performed in October is 5, and the time interval between the second and third is 6 days. This process is repeated until all the time intervals are found.

The next step is to compute the daily disposal rate of each route ($KgRD_i$). According to Nuortio, (2006), the daily waste disposal is considered stochastic, thus, this value variates between each route. The $KgRD_i$ is calculated dividing the waste collected by the time interval, for each route. Table 9 adds the $KgRD_i$ to the information in Table 8.

Table 9:Daily disposal rate calculation for Soure 1 paper/cardboard

Date	Waste Collected (Kg)	$Tint_i$ (Days)	$KgRD_i$ (Kg)
28/10/2017	840	4	210,00
24/10/2017	1820	8	227,50
16/10/2017	860	6	143,33
10/10/2017	660	5	132,00
05/10/2017	1800	-	225,00

Therefore, in table 9 the different values in $KgRD_i$ indicate how much waste is deposited daily in all the route´s bins, during the time interval of two consecutive routes. Therefore, in the last route performed in October (28/10/2017), the daily disposal rate was 210 kg/day during 4 days, resulting in the 840 kg of paper/cardboard collected in the route.

The last step of the heuristic is to calculate the route´s optimum frequency (OF_i), given the vehicle´s maximum weight capacity (Li). To compute the OF_i, Li is divided by the daily disposal rate for each route ($KgRD_i$). The OF_i then is time interval that it should had had in order to collect the maximum amount of waste the vehicle can hold, while travelling the same distance. Table 10 adds the OF_i to the information pool, considering Li = 2200 kg.

Table 10:Collection route´s data for Soure number 1 paper/cardboard collection

Date	Waste Collected (kg)	$Tint_i$ (days)	$KgRD_i$ (kg)	OF_i (days)
28/10/2017	840	4	210,00	10
24/10/2017	1820	8	227,50	9
16/10/2017	860	6	143,33	15
10/10/2017	660	5	132,00	16
05/10/2017	1800	8	225,00	9

Table 10 shows the different optimum frequencies for each performed route in October. By finding all the optimum frequencies for each route, the overall frequency for the route can be found as the minimum value of all the OF_i. Thus, the stipulated time interval allows to find an improved frequency that assures that the vehicle´s maximum capacity never gets surpassed. In the case of the example given, the overall frequency of the route 1 for Paper/Cardboard in Soure is 9 days.

4.3 Smart Waste Collection Route Problem (SWCRP)

The second approach that will be applied is the one developed by Ramos et al (2018), the Smart Waste Collection Routing Problem (SWCRP), that considers the real-time information about the bins´ fill-level to determine the number of bins to visit (if any) and the best visiting sequence.

In an ideal setting, the real-time information regarding the fill-level is given by volumetric sensors placed inside the bins. However, such setting is not possible in this case study since no sensors are installed at ERSUC. Thus, in this case, the information registered by the drivers will be used as the "sensors readings", to simulate a scenario where that information is known *a priori*, i.e., before a route is performed.

The objective function is to maximize the profit, as a result of subtracting the value gained by selling the recyclable waste, by the transportation cost of collecting it.

The data needed is:

- The geographic coordinates of the depot and the bins:
- The distances between each pair of bins and depot, in km:
- The waste quantity in each bin, in kg:
- The bins´ daily accumulation rate, in kg:
- The bins´ capacity, in kg:
- The vehicle´s capacity, in kg.

The model will then determine:

- The number of bins collected:
- The collection sequences:
- The total quantity collected, in kg:
- The total distance travelled, in km.

Additionally, a heuristic developed by Ramos et al (2018) is used to complement the VRPP model, defining the service level, or the number of bins that are allowed to overflow. This way, the model only runs when it is necessary, and routes are developed only when there is expected that at least one bin is about to overflow during that day.

Figure 10 illustrates the heuristic.

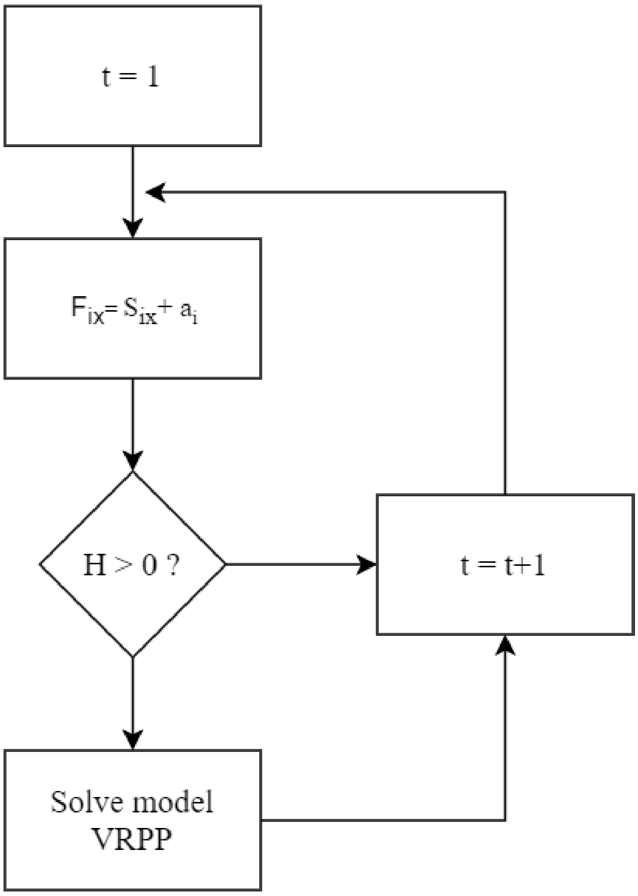

Figure 8:SWCRP heuristic

For each day *t* and each bin *i*, the heuristics analyses its amount of waste (S_{ix}) provided by the optical measures of the drivers, and its expected accumulation rate during the day (a_i), calculated previously. If it surpasses the maximum capacity of the bin (Ei), then the number of bins overflowing (*H*) is bigger than 0, and the VRPP model creates a route to collect the waste. However, if there are no bins that reach its maximum capacity, then there is no need to run the model.

Table 11 provides an example of 6 different paper/cardboard bins located in Condeixa, during days 26 and 27 of November.

Table 11: S_i, a_i of paper bins in Condeixa

Day	**Bin**	S_i	a_i	**Run the Model?**
26/11/2017	3210	0%	0,00%	No
26/11/2017	3301	40%	0,00%	
26/11/2017	3370	76%	12,00%	
26/11/2017	3420	76%	10,00%	
26/11/2017	3422	76%	9,34%	
26/11/2017	3484	95%	1,90%	
27/11/2017	3210	0%	0,00%	Yes
27/11/2017	3301	40%	0,00%	
27/11/2017	3370	88%	5,00%	
27/11/2017	3420	86%	18,80%	
27/11/2017	3422	86%	18,90%	
27/11/2017	3484	97%	31,40%	

As seen in table 11, the Si and ai are presented for the 6 different bins during the both days. On day 26, the model does not run since there is no bin that surpasses its maximum capacity (100%). However, the S_i on day 27 is equal to the Si plus the ai of day 26, meaning that bin 3484 surpasses the 100% when considering its a_i, thus, a route must be created to collect the waste on, at least, that bin.

Regarding the mathematical formulation of the VRPP, the model presented by Ramos et al (2018) is based on the Two Commodity Flow Formulation (Baldacci et al, 2004). This formulation consists on adding a copy of the depot to the initial set, and uses two types of decision variables: the first is a binary variable, the x_{ij}, that indicates if an edge (i,j), is visited. The second is a flow variable, y_{ij} and y_{ji}, which represent the waste carried by the vehicle, and its empty space, respectively, after visiting each edge (i,j). In addition, two paths are created: one where the vehicle starts at the real depot and ends in the copy depot, and another where the vehicle starts in copy depot and ends on the real depot (see Figure 9).

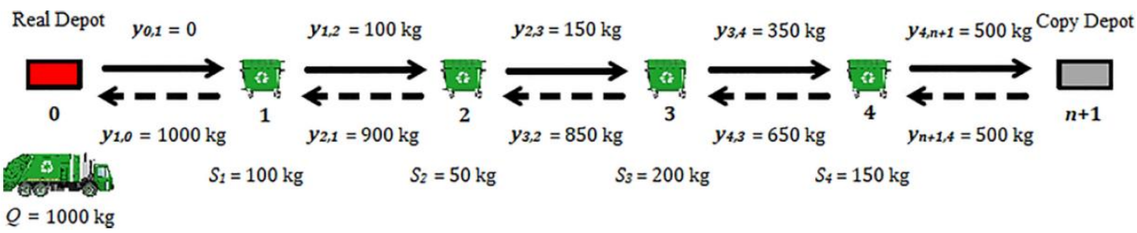

Figure 9:Two-commodity flow representation (Ramos et al, 2018)

The VRPP model can be described as:

Index Sets

$I = \{0,1,2,\dots,n+1\}$ Set of n waste bins, where the real depot is 0 and the copy depot n+1

Parameters

K number of available homogeneous vehicles

R selling price per kg of recyclable waste (in €/kg)

Ω penalty for the use of the vehicles (in €/km)

Q vehicle capacity (in kg)

C travelling cost per distance unit (in €/km)

B Waste density (in kg/m^3)

d_{ij} distance between node i and node j (in km)

S_i Amount of waste in kg at bin i (calculated using the information by the vehicle´s drivers (in m^3) and the waste density (in kg/m^3)

a_i expected daily accumulation rate of bin i (in kg)

E_i capacity of bin i

H number of waste bins for which $S_i + a_i \geq E_i$

Decision Variables

x_{ij} Binary variable indicating if edge (i,j) is visited (i,j Є I)

y_{ij} Positive variable representing the flow between node i and node j, (i,j Є I)

g_i Binary variable indicating if waste bin i is visited, (i,j Є I\ {0,n+1})

v integer variable on the number of vehicles to use

Model

$$\max P = R \sum_{i \in I\{0,n+1\}} S_i g_i - \left(0.5\left(C \sum_{i \in I} \sum_{j \in I,(j \neq i)} x_{ij} d_{ij}\right) + v\Omega\right) \quad (1)$$

s.t.

$$\sum_{j \in I,(j \neq i)} \left(y_{ij} - y_{ji}\right) = 2S_i g_i, \qquad \forall i \in I \setminus \{0, n+1\} \quad (2)$$

$$\sum_{i \in I \setminus \{0,n+1\}} y_{in+1} = \sum_{i \in I \setminus \{0,n+1\}} S_i g_i \quad (3)$$

$$\sum_{j \in I \setminus \{0,n+1\}} y_{n+1j} = QK - \sum_{i \in I \setminus \{0,n+1\}} S_i g_i \quad (4)$$

$$\sum_{i \in I \setminus \{0,n+1\}} y_{i0} \leq QK \quad (5)$$

$$\sum_{j \in I \setminus \{0,n+1\}} y_{0j} = 0 \quad (6)$$

$$g_i = 1, \qquad \forall i \in I \setminus \{0, n+1\} : S_i \geq E_i \quad (7)$$

$$\sum_{i \in I,(j \neq i)} x_{ij} = 2g_i, \qquad \forall j \in I \setminus \{0, n+1\} \quad (8)$$

$$y_{ij} + y_{ji} = Q x_{ij}, \qquad \forall i, j \in I, i \neq j \quad (9)$$

$$x_{ij}, g_i \in \{0,1\}, \qquad \forall i, j \in I, i \neq j \quad (10)$$

$$y_{ij} \in \Re^+, \qquad \forall i, j \in I, i \neq j \quad (11)$$

$$v \in \Im^+ \quad (12)$$

The objective function (1) considers the maximization of the profit (*P*), defined as the difference between the revenue gained by selling the collected waste by its transportation cost. The first term of the equation - the revenue - results of multiplying all the amount of waste collected in each bin by its selling price. The second term - the transportation cost - considers the distance between the collected bins and the depots times the travelling cost, plus a penalty to force the model to use the minimum number of vehicles. Since the model is based on a two-commodity flow, then total distance needs to be cut in half.

Constraint (2) ensures that, for each bin collected, the outflow minus the inflow equals two times the quantity collected.

Constraints (3) and (4) mention the inflow and outflow of the copy depot. Constraint (3) secures that the total inflow of copy depot is equal to the amount of waste collected from the bins. Constraint (4) guarantees that the total outflow that leaves the copy depot equals to the total amount of waste collected from the bins. This way, all the waste is transported to the real depot.

Constraints (5) and (6) are related with the flows for the real depot. The first assures that the total inflow of the real depot cannot surpass the total capacity of the vehicles used, while the second specifies that the outflow of the real depot must be equal to 0.

Constraint (7) makes sure that a bin that is overflowing does not remain this way for a long period of time.

Constraints (8) and (9) are for the bin. The first connects both the decision variables guaranteeing that the sum of the flows in every edge must be equal to the vehicle´s capacity, while the second makes sure each bin has 2 edges.

Constraints (10), (11) and (12) refer to the domain of the variables.

4.4 Chapter´s conclusions

In this chapter, two different approaches were described, one for each scenario, in order to eliminate some of ERSUC´s limitations regarding waste collection routes.

The Frequency Optimization model attempts to create optimum route frequencies for the current defined routes ERSUC has, while never surpassing the maximum waste quantity the vehicle can transport. A heuristic was developed that acts on each time a type of route was performed and calculates its optimum frequency. Then, the overall optimum frequency for the route is the minimum value of all the iterations, assuring that the vehicle never surpasses its capacity.

The SWCRP, developed by Ramos et al (2018), attempts to maximize the difference between the profit gained by the amount of waste collected and the cost of collecting it, while optimizing the route sequence. Additionally, a heuristic developed by Ramos et al (2018) complements the model, only allowing it to run when there is a bin that reaches its maximum capacity, so route frequency can be optimized.

5. Data Treatment

5.1 Introduction

ERSUC provided all the data regarding each route performed on all the 36 different districts that the company acts on, during the year 2017. More specifically, a set of Excel files with the following data were provided:

- Data about each route: the type of recyclable waste collected, duration time, arrival date, fuel consumed, distance travelled, amount of waste collected and driver that performed the route.
- Data regarding each bin: its geographic coordinates, type of waste it holds, district where it is placed, and which route collects its waste
- The fill-levels of the bins in the districts of Soure and Condeixa: its percentages, the dates and routes when the measures were made and which driver took the measure.

The treatment of this data will be explained and examples will be given in this chapter.

Since the information was considered so abundant, it was agreed to narrow its range in order to be able to have a comparison between all the outcomes of the different models. Thus, from the 36 districts, a sample of 2 – Soure and Condeixa - were chosen based on its data reliability. The routes performed on these districts are indicated in table 12.

Table 12: Routes in Soure and Condeixa

District	Route	Waste collected
Soure	Soure P01	Paper/Cardboard
	Soure P02	Paper/Cardboard
	Soure E01	Plastic
	Soure E02	Plastic
	Soure V01	Glass
	Soure V02	Glass
Condeixa	Condeixa P01	Paper/Cardboard
	Condeixa E01	Plastic
	Condeixa V01	Glass
	Condeixa V02	Glass

Additionally, the time horizon was also narrowed to one month, November, so that the total number of model iterations decreased. Table 13 shows the impact percentage of the chosen month and districts when compared to the total information given, regarding the amount of waste collected and the distance travelled.

Table 13: Comparison between the amount of waste collected and distance travelled of the districts and month chosen, with the rest of the data

Type	Districts	November	Year 2017	Impact %
Amount of waste collected (kg)	Soure	420 201	26 341 765	1,60%
	Condeixa	418 095	26 341 765	1,59%
	Soure + Condeixa	838 296	26 341 765	3,18%
Distance Travelled (km)	Soure	38 315	1 555 446	2,46%
	Condeixa	19 577	1 555 446	1,26%
	Soure + Condeixa	57 892	1 555 446	3,72%

5.2 Data Treatment for the Frequency Optimization Model: Outliers

Since the amount of waste deposited in the bins is stochastic, the total amount of waste collected per iteration variated significantly. Thus, some of the values were so out of the range that were not considered for the calculation of the overall frequency. Those values are the outliers, and were removed in order to obtain a more realistic frequency. Table 14 illustrates one of the routes performed in 2017 to collect glass, in Condeixa.

Table 14: Routes performed in Condeixa to collect glass

Date	Distance (km)	Waste Collected (kg)	$Tint_i$ (days)	$KgRD_i$ (kg)
02/02/2017	108	3640	16	227
23/02/2017	117	5680	21	271
15/03/2017	110	3060	20	155
30/03/2017	124	4020	15	263
29/04/2017	115	9580	30	320
13/05/2017	109	5320	14	380
01/06/2017	112	5000	19	263
21/06/2017	136	5220	20	265
19/07/2017	107	8220	28	290
09/08/2017	137	8000	21	381
30/08/2017	119	8860	21	422
13/09/2017	128	4460	14	319
05/10/2017	113	5620	22	259
21/10/2017	121	3640	16	223
11/11/2017	120	5500	21	266
08/12/2017	111	8400	27	311

In table 14, the daily disposal rate of each route (*$KgRD_i$*) is indicated and is the one used to calculate the possible outliers. According to Tukey (1977), the first step to identify outliers in a set of information is to determine the first and third quartile of the set. Therefore, Quartile 1 of the *$KgRD_i$* is 262 kg and the Quartile 3 is 319 kg. The second step is to find the Interquartile Range, which is the difference between Quartile 3 and Quartile 1. In this case, the Interquartile Range is equal to 57 kg.

The last step is to determine the lower and upper bound. The values that lie outside these two ranges value are considered outliers. The lower bound is equal to Quartile 1 minus 1.5 (value defined by Tukey, 1977) times the Interquartile Range. The upper bound is the Quartile 3 plus 1.5 times the Interquartile Range. Table 15 shows the outlier values of the route.

Table 15: Outliers of one of the Condeixa routes that collect glass

Date	Distance (Km)	Waste Collected (Kg)	$Tint_i$ (Days)	$KgRD_i$ (Kg)	Lower Bound (kg)	Upper Bound (kg)	Outlier?
02/02/2017	108	3640	16	227	176	404	No
23/02/2017	117	5680	21	271	176	404	No
15/03/2017	110	3060	20	155	176	404	Yes
30/03/2017	124	4020	15	263	176	404	No
29/04/2017	115	9580	30	320	176	404	No
13/05/2017	109	5320	14	380	176	404	No
01/06/2017	112	5000	19	263	176	404	No
21/06/2017	136	5220	20	265	176	404	No
19/07/2017	107	8220	28	290	176	404	No
09/08/2017	137	8000	21	381	176	404	No
30/08/2017	119	8860	21	422	176	404	Yes
13/09/2017	128	4460	14	319	176	404	No
05/10/2017	113	5620	22	259	176	404	No
21/10/2017	121	3640	16	223	176	404	No
11/11/2017	120	5500	21	266	176	404	No
08/12/2017	111	8400	27	311	176	404	No

5.3 Data Treatment for the SWCRP Model

The collection and data treatment for the SWCRP model will be described according to the following categories: waste, bin and distances. All the processes and assumptions will be identified.

5.3.1 Waste Streams

5.3.1.1 Typology

ERSUC is responsible for collecting 3 different types of recyclable waste: paper/cardboard, packaging and glass. Each one has different specifications: thus, data treatment and assumptions will be modified accordingly.

5.3.1.2 Density

To calculate the amount of waste collected in a route developed by the SWCRP, one of the information required and provided by the company is the density that each type of waste contains inside the bins. Additionally, to calculate the vehicle´s maximum capacity, the density inside the vehicle of each type of waste is also needed. These values in the paper/cardboard and packaging waste variate significantly due to a compressor that exists inside the vehicles. Table 16 shows the values for each type of waste.

Table 16: Density of each type of waste inside the bin and the vehicle

Type of Waste	Density inside Bin (kg/m^3)	Density inside Vehicles (kg/m^3)
Paper/Cardboard	40	90
Packaging	30	80
Glass	244	340

5.3.2 Bins

5.3.2.1 Collecting Sites

Since the model works with information regarding each bin´s fill-level, then it also considers each bin as a collecting site. Therefore, for each type of waste, all the bin´s geographic coordinates are introduced in the model along as the ones for the depot.

Table 17 indicates the total number of bins in the two districts, Soure and Condeixa.

Table 17: Number of bins in Soure and Condeixa

Districts	Waste	Number of bins
Soure	Paper/Cardboard	77
	Plastic	77
	Glass	93
Condeixa	Paper/Cardboard	63
	Plastic	67
	Glass	80

Additionally, Figure 10 shows geographically all the 93 glass bins in Soure as an example:

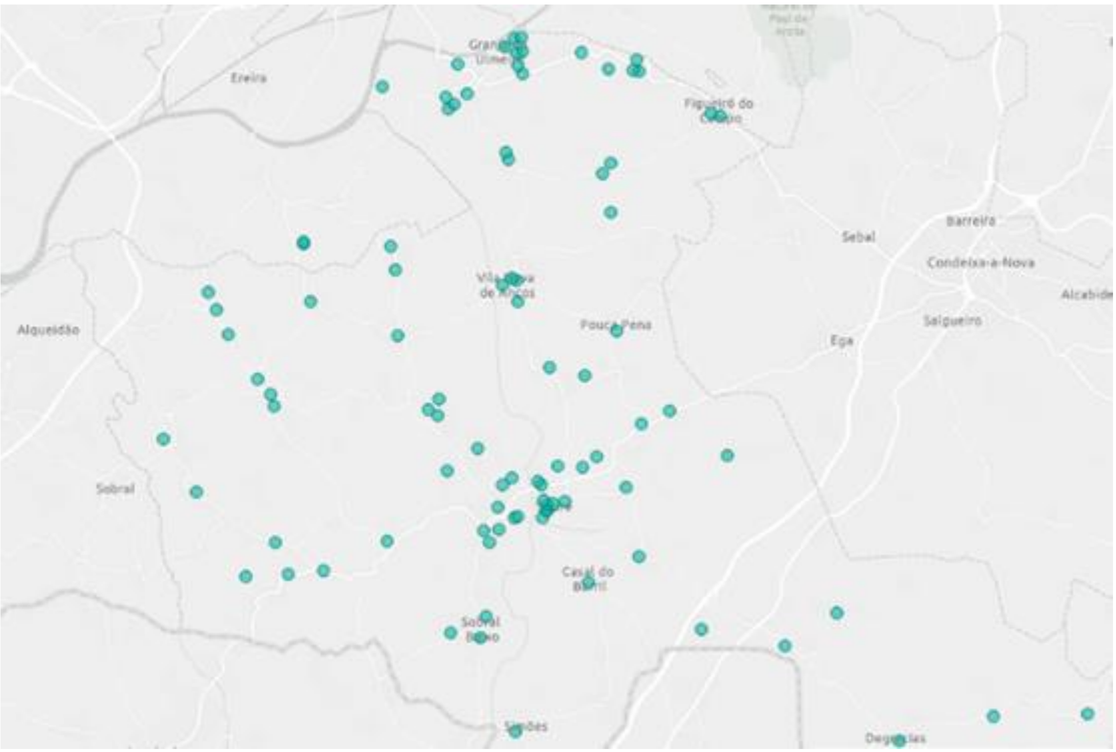

Figure 10:Geographic location of the glass bins in Soure

5.3.2.2 Quantity to Collect

For each bin, the model uses two different parameters: The initial amount of waste (Si) and the expected daily accumulation (ai). Both parameters will be defined below, along with the adaptations required to fit in the model.

5.3.2.2.1 Initial Amount of Waste (S_i)

The initial amount of waste, or S_i, is the amount of waste each bin contains at the beginning of each day. In an ideal setting, this information is given by sensors placed inside the bins. However, due to their unavailability, it was assumed that this information was rather given by the information given by the drivers. Table 18 presents an example of the information given for bin 3279 (paper/cardboard) in Condeixa, during the month of November.

Table 18: Optical measures of bin 3279

Date	Waste collected in the route	Measure (%)
15/11/2017	Paper/cardboard	38,00
16/11/2017	-	-
17/11/2017	-	-
18/11/2017	-	-
19/11/2017	-	-
20/11/2017	-	-
21/11/2017	-	-
22/11/2017	Paper/cardboard	63,00
23/11/2017	Plastic	13,00
24/11/2017	-	-
25/11/2017	-	-
26/11/2017	-	-
27/11/2017	Paper/cardboard	13,00
28/11/2017	-	-
29/11/2017	Plastic	13,00
30/11/2017	-	-

As can be seen in table 18, the first measure of the month for the bin was on day 15, meaning that no routes were performed until that moment. Additionally, each bin has a zone, which is an area with 1 or more bins, for a different type of waste stream. Therefore, each time a route is performed to collect a bin in the zone, measures are taken for all the bins, but only one can be collected (if it is). This explains the fact that on day 23 and 29, a route to collect plastic could also give measures for the bin 3279, since it passed through its zone 1312. The range of the measures are: 13, 38, 63, and 88. These are the rounded mean values for each of the 4 different ranges in the optical measures that indicate the bin´s fill-level, in percentage: 0%-25%, 25%-50%, 50%-75% and 75%-100%.

These measures are an important input for the model, however, more information is required since the model runs on a daily basis, and the only information of bin 3279 fill-level is only for days

15,22,23,27 and 29. Thus, the bin´s fill-level on the remaining days is calculated through a linear waste variation occurred between two measures. Table 19 adds the total waste increment and the daily waste increment for bin 3279.

Table 19: Waste increment of bin 3279

Date	Waste collected in the route	Optical Measure (%)	Waste Increment (%)	Daily Increment (%)
15/11/2017	Paper/cardboard	38	0,00	0,00
16/11/2017	-	-	25,00	3,57
17/11/2017	-	-		3,57
18/11/2017	-	-		3,57
19/11/2017	-	-		3,57
20/11/2017	-	-		3,57
21/11/2017	-	-		3,57
22/11/2017	Paper/cardboard	63	0,00	0,00
23/11/2017	Plastic	13	13,00	13,00
24/11/2017	-	-	0,00	0,00
25/11/2017	-	-		0,00
26/11/2017	-	-		0,00
27/11/2017	Paper/cardboard	13	0,00	0,00
28/11/2017	-	-	0,00	0,00
29/11/2017	Plastic	13	0,00	0,00
30/11/2017	-	-	0,00	0,00

As indicated on table 19, during days 15 until 22, the optical measure variated from 38 to 63, meaning that there was an increment of 25%. This represents a daily increment of 25/(22-15) = 3,57%. Also, on day 22 the bin 3279 was collected, and on day 23, its fill-level is 13%. Therefore, it is considered that there was an increment of 13% in the fill-level.

Once the daily increment is calculated, then the S_i for bin 3279 can be found. The S_i is the daily initial measure, and it is used as an input to the VRPP approach. Its value increases daily since the daily increment is added.

Table 20 adds the S_i to the table 19.

Table 20: Daily and total waste increment of bin 3279

Date	Waste collected in the route	Optical Measure (%)	S_i Model (%)	Waste Increment (%)	Daily Increment (%)
15/11/2017	Paper/cardboard	38	38	0,00	0,00
16/11/2017	-	-	41,57	25,00	3,57
17/11/2017	-	-	45,14		3,57
18/11/2017	-	-	48,71		3,57
19/11/2017	-	-	52,28		3,57
20/11/2017	-	-	55,85		3,57
21/11/2017	-	-	3,57		3,57
22/11/2017	Paper/cardboard	63	3,57	0,00	0,00
23/11/2017	Plastic	13	16,57	13,00	13,00
24/11/2017	-	-	16,57	0,00	0,00
25/11/2017	-	-	16,57		0,00
26/11/2017	-	-	16,57		0,00
27/11/2017	Paper/cardboard	13	16,57	0,00	0,00
28/11/2017	-	-	16,57	0,00	0,00
29/11/2017	Plastic	13	16,57	0,00	0,00
30/11/2017	-	-	16,57	0,00	0,00

As shown on table 20, the values of the S_i variate from the values of the optical measures. In day 15, both values are 38%, however, on day 22 the values differ (63% and 3,57%). This occurs because one of the variables that define the amount of waste inside the bins is the route frequency. In this case, the bin was collected on day 22 (when its fill-level was at 63%) by ERSUC, however, the model developed a route on day 20 that collected the bin, thus, on day 21 the bin´s S_i is equal to its daily increment.

5.3.2.2.2 Expected Daily Accumulation Rate (a_i)

The expected daily accumulation rate (a_i) is needed to forecast the amount of waste that will be generetad during the day, since the sensors readings (in this case, the driver´s measures) are assumed to be transmitted in the morning. This value is computed based on data regarding the amount of waste variations inside each bin during a specific time horizon. In other words, it is the average daily S_i increment for each bin.

As an example, table 21 displays the measures registered for bin 5784 that stores paper/cardboard in Soure, during three months (April, May and June 2017).

Table 21: Optical measures for bin 5784

Date	**Bin**	S_i	S_i **Increment**
05/04/2017	5784	63%	13%
06/04/2017	5784	13%	25%
12/04/2017	5784	38%	0%
17/05/2017	5784	0%	13%
23/05/2017	5784	13%	25%
26/05/2017	5784	38%	25%
02/06/2017	5784	63%	13%
03/06/2017	5784	13%	0%
14/06/2017	5784	13%	50%
16/06/2017	5784	63%	0%
22/06/2017	5784	63%	38%
24/06/2017	5784	38%	50%
29/06/2017	5784	88%	-
αi	-	-	**0,23%**

In table 21, the column S_i increment indicates the amount of waste placed, in percentage of bin capacity. As mentioned above, this value is calculated as the difference between two consecutive optical measures when there is an increment, and when there a collection is assumed, only one of the values is taken into account. With all those values, the a_i then is the average value (21%) divided by the amount of days passed (91 days), which results in a 0,21% daily increase during those 3 months. This process repeats for each bin, but from January until October, is the pool data up until November, which is the month that is being used into the models.

5.3.3 Distances

As mentioned before, one of the model inputs were the geographic coordinates of each of the waste bins and the depot, and since there is a high number of them, the immense complexity of considering real distances between them needed to be reduced. Therefore, another approach was considered.

The approach is the Euclidian distance, considering straight lines between the sites, and corrected by a circuit factor, whose objective is to approximate the linear distances to the real ones. The circuit factor used for this case study was 1.65

The formula to calculate the distances is:

$$d(i,j) = \sqrt{(lon_i - lon_j)^2 + (lat_i - lat_j)^2} \times 74{,}24 \times 1{,}65$$

The value 74,24 converts degrees into kilometers and was obtained using the formula:

$$\frac{2\pi \times 6378 \times \cos(40°)}{360°}$$

Where 6378 is the number of kilometers of the equatorial radius of the earth and 40 is the latitude value of the districts considered.

5.4 Chapter´s Conclusions

In this chapter the treatment of the data given by ERSUC and used as inputs in both models was described.

For the Frequency Optimization Model, the removal of outliers prevented from obtaining a value that did not represented the overall optimum frequency on the routes.

Regarding the SWCRP, the data treatment could be divided into three big categories: waste, bin and distances. The first category, waste, mentioned the different types of waste to be collected, as well as the different densities in each. The second category, bins, explained the assumptions necessary to identify as accurately as possible the amount of waste inside each one and its expected daily accumulation. The last category, distances, mentioned the formulas used to approximate the real distances with the Euclidian distances, in order to reduce the complexity of the model.

6. *Results*

6.1 Introduction

On chapter 4 the different approaches to mitigate the most impactful limitations on waste collection operations were described. Moreover, the treatment of the data inputs for the approaches were discussed on chapter 5. In this chapter, the outputs of the approaches will be discussed and compared.

Three scenarios will be considered. The first scenario is the current situation of the company, where there is no standardized route frequency and the route sequence is static. The second scenario is the Frequency Optimization approach, where for each route the best route frequency that avoids surpassing the vehicle´s capacity limit is calculated. The third and last scenario is the SWCRP approach, where route frequency and sequence are dynamic in order to minimize the total distance travelled when collecting the waste. All the scenarios will be compared only for the month of November of 2017 for the districts of Soure and Condeixa.

6.2 Current Scenario

The current scenario refers to the real performed routes during the month of November 2017, in the districts of Soure and Condeixa.

Through the data given by the company, a number of Key Performance Indicators (KPIs) could be calculated, that will help to evaluate and identify the efficiency of the routes. The KPIs are: number of bins, number of performed routes, route frequency, total quantity collected, total distance travelled, ratio between quantity collected and distance travelled (Kg/Km), and percentage of vehicle occupation.

Table 22 displays the KPIs for each of the routes in the districts of Soure and Condeixa.

Table 22: Current Situation KPIs for the routes in Soure and Condeixa during November 2017

Districts	Number of bins	Number of Routes	Time Interval (days)	Total Quantity Collected (kg)	Total Distance (km)	Kg/Km	Vehicle ocupation
Soure P01	39	4	7	3425	579	5,92	39%
Soure P02	38	4	7	1513	714	2,12	17%
Soure E01	38	4	7	2967	565	5,25	39%
Soure E02	39	5	7	2577	796	3,24	27%
Soure V01	46	2	20	7516	279	26,94	39%
Soure V02	47	1	20	6911	178	38,83	73%
Condeixa P01	64	5	6	10775	617	17,46	98%
Condeixa E01	67	5	6	8018	644	12,45	84%
Condeixa V01	40	1	20	6789	89	76,28	71%
Condeixa V02	40	1	20	7637	120	63,64	80%

As shown in table 22, glass routes (Soure V01, V02 and Condeixa V01 and V02) contain the lowest overall number of routes performed, which is directly correlated to the time interval between routes. Additionally, glass routes have the highest values for quantity collected, which can be explained by the highest density of glass when compared to the densities of paper/cardboard and plastic.

Regarding the Kg/Km ratio, the lowest overall score occurs in the routes that collect plastic since they contain an elevated number of routes (which translates into high values of total distance travelled) with low values of total waste collected. However, the route with the worst score is the paper/cardboard route Soure P02 with only 2,12 kg of waste collected per km. The highest ratio occurs in the glass routes due to lowest route frequency combined with a greater quantity collected, especially in Condeixa V01, with a ratio of 76,28 kilograms per kilometer.

The vehicle occupation percentage is calculated dividing the total quantity collected by the vehicle´s maximum capacity (2200 kg for paper/cardboard, 1920 kg for plastic and 9530 for glass), times the number of routes. This value indicates the capability of modifying the route´s frequency, since an increase in this value will also increase the percentage. The route with the highest percentage is Condeixa P01, with 98%, while Soure P02 is the lowest with only 17%.

6.3 Frequency Optimization Scenario

The Frequency Optimization Scenario consists on obtaining an overall optimum frequency for each route, with the data provided by ERSUC. Table 23 displays the KPIs for each route performed in both districts, during the month of November 2017.

Table 23: Frequency Optimization KPIs for the routes in Soure and Condeixa in November 2017

Districts	Number of bins	Time Interval (days)	Number of Routes	Total Quantity Collected (kg)	Total Distance (km)	Kg/Km	Vehicle ocupation
Soure P01	39	8	3	2740	434	6,31	42%
Soure P02	38	12	2	1210	357	3,39	28%
Soure E01	38	7	4	2769	565	4,90	36%
Soure E02	39	9	3	2319	478	4,86	40%
Soure V01	46	19	1	4760	140	34,12	50%
Soure V02	47	23	1	5298	178	29,77	56%
Condeixa P01	64	4	7	10057	864	11,64	65%
Condeixa E01	67	5	6	8018	773	10,38	70%
Condeixa V01	40	23	1	5205	89	58,48	55%
Condeixa V02	40	25	1	6364	120	53,03	67%

The overall optimum time interval for each route is represented in Table 23. The routes that collect glass contain the highest values of time interval, the highest being 25 days for Condeixa V02. The lower values go to the routes that collect paper/cardboard and plastic, Condeixa P01 and Condeixa E01, with 4 and 5 days, respectively.

With optimum time interval, the number of routes performed in November could be found, for each route. The number of routes is the result of dividing the time interval by 30, the number of days in November. Therefore, the route which was performed the most was Condeixa P01, performed 7 times, followed by Condeixa E01, performed 6 times. Glass routes were only performed once during the entire month due to its high time interval.

With the number of routes performed, the quantity collected, and distance travelled for each route could be estimated. The first KPI is the result of multiplying the daily waste growth rate of each route with the route´s time interval and the number of performed routes, the distance travelled is the result of multiplying the number of routes per the average values of distance travelled in November 2017, respectively. Since these KPIs are directly correlated with the number of routes performed, then the highest values for waste collected and distance travelled go to the routes of Condeixa P01, with 10057 kg of paper/cardboard, and 864 km travelled. The route with the lowest quantity collected, with 1210 kg, is Soure P02 and the lowest distance travelled is in Condeixa V01, with only 89 km.

The Kg/Km ratio measures the quantity of waste collected per kilometer, and since glass is the type of waste with the highest density, the highest Kg/Km values go to the glass routes: Soure V01, Soure V02, Condeixa V01 and Condeixa V02. Moreover, the vehicle occupation achieves its highest percentage in Condeixa E01, with 70%, and its lowest in Soure P02, with 28%.

6.4 SWCRP Scenario

The Smart Waste Collection Routing Problem obtains the optimum route frequency and route sequence using information of the bin´s fill-levels, in this case, provided by the driver´s measures. In this scenario, for each district routes will be developed to collect each type of waste. Table 24 displays the types of waste collect in both districts.

Table 24: Routes in Soure and Condeixa for the SWCRP

District	Waste collected
Soure	Paper/Cardboard
	Plastic
	Glass
Condeixa	Paper/Cardboard
	Plastic
	Glass

Table 25 shows the aggregated results for the routes in Soure and Condeixa, during the month of November 2017.

Table 25: SWCRP KPIs for the routes in Soure and Condeixa

Districts	Type of waste	Average bins Collected	Number of Routes	Total Quantity Collected (kg)	Total Distance (km)	Kg/Km	Vehicle ocupation
Soure	Paper	46	4	6267	465	13,48	71%
	Plastic	47	5	7022	575	12,21	73%
	Glass	69	2	18093	296	61,13	95%
Condeixa	Paper	43	5	10321	454	22,72	94%
	Plastic	49	3	7387	272	27,19	96%
	Glass	37	2	19059	135	141,42	100%

For example, to collect the paper bins in Soure during November, 4 routes must be done, where on average 46 bins are collected in each route. The higher average value of bins collected per developed route e in Soure glass, and the lower average value is in Condeixa glass.

Regarding the total quantity collected, glass routes also have the highest values due to the density of glass. The highest value goes to glass in Condeixa, with 19059 kg collected, while paper in Soure has the lowest quantity collected. This KPI was obtained by calculations of the VRPP model with the information of the driver´s when measuring the fill level of each bin.

The total distance per each route was calculated by the model using as an input the geographic coordinates of each bin. The route with the most distance travelled is to collect plastic in Soure with 575 km, while the routes developed to collect glass in Condeixa have lowest distance travelled, with 135 km. Moreover, since glass in Condeixa has the highest quantity collected and the lowest distance travelled, then it will also contain the highest Kg/Km, with 141,42 kg per km performed. The route with the lowest value of Kg/Km are the ones to collect plastic bins in Soure, with only 12,21 kg per km travelled.

Finally, Condeixa´s glass bins routes have the highest vehicle occupation percentage, with 100%, meaning that in both routes performed, the quantity collected was the maximum the vehicle can hold, which is 9530 kg. paper collection routes in Soure have the lowest vehicle occupation percentage, with 71%.

For a more specific display of the KPIs, appendix 2 demonstrates the KPIs values for each route developed by the VRPP model.

6.5 Results Analysis and Comparisons

In the previous sections, the KPIs for the three scenarios were displayed. In this section, all the KPIs will be compared and analyzed in order to identify the most optimal scenario. These scenarios will be compared by district and type of waste collected. Therefore, in the first 2 scenarios (current situation and frequency optimization), the KPIs of the routes of Soure and the glass routes of Condeixa were aggregated in order to be compared with the results of the SWCRP scenario.

The first KPI is the Time interval between routes during November 2017. Since the SWCRP scenario develops dynamic routes, only the current situation and the frequency optimization scenario will be compared. Figure 11 indicates the route frequency for of the two scenarios in all their routes.

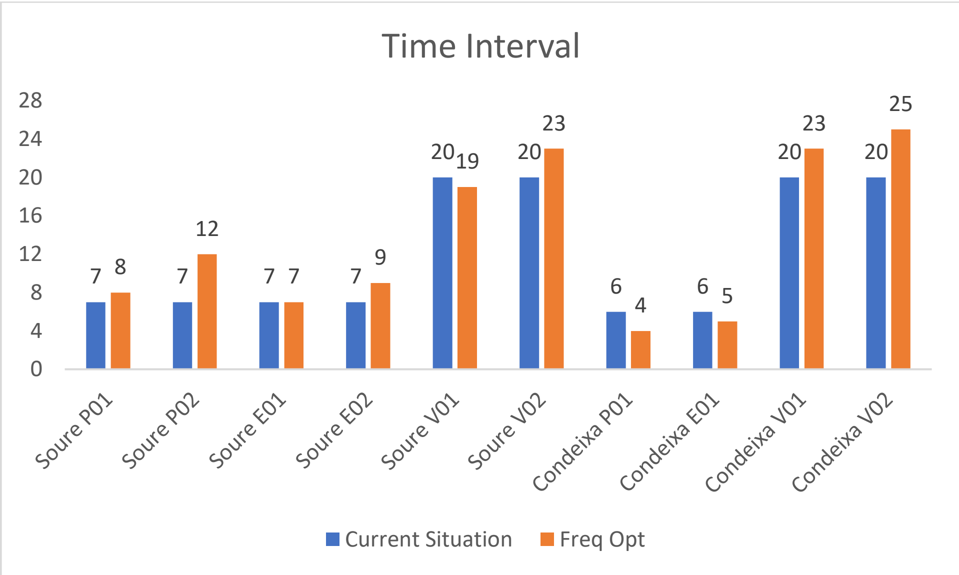

Figure 11:Time interval KPI for all routes in current situation and frequency optimization scenario

As indicated in figure 11, the frequency optimization scenario increased the time interval of routes Soure P01, Soure P02, Soure E02, Soure V02, Condeixa V01 and Condeixa V02, while in Soure V01, Condeixa P01 and Condeixa E01, the time interval is smaller when compared to the current situation.

The second KPI to be presented is the number of routes performed, displayed in figure 12.

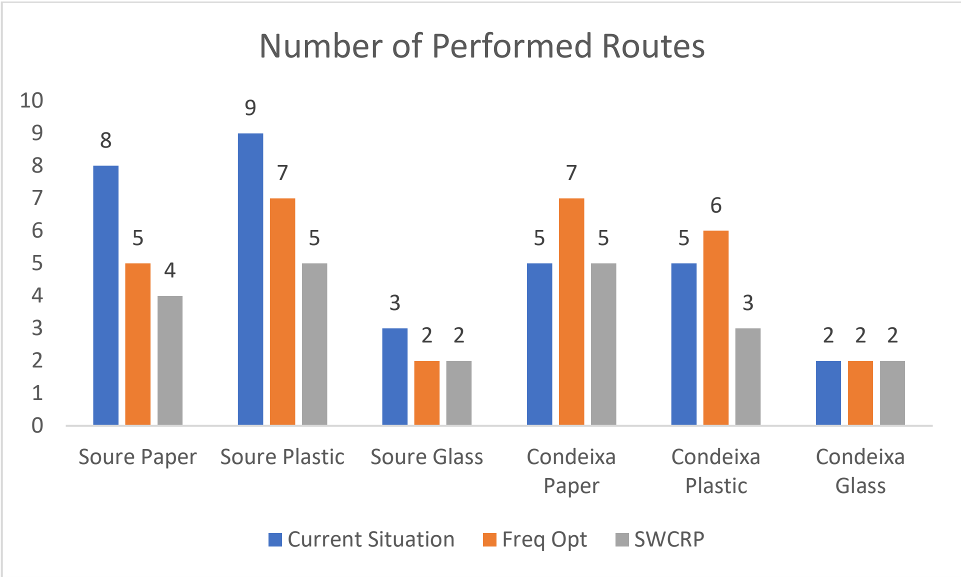

Figure 12:Number of routes performed for the three scenarios

As shown in figure 12, the scenario with the lowest overall number of routes performed is the SWCRP scenario, obtaining a lower value in every route except in Soure glass and Condeixa paper. This result can be explained due to the aggregation of this KPI value for the current situation and frequency optimization scenarios. This means that for example, in the frequency optimization scenario the number of routes for Soure P, 5, is equal to the number of routes performed on route Soure P01, 3, plus the routes performed on Soure P02, 2. Another reason is that for the SWCRP scenario the route is only performed when a bin is overflowing or about to, while for the other scenarios the route frequency is static.

The third KPI is the total quantity collected, displayed in figure 13.

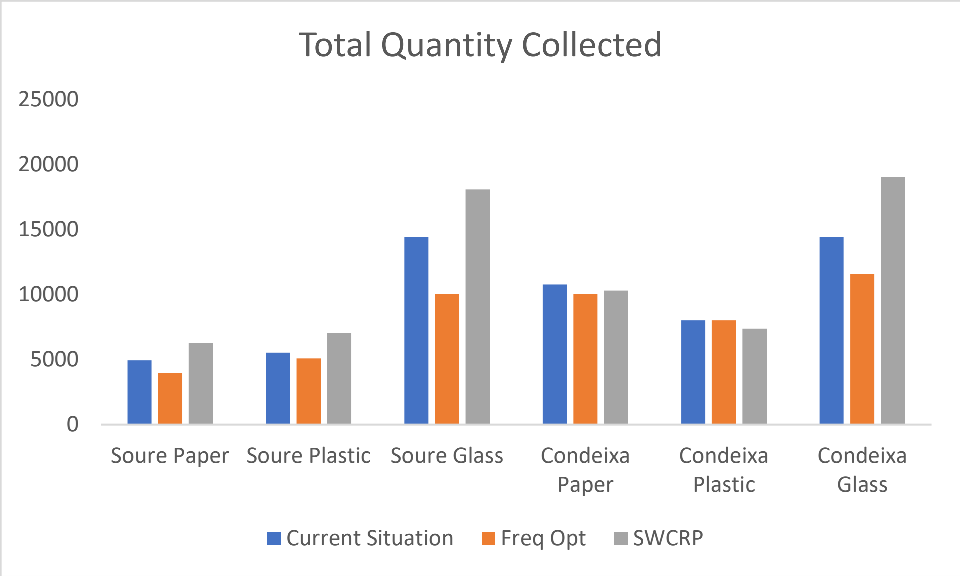

Figure 13:KPI total quantity collected for the three scenarios

As shown in figure 13, the quantity collected in each route differs significantly in the glass routes, where in the SWCRP scenario there is an increase of 20% and 40% when compared to the current situation and frequency optimization scenario, respectively, for Soure glass, and 39% and 24% for Condeixa glass. However, for the rest, the values remain similar. It is worth mentioning that the information used to calculate the quantity collected for each scenario was given by the driver´s, instead of using the weight of the vehicles after performing the route. This way, these values can be biased.

Regarding the distance travelled, the KPI is represented in figure 14.

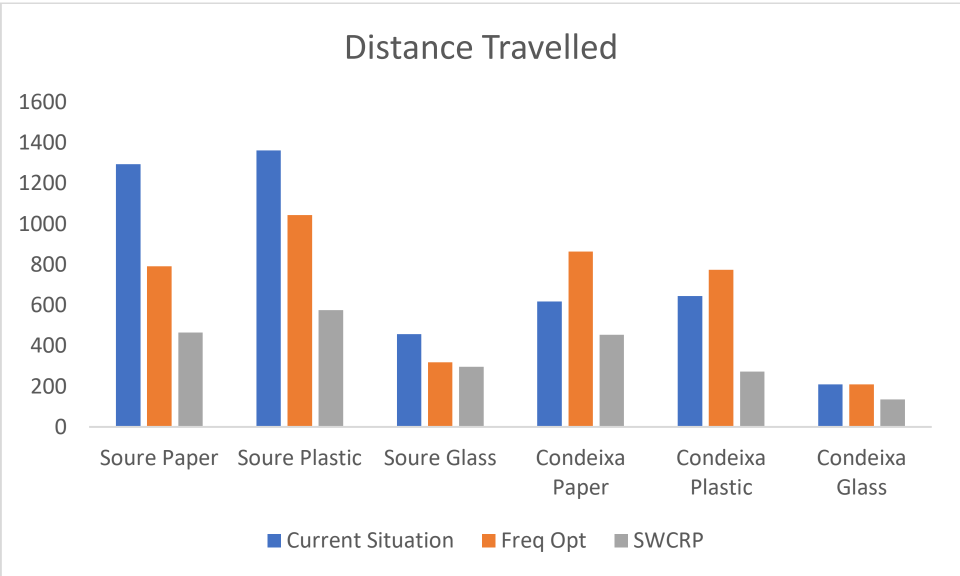

Figure 14:: KPI of the total distance travelled for the three scenarios

As seen in figure 14, the lowest overall distance travelled for each route is in the SWCRP scenario. The reason is that the SWCRP model optimizes the route sequence in order to obtain the maximum profit, or the difference between the quantity collected and the distance travelled. This optimization allows for a significant drop in the distance travelled when compared to the other scenarios especially in the routes performed in Soure, where differences reach 278% and 170% less when compared with the current situation and frequency optimization, respectively, for the paper routes, and 236% and 181% less for plastic routes. Regarding the frequency optimization scenario when compared to the current situation, its KPIs values are lower in the routes performed in Soure, but higher in the routes performed in Condeixa.

The fifth KPI is the Kg/Km ratio, which allows for a better evaluation of the scenarios in terms of performance. The KPI is displayed in figure 15.

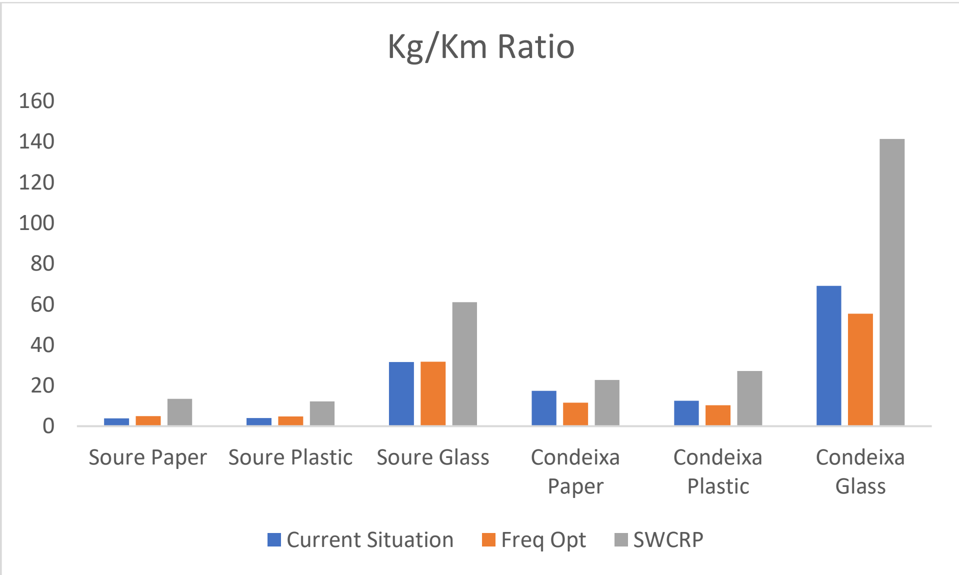

Figure 15:KPI of the kg/km ratio for the three scenarios

As shown in figure 15, the SWCRP scenario contains the highest values of the ratio, meaning that it is the scenario that collects the most waste per kilometer. The highest difference occurs in Condeixa glass, where in the SWCRP, the ratio is 141 kg/km, compared with 51 kg/km in the frequency optimization scenario, and 48 kg/km in the current situation.

The last KPI is the percentage of vehicle occupation, presented in figure 16.

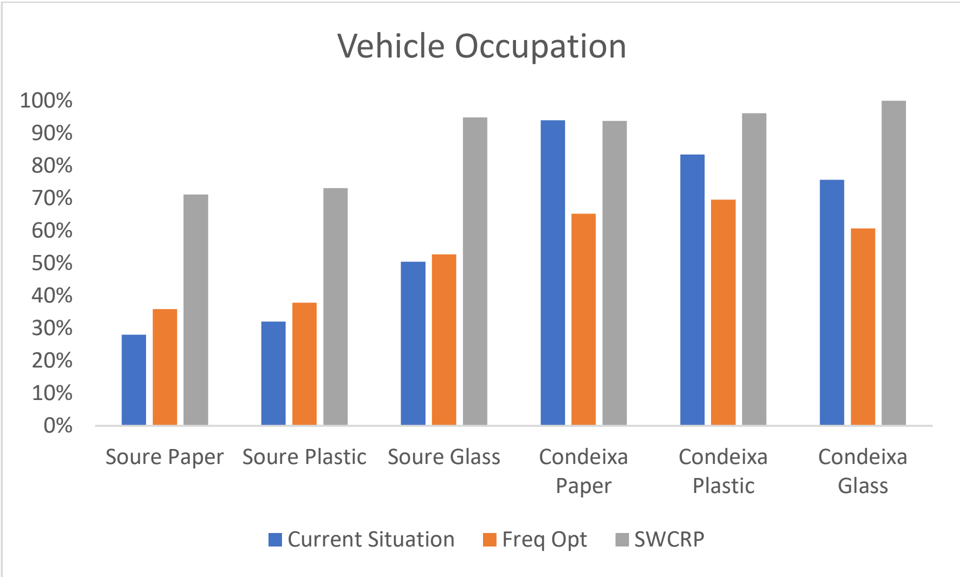

Figure 16:KPI of vehicle occupation for the three scenarios

In figure 16, again the SWCRP scenario contains the highest values when compared with the other two scenarios, especially in Condeixa glass, where the vehicle´s capacity reaches 100%, a difference of 39% and 24% when compared to the percentage in the frequency optimization scenario and current situation, respectively. Thus, it is the scenario where the vehicles are used best in regard to their maximum capacity.

For a better understanding, a comparison in percentage variations of the more relevant KPIs between the two proposed scenarios and the current situation is displayed in Table 26, in order to help determining in which KPIs one scenario outstands the others.

Table 26: Percentage variations of the KPIs between scenarios

Scenario	District	Type of waste	KPIs: Distance travelled (km)	KPIs: Kg/Km	KPIs: Vehicle Occupation
Frequency Optimization	Soure	Paper	39%	24%	22%
		Plastic	23%	17%	15%
		Glass	31%	0%	4%
	Condeixa	Paper	-40%	-50%	-44%
		Plastic	-20%	-20%	-20%
		Glass	0%	-25%	-25%
SWCRP	Soure	Paper	64%	72%	61%
		Plastic	58%	67%	56%
		Glass	35%	48%	47%
	Condeixa	Paper	26%	23%	0%
		Plastic	58%	54%	13%
		Glass	36%	51%	24%

Upon analyzing Table 26, the frequency optimization scenario contains some negative values when compared to the current. This negative impact occurs specially on Condeixa, where all the KPIs are worst than the current scenario with exception to the distance travelled in Condeixa glass, where there is no variation. Nevertheless, in the Soure district the frequency optimization scenario is a better approach than the current scenario for all the routes.

Regarding the SWCRP, there is no doubt that it is the best scenario of three, since every KPI is superior when compared to the other two scenarios except one where there is no variation. The biggest improvement occurs in Soure paper and Soure plastic, where every KPI is above the 50%, and the least improved is Condeixa paper, where the vehicle occupation suffers no improvement improvement on the vehicle occupation, maintaining its value on 94%.

For a further analysis, figure 17 compares the Total distance of the routes performed by the three different scenarios.

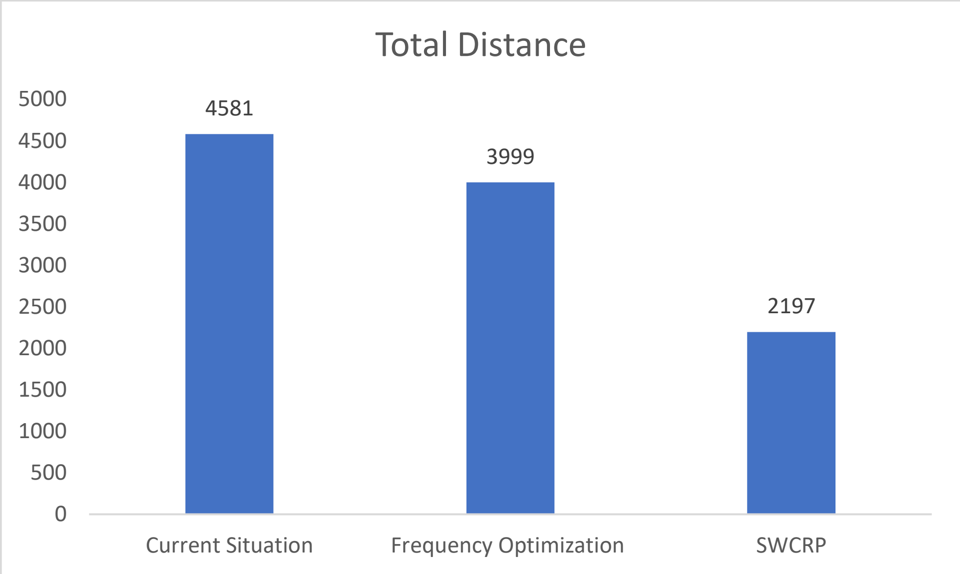

Figure 17: Total distance of all three scenarios

As shown in figure 17, the scenario that contains the least overall distance performed is the SWCRP, with only 2197 kilometers, followed by the Frequency Optimization scenario with 3999. This results in a 52% and 13% decrease when compared to the current situation and frequency optimization scenario, respectively.

6.6 Route Sequence Analysis

The route sequence is an important factor that defines the route optimization. At the moment, the route sequence in ERSUC is pre-defined and does not change. For the frequency optimization scenario, the route sequence was maintained. However, for the SWCRP, the route sequence is dynamic, since the model calculates the best sequence in order to maximize the profit. In this section, the route sequence of the SWCRP scenario will be compared with the other two, in order to observe if there are major variations.

Since there are an elevated number of bins and multiple routes, the comparison will be narrowed to only one route performed in a specific date. Additionally, for a better understanding, the area chosen must be one that suffered no aggregations. Therefore, the paper/cardboard in Condeixa will be studied.

Table 27 compares the route sequence of the current situation versus a route calculated by the VRPP model in the SWCRP scenario in November 4, identifying which bins were visited and the sequence:

Table 27: Route sequences of Condeixa paper

Current Sequence	Bin Location	SWCRP Sequence
1º	Eira Pedrinha-Largo Almas	Not visited
2º	Condeixa-Est.Principal	Not visited
3º	Condeixa-Escola EB 2 3	Not visited
4º	Condeixa-Bairro Fonte da Nogueira	Not visited
5º	Arrifana-R.da Escola	Not visited
6º	Salgueiro-est.principal j. a capela	Not visited
7º	Condeixa-R.da Bretanha	9º
8º	Condeixa-Centro Educativo	Not visited
9º	Condeixa-Piscinas Municipais	6º
10º	Condeixa-GNR	Not visited
11º	Condeixa-Largo Central	Not visited
12º	Condeixa-Ant.Centro de Saude	13º
13º	Condeixa-Centro de Saude	Not visited
14º	Condeixa-R.Manuel Ramalho	10º
15º	Condeixa-Mercado	11º
16º	Condeixa-Urb.Quinta S`Tome	Not visited
17º	Condeixa-Bairro Quinta S' Tomé	6º
18º	Condeixa-a-Velha-Est.Principal	4º
19º	Condeixa-Café Simões	5º
20º	Atadoua-Est.Principal	7º
21º	Alcabideque-Est.Principal	Not visited
22º	Beiçudo-Est.Nacional 342	2º
23º	Bruscos-Est.Principal	1º
24º	Vila Seca-Centro de Convivio	Not visited
25º	Bendafe-junta Freguesia	Not visited
26º	Alcouce-Centro de Convivio	Not visited
27º	Furadouro-R. da Igreja	Not visited
28º	Urb.do Gorgulhao-J.ao Edificio Gorgulhão	8º
29º	Barreira-Intermarche	Not visited
30º	Condeixa-Edificio Palomas	Not visited
31º	Urb.Quinta das Cerejeiras-Estacionamento	Not visited
32º	Condeixa-Bairro Conimbriga 2	Not visited
33º	Condeixa-Urban.Palhacana	Not visited
34º	Condeixa-Bairro Conimbriga 1	Not visited
35º	Condeixa-Bairro Conimbriga 1	3º
36º	Condeixa-Parque de Maquinas	Not visited

37º	Condeixa-Urb. Fornos de Castel	Not visited
38º	Condeixa-Urb.Quinta do Barroso	Not visited
39º	Condeixa-Urb.Quinta do Barroso	14º
40º	Sebal-Rotunda Junto a Escola	Not visited
41º	Sebal-Campo de Futebol	17º
42º	Rebolia de Cima-Est.Principal	15º
43º	Ega-R.Jose Maria Gaspar	16º
44º	Ega-Largo dos Semaferos	Not visited
45º	Ega-R.Casal do Rossio	Not visited
46º	Ega-Largo Alto da Barreira	18º
47º	Campizes-R.da Escola	20º
48º	Campizes-R.Fonte de Campizes	Not visited
49º	Casal do Missa-Junto à Associação	Not visited
50º	Casevel-Est.Principal	22º
51º	Casevel-Ladeira de São Joao	Not visited
52º	Belide-Est.Principal	Not visited
53º	Venda da Luisa-Igreja	24º
54º	Sobreiro-Cruz.	23º
55º	Avenal-R.de S.Tome	Not visited
56º	Sobreiro-Estª Principal	Not visited
57º	Anobra-Largo do Cruzeiro	26º
58º	Anobra-Largo	25º
59º	Casal do Carrito-Associação	Not visited
60º	Casal de S.João-Gimnodesportivo	Not visited
61º	Lameira de Baixo-Est.Principal	21º
62º	Eira Pedrinha-R.das Ameixeiras	Not visited
63º	casal da Legua-Igreja	27º

As seen in table 27, all the bins are visited in the first two scenarios, while only 27 are visited in the SWCRP scenario.

Figures 18 and 19 display the geographic coordinates of the bins collected in the first two scenarios and in the SWCRP scenario, respectively.

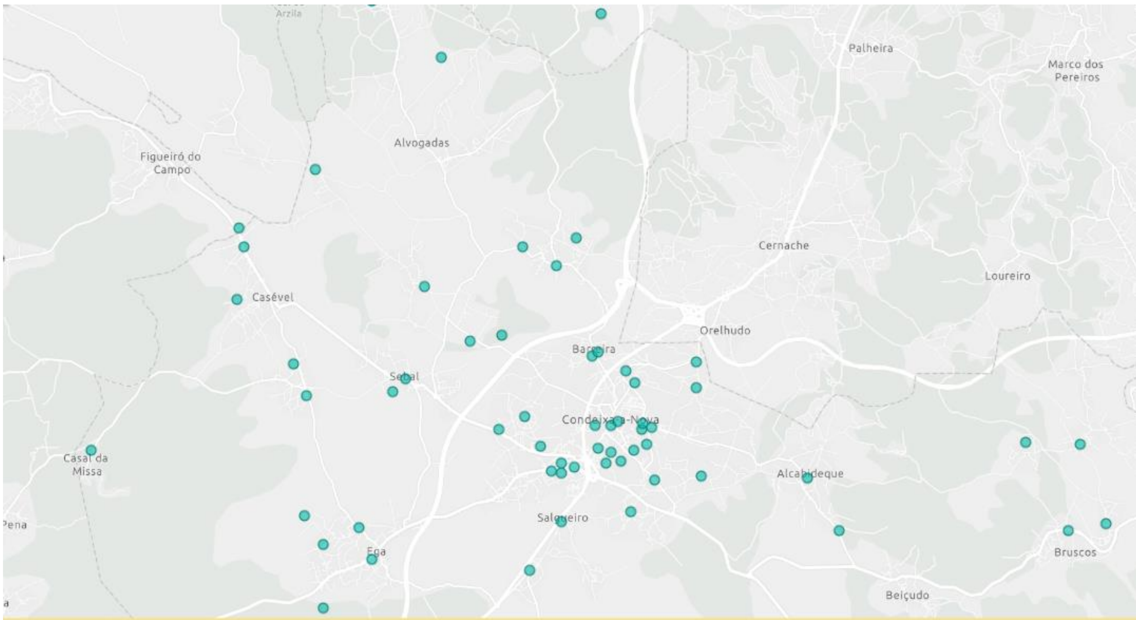

Figure 18:Geographic position of bins collected in the first two scenarios

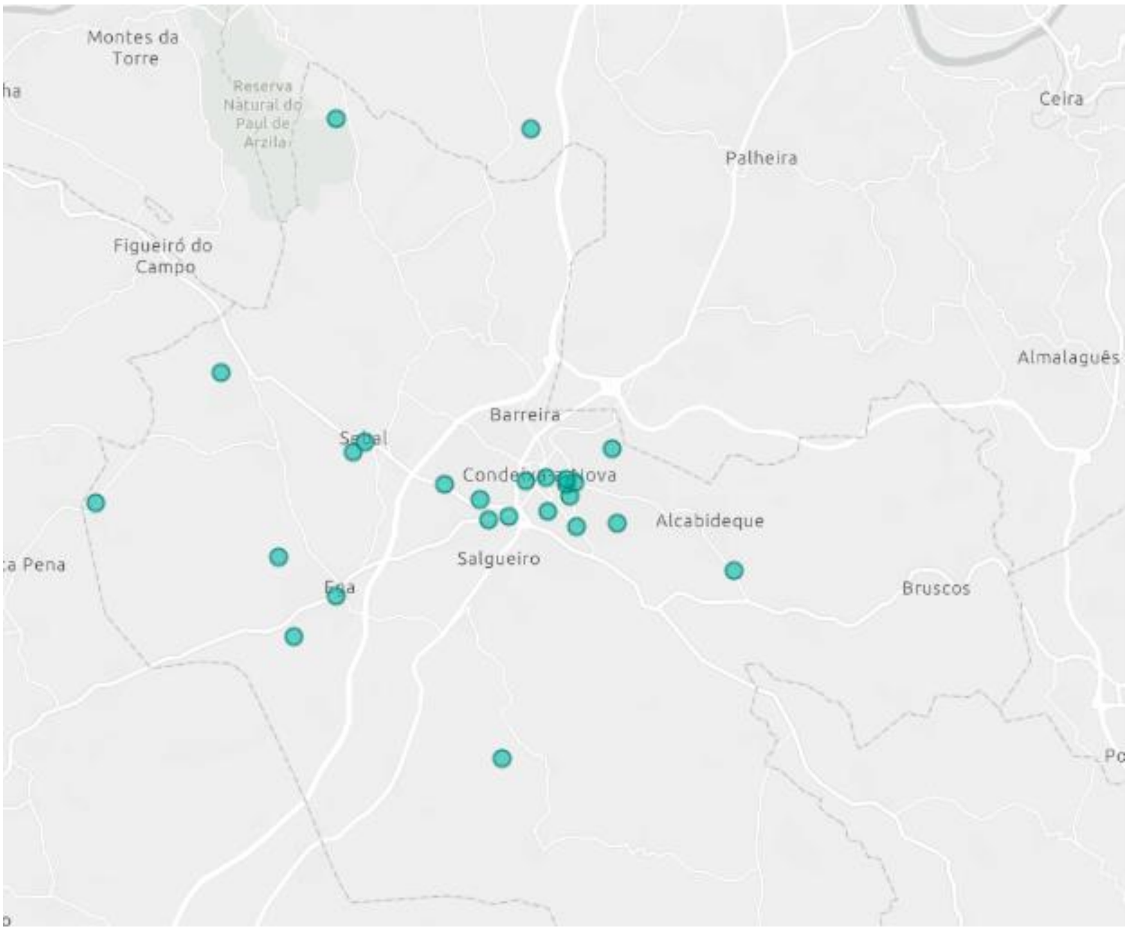

Figure 19:Geographic position of bins collected in the SWCRP scenario

In order to identify the impact of this route sequence, the KPIs total quantity collected, distance travelled and Kg/Km ratio need to be compared. Table 28 displays the different KPIs values, using the average values of quantity and distance of 2017 for the route, versus the model´s outputs:

Table 28: Route sequence KPIs the three scenarios

Scenario	Quantity Collected (kg)	Distance Travelled (km)	Kg/Km
Current	1761	122	14,43
SWCRP	2199	68	32,29
Variation	20%	44%	55%

In table 28 the impact can be observed in the variation of the different KPIs. Regarding the quantity collected, in the SWCRP scenario this value is a result of the quantity collected inside the bins visited, while for the current situation, the bins of the routes all are visited however, if they are not above 50%, they are not collected. Both factors explain the variation presented. However, the route sequence has a significant impact on the distance travelled, since in this case, reduces up to 44% when avoiding visiting all the route´s bins. Such results on a higher Kg/Km ratio.

6.7 Computational Results

In this section the computational results of the SWCRP scenario of all the routes performed over Soure and Condeixa are displayed on Tables 29 to 34.

Table 29: Computational results of SWCRP for Soure P

Soure P				
Date	**Time (sec)**	**Iterations**	**Deviation to optimum**	**Optimum Value (€)**
05/11/2017	23	157040	0%	86,77
11/11/2017	176	2787579	0%	43,99
16/11/2017	65	728341	0%	95,71
25/11/2017	33	363094	0%	80,01

Table 30:Computational results of SWCRP for Soure E

Soure E				
Date	**Time (sec)**	**Iterations**	**Deviation to optimum**	**Optimum Value (€)**
04/11/2017	66	814785	0%	125,41
11/11/2017	269	4010538	0%	127,15
14/11/2017	220	30359208	0%	59,36
21/11/2017	435	5135483	0%	79,53
27/11/2017	1930	17272098	0%	100,93

Table 31:Computational results of SWCRP for Soure V

Soure V				
Date	**Time (sec)**	**Iterations**	**Deviation to optimum**	**Optimum Value (€)**
01/11/2017	293	4070122	0%	828,14
11/11/2017	128	1268314	0%	707,05

Table 32: Computational results of SWCRP for Condeixa P

Condeixa P				
Date	**Time (sec)**	**Iterations**	**Deviation to optimum**	**Optimum Value (€)**
04/11/2017	2	2615	0%	166,60
07/11/2017	12	221088	0%	159,01
13/11/2017	82	3085502	0%	101,04
20/11/2017	15	416640	0%	170,64
27/11/2017	4	7126	0%	101,23

Table 33: Computational results of SWCRP for Condeixa E

Condeixa E				
Date	**Time (sec)**	**Iterations**	**Deviation to optimum**	**Optimum Value (€)**
08/11/2017	157	3653203	0%	256,30
15/11/2017	33	462234	0%	139,16
23/11/2017	10	174839	0%	137,60

Table 34: Computational results of SWCRP for Condeixa V

Condeixa V				
Date	**Time (sec)**	**Iterations**	**Deviation to optimum**	**Optimum Value (€)**
13/11/2017	52	783299	0%	873,44
20/11/2017	768	8183498	0%	853,50

It can be seen that all instances were solved optimally in few minutes. The optimum value refers to the money gained within each route, since the objective of the mathematical model is to maximize the profit.

6.8 Chapter´s Conclusions

In this chapter, the KPIs of the three scenarios were displayed and compared in order to find the best approach for the waste collection operation of ERSUC. After comparing the KPIs variations of the two proposed scenarios *versus* the current situation, the SWCRP scenario was proved to be the best scenario in all categories, especially in the KPIs distance travelled and Kg/Km ratio. Additionally, a route sequence analysis was performed to evaluate the potential impact of a static route sequence versus a dynamic route sequence in a specific route, proving that a dynamic route can have a very significant impact on the distance travelled.

7. Conclusions and Future Remarks

7.1 Conclusions

Nowadays, companies face an extreme competitive environment that requires constant improvements in order to maintain their position in the market. One of the urges for development is associated to the processes' inefficiencies, and for ERSUC, this inefficiency is specially portrayed in its waste collection operations. Such problem led to the creation of this case study, which attempts to improve the waste collection operation through the maximization of its overall profit.

ERSUC is responsible for the waste management operations of 36 districts along Aveiro and Coimbra, with 13625 waste bins, 5324 for glass disposal, 4166 for paper/cardboard and 4135 for plastic/metal. Regarding its waste collection routes, the company has 262 static routes, 108 to collect glass and 77 for paper/cardboard and plastic. Their average route frequency values is 18 days for glass routes, 5 days for paper/cardboard and 6 for plastic, and the average percentage of fill-level of the bins collected in these routes is around 50%.

Upon a more extensive analysis of the routes, its constraints were identified. Among all, the sequence of bins visited in a route and its frequency are considered the ones with higher impact. To mitigate these limitations, two alternative scenarios for the waste collection operation are proposed. The first scenario attempts to optimize the overall frequency of the routes without ever surpassing route´s restrictions. The second optimizes the route sequence, in order to maximize the profit.

Afterwards, a literature review was performed in order to obtain the best practices to be implemented in the previously defined scenarios. It was found that recent advances in technology allow an accurate real-time information of the bin´s fill-levels, and conjugated with a mathematical algorithm, such can potentially increase the efficiency of waste collection operations. In particular, the model of Ramos et al (2018) is the SWCRP (smart waste collection routing problem), which conjugates a VRPP (vehicle routing problem with profit) mathematical model with real-time information provided by ICTs (information and communication technologies). This way, bins are visited according not only to its fill-level, but to its "attractiveness", or potential profit, resulting in very satisfactory results.

The inputs used on the scenarios are information given by the company that suffered extensive treatment together with a set of assumptions required to complement some data flaws. Since ICTs could not be used to feed the models in this case study, the initial amount of waste inside the bins and their daily accumulation rate were calculated using the driver´s measures of the bins when performing the routes to collect the waste. This adaptation led to several data adjustments and assumptions, such as calculations of the daily incrementations of waste levels inside the bins, that increased the complexity of the problem. Therefore, the time horizon of the case study was narrowed to one month, and only a set of routes covering two districts were studied.

Once the models ran, the outcomes could be analyzed and compared. A set of KPIs, such as the total quantity collected, distance travelled, Kg/Km ratio and vehicle occupation were considered for a better comparison of the scenarios and the current waste collection operation. This way, the SWCRP scenario was identified as the better approach, since its KPIs were considerable better than the two other scenarios. More specifically, the SWCRP scenario minimized the overall distance is 52% and 13% when compared to the current operation, and frequency optimization scenario, respectively, while increasing the Kg/Km ratio and vehicle occupation.

7.2 Future Remarks

As future remarks some suggestions are described in order to further compare the waste collection operation with the scenarios implemented.

The first suggestion is the use of ICTs, more specifically, sensors placed inside the waste bins to indicate its fill-level. The implementation of real-information should be analyzed in order to identify the real benefits of the SWCRP scenario.

The second suggestion is to study the scenarios for all the districts, instead of only two. Each district variates in terms of number of bins, overall travel distance and waste disposal rate. Such variations impact on the overall results of the scenarios, which can lead to different overall outcomes.

The third suggestion is to increment the time horizon. Different seasons contain different values on the disposal rate, variating in terms of quantity and disposal location.

The fourth and last suggestion to implement a route service level. The service level is the number of bins that are allowed to overflow. In this dissertation, the service level was considered as 100%, meaning that in the SWCRP scenario, a route was developed every time a bin was overflowing or, or about to, in a specific day. The variation in the service level contains an impact on the routes developed, which ultimately impact the profit of the waste collection operation.

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Appendix

Appendix 1: Brand, acquisition year, typology, registered tare, weight capacity and volume capacity of waste collection vehicles in Coimbra.

District	Brand	Aquisition Year	Typology	Registered Tare (kg)	Weight Capacity (kg)	Volume Capacity (m3)
Coimbra	Volvo	1996	Cargo net	12480	6520	28
	Volvo	2002	Cargo net	11740	7260	28
	Volvo	2002	Cargo net	11700	7300	28
	Volvo	2002	Cargo net	11620	7380	28
	Volvo	2002	Cargo net	11720	7280	28
	Volvo	2002	Electric System	11920	7080	28
	Volvo	2002	Electric System	11800	7200	28
	Volvo	2002	Electric System	11820	7180	28
	Volvo	2002	Electric System	11800	7200	28
	Scania	2009	Electric System	11260	7740	28
	Scania	2009	Compactor	13960	5040	22
	Scania	2009	Compactor	16200	2800	22

	Scania	2010	Compactor	13980	5020	22
	Scania	2010	Compactor	13980	5020	22

Appendix 2: Developed routes of the SWCRP during November 2017 for the districts of Soure and Condeixa.

Districts	Type of waste	Number of bins	Date of Route	Number of Bins Collected	Quantity Collected (kg)	Distance (km)	Kg/Km	Vehicle ocupation	Number of Vehicles Used
Soure P	Paper	77	05/11/2011	53	1618	108	15,00	74%	1
	Paper		11/11/2011	42	1184	110	10,72	54%	1
	Paper		16/11/2011	42	1766	116	15,21	80%	1
	Paper		25/11/2011	46	1699	131	13,01	77%	1
Soure E	Plastic	77	04/11/2011	40	1919	92	20,93	100%	1
	Plastic		11/11/2011	31	1920	89	21,57	100%	1
	Plastic		14/11/2011	57	1515	136	11,11	79%	1
	Plastic		21/11/2011	55	1168	142	8,21	61%	1
	Plastic		27/11/2011	53	500	116	4,32	26%	1
Soure V	Glass	93	01/11/2019	71	9526	124	76,96	100%	1
	Glass		11/11/2019	68	8567	172	49,75	90%	1
Condeixa P	Paper	64	04/11/2011	27	2199	68	32,29	100%	1
	Paper		07/11/2011	53	2195	80	27,51	100%	1
	Paper		13/11/2011	55	1669	93	18,02	76%	1
	Paper		20/11/2011	32	2199	62	35,66	100%	1
	Paper		27/11/2011	48	2059	152	13,53	94%	1
Condeixa E	Plastic	67	08/11/2011	61	3548	130	27,27	92%	2
	Plastic		15/11/2011	42	1918	69	27,64	87%	1
	Plastic		23/11/2011	43	1920	72	26,61	87%	1
Condeixa V	Glass	80	13/11/2011	33	9530	51	185,66	100%	1
	Glass		20/11/2011	42	9529	83	114,21	100%	1