Sub-contraction in waste management

Evaluation of the performance of a waste collection service. A case study at Avery Dennison.

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This thesis is the repository version, an adjusted version, confidential information omitted.

Preface

This thesis is the final product for my degree on Master of Science in Transport, Infrastructure and Logistics at the Delft University of Technology. This research has been conducted in cooperation with Delft University of Technology and Avery Dennison. The present work aims to present a scientific work by applying the knowledge obtained by the Master's courses.

At this point I would like to express my gratitude to the people who assisted me on conducting this thesis project. First of all, I would like to thank the graduation committee for the support and the advice that each one provided throughout the conduction of the project. I would like to express my gratitude towards my supervisors Dr. Yousef Maknoon and Ir. Mark Duinkerken for our weekly calls, the advice and the guidance while developing the models and writing the report. Next, I would like to thank Dr. Jafar Rezaei for motivating me and for providing guidance. I would like especially to thank my daily supervisor Dennis Wagner from Avery Dennison for your flexibility, your understanding and the long conversations we had during which you provided me useful feedback. Furthermore, I would like to acknowledge and extend my gratitude towards every team member from Avery Dennison. Thank you all for your contribution and your valuable feedback.

Finally, I would like to express my gratitude to my family, my friends and my partner for the unparalleled love, help and moral support.

Theonymfi Xydianou
Delft, August 2020

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1 Introduction

This chapter is organised as follows. In section 1.1 we provide general information about the management of the waste. In section 1.2 we introduce the problem that is addressed with this thesis. In section 1.3 we report the main research question and the research sub-questions. Thereafter in section 1.4 we describe the research methodology that we followed. Then in sections 1.5 and 1.6 we report the contribution of this thesis from a practical and a scientific perspective. Lastly, in section 1.7 we present the outline of the thesis.

1.1. Background

The take-make-dispose mindset has been dominant for long in the business practices (Kennishkaarten, nd). That being said, the resources are extracted, goods are produced and the consumers' waste are disposed. The excessive generation of waste affects the ecosystem negatively in various ways such as with emissions of pollutant gases, consumption of water, soil pollution (Mac Arthur, 2015). As a result, because of the severe societal impact the management of the waste has become a major concern (Hannan et al., 2018).

The collection of the municipal waste is one of the most important and expensive logistics activity with regards to the waste management (Markov et al., 2020). Vecchi et al. (2016) has reported that the collection and the transportation of the waste carry approximately half of the sanitary budget of the municipalities. The challenge is that because of the lack of real time information about the amount of waste at the collection spots (Hannan et al., 2018) and because the quantity of the waste generated by the municipalities it is hard to be predicted (Markov et al., 2020) the available resources that are required for the operations. As a consequence, every step of the collection and transportation process has to be planned carefully in order to be cost-efficient. The collection process includes the routing, the idling time, the availability and location of the disposal locations. Among all, the routing is what influences the most the cost of the collection (Sarmah et al., 2019).

The transport problems that examine only routing decisions fall under the classification of the vehicle routing problem (VRP). If inventory decisions are integrated then the problem can classified as inventory routing problem (IRP) (Cárdenas-Barrón et al., 2019). The vehicle routing problem refers to the planning of routes performed by a specific number and with specific characteristics trucks with the objective to serve a number of customers with known demand (Vecchi et al., 2016). Conventional, heuristic and meta-heuristic algorithms have been applied for the optimization of waste collections. The conventional approach is appropriate only for small scale problems when the process becomes over-complicated. The heuristic approaches require much computational effort. The meta-heuristics can provide sufficiently good solutions even if there is available limited information (Hannan et al., 2018). There is rich literature available with a focus on VRP because of its practical perspective and the broad possibilities for extension (Braekers et al., 2016). The Inventory Routing Problem (IRP) integrates the distribution and inventory management and incorporated the dimension of time. The objective of the IRP is to minimize the cost of a distribution within a finite planning horizon considering the routing and the inventory costs (Archetti et al., 2019). This particular problem examines the quantity of products that has to be transported, how often and how it can be combined into the routes (Coelho and Laporte, 2013).

The logistics activities require resources in terms of time, people and equipment. A common practice for management of assets and resources is the cooperation with external organisations to perform several functions (Van Laarhoven et al., 2000). Between the two parties there is a contract in place according to which the subcontracted parties are compensated for the services they provide. Eventually, the cost the main contractor has to cover depends on the type of the sub-contraction (Lundin and Hedberg, 2012b).

The literature provides a wide range of models regarding the routing problems. However there is limited research available that incorporates practical issues such as the sub contraction. To the best of our knowledge, there is limited research regarding how the waste collections can be managed with sub-contracted parties. To this end, the main focus of this research lies on how the decision making of the contractor can be improved on the basis of the different types of sub contraction with regards to the problem of waste management.

1.2. General problem description

This study is conducted in the headquarters of Avery Dennison (referred to hereafter as 'the company'), a company that manufactures and distributes globally labeling materials. [redacted] The waste generators produce a known quantity of waste of each type which is collected by trucks and transported to recovery facilities. The collections are planned during a predefined time horizon with multiple periods of activation. This problem is different from the collection of domestic waste for three reasons. First, the waste is generated by businesses and not households. As a consequence the area of operation is different. Second, the demand is not daily but periodical while a time horizon applies. Third, we study the collection of one type of waste only. Because of that the quantities are much lower.

The shipment of the waste to the recovery facilities can be performed with three different transport methods: either directly or indirectly via a warehouse or via milk runs. Regarding the direct transportation, a truck visits one waste generator at a time. As for the indirect transportation multiple trucks visit pick up material at locations and deliver the it to a warehouse for consolidation. From there, when there is enough quantity that a truck can be fully loaded, a transport to the recovery facility is planned.

It has to be noted, that the transportation and the inventory services are provided by an external organisation. The current agreement regarding the operations of the waste collection service is identical with the one for other operations. The contract among the contractor and the subcontracted entity documents the responsibilities of the parties involved, the shipping method(s), fees, costs and all the important details of the outsourced services. The agreement that is in place makes sure that the external party to provide the resources for the collection in terms of human resources and assets (trucks, warehouses) at any moment within the length of the agreement. The decisions related to the transportation (method of shipment, inventory and routing) are made by the managers of the company.

There are many benefits from the side of the contractor when a subcontracted firm performs the logistics operations. However, the managers of the company have observed that the operations could be improved in terms of asset utilisation. Specifically, they have observed that the capacity of the trucks is not fully utilised resulting to high transport costs per unit of load. On top of this, the waste collections are performed periodically in time and not on a daily basis. Because of that the operations of the waste collection service differ considerably from the other logistics systems of the company. Consequently, the current type of contract is not aligned with the peculiarities of the collection service. Hence, we understand that for this particular system there is room for improvement from the side of the company as far as the profitability and the logistical efficiency are concerned.

We recognize that the cost of the waste collections depends closely on the type of the agreement and on the routing decisions. Therefore, it is essential that the type of contract is in line with the needs and specifications of the operations. Since negotiation is a procedure that the contractor and the subcontracted firm follow before reaching an agreement we introduce an overview of the different types of sub-contraction with the shape of a framework to help the managers of the company to be better prepared when negotiating. Additionally, we investigate how the collection service can be modelled such that sub-contraction is taken into account. The implementation of the model allowed us to investigate the impact of the type of contract on the cost-efficiency. Considering the above, we formulate the problem statement which is the core of this research as follows:

The type of contract among the contractor and the subcontracted organisation is not aligned with the specifications of this waste collection service. It is not clear how the logistical performance of the waste collections is affected by the type of sub-contraction.

Taking all the above into consideration, the scope of this research is twofold. First, to explore the different types of sub-contraction. Second, to formulate a mathematical model for this particular waste collection service that takes into consideration different types of sub-contraction. The outcome of this study does not constitute a tool for decision making but it aims at assisting the managers to make decisions in order to achieve a better logistical performance.

1.3. Research objective and research questions

The objective of this study is to compare how the different types of sub-contraction can influence the logistical performance. Furthermore, there is a focus on investigating the incurred costs for the waste collection service in which several functionalities are performed by an external organisation. The main research question and the sub-questions with which the main research question will be answered are following.

How to improve the decision making given the different types of sub-contraction?

1. Which are the entities involved in the waste collection service and how does it operate?

2. How can we unify the different types of sub-contraction in a framework?

3. How can the decision making be optimised for this category of problems?
4. How can we assess the logistical performance of the waste collection service?
5. How can we develop a model that takes into account different types of sub-contraction regarding this system?
6. How would the different types of sub-contraction influence the logistical performance of the collection service in comparison with its current state?

1.4. Research methodology

We are interested in finding out how the decisions can be optimized given the impact of the sub-contraction on the performance of the waste collection service. Because of the practical perspective of the problem statement a combination of qualitative and quantitative methods were followed and primary data and secondary data were used. The methodological approach is presented in figure 1.1.

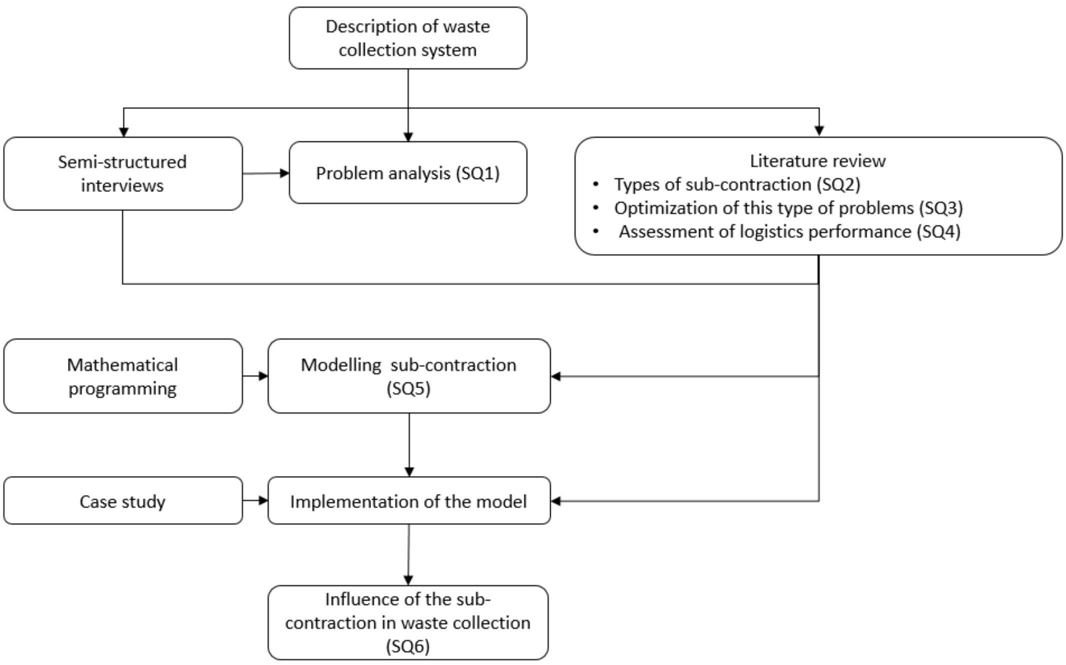

Figure 1.1: Methodological approach for the thesis project

It is essential to get a good overview of how the operations are performed from all perspectives. The information we wanted to gather from the first sub question was to describe how the collections are carried out, explain which are the parties involved and what are their responsibilities. For that, interviews were conducted in order to gather the required information. The interviews were performed in a semi-structured manner. Several questions were prepared, however there was some room for improvisation.

Following, to answer the second sub question secondary data from the literature is used. Therefore, scientific articles were selected from Scopus, ScienceDirect and Google Scholar. Thereafter, their content was analyzed. The method of literature review along with the data gathered from the interviews were used in order to give an answer to the third and fourth sub questions. Based on the problem description, we can understand that the waste collection system incorporates both routing and inventory decisions (see section 1.2). Therefore, it shows similarities with the vehicle routing problem and the inventory routing problem. There is a rich body of literature with regards to these two problems. For example Vecchi et al. (2016); Hannan et al. (2018) and (Reihaneh and Ghoniem, 2019) focused on the vehicle routing problem while Coelho et al. (2012) has introduced the Inventory Routing Problem with Transshipment. Additionally, the sub-contraction has to be included in the mathematical model. Kopfer and Krajewska (2007) and Wang et al. (2015b) have studied the integration of the different types of sub-contraction in the transportation planning problem. These two research papers provided useful guidelines on how the sub-contraction can be modelled.

There are many models for evaluating the performance of the logistics activities such as: Key Performance Indicators (KPIs), Balanced Scorecard (BSC) model, Business Excellence Model (EFQM), Performance Prism model etc (Paddeu, 2016). However, in this study we focus on the logistics activities of waste collection which does not include the production process of the generated waste but only the collection and transportation to recycling facilities. Because of that, the key performance indicators (KPIs) is the most suitable model to use (Paddeu, 2016). To identify the indicators for assessing the performance of the waste collection system information was used from the literature research and the interviews.

Next, the method of mathematical programming was used to model the decision making of the waste collection and the sub-contraction. To do so, the outputs of the first, second and third sub-question were used as inputs in order to develop a model capable of describing the system. For the last sub question, since the collection of the waste is a contemporary real-life problem, the approach of the case study was followed (Ellram, 1996). For that, data was provided by the company. The developed model was implemented with the given real-life data and for the different types of sub-contraction. The output of the implementation showed the extent to which the performance the waste collection service is influenced. To quantify the impact we used the performance indicators that had been identified (SQ4). In that way the sixth sub question was answered.

1.5. Scientific contribution

The scientific community has researched a lot the transport problems: vehicle routing problem (Yeun et al., 2008; Li et al., 2020; Larrain et al., 2018) , inventory routing problem (Coelho et al., 2012; Archetti et al., 2019; Coelho et al., 2014) scheduling problem, milk run problem (Meyer, 2015), etc. The combinational research of the waste collection and the different variations have also been researched a lot (Sarmah et al., 2019; Kim et al., 2006).

Yeun et al. (2008) researched how the VRP and its variations can be modelled and solved. The authors provide useful information about the methods used for solving VRP but they do not examine a practical case study. Li et al. (2020) proposed an algorithm that can solve the VRPTW with high efficiency. In their research they highlight the need for studying the routing problem with more realistic constraints. Sarmah et al. (2019) studied the municipal waste collection and they implemented their model at a real case. The authors focused on how to solve the VRP on a daily basis; a time horizon was not included in their study. Kopfer and Wang (2009) studied the vehicle routing problem with sub-contraction. The authors recommended further research on the impact of subcontracting on the operations' cost.

Taking the above into consideration, the novelty of this thesis proect lies in two parts. First, we consider a problem of collection of industrial waste of a specific type. The collection of industrial waste is different from the collection of the municipal waste with regards to the quantity and the frequency. The waste is generated with a constant rate on a period basis during a predefined planning horizon. Second, we incorporate in our models the different types of sub-contraction. Our scope is also twofold. First, to explore the different types of sub-contraction. Second, to formulate a mathematical model for a waste collection problem that takes into consideration the different types of sub-contraction.

1.6. Contribution from practical perspective

The present thesis has apart from a scientific contribution a practical contribution. From a practical perspective, the results of this thesis will give insights to the management team in how the performance of the waste collection service would change under different circumstances. The focus of the study is how the cost of the collections would change when considering different types of sub-contraction. The knowledge that we provide about how the cost and the performance could change with different types of agreement would help the management team when negotiating with the organisations they are working with.

1.7. Research outline

The outline of the research project is presented in figure 1.2. The overview of the content of each chapter is given below.

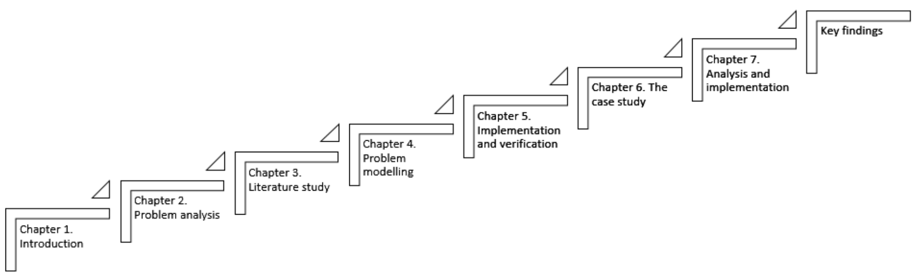

Figure 1.2: The outline of the research project

Chapter 1 introduces the scope and the reasoning of the project. It includes the research elements: the research questions and sub-questions, the problem statement and the contribution of the master thesis from a theoretical and practical perspective. In chapter 2 we present the analysis of the problem that is researched with this thesis project. In chapter 3 the literature study is presented. More specifically it includes all the information that is retrieved from the literature review. In chapter 4 we present how the collection system is modelled. In chapter 5 we explain how the developed model are implemented. In this chapter, the verification of the models is given. In chapter 6 the results of implementation of the models for the case study is presented. In chapter 7 the results of the implementation of the models for various cases are presented. In chapter 8 the answers for the main research question and the sub-questions are provided. The key contributions and recommendations from a scientific and a practical perspective are given.

2
Problem analysis

In this section we present the problem that is analysed with this thesis project. The structure of this chapter is as follows. In section 2.1 we describe the physical system: the physical entities, the boundaries and the operations that take place. In section 2.2 we report the entities that are involved, the decisions they make and the focus of each one. Following, in section 2.3 the restrictions from legal and operational perspective are mentioned. In section 2.4 we introduce the transport problem of the waste collection service. Last, in section 2.5 we present the key points of the problem analysis.

2.1. System description

In order to analyze the problem it is important to understand which are the physical components of the system, which operations are necessary to be performed, what are the restrictions and what is the expected output of the system. The system has three sets of physical entities: the warehouses, the recovery facilities and the waste generators. At the sites of the waste generators, the waste is prepared to be picked-up. From there, the waste is transported by the means of truck either to a recovery facility (direct transport or milk run) or to a warehouse for intermediate storage (indirect transport). At the site of the warehouses, the waste is temporarily stored before being transported to the recovery facility. The final destination of the waste is a recovery facility, no matter the transport method (direct or indirect) that was chosen. The system operates at discrete times within the time horizon; a time step applies. Every waste generator can be visited more than once during the time horizon, but up to one time at each period (see appendices B.1, B.2).

The physical entities are conceptually connected. The waste generators are connected with the warehouses and the recovery facilities. The warehouses are connected with the recovery facilities. These connections illustrate the boundaries of the system. We focus only on what is happening within these boundaries. The physical entities do not form a fully connected graph. Because of this, the trucks can traverse specific routes.

There are several requirements that have to be met in order for the system to function properly. A truck can travel up to a specific distance in a day of operation. If a chosen route exceeds this limit, then more than one day of operation will be needed. Besides the restrictions regarding the shape of the network, further restrictions apply with regards to the number of the available trucks, the loading capacity of the trucks and the storage capacity of the waste generators. Moreover, the quantity of the waste has to overpass a specific amount such that a pick-up can be allowed (see appendix B.1). Also, there are legal requirements. The legal requirements are out of the scope of this research though they will be mentioned in section 2.2.

From operations' perspective, the objective of the system is to minimize the cost of transporting waste from the waste generators to the recovery facilities (see appendix B.1). Therefore, the number and the location of the waste generators, the recovery facilities and the warehouses are key inputs. Trucks are used for the transport. Consequently, the load capacity and the number of available trucks are considered as hard constraints and have to be respected (see appendix B.3). The expected outputs of the system are: the quantity of waste delivered at the recovery facilities, the frequency of the pick ups at every waste generator, the frequency of the collections, the method of transport (milk run, direct, indirect), the route and the days of operation (see appendix B.2).

From the system description we can also understand that there are two levels of decisions that affect the performance: the tactical level and the operational level. The frequency of the pick ups, the frequency of the collections, the transport method and the quantities that are picked up have been classified as tactical level decisions. The days of operations have been classified as an operational level decision. By taking into consideration, the requirements, the objective, the classification and the output of the system we can summarize its characteristics in the lists below.

The inputs of the system.

- Quantity of waste at the site of the waste generators
- Locations of the waste generators
- Locations of the recovery facilities
- Locations of warehouses
- Number of waste generators
- Number of recovery facilities
- Number of warehouses
- Connecting arcs
- Time horizon
- Periods of operation

The requirements of the system.

- Respect the capacity of the trucks
- The number of available trucks is limited
- Respect the capacity of the storage capacity of the waste generators
- Minimum quantity of waste at the sites of the waste generators
- The distance travelled per day of operation is limited
- There are legal requirements

The objective of the system.

- Minimize the transport cost

Tactical level decisions

- Frequency of pickups
- Frequency of collections
- Quantity picked-up
- Transport method

Operational level decisions

- Days of operations

2.2. Stakeholders involved and their objective

The waste collection service has one main function: to collect waste from the locations of the end-users (waste generators) and transport it to the locations of the recovery facilities. The transportation is performed by an external organisation, the waste carrier. Since the company is organising the collections, this entity is named as "the waste broker". The objective is to establish a concrete operational structure and minimize the cost (see appendices B.1 and B.2). Considering the above, four main entities are involved: the waste generators, the waste broker (the company), the waste carrier and the recovery facility. Figure 2.1 illustrates the entities and their key functionalities.

<Removed due to confidentiality>

Figure 2.1: The stakeholders involved.

Currently, the frequency of the service depends on the waste generators. Upon their request, collections are performed. The company (waste broker) functions as an intermediate party (see appendix B.2). The company coordinates and arranges the collections from end to end. The waste carrier is the entity that transport the waste for recovery. The company (waste broker) is the system owner, responsible for coordinating the operations. As for the logistical and service performance, there is no strict target that has to be met. Though, the intention is to improve the cost-efficiency. Despite the fact that the waste generators request the collections, the company is responsible for determining the frequency (when and how often). Along with the responsibilities that are related to coordination and monitoring, the company is partly responsible for the following operational decisions: scheduling, routing, warehousing, intermediate storage. These decisions are made in collaboration with the the waste carrier; before every collection request the operational conditions are discussed and defined. Looking only from the side of the waste carrier, the availability of the trucks and of human resources is their responsibility.

2.3. Transport restrictions

Restrictions apply from logistical and legal perspective. From a legal perspective, the Dutch companies have to follow to the restrictions of EVOA (Europese Verordening Overbrenging Afvalstoffen). The waste carrier has to own the relevant license according to the NIWO (Nationale en Internationale Wegvervoer Organisatie). The license is mentioned as 'Besluit inzamelen afvalstoffen & regeling vervoerders, inzamelaars, handelaars en bemiddelaars (see appendix B.3).

From a logistical perspective, restrictions apply regarding the number of licensed capacitated trucks. Other restrictions apply regarding the quantity that is available for collection. A minimum quantity has to be already available in order to schedule a pick up. Furthermore, the collections are performed on anticipation of orders coming from the waste generators and a specific number of collections can be performed within a day of operation (see appendix B.3).

2.4. Collections' transport problem

The collections are planned within a time horizon of multiple periods. The area of the collections incorporates the locations of the waste generators, one location for intermediate storage (warehouse) and a recovery facility. One type of waste is collected from the sites. At each location, a known quantity of waste per period is generated. The waste is stored in specially designed packages that are put on top of pallets. The pallets have standard dimensions and can carry specific quantity of waste. The minimum amount of pallets that can be picked up at one location is specified by the company.

To collect the waste, three transport methods apply: the direct transportation, the indirect transportation with intermediate storage in the warehouse and the milk run. The company does not own a fleet of trucks but the orders are forwarded to the waste carrier. The waste carrier owns a fleet of licensed trucks with a specific capacity (see appendix B.3). The cost of the collections has several components which are determined by the contract among the company and the waste carrier. The main costs are the transport costs and the storage cost. The waste carrier offers dedicated services and the freight cost approaches a function of the transported quantity and the travelled distance (see appendices B.3 and B.1).

2.5. Concluding remarks

From the problem analysis that was presented in the paragraphs above we can answer the first sub-question: ***'Which are the entities involved in the waste collection service and how does it operate?'***. Three active stakeholders are involved in the waste collection service: the company, the waste generators and the waste carrier. The objective of the system is to minimize the cost of transporting waste from the sites of waste generators to the recovery facilities.

The boundaries of the system that we are analyzing are shaped based on the connecting arcs among the physical entities. The system functions according to tactical and operational level decisions given that a number of legal and logistical requirements are satisfied. The legal requirements are outside of the scope of this these therefore they will not be analyzed.

Based on the characteristics of the system, the decision makers have to decide on the frequency of the service, the transport method, the collected quantities and the routing. In order to analyze the system, it is important to develop a model in a way that all the characteristics of the system are captured. Moreover, in order to assess the performance of the system, indicators are going to be used, extracted from the problem analysis but also from literature study. These will be explained in the following sections (see section 3).

3

Literature study

The problem that we research has many features. Because of that we identify four different streams of literature: the Vehicle Routing Problem (VRP), the Inventory Routing Problem (IRP), the different types of sub-contraction and the indicators with which the performance of the logistics operations can be assessed. The structure of this chapter is as follows. In section 3.1 we explain the different transport methods. In section 3.2 we provide a review of several researches with a focus on the Vehicle Routing Problem and its variations. Next, in section 3.3 attention is given to the Inventory Routing Problem. Finally, in sections 3.5 and 3.4 we present an overview of the literature related to the assessment of the logistics operations and the different types of sub-contraction.

3.1. Transport methods

Meyer (2015) presented a classification of the road transport concepts based on the German Association of the Automotive Industry (VDA). He reported three standard transport methods: direct, groupage service by area contract freight forwarders and milk runs. The direct transport method refers to a point to point connection. At this case, the company gives the order to the freight forwarder a few days before the pick up. The cost for this service depends on the driving distance, the tour duration and the weight or volume of the cargo. At the case of the groupage service by area contract freight forwarders, the transported loads are consolidated and then are distributed to the destination centres. The cost of this method is based on tariff tables. It depends on the weight and the distance traveled. Setiani et al. (2018) studied the milk run logistics method. The milk runs are defined in the literature as routes with fixed pick up and delivery dates. More than one sites are visited such that a truck is fully loaded. They defined milk runs as the transport system in which vehicles are rotated based on a predefined schedule. The key characteristic of the milk run logistics method is the regularity. Pick ups and deliveries are scheduled at a specific time on a predefined route.

The vehicle routing problem is applicable to numerous practical problems. Due to its broad applicability, the current models are trying to incorporate real-life constraints and features such as: time windows for pick up and delivery, variable demand and frequency of service (Braekers et al., 2016). There are many variations of the vehicle routing problem, many of them take into account the time horizon. For instance, the period vehicle routing problem. Other variations take into account the storage costs such as the inventory routing problem (IRP). Another variation is the period vehicle routing problem with service choice where the frequency of the service is a decision variable and not a parameter.

3.2. Vehicle routing problem

Vecchi et al. (2016) and Hannan et al. (2018) studied the vehicle routing problem for the collection of waste at a city environment. Reihaneh and Ghoniem (2019) examined the vehicle routing allocation problem. These studies examined the optimisation of the routing decisions under conditions of static demand and infinite time horizon. Braekers et al. (2016) conducted an extensive literature review and presented a taxonomy of the variations of the vehicle routing problem. Yeun et al. (2008) gave a detailed overview of the different mathematical models that have been used for solving the vehicle routing problem. There are exact algorithms, heuristics such as: tabu search and simulation annealing algorithms, meta-heuristic algorithms such as genetic algorithms and hybrid approaches such as neural networks and ant colony optimisation.

Vecchi et al. (2016) developed a three-phase sequential approach for optimizing the routes of trucks that collect solid waste. Heuristics are frequently used to solve the vehicle routing problem problem more efficiently. However, this method is complex because of the formation of sub-routes, the number of which is increasing with the increasing number of nodes and arcs. The methodology that is presented by Vecchi et al. (2016) allows the extraction of solutions without the formation of sub-routes. At the first phase, an adapted version of the p-median problem is used to divide the area that has to be served by the vehicles. At the second phase the capacitated arc routing problem was used. At the third phase, an adapted version of the hierholzer algorithm is applied to generate the routes of the trucks. Hannan et al. (2018) researched the problem of the waste collection with the objective to minimize the financial and environmental impact. In order to solve the problem the authors proposed an adapted version of the particle swarm optimization algorithm. Thereafter, in order to validate the model six different data sets were used for a hypothetical area with the same amount of identical vehicles with fixed capacities and static demand.

Reihaneh and Ghoniem (2019) examined the vehicle routing allocation problem. They examined the decision making about the allocation of goods and services to locations and the routing of the vehicles from the central depot to the customers. They introduced a branch-and-price algorithm to solve the problem. Firstly, the authors presented the problem as a set partitioning model. Instead of using one of the commercial solvers they developed a branch and price algorithm. For the pricing sub-problem the authors used an exact dynamic programming algorithm and five heuristic variants to maintain the computational effort within rational boundaries.

Sarmah et al. (2019) proposed a cost minimization model for vehicle routing problem and the Clark and Wright heuristic algorithm was applied. For the optimization, they used the ArcGIS tool. The demand was periodic. Li et al. (2020) investigated the vehicle routing with time windows and synchronized visits. They proposed an improved ABC algorithm and they considered a realistic application. Firstly, they modelled the dispatching problem with synchronized visits and thereafter they took into consideration the constraints derived from the practical application. They considered the demand as static. Chao et al. (1995) studied the periodic vehicle routing problem (PVRP) where the planning period is M days instead of one day. In their study they considered the frequency as a parameter and the schedule as a variable.

Francis et al. (2006) introduced the periodic routing problem with service choice. The periodic vehicle routing problem is the generalisation of the vehicle routing problem. The difference is that the time horizon is incorporated. The vehicle routes are synthesized for a t-day period. In addition, the frequency is modelled as a decision variable. The authors developed an heuristic variation of the exact method that can solve large problems. They concluded that the introduction of the service choice improved the performance of the system. Hosseini et al. (2014) proposed a model that takes into account three transport methods: direct transportation, indirect transportation with cross-docking and milk run. To solve the problem they applied the hybrid approach of harmony search and simulated annealing. They reported that the proposed model can solve large problem instances.

3.3. Inventory routing problem

Archetti et al. (2019) focused on the inventory routing problem with logistic ratio (IRP-LR). They examined the minimization of the cost of the distribution of products from one depot to a set of customers during a finite time horizon composed of days. The logistic ratio refers to the ratio among the routing cost and the amount of distributed products. The authors proposed an exact algorithm which allowed them to extract a solution for a large number of customers and a long time horizon. Coelho et al. (2014) studied several variations of the Inventory Routing Problem under a dynamic and stochastic environment. The authors solved the dynamic and stochastic version of the problem by considering the current state of the inventory and by forecasting the demand. Additionally they incorporated lateral transshipments within a rolling time horizon. Coelho and Laporte (2013) developed a branch-and-cut algorithm to find an exact solution for several Inventory Routing Problems. They solved the problem under different inventory policies, with transshipments, homogeneous and heterogeneous fleet and consistency features as far as the driver is concerned. Bertazzi et al. (2019) solved the multi-depot Inventory Routing Problem whereas the customers were assigned to different depots. The variation of IRP that the authors studied incorporated static demand and a finite time horizon whereas the number of customers that had to be assigned to a depot was not constant but it could be flexible. They proposed a thee-phase matheuristic algorithm based on a decomposition approach in which firstly the customers were clustered, then the routes were constructed and lastly the optimal solution regarding the route and the quantity transported was found. The matheuristic algorithm was applied at real case which demonstrated its effectiveness. Coelho et al. (2012) studied the inventory routing problem with transshipment. The authors developed an adaptive large neighborhood search heuristic to solve four variations of the problem: with transshipment (IRPT), without (IRP) under an order-up-to policy (OU) and under a maximum level (ML) policy. The OU policy considers that the transported quantity fills in the capacity offered by the customer while the ML that the suppliers determined the amount as long as the capacity of the customer is respected.

Markov et al. (2020) researched the stochastic version of inventory routing problem for optimizing the collection of recyclable waste. The authors developed a neighborhood algorithm and they considered a heterogeneous fixed fleet and every type of waste flow was considered as a different problem. In addition, time windows regarding the visited facilities are taken into account in the model and the duration of each tour based on the the legal restrictions. The developed model was stochastic and dynamic the capture the fact that the container level was changing daily.

3.4. Vehicle routing problem with sub-contraction

Lundin and Hedberg (2012a) researched the different types of contracts between a shipper and a forwarder. They identified four different types of contracts: dedicated services, periodical services, truckload services and less-than-truckload services and they compared them on a basis of service costs, utilization and coordination costs. The authors classified the contracts as "behavior" and "outcome". The dedicated and periodical services fall under the former classification and the truckload service and less than truck load service under the latter. The main difference among the behavior oriented contracts is the length of the service commitment. For the dedicated service contracts the truck owner has to be compensated for the number of hours and distance travelled. However, the periodical service contracts dedicate the trucks for specific period(s) of time within the length of the contract. With regards to the outcome oriented contracts, the truck owners are compensated based on the number of hauls. Since the shipments can be either with fully loaded trucks or with less that fully loaded trucks, the type of contract is different in each case and the cost per haul varies.

Kopfer and Krajewska (2007) studied the approaches that can be followed in order to integrate the sub-contraction in a transportation planning problem. They reported that in case of less than full truck load transport fixed tariffs are imposed and for full truck load transports two different types of sub-contraction are considered. First, complete tours are charged on a basis of fixed tariffs that depend on the distance to be driven. Second, the subcontractors charge the contractor on a daily basis with a flat rate. Moreover, Kopfer and Wang (2009) studied how the different types of sub-contraction can integrated into the Vehicle Routing Problem. The authors developed a mixed integer linear programming model. Their findings showed a reduction in the total transportation cost. However, because of the complexity the size of the problem solved was very limited.

Table 3.1: Overview of the types of sub-contraction based on the literature

Transportation agreement	Description	Compensation	Literature support
Daily basis	Provide an agreed number of trucks.	Multiply the route length with the tariff rate per DU	(Wang et al., 2015a) ; (Kopfer and Wang, 2009)
Tour basis	The predefined flat-rate is paid for a complete day without violating the max traveled distance.	The predefined flat-rate is paid for a complete day	(Wang et al., 2015a)
Dedicated	The forwarder is charged on a base of a cost function. Trucks are dedicated for shipments at any moment within the duration of the contract.	tariff/ time unit and tariff/distance unit	(Lundin and Hedberg, 2012a)
Periodical	The forwarder is charged on a base of a cost function. Trucks are dedicated for shipments at specific periods of time within the duration of the contract.	tariff/ time unit and tariff/distance unit	(Lundin and Hedberg, 2012a)
Truclkload service	Prices are specified per haul.		(Lundin and Hedberg, 2012a)
LTL	Prices are specified per truck space.		(Lundin and Hedberg, 2012a)
On route basis	LTL are combined to FTL orders	tariff/distance unit	(Kopfer and Krajewska, 2007)
On flow basis	The service is measured based on the flows of the carried cargo.	tariff/distance unit+tariff/ DU	(Kopfer and Wang, 2009)

3.5. Assessment of the logistics performance

The logistics systems incorporate the management of the supply chain, the supply of the materials, the production process, the inventory and the transportation of goods. The transport and the logistics activities are related to the customer satisfaction and to the success of a business (Paddeu, 2016). As a result, the efficiency of the logistics operations is vitally important for the successful operation of a system. The most commonly used models for evaluating the performance of the logistics activities are the following (Paddeu, 2016):

- Key Performance Indicators (KPIs)
- Balanced Scorecard (BSC) model
- Business Excellence Model (EFQM)
- Performance Prism model
- Supply Chain Operations Reference (SCOR) model

The focus of this study is on the logistics activities of a collection system which does not include the production process but only the collection and transportation. Because of this we consider the key performance indicators as the most suitable model to use. Paddeu (2016) proposes several indicators for measuring the performance of logistics activities such as: days order late, logistics cost per unit, percent error pick date. The authors reviewed the methods and the indicators for assessing the performance of the whole supply chain. From their literature review they concluded that the measurement of the performance is necessary for planning the activities during the decision making procedure. Caplice (1995) reported that a performance measurement system can provide guidance to the decision makers for deciding which actions have to be taken. Odette (2007) presented a list of key performance indicators for carriers and logistics service providers. They proposed the time, the security, the alert and the efficiency as the main criteria for evaluating the logistical performance. As for the indicators they proposed the arrival precision, the pick up discrepancy alert, the accidents and the late delivery alert.

Šimková and Konečný (2014) studied the key performance indicators for logistics and road transport. They mentioned that the KPIs can demonstrate how the logistics system evolves over time and they highlight the importance of having clear and easy to understand indicators. The KPI's aims at helping the managers in making decisions at a strategic level and at operational they illustrate which areas have to be improved the most. They propose the transport performance index for assessing the road transport which incorporates six core areas: cost, operational, service, compliance, maintenance, and environment. In order to select the most important indicators they conducted a questionnaire based study; more than 1000 road transport companies answered. Additionally they mention a list of indicators that are measurable: fuel efficient, transport performance [tons/km], number of orders, number of satisfied customers, and number of damaged goods. The authors suggest that a method on how to collect the data for the indicators has to be further researched.

Krauth et al. (2005) conducted a literature review survey and came up with a framework that can capture the dynamic nature of the key performance indicators on logistics. They clustered the indicators based on the perspective (internal or external) and as short term or long term. To validate the framework an expert was interviewed. From the internal perspective, the effectiveness, the efficiency satisfaction, the innovation, the number of trips per unit of time, the labour utilization, the on time deliveries were a few of the suggested indicators. From the external perspective, the society's point of view, the transparency to the customer, the order size flexibility and the transportation price were some of the proposed indicators.

Table 3.2: Overview of Key performance indicators extracted from the literature

Performance Indicator	Literature support
On time delivery Percentage	(Paddeu, 2016; Caplice, 1995; Odette, 2007; Liberatore and Miller, 2016; Krauth et al., 2005; Limsomkiat and Vanichchinchai, 2019)
Logistics costs as percentage of revenue	(Paddeu, 2016)
Average order cycle time	(Paddeu, 2016)
Percent errors pick rate	(Paddeu, 2016; Caplice, 1995; Krauth et al., 2005; Šimková and Konečný, 2014)
Logistics costs per unit	(Paddeu, 2016; Šimková and Konečný, 2014; Krauth et al., 2005; Liberatore and Miller, 2016; Limsomkiat and Vanichchinchai, 2019)
Ton-Miles transported	(Caplice, 1995; Šimková and Konečný, 2014; Krauth et al., 2005)
Number of items stored	(Caplice, 1995)
Number of units packed and loaded	(Caplice, 1995; Šimková and Konečný, 2014; Sangwan, 2017; Krauth et al., 2005)
Pickup discrepancy alert	(Odette, 2007)
Number of accidents	(Odette, 2007)
Late/early delivery alert	(Odette, 2007)
Filling rate in transport	(Odette, 2007; Krauth et al., 2005)
Handling cost	(Sangwan, 2017; Liberatore and Miller, 2016; Limsomkiat and Vanichchinchai, 2019)
Storage cost	(Sangwan, 2017; Liberatore and Miller, 2016; Limsomkiat and Vanichchinchai, 2019)

Sangwan (2017) investigated the activities, the decisions and the performance indicators related to the reverse logistics. Firstly, the authors reported the location-allocation of the collection centers as a decision variable assessed by the collection cost, waste generation and the customer satisfaction. With regards to the methods of collection, the authors proposed: by the manufacturer, with retailers and with third party logistics providers. The evaluation criteria were based on the quantity transported, the operating cost, and the initial investment. The author additionally suggested that further research is needed to fine tune the different performance indicators for other industry segments.

J. Liberatore (2015) analyzed the performance metrics data from 247 manufacturing and service firms. The scope of their study was to cluster the firms based on their operational and planning priorities. What is interesting from their research are the metrics they used: Inventory carrying cost (% of revenue), warehouse management cost % of revenue), obsolete inventory (% of inventory value), transportation spend (% of revenue), supply chain planning cost, on-time delivery performance, forecast accuracy (%), days in inventory (number of days). Their analysis (PCA followed by cluster analysis) revealed four

Table 3.3: Classification of reviewed studies

Problem	Author	Algorithm	Demand	Inventory	Time Horizon	Frequency	
						No/Yes	Decision Variable/ Parameter
VRP	Sarmah et al. (2019)	Heuristic	Stochastic	No	No	No	-
VRP	Li et al. (2020)	Heuristic Meta-heuristic	Deterministic	No	No	No	-
VRP	Yeun et al. (2008)	Heuristic	Deterministic	No	No	No	-
Milk Run	Hosseini et al. (2014)	Hybrid	Deterministic	Yes	Yes	Yes	Decision~ variable
PVRP	Chao et al. (1995)	Heuristic	Deterministic	No	Yes	Yes	Parameter
PVRP-SC	Francis et al. (2006)	Heuristic Exact	Deterministic	No	Yes	Yes	Decision variable
IRP	Coelho and Laporte (2013)	Exact	Deterministic	Yes	Yes	No	-
IRP~	Coelho et al. (2012)	Heuristic	Deterministic	Yes	Yes	No	-
IRP	Archetti et al. (2019)	Exact	Deterministic	Yes	Yes	No	-
IRP	Coelho et al. (2014)	Heuristic	Deterministic Stochastic	Yes	Yes	No	-
MPIRP	Our problem	-	Deterministic	Yes	Yes	Yes	Parameter

different types of firms. A interesting conclusion of theirs was that no matter the logistics orientation of the firms, the profitability was not different statistically. From that, they concluded that the firms can be superior between each other given the logistics operational approach. Limsomkiat and Vanichchinchai (2019) explored the satisfaction levels among the shippers and international freight forwarders. They conducted a survey that was filled in by companies in the furniture industry. The authors analyzed statistically the results. The authors distinguished the performance in six dimensions: reliability, assurance, tangibles, empathy, responsiveness and service cost. The analysis showed that the service cost was the most important logistics service quality indicator for the shippers. The researchers recommended that the measurement instruments should be also applied to other types of logistics providers.

3.6. Concluding remarks

In section 2.5 we mentioned that in order to analyze the system, we have to develop a model in such a way that its characteristics are captured: requirements, physical entities, objective, decisions, boundaries etc. In addition to this, it is important to find several performance indicators in order to better understand the output of the system. The literature study allowed us to find out how to model this particular system and how it can be assessed.

First, we researched into the literature the different transport methods, the vehicle routing problem and its variations, the types of sub-contraction and the logistics performance indicators. This information was necessary in order to understand how the problem of this thesis project can be modelled. Next, we made an overview of the types of sub-contraction and an overview of the logistics performance indicators.

While looking in the studies relevant to the routing problems, we made a classification based on four aspects: the demand (deterministic or stochastic), the time horizon (one day or t-day period), the inventory (storage cost are taken into account or not) and the frequency of service (parameter or decision variable). Table 3.3 shows the classification of the studied problems that were met in the literature.

At this point we can conclude that with the information gathered from the literature study we have answered the second, the third and the fourth sub-question. Regarding the second sub-question: ’***How can we unify the different types of sub-contraction in a framework?’***. Figure 3.1 depicts the different types of sub-contraction with the shape of a framework. From the literature we found out that the types of sub-contraction can be classified on dedicated and periodical services. The dedicated services provide transport services at any moment in time. The periodical services offer services at discrete moment within the length of the contract.

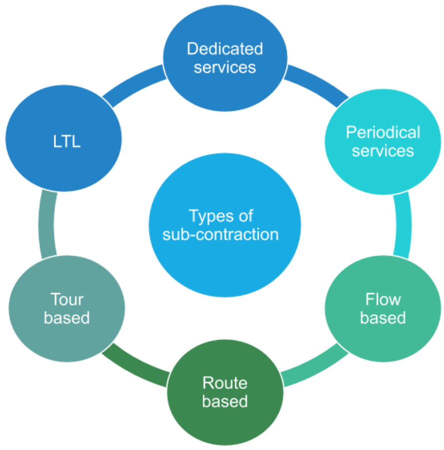

Figure 3.1: Framework of different types of sub-contraction

From a cost perspective, we found out that the relevant types of sub-contractions are: route based, tour based, flow based and less-than-truckload. The cost function of the route based type of sub-contraction depends only on the distance. For the tour based, the cost function depends on the number of tours that are performed. As for the flow based, the cost is a function of the quantity transported and the distance travelled.

Regarding the third sub-question: ***’How can the decision making be optimised for this category of problems?’***, we can conclude that the tactical level decisions of the system (see section 2.1) can be modelled as a multi-period inventory routing problem. The study of the literature gave useful insights in how to optimize the tactical level decision making. We model the decisions at operation level with a simplistic model, based on logical thinking, without consultation from the literature (see section 4). What we want to achieve with modelling the system is to understand how the decision making can be improved and towards which parameter it is more sensitive. In the paragraph below we refer to the ’modelling of the decisions at tactical level’ as ’our problem’.

Table 3.3 demonstrates the scientific studies that were studied along with our problem. The problem that we analyze has deterministic demand, inventory cost, applies at a specific time horizon and the frequency is represented with a time step. From the literature study we understood that our problem has similarities with the inventory routing problem and the period-vehicle routing problem. With the first one, there is an overlap in modelling of the inventory (storage). With the second one it is common the fact that the planning period is greater than one day. On top of this, the service has to be offered at multiple times within the time horizon. Taking the above into consideration, we concluded that our problem falls into the category of the multi-period inventory routing problem.

Regarding the fourth sub-question: ***'How can we assess the logistical performance of the waste collection system?'***, we used inputs from both section 2 and this one. From section 2, we use information from the decomposition of the problem. Three transport methods are used to transport waste: direct, indirect and milk run. Furthermore, the focus of the system is to transport waste at the recovery facilities with the minimum transport cost. Therefore, we can conclude that the number of collections per transport method, the days of operation and the transport cost can be used to assess the logistical performance of the system. From this section, we use information that is illustrated in table 3.2 where we summarise the key performance indicators. From this table we found useful: the cost/unit of load and the filling rate in transport.

4
Problem modelling

The structure of this chapter is as follows. First in section 4.1 we explain the linkage of this section with the previous one. In section 4.2, the design alternatives and the motivation for modelling them is reported. Thereafter, in section 4.4, we present the indicators with which the results will be assessed. Then in sections 4.5 and 4.6, the developed models regarding the tactical/operational-level decisions are presented. Following, in section 4.7 we present how the different types of sub-contraction will be modelled.

4.1. General approach

The problem analysis revealed several aspects of the waste collection service that need to be investigated. In order to investigate how the collections can be managed with the minimum cost, we modelled the decision making at tactical and operational level. The scope of the investigation is limited by the boundaries of the system (see section 2.1).

For modelling the decisions at tactical level, we collected information from the literature (see section 3.6). For the operational level, we developed a simple model based on logical thinking. The decisions at each level are modelled separately. The connecting link among the two models is that part of the results from the implementation of the model of the tactical level decisions is used as input for the implementation of the model of the operational level decisions. In section 4.3 we explain better the modelling process in a conceptual manner. It must be noted that while developing the models we took into consideration the fact that we should be able to implement the models with several (hypothetical) cases. The different cases that the model should be capable of implementing are considered as requirements. The requirements are presented in section 4.2.

For the mathematical formulations we used information from the literature. One of the conclusions of the literature study (see section 3.6) was that the problem falls in the category of the multi-period inventory routing problem. The formulation presented by Coelho and Laporte (2013) is the basis of the model for modelling the decisions at tactical level. Further details about the mathematical formulation of the author is given in the appendix C. After the implementation of the models with the data from the company, we evaluated the performance with several indicators derived from the literature and the interviews. These indicators are presented in section 4.4.

4.2. Model requirements

The analysis of the problem is presented in section 2. The system's characteristics are: the locations of the waste generators, the quantities generated, the capacity of the warehouse facilities at the waste generators' locations etc (for a more detailed description see section 2.1)

In the literature study we found literature support from several studies who have already investigated and modelled this type of problems. The literature support along with the implementation of the model in a real case from the industry will help us to validate the models. Li et al. (2020), Yeun et al. (2008), Hosseini et al. (2014), Coelho and Laporte (2013) have considered the demand as deterministic in their models. Furthermore, we met into the literature studies that modelled distance restrictions, for instance in the study of Kopfer and Wang (2009).

In table 4.1 we present the hypothetical cases that we intent to examine with regards to variations in demand, storage capacity, number of warehouses/recovery facilities/waste generators and types of sub-contraction. The implementation of the model with these scenarios will illustrate the extent to which the parameters of the transport problem influence the transport efficiency and the cost.

Table 4.1: Model requirements

Sub-contraction	Capacity	Constant Demand	Deterministic Demand	Multiple warehouses	Multiple recovery facilities	Waste generators
Tour based	·	·	·	·	·	·
Route based	·	·	·	·	·	·
Flow based	·	·	·	·	·	·

We want to study three main domains of scenarios. Each one of these concerns a different type of sub-contraction: route based, tour based and flow based. We consider that the transport services can be offered at any moment within the length of the contract (see appendix B.1). As a result, these types of sub-contraction are under the umbrella of the dedicated services type of sub-contraction (see section 3). For every type of sub-contraction the cost has different components.

The hypothetical cases that should be implemented with the model are related to different storage capacities (including uncapacited). Other cases present differences in how the demand is distributed over the time horizon. More specifically, with the constant demand we considered that the quantity of waste that is available at the locations of the waste generators is known and constant per month. With the deterministic we examined the case where the demand varies. For all the examined cases the quantities are known. The last three sets of cases are related to different networks of collections with multiple warehouses, multiple recovery facilities and different distribution over the space of the waste generators.

4.3. Conceptual process of modelling

In section 2.1 we discussed about the boundaries and the requirements of the system. We dis-aggregated the decision making in tactical level and operational level. Figure 4.1 shows the conceptual design of the modelling of the decision making and illustrates the inputs and the outputs at both levels of decision making.

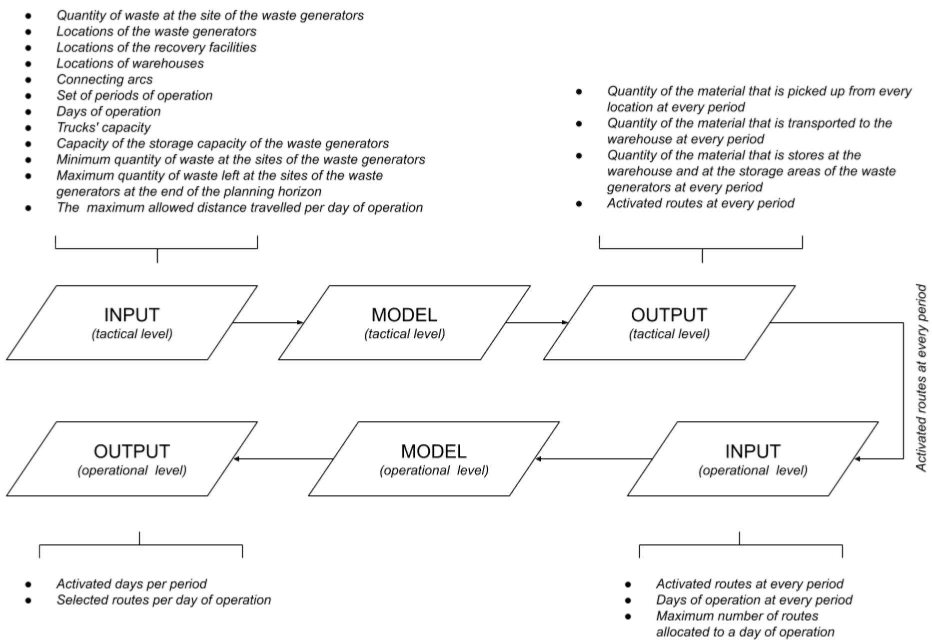

Figure 4.1: Conceptual design of the modelling process.

For modelling the decision making at tactical level, information related to the network of collections is required such as: the locations of the waste generators/recovery facilities/warehouses, the connecting arcs etc. Moreover, information with regards to the demand for collection will be used and the available storage capacity of the waste generators and the warehouses. As far as the planning of the collections is concerned, data about the periods of operation, the minimum quantity of waste for pickup and the maximum quantity that can be left at the end of the time horizon is also used. Besides that, data related to the capacity of the trucks is used.

Following, the output of the model for the tactical level decision making will give us results about the quantities transported, the frequency and the selection of the followed path. From these results, the selected paths at every period will be used as input for the model of the operational level decisions. Along with this input, information about the days of operation at every period is used. To be more specific, we took into account that every period consists of a set of available days of operation. With this model we aim at allocating the activated paths to days of operation. The modelling of the operational level decisions will provide the total number of activated days of operation within the planning horizon. Besides that, it will also show the allocated paths to the avalable days of operation.

4.4. Evaluation and assessment

To investigate how the state of the system of the collections could change (see table table 4.1) several indicators (see section 3.5) are used. These indicators were extracted from the literature review and the interviews with the managers of the company. By using these metrics we interpreted the results obtained from the implementation of the models. Below, the performance indicators are enlisted:

- Frequency of pickups (see section 2.1)
- Quantity of material collected within the time horizon (see section 2.1)
- The cost per unit of load (Caplice, 1995; Krauth et al., 2005; Šimková and Konečný, 2014)
- Frequency of collections with direct/indirect/milk run transport method (see section 2.1).
- Total number of the days of operations (see section 2.1).
- Filling rate in transport (Krauth et al., 2005; Odette, 2007)

We distinguish the frequency of pickups and the frequency of the collections. With the frequency of pickups we define how many times a truck has picked up waste from a waste generator during the planning horizon. With the frequency of collections we define how many routes are performed via which waste has been picked up from one or more waste generators.

4.5. Modelling the decisions at tactical level

In this section, we present the mathematical formulation for modelling the decisions at tactical level. As discussed in the paragraphs above, the problem of modelling these decisions has been categorized as multi-period inventory routing problem (refer to hereon as MP-IRP). The MP-IRP is defined on a graph $G(N, A)$. Let A be the arc set and $N = WG \cup W \cup F \cup D = \{0, \ldots, n\}$ the vertex set whereas WG represent the set of waste generators, F the set of recovery facilities, W the set of warehouses and D the depot. Let $T = \{1, \ldots, p\}$ be the set of periods of the time horizon. The storage capacities I_i^t of the waste generators I_w^t are constrained by $IMax_i$ during the whole time horizon T. The warehouse is uncapacitated. The holding cost f_2 represents the storage cost when material is kept in the warehouse during a period of time. The cost f_4 represents the cost of waiting. Since a truck can travel a maximum number of kilometers in a day, a path may need more than one day in order to be completed. For every additional day required a cost f_5 for waiting is incurred. Additional costs H are incurred for transporting the waste to a warehouse $w \in W$.

At the first period of the time horizon, there is no stored material at the facilities of the waste generators and the warehouse. During the time horizon, v_i quantity of material is added at the storage facility I_i^t of the waste generators $i \in WG$ at every $t \in T$. Further, collections can be offered during every period $t \in T$. Nonetheless, arranging collection in every period is not considered as a hard constraint. All trucks start their trips from the depot D. The quantity of the material within one route has to be less than $QMax$ such that the trucks' capacities are respected. At the end of the planning horizon T, the material at the warehouse and the storage areas of the waste generators should not be higher than P units of load. Given the network of collections, a feasible set of routes $R = \{0, \ldots, r\}$ exists. The feasible routes apply on the directed graph $G(N, A)$.

The goal of this model is to minimize the cost. The cost of the waste collections has four main components: the transport cost, the storage cost of the waste generators, the additional cost incurred when waste is transported to the warehouse and the cost of waiting. The problem of the waste collections service is subject to the constraints mentioned below.

- The trucks' capacity should not be exceeded
- The storage facilities' capacities should not be exceeded
- The warehouses' capacities should not be exceeded
- All routes start from the depot
- The stored material at all storage facilities is always positive or zero
- The waste generators can be visited up to one time in a period $t \in T$
- The material at every storage facility at the end of the time horizon should be equal to or less than P units of load.

The model decides for the following:

- The quantity of material that is picked up from each waste generator and the warehouse at each period
- The quantity of the transported material to the warehouse at each period
- The activated routes at each period
- The quantity of material stored at the facilities of the waste generators and the warehouse at each period

We made the following assumptions:

- A truck is available at any moment in time
- At the first period of the planning horizon there is no waste stored at the warehouse or the waste generators

In the mathematical formulation of the model for the waste collections the following decision variables have been introduced. Let y_r^t be a binary variable, equal to one if the route $r \in R$ is used at $t \in T$, q_i^{rt} be a continuous variable equal to the amount of material that is picked up from every waste generator $i \in WG$ and warehouse $w \in W$ during route $r \in R$ at period $t \in T$. Let x_{iw}^{rt} be a continuous variable equal to the quantity of the transported material from the waste generators $i \in WG$ to the warehouse $w \in W$ via the route $r \in R$ in period $t \in T$. Let I_i^t be a continuous variable that shows how much waste is stored at the facilities of the waste generators and the warehouse $i \in WG \cup W$ in period $t \in T$. We also denote a_i^r as the parameter that shows whether vertex $i \in N$ belongs or not to route $r \in R$ and the parameter $Waiting\ time_r$ that shows how many additional days are needed for a route in order to be completed. The objective function minimizes the cost:

$$\begin{aligned} Minimize: & \\ & \sum_{t \in T} \sum_{r \in R} c_r y_r^t + f_2 \sum_{t \in T} \sum_{w \in W} I_i^t + H \sum_{i \in WG} \sum_{r \in R} \sum_{t \in T} \sum_{w \in W} x_{iw}^{rt} + \\ & + f_4 \sum_{r \in R} \sum_{t \in T} (Waiting\ Time_r) y_r^t \end{aligned} \tag{4.1}$$

The transport is performed by an external organisation. As a result the routing cost depends on the type of sub-contraction. How this is incorporated in the mathematical formulation is specified in section 4.7. The storage cost and the additional costs depend on the quantity of the transported material. The notation used in the model is summarised in table 4.2 and the constraints are presented at the equations from 4.2 to 4.19.

Table 4.2: Notation used in the mathematical formulation of modelling the tactical level decisions

Symbol	Indices	Type	Meaning
WG		Set	Set of waste generators
R		Set	Set of feasible routes
T		Set	Set of periods
F		Set	Set of recovery facilities
W		Set	Set of warehouses
v_i	$i \in WG$	Parameter	Demand
f_2		Parameter	Holding costs
H		Parameter	Additional costs
f_4		Parameter	Cost of waiting one day
$Waiting\ Time_r$	$r \in R,\ t \in T$	Parameter	Waiting days per route r
OD_r	$r \in R$	Parameter	Days of travelling per route r
$QMax$		Parameter	Capacity of vehicle
$IMax_i$	$i \in WG$	Parameter	Capacity of storage facilities
P		Parameter	Minimum quantity of P that can be picked up at the storage facilities of the waste generators
c_r	$r \in R$	Parameter	Cost of route r
a_i^r	$i \in WG \cup W \cup F\ r \in R$	Parameter	1 if i belongs to route r , 0 otherwise
M		Parameter	Big number
y_r^t	$r \in R,\ t \in T$	Decision variable	1 if route r is selected in period T, 0 otherwise.
q_i^{rt}	$i \in WG \cup W,\ r \in R$ $t \in T$	Decision variable	Quantity of the material that is picked up from the location i at period t.
x_{iw}^{rt}	$i \in WG,\ w \in W,\ r \in R,\ t \in T$	Decision variable	Quantity of the transported material from the waste generator i to the warehouse w at period t.
I_i^t	$i \in WG \cup W,$ $t \in T$	Decision variable	Quantity of waste stored at location i in period t.

$$\sum_{r \in R} y_r^t a_i^r \leq 1 \quad \forall\ t \in T,\ i \in WG \tag{4.2}$$

$$q_i^{rt} - P \sum_{f \in F} y_r^t a_i^r a_f^r \geq 0 \quad \forall\ i \in WG \cup W.\ t \in T,\ r \in R \tag{4.3}$$

$$q_i^{rt} \leq M \sum_{f \in F} y_r^t a_i^r a_f^r \quad \forall\ r \in R,\ t \in T,\ i \in WG \cup W \tag{4.4}$$

$$\sum_{f \in F} y_r^t a_i^r a_f^r - q_i^{rt} \leq 0 \quad \forall\ r \in R,\ t \in T,\ i \in WG \cup W \tag{4.5}$$

$$q_w^{rt} \leq M \sum_{f \in F} y_r^t a_w^r a_f^r \quad \forall\ r \in R,\ t \in T,\ w \in W \tag{4.6}$$

$$x_{iw}^{rt} \leq M y_r^t a_i^r a_w^r \quad \forall\ t \in T,\ r \in R,\ i \in WG,\ w \in W \tag{4.7}$$

$$y_r^t a_i^r a_w^r - x_{iw}^{rt} \leq 0 \quad \forall\, t \in T,\, r \in R,\, i \in WG,\, w \in W \tag{4.8}$$

$$I_i^t = I_i^{t-1} + v_i - \sum_{r \in R} q_i^{rt} - \sum_{w \in W} \sum_{r \in R} x_{iw}^{rt} \quad \forall\, t \in T,\, i \in WG \tag{4.9}$$

$$I_w^t = I_w^{t-1} - \sum_{r \in R} q_w^{rt} + \sum_{i \in WG} \sum_{r \in R} x_{iw}^{rt} \quad \forall\, t \in T,\, w \in W \tag{4.10}$$

$$I_r^t \geq 0 \quad i \in WG \cup W \tag{4.11}$$

$$I_i^{t=p} \leq P \quad \forall\, i \in WG \tag{4.12}$$

$$I_i^t \leq IMax_i \quad \forall\, i \in WG \cup W \tag{4.13}$$

$$\sum_{i \in WG \cup W} q_i^{rt} \leq QMax \quad \forall\, t \in T,\, r \in R \tag{4.14}$$

$$\sum_{i \in WG} x_{iw}^{rt} \leq QMax \quad \forall\, t \in T,\, r \in R,\, w \in W \tag{4.15}$$

$$y_r^t \in \{0,1\} \quad \forall\, t \in T,\, r \in R \tag{4.16}$$

$$x_{iw}^{rt} \geq \quad \forall\, t \in T,\, r \in R,\, w \in W,\, i \in WG \tag{4.17}$$

$$I_i^t \geq 0 \quad \forall\, t \in T,\, i \in WG \cup W \tag{4.18}$$

$$q_i^{rt} \geq 0 \quad \forall\, t \in T,\, i \in WG \cup W,\, r \in R \tag{4.19}$$

Equation 4.2 shows that at every period $t \in T$, all waste generators are visited up to one time. Equation 4.3 shows that in order for a pickup to be decided, at least P units of load have to be available at the locations of the waste generators and/or the warehouse. Equations 4.4 and 4.5 show that material is picked up from the waste generators only if the route that traverses the relevant location is selected. Equation 4.6 show that material is picked up from the warehouses only when the routes that traverse both the warehouse and the recovery facilities are activated. Equations 4.7 and 4.8 show that in each period t of the planning horizon material is transported to a warehouse only when the routes that traverse both a waste generator and a warehouse are activated. Equation 4.9 show that the stored material at each waste generator in period t is given by its previous state in period $t-1$ plus the material v_i that is generated at period t minus the quantity that is picked up at period t and minus the quantity transported to the warehouses at period t. Equation 4.10 show that the stored material at each warehouse in period t is given by its previous state in period $t-1$ plus the material v_i that is dropped off at period t minus the quantity that is picked up at period t. Equation 4.11 show that the stored material at each waste generator at each period t is positive or zero. Equation 4.12 show that the stored material at each waste generator and at each warehouse at the end of the planning horizon $(t = p)$ is less than P. Equation 4.13 makes sure that the capacities of the storage areas of the waste generators are respected. Equations 4.14 and 4.15 show that the sum of the quantities transported either to the warehouse or to the recovery facility at each route $r \in R$ has to be less than $QMax$ in order to respect the capacity of the truck. The equations 4.16 to 4.19 represent the domain of variables.

4.6. Modelling the decisions at operational level

In this section the mathematical formulation for the model with regards to the decisions at operational level is presented. We use the set of selected routes $ActR = \{ActR_1, ..., ActR_n\}$ that were obtained from the implementation of the model for the decisions at tactical level. Let $T = \{1, ..., p\}$ be the set of periods, same as in the model for the decisions at tactical level. A set of the available days of operation $\{1, ..., m\}$ for every period $t \in T$ is also used. We also denote Tw_{tr} as a parameter equal to one when material is transported to a warehouse during period $t \in T$ and zero otherwise. Tf_{tr} is a parameter equal to one when material is picked up from a warehouse during period $t \in T$, otherwise is equal to 0. Moreover, within a day of operations up to $RMax$ routes can be performed. The goal of this model is to minimize the summation of the days of operation. The mathematical model of the operational level's decisions is subject to the following constraints:

- Up to $RMax$ routes per day can be activated.
- The routes in which material is transported to the warehouses can not be scheduled the same day with the routes in which material is picked up from there.
- If a route requires more than one day of operation in order to be completed, then it is allocated to more than one day.

This mathematical model will give the following outputs.

- Allocation of the activated routes to days of operation
- The activated days of operation per period

We made the following assumptions:

- A truck is available at any available day of operation
- There are no time related restrictions from the side of the waste generators, the warehouse or the recovery facility. Having said that, we assume that the operations (loading, unloading etc) take place always within working hours.

For the mathematical model we introduced two binary decision variables. Let z_d^t be equal to one if day $d \in D$ is activated at period $t \in T$ and l_d^{rt} equal to one if route $r \in ActR$ is allocated to day of operation $d \in D$ during period $t \in T$. The objective function minimizes the total number of days of operation within the planning horizon. Equation 4.20 shows the objective function and the equations 4.21 to 4.29 the constraints of the mathematical model. Table 4.3 presents the notation.

$$Minimize: \sum_{d \in D} \sum_{t \in T} z_d^t \tag{4.20}$$

Table 4.3: Notation for the mathematical formulation of the model for the operational level's decisions.

Symbol	Indices	Type	Meaning
D		Set	Set of available days of operation
T		Set	Set of periods
$ActR$		Set	Set of activated routes
OD_r	$r \in ActR$	Parameter	Days of travelling per route r
Tf_{tr}	$t \in T, r \in ActR$	Parameter	1 if the recovery facility is traversed by route r, 0 otherwise
Tt_{tr}	$t \in T, r \in ActR$	Parameter	1 if the recovery facility is traversed by the route r, 0 otherwise
$RMax$		Parameter	Maximum number of transports performed in a day of operation
l_d^{rt}	$t \in T$, $r \in ActR$, $d \in D$	Decision variable	1 if route $r \in ActR$ is activated in day d
z_d^t	$t \in T$, $d \in D$	Decision variable	1 if day d is activated during period t

$$l_d^{rt} \leq z_d^t \quad \forall\, d \in D,\, t \in T,\, r \in ActR \tag{4.21}$$

$$z_d^t - z_{d+1}^t \leq 0 \quad \forall d \in D, t \in T \tag{4.22}$$

$$\sum_{r \in ActR} l_d^{rt} \leq RMax \quad \forall d \in D, t \in T \tag{4.23}$$

$$\sum_{t \in T} \sum_{d \in D} l_d^{rt} \geq 1 \quad \forall r \in ActR \tag{4.24}$$

$$\sum_{d \in D} l_d^{rt} - OD_r = 0 \quad \forall t \in T,\, r \in ActR \tag{4.25}$$

$$\sum_{r \in ActR} I_d^{rt} Tf_{tr} + \sum_{r \in ActR} l_d^{rt} Tt_{tr} \leq 1 \quad \forall d \in D,\, t \in T \tag{4.26}$$

$$l_{d+1}^{rt} Tt_{tr} - I_d^{rt} Tf_{tr} \leq 0 \quad \forall\, t \in T,\, r \in ActR,\, d \in D \tag{4.27}$$

$$l_d^{rt} \in \{0,1\} \quad \forall\, t \in T,\, r \in ActR,\, d \in D \tag{4.28}$$

$$z_d^t \in \{0,1\} \quad \forall\, t \in T,\, d \in D \tag{4.29}$$

Equation 4.21 shows that a route can be activated only if it is assigned to an day of operation. Equation 4.22 makes sure that the days of operation are ordered. Equation 4.23

shows that within one day of operation up to $RMax$ routes can be activated. Equation 4.24 shows that all routes that belong to the solution of the mathematical problem of the model for the tactical level's decisions have to be allocated to one day (at least). A route may need for more than one day to be completed. Equation 4.25 shows that every route has to be allocated to as many days as required in order to be completed. Equation 4.26 shows that the routes via which material is transported to the warehouse and the routes via which the material is transported to the facility cannot be allocated to the same day. Equation 4.27 makes sure that the routes via which material is dropped off at the warehouse have to scheduled before the deliveries to the recovery facilities.The equation 4.28 and 4.29 define the domain of the variables.

4.7. Modelling sub-contraction

The types of sub-contraction: flow based, route based and toured based are incorporated in the objective function of the modes for the decision making at tactical level. The mathematical formulation proposed by (Kopfer and Wang, 2009) is used. The notation is included in table 4.2

For the first type of sub-contraction (flow basis), the transport cost depends on the distance c_r travelled and the quantity of the transported material q_i^{rt}, x_{iw}^{rt} (Kopfer and Wang, 2009). The parameter $Rate_1$ represents how the sub-contracted organisation charges the contractor for the offered services per unit of load and unit of distance travelled. The transported quantity is given by the decision variables q_i^{rt} and x_{iw}^{rt}. We assume a linear rate function that depends on the quantity transported within a single route. The objective function is shown in equation 4.30.

$Minimize:$

$$\sum_{i\in WG\cup W}\sum_{r\in R}\sum_{t\in T}\sum_{w\in W} Rate_1\cdot c_r(q_i^{rt}+x_{iw}^{rt}) + f_2\sum_{t\in T}\sum_{i\in W} I_i^t + H\sum_{i\in WG}\sum_{r\in R}\sum_{t\in T}\sum_{w\in W} x_{iw}^{rt} + \\ + f_4\sum_{r\in R}\sum_{t\in T}(Waiting\ Time_r)y_r^t \tag{4.30}$$

For the route based type of sub-contraction the transport cost depends only on the distance travelled (Kopfer and Wang, 2009). We use the parameter $Rate_2$ to present how much the sub-contracted organisation charges the contractor per unit of distance travelled. In this case the objective function becomes as shown in equation 4.31.

$Minimize:$

$$\sum_{r\in R}\sum_{t\in T} Rate_2 c_r y_r^t + f_2\sum_{t\in T}\sum_{i\in W} I_i^t + H\sum_{i\in WG}\sum_{r\in R}\sum_{t\in T}\sum_{w\in W} x_{iw}^{rt} + \\ + f_4\sum_{r\in R}\sum_{t\in T}(Waiting\ Time_r)y_r^t \tag{4.31}$$

For the tour based type of sub-contraction the transport cost depends only on the days of travelling Kopfer and Wang (2009). With the parameter $Rate_3$ we show how much the sub-contracted organisation charges the contractor per day of travelling. In this case the objective function becomes as shown in equation 4.32. The cost of waiting is not included in this cost function.

$Minimize:$

$$\sum_{r\in R}\sum_{t\in T} Rate_3 OD_r y_r^t + f_2\sum_{t\in T}\sum_{i\in W} I_i^t + H\sum_{i\in WG}\sum_{r\in R}\sum_{t\in T}\sum_{w\in W} x_{iw}^{rt} \tag{4.32}$$

4.8. Concluding remarks

In this chapter, we discussed how the decision making can be modelled for our problem. With the information provided in this section we can answer the fifth sub-question: ***'How can we develop a model that takes into account different types of sub-contraction regarding this system?'***.

We used information from the study of (Kopfer and Wang, 2009) in order to take into account the types of sub-contraction in our models. The author suggests to model the types of sub-contraction by changing the transport cost in the objective function. At every sub-contraction the transport cost is calculated in a different way and different fees apply at each one. The flow based type of sub-contraction depends on the quantity of the transported material and the distance travelled. The route based type of sub-contraction depends on the distance travelled. The tour based type of sub-contraction depends on the days of travelling. At all types of sub-contraction, the storage and the holding cost is modelled in the same way.

5

Implementation and verification

This chapter contains the description of the steps that were followed for the implementation of the models that we presented in section 4. This chapter also presents the procedure that was followed to verify the models. More specifically, the structure of this section is as follows. First, in section 5.1 the implementation of the models is described. Then, in section 5.2 the verification tests that were performed are provided and the results are presented. Thereafter, in section 5.3 the concluding remarks are given.

5.1. Implementation

The implementation is run using a laptop computer with a processor Intel i5, CPU running at 2.5GHz with 8.00 GB of RAM. The developed models (refer to section 4) were implemented with the programming language python and with the help of the solver Gurobi. For the verification tests we implemented the models with a small scaled problem.

To represent the connections between the nodes we used the basic concepts of the graph theory. A graph is defined as *"a set of points and lines connecting some pairs of points. The points are called vertices and the line vertices"* (Voloshin, 2009). The vertices in our case are the locations of the waste generators, the warehouses and the recovery facilities (see sections 2 and 4). The direction of the arcs is meaningful in our case. We represented our graph with a list of adjacent vertices. For every vertex we enumerated its neighbors. Figure D.1 shows the list of adjacent vertices in the small instance problem that was used for the verification of the models. The figure D.2 illustrates the graph that was shaped from the list of edges. In order to extract the edges we used the function published by Bernd Klein, Bodenseo (2011) [1].

Then, we generated the paths that connect the starting point and the recovery facilities, the paths connecting the starting point and the warehouse and the paths that connect the warehouse and the recovery facilities. Given the specifications of the collection network, the paths were filtered based on the following conditions:

- The paths connecting the warehouse and the facility should not traverse the location of a waste generator.

[1] https://www.python-course.eu/graphs_python.php. © 2011 - 2020, Bernd Klein, Bodenseo; Design by Denise Mitchinson adapted for python-course.eu by Bernd Klein

- The warehouse, the waste generators and the recovery facilities should not be traversed by the same path.
- The paths connecting the waste generators and the warehouses should not traverse the recovery facilities.
- Up to (including) three waste generators can be visited by the same truck in order to respect the capacity of the truck. This is an assumption we made to keep the computational time low. Further testings with regards to the efficiency of the models are presented in section 7.

By putting these conditions we ensured that the generated paths are consistent with the network of collections (see chapters 3 and 2). Another reason for filtering the generated paths was to limit the computational time. While implementing the models we made the assumption that up to three waste generators can be incorporated in a path. In that way, the computational time was further reduced. After having extracted and filtered the paths from the graph we calculated the cost for each one of them. A high level description of the cost function for every type of sub-contraction is given below.

- Route based type of sub-contraction
  - Transport cost: function of distance and cost of waiting
  - Additional cost
  - Holding cost
- Flow based type of sub-contraction
  - Transport cost: function of the quantity transported and the distance travelled based and waiting cost
  - Additional cost
  - Holding cost
- Tour-based type of sub-contraction
  - Transport cost: fixed.
  - Additional cost
  - Holding cost

The models for the tactical and the operational level decisions are solved in the same .py file. As shown in section 4.3 part of the results obtained from the implementation of the model for the tactical level decisions are used as inputs for the operational level decisions. For a small instance problem (see figure D.1) 32 feasible paths are generated. At the implementation 95 nodes are explored (520 simplex iterations) in 0.18 seconds and the optimal solution is found. Part of the output of the implementation of the models for the small instance problem is shown in the appendix D (see figure D.3).

5.2. Verification assessment

While verifying the model we wanted to check if the model is right. To understand if the models that were developed give us the results as we expected them to do we performed several tests:

- Balance tests
- Input tests
- Consistency tests
- Fault injections
- Manual checks

If the output of these tests matched the expected output, then we could confirm that the models were correctly implemented. To model the three types of sub-contraction we used three variation of the basic model as presented in chapter 4. We tested all variations separately in order to assess them. Table 5.1 summarises the tests that were performed in order to verify the model for the tactical level decisions.

Regarding the modelling of the tactical level decisions, in total nine verification test runs were performed. First, with three balance checks we wanted to verify that there is balance with regards the quantity delivered to the recovery facilities, the quantity transported to the warehouse, the quantity stored at the locations of the waste generators and the warehouse. With the first test, we wanted to confirm that there is a balance between the quantity delivered at the recovery facilities, the quantity of the generated waste and the material left either at the warehouse at the end of the planning horizon or at location of the waste generators. Considering the time horizon as a whole the equation 5.1 should be respected.

$$Waste\, generated = Waste\, transported + Waste\, stored \tag{5.1}$$

Table 5.2 shows the results of the manual check for the first balance check. For the three types of sub-contraction the equation 5.1 is satisfied. In total, the quantity of the generated waste is equal to the quantity transported minus the waste not picked up.

Following, we turned our attention at the locations of the waste generators and the warehouse. With the second balance check, we wanted to investigate if there is balance at the storage areas of the waste generators over the time. For that we used equation 5.2.

$$Inventory[t] - Inventory[t-1] = Waste\, generated[t] - Waste\, Transported \tag{5.2}$$

With the third balance check we focused on the warehouse. By using the equation 5.3 we checked if there balance between the waste stored, transported and picked up at the warehouse.

$$Inventory[t] - Inventory[t-1] = Waste\, transported\, to\, warehouse - Waste\, picked\, up \tag{5.3}$$

Table 5.1: Verification plan focusing on the tactical level decision.

#	Test	Experiment	Expected output
1	Balance test	Waste generated = Waste transported + Waste stored	The total quantity of waste delivered to the recovery facility is equal to the quantity generated minus the quantity that is left at the end of the time horizon.
2	Balance test	Inventory[t]-Inventory[t-1]=Waste generated[t] - Waste Transported	The quantity of waste picked up from a waste generator is equal to the inventory at the end of this period minus the inventory at the end of the previous period plus the quantity generated at that period.
3	Balance test	Inventory[t]-Inventory[t-1]=Waste transported to warehouse - Waste picked up	The quantity of the stored waste at the warehouse should be equal to the quantity of waste picked up from the warehouse minus the quantity transported to it at any period of time.
4	Fault injection	Set capacity to zero	No solution found
5	Consistency test	Increase slightly (by 25%, 50%) the demand	More frequent collections.
6	Consistency test	Set the demand equal to the trucks' capacity	No milk runs
7	Consistency test	Set warehousing costs to zero	Indirect transport is chosen
8	Consistency test	Set warehousing cost to an extreme value	Indirect transport is not chosen.
9	Manual check	Calculate the cost components separately	The value of the objective function should be equal to the sum of the components.

Table 5.2: Results of the balance check 1.

Type of sub-contraction	Waste Transported	Waste Stored	Manual Check	Check	Waste Generated
Flow-based	240	18	258	TRUE	258
Route-based	234	24	258	TRUE	258
Tour-based	240	18	258	TRUE	258

Table D.1 shows the results of the balance checks 2 and 3 with regards to the flow based type of sub-contraction. The results for the route and tour based types of sub-contraction are presented in appendix D. The results indicated that there is consistency between the quantities transported to the warehouse, delivered to the recovery facilities and the material stored at the inventories. It is also clear that the inventories are consistent over the time. That being said, no material 'appears' or 'disappears' over the time.

Following the balance checks, we set a parameter of the model at a non-logical value. The reason for doing so, was to check if the model will give an error output or not. In our example, we set the carrying capacity of the trucks equal to zero. In this way, no quantities could be transported and consequently no solution would be possible to be found. Figure D.4 shows the output of the models in these cases; indeed no solution could be found.

Next, we performed six consistency tests. The intention was to check the ability of the model to select the most appropriate path. With an increase in the generated waste we expected to see changes in the frequency of the collections and in the filling rates of the trucks. With an extreme increase, we expected that no solution would be possible to be found. The reason for that is that a waste generator can be visited up to once per period, the trucks have a specific capacity and at the end of the planning horizon the most part of the waste generated should be transported to the recovery facility.

Table 5.3: Testing the consistency of the objective function.

Sub-contraction	Travel cost	Storage cost	Handling cost	Waiting time	Total	Objective function	Match?
Flow-based	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	TRUE
Route-based	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	TRUE
Tour-based	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	TRUE

We implemented the models for the following instances of demand: increase by 25%, 50%, set equal to the trucks' capacity and set equal to an extreme value. Tables D.5, D.4, D.6 demonstrate the number of the activated paths for every case. Thereafter, we set the warehousing costs (handling cost and distance from the warehouse to the recovery facility) to zero, to check if the indirect transport will be preferred. After this, we set the warehousing costs to a very high value in order to check if the other two transport methods will be selected. Tables D.7, D.8 and D.9 show the results of the testings. Furthermore, with another consistency test we checked whether the objective function reflects the transport cost the way it should. To do that, we calculated every cost component separately and then we checked if the summation is equal to the value of the objective function.

Table 5.4: Verification plan with focus on the operational level decisions

#	Test	Experiment	Expected output
1	Consistency test	Manual calculation of total number of days>sum (days required per route)	Manual calculation of total number of days> (days required per route)
2	Manual check	In the case of indirect transport, count manually the number of days required.	The routes for transport to the warehouse should not be assigned the same day with the routes of delivering waste to the recovery facility
3	Manual check	Study the output to see if the results of the model for the tactical level decisions is used as input in the model for the operational level decisions.	Only the activated routes are used as inputs in the implementation of the model for the operational level's decisions

With regards to the modelling of the decisions at operational level we performed three checks in total: a consistency, a manual and an input check (see table 5.4). With the consistency test we wanted to check if the model optimizes the days of operation. For that, we calculated manually the total number of days that would be required based on the average distance travelled per day. We expected to see the objective function to demonstrate a number lower than the one we calculated manually. Moreover, we studied the output to ensure that for the indirect transport method two routes are activated. Last but not less important, we studied the input of the the model for the decisions at operational level to ensure that is derived from the output of the model for the decisions at tactical level. Only the routes activated at the tactical level should be assigned to a day of operation.

Tables D.10 - D.12 show the selected routes per period and the day they were assigned to. From the obtained results we can confirm that the routes are consistent and logical. The routes that transport waste to the warehouse are performed before the the transportation from the warehouse to the facility. Also, given the length of each route one or two days are occupied. For instance, in the case of the tour based type of sub-contraction where more milk runs are selected, it takes more than one day to complete a route. From the outputs we can also see that all routes have been assigned to a day of operation.

5.3. Concluding remarks

In this chapter we presented how the models were implemented and how they were verified. From the results obtained from the verification tests (see section 5.2) we can conclude that the models are correct because the give the expected results. The modelling of the tactical level decisions, give consistent results with regards to the quantities picked up from the waste generators, delivered to the recovery facility and the transport method selected for each route. The model with regards to the operational level decision give a consistent schedule of collection per period of time. Since the models are verified, the models as presented in chapter 4 can be implemented to a case study. In that way, we will understand how the decision making could be improved. The implementation of the models will allow us to answer the last research sub-question: ***How would the different types of sub-contraction influence the logistical performance of the collection service in comparison with its current state?***.

6

The case study

In order to answer the last research sub question: ***"How would the different types of sub-contraction influence the logistical performance of the collection service in comparison with its current state?"***, we introduce a case study from the company. In this chapter, the data of the company will be presented and analyzed (see sections 6.1 and 6.2). We implemented the models (see section 4) for the decision making at tactical and operational level. The results of the models (see section 6.3) will provide insights in how the sub-contraction will affect the collection service. Thereafter, in section 6.4 the concluding remarks of the analysis are presented.

6.1. The data

Data related to the collections of the waste was provided by the company. The data sets consist of locations, demand, the observed schedule of collections within a six-period time horizon, capacities, the selected transport methods and the collections' cost. Table 6.1 shows the quantity generated on a periodical basis. The quantities are constant per period for every waste generator. The unit for measuring the load of waste is pallets. Tables 6.1 and 6.2 show the data related to the generation of waste at every location. The capacities of the storage facilities of the waste generators are also presented.

Table 6.1: The data provided by the company

<Removed due to confidentiality>

At the current state of the system, 14 collections are performed within six periods. In total, 262 pallets were collected from nine waste generators. The minimum cost/pallet that was observed was [redacted] per pallet, the maximum [redacted] and the average [redacted]. Overall, four collections were performed with milk runs, three with direct transport and seven with indirect. The days of operation that were required were eleven. For the implementation of the models that were presented in the previous sections (see chapter 4) we considered that for every additional day required to complete a route, a penalty is imposed. Furthermore we considered that within a day up to [redacted] can be travelled.

Other information provided by the company was related to the collections within six periods. This information will form our base case with which our results will be compared. The information is mentioned below.

Table 6.2: The data of the company that were used for the implementation of the models.

Symbol	Meaning	Value
$Rate_1$	Travel cost for the flow based	[redacted]
$Rate_2$	Travel cost for the route based	[redacted]
$Rate_3$	Travel cost for the tour based	[redacted]
f_2	Holding costs	[redacted]
H	Additional costs	[redacted]
f_4	Cost of waiting	[redacted]
$QMax$	Capacity of the trucks	[redacted]
P^1	Maximum number of pallets at the end of the time horizon	[redacted]
P	Minimum amount of pallets for pickup	[redacted]
DMX	Maximum distance travelled in a day	[redacted]
$RMax$	Maximum number of routes per day	2 routes
WG	Set of waste generators	9 waste generators
T	Set of periods	6 periods
D	Set of available days of operation per period	20 days
F	Set of recovery facilities	1
W	Set of warehouses	1

- Frequency of pickups: [redacted]
- Frequency of collections:[redacted]
- Quantity picked up: 262
- Average cost per pallet: [redacted]
- Milk runs: 4
- Indirect transport: 7
- Direct transport: 3
- Days of operation: 20 in a period
- Average truck's filling rate: 79.6%
- Unit of load: pallet

The information given in the aforementioned paragraphs, constitutes the current state of the system.

Table 6.3: Numerical analysis of the quantity of the waste that was actually transported

Total of quantity of the waste generated in six periods (pallets)	Average of quantity of the waste generated in six periods (pallets)	Minimum of quantity of the waste generated in six periods (pallets)	Maximum of quantity of the waste generated in six periods (pallets)	Standards deviation of the quantity of the waste generated in six periods (pallets)
276	5	1	12	4

6.2. Data analysis

In total, 276 pallets with waste are available for pick up within a 6-period time horizon. On average, at every location, five pallets are available for pick up per period. The lowest quantity generated per period is only one pallet and the maximum is 12 pallets per period.

With regards to the capacities of the storage areas of the waste generators, an average 17 pallets can fit, the maximum 30 and the lowest only six pallets (see table 6.4). In a period, no storage facility are fully filled in (see table 6.6). The maximum filling rate is 60% and the lowest 6.67%. By translating these numbers into filling rate of a truck, only one location could fill in a truck up to 40%. The average occupation in terms of trucks' capacity is 17.04%. That means that no waste generator can provide in a period such quantities that a truck could be fully filled in (see table 6.5).

Table 6.4: Numerical analysis of the capacity of the storage facilities of the waste generators.

Lower capacity (pallets)	Average capacity (pallets)	Maximum capacity (pallets)	Standard deviation (pallets)
10	17	30	6

Table 6.5: How much truck's space a waste generator require per period.

Lower filling rate (pallets)	Average filling rate (pallets)	Maximum filling rate (pallets)	Standard deviation (pallets)
6.67%	28.52%	60%	18.79%

Table 6.6: The periodic demand of the waste generators as percentage of storage capacity of their facilities.

Lower utilization rate of the storage facilities (pallets)	Average utilization rate of the storage facilities (pallets)	Maximum utilization rate of the storage facilities (pallets)	Standard deviation (pallets)
3.33%	17.04%	40%	12.85%

Considering that on average five pallets are generated per period at every waste generator, which is equivalent to 16.6% to the truck's capacity, we understand that it may not be efficient to visit all generators at every period of time.

6.3. Results

To understand how the collections can be influenced with the different types of sub-contraction we implemented the models with the case study that was provided by the company (see section 6.1). In the following paragraphs (sections 6.3.1, 6.3.2, 6.3.3) we demonstrate the results with regards to the implementation for the flow based, the route based and the tour based type of sub-contraction.

6.3.1. Flow based type of sub-contraction

The frequency of pick ups for the majority of the waste generators ($WG2$, $WG3$, $WG5$, $WG7$, $WG8$) is one pick up within the planning horizon (see table 6.7). The highest frequency that was reported in the results is five times; almost at every period. The higher the quantity a waste generator produces per period, the more frequent the collections. Moreover, the results show that all waste generators are assigned to a specific transport method only: either direct or indirect or milk run. The direct transport method was selected in the cases that the truck could travel within one working day from the location of the waste generator to the recovery facility. If more than one day was needed, the indirect method was chosen. In that way, no waiting cost was added. More specifically, the collections at the $WG0$, $WG1$, $WG2$, $WG6$, $WG7$ were arranged with direct transport. The rest were arranged with indirect transport. In that way the pallets were stored temporarily at the warehouse.

In terms of the routing decisions, the majority of the paths connect directly the waste generators with the recovery facility. Furthermore, for the waste generators with demand of one or two pallets per period, the quantities were gathered in the warehouse at the last period of the planning horizon. The reason for not collecting that frequently from these locations is that the minimum amount of pallets (six pallets) was not respected until that moment. From the warehouse, opposed to the direct transport transports the trucks had high filling rates (>90%).

Table 6.7: Summary of the results regarding the flow-based type of sub-contraction

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Interestingly, not all available pallets are picked up from the pick up sites. We can understand that from the total quantity transported: 236 pallets while 276 pallets were available. While modelling the decisions at tactical level, picking up all available material was not taken as a hard constraint. What we considered is that at every waste generator up to five pallets could be left at their storage facilities.

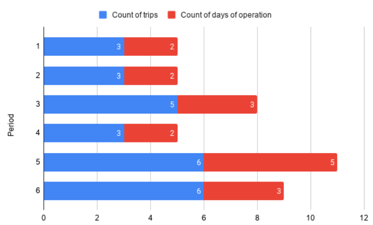

Figure 6.1: Count of trips and days of operations, flow based type of sub-contraction

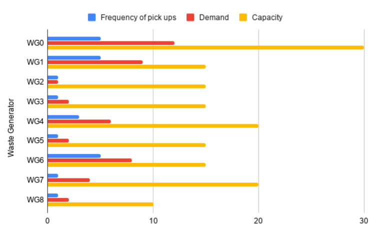

Figure 6.2: The frequency of the pick ups towards to the demand and the capacity of the waste generators, flow based type of sub-contraction

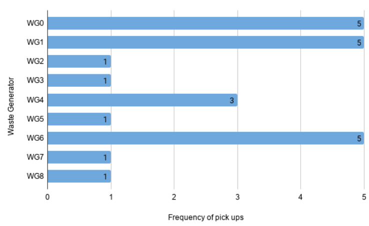

Figure 6.3: The frequency of the collections, flow based type of sub-contraction

From the perspective of the daily operations (see figure 6.1), the fifth period is the most active. During that period, the waste from four waste generators ($W3, W4, W5, W8$) was picked up and consolidated to the warehouse.

<*Removed due to confidentiality*>

Figure 6.4: Collection plan for period 1, flow based type of sub-contraction

<*Removed due to confidentiality*>

Figure 6.5: Collection plan for period 2, flow based type of sub-contraction

<*Removed due to confidentiality*>

Figure 6.6: Collection plan for period 3, flow based type of sub-contraction

<*Removed due to confidentiality*>

Figure 6.7: Collection plan for period 4, flow based type of sub-contraction

<*Removed due to confidentiality*>

Figure 6.8: Collection plan for period 5, flow based type of sub-contraction

<*Removed due to confidentiality*>

Figure 6.9: Collection plan for period 6, flow based type of sub-contraction

At the tactical level of decision making the focus is on how to allocate the collections to the available days of operations. The figures 6.4 - 6.9 illustrate the results about how the operations could be arranged in every period. These figures show the connections at every period. The fact that at the first, the second and the fourth period the network of connections is the same implies a regularity. In the last period of the planning horizon, more collections are planned.

By comparing the performance as resulted by the implementation of the model with the case from the company, we see differences from many perspectives. The frequency of the collections has increased by 64.24%; nine more collections are arranged. The total quantity of the waste delivered to the recovery facility has reduced by 9.92%. On average the cost per pallet transported has been reduced by 37.29% (from [redacted] to [redacted]). At the current state the decisions regarding the transport methods show a preference in indirect transport. The results for the flow based type of sub-contraction show that the majority of the collections (17 out of 23) are planned with direct transport and low truck filling rates (average rate is 34.20%). On the contrary, at the current state the average truck filling rate is much higher, the average rate is 79.6%.

6.3.2. Route based type of sub-contraction

Totally, 236 pallets are transported from the waste generators to the recovery facility. Same as with the results for the flow based type of sub-contraction the results of the route based illustrate a relation between the demand of every waste generator and the frequency of pickups. The pickups at the $WG0, WG1$ *and* $WG6$ were the most frequent of all. The collections are not performed only with a single transport method only but the results show combinations of methods. For instance, the pickups at the site of $WG0$ are organized with both direct and milk runs. Furthermore, only the waste generator ($WG0$) which has the highest demand was assigned to the direct transport method.

Table 6.8: Summary of the results for the route-based type of sub-contraction

<*Removed due to confidentiality*>

Most of the collections are performed with milk runs (13 out of 15) and quite high trucks' filling rate is reported ($\geq 90\%$). The pickups of low quantities (six or seven pallets) are always performed with milk runs. The milk runs are determined based on the distance between the locations and the quantities provided at every period (see table 6.8). The obtained results show how the pickups are combined such that the trucks are utilized the most.

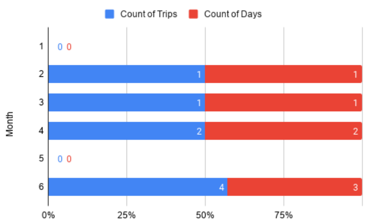

Figure 6.10: Count of trips and days of operations, route based type of sub-contraction

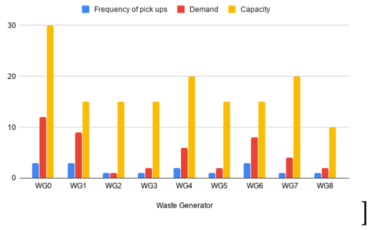

Figure 6.11: The frequency of the pick ups towards to the demand and the capacity of the waste generators, the route based type of sub-contraction

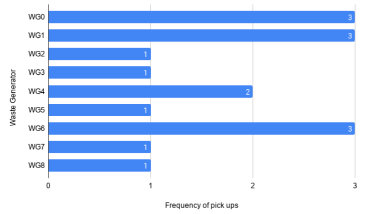

Figure 6.12: The frequency of the collections, route based type of sub-contraction

From operational perspective (see figures 6.10 - 6.12), up to three days within a period are required and up to six trips are performed. Seven days of operation are required and collections are not be planned at every period. During the first and the fifth period no collections are scheduled while most of them are scheduled during the third and the last period.

By looking at the collection plan (see figures 6.13 - 6.18), the figures 6.13 and 6.17 have different colour from the others because we wanted to highlight two observations. First, that at both periods, no collection is planned. Second, that this implies a regularity.

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Figure 6.13: Collections for period 1, route based type of sub-contraction

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Figure 6.14: Collection plan for period 2, route based type of sub-contraction

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Figure 6.15: Collection plan for period 3, route based type of sub-contraction

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Figure 6.16: Collections for period 4, route based type of sub-contraction

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Figure 6.17: Collections for period 5, route based type of sub-contraction

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Figure 6.18: Collections for period 6, the route based type of sub-contraction

By comparing the results obtained from the implementation of the model with the current state of the case study, the total transported quantity was reduced by 9.92% (from 262 to 236 pallets) and the average cost per pallet by 13.17% (from [redacted] to [redacted]). In order for the waste to be transported, 16 pickups incorporated in eight collections are planned. Compared to the current state, six collections less are planned and the majority of them is organised with milk runs. In the current state the indirect transport was the most preferred. With the more frequent milk runs the average truck's filling rate is increased by 23.53% (from 79.6% to 98.33%). In addition to the above, the days of operation decreased from 20 to 7 days.

6.3.3. Tour based type of sub-contraction

The result of the implementation of the model for the tour based type of sub-contraction showed that in total 236 pallets are picked up from the nine waste generators. In total, 16 pick ups are incorporated in nine collections. The collections are performed at their majority with milk runs. Seven out of the nine collections were performed with milk runs and two with direct transport. For four out of nine, the waste generators ($WG2.WG3, WG5, WG8$) a pickup is scheduled once during the whole planning horizon. The most frequent collections concern the waste generators $WG0$ *and* $WG1$, in total four pickups during the six periods. The low quantities are combined with milk runs to make a full truck and the high quantities are transported directly to the recovery facility (see table 6.9).

Table 6.9: Summary of the results regarding the tour based type of sub-contraction

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The obtained results show that the average filling rate of the trucks is 87.41%. During the first and the fifth period no collections are performed 6.22 - 6.27). The non-active periods (period 1 and period 5) are highlighted with blue colour. The figures mentioned above, demonstrate that the last period is the most active of all with four collections to be scheduled (see figures 6.19 - 6.27).

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Figure 6.19: Count of trips and days of operations with regards to the tour based type of sub-contraction

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Figure 6.20: The frequency of the pick ups towards to the demand and the capacity of the waste generators with regards to the tour based type of sub-contraction

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Figure 6.21: The frequency of the collections with regards to the tour based type of sub-contraction

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Figure 6.22: Collection plan for period 1, tour based type of sub-contraction

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Figure 6.23: Collection plan for period 2, tour based type of sub-contraction

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Figure 6.24: Collection plan for period 3, tour based type of sub-contraction

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Figure 6.25: Collections for period 4, tour based type of sub-contraction

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Figure 6.26: Collections for period 5, tour based type of sub-contraction

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Figure 6.27: Collections for period 6, tour based type of sub-contraction

Comparing the status of the system with the results from the implementation of the model for the tour based type of sub-contraction we see that the truck's filling rate is higher by 9.81% (from 79.6% to 87.41%). The days of operation have been decreased by 65% (from 20 to 7) and the average cost per pallet transported has increased by 13.91% (from [redacted] to [redacted]). Overall, the number of collection was reduced by five and the quantity transported by 9.92%(from 262 to 236 pallets).

6.4. Concluding remarks

In this section we present the concluding remarks of the implementation of our models with the data provided by the company. Table 6.10 summarises the results of the models. The results obtained from the flow based type of sub-contraction show the lowest average cost per pallet [redacted]). As for the quantity of the waste transported to the recovery facility, there was no difference between the different types of sub-contractions. At both three implementations, the total quantity transported was lower than in the case study by 9.92%.

For what concerns the days of operations, at both three types of sub-contraction they are less than in the current state of the system. An explanation for obtaining this result is that we considered that up to two transports can be performed per day. Moreover, we made the assumption that a truck can be available at any moment in time within the length of the contract, something that may not be always the case. That being said, we can not conclude whether the days of operation are realistic at any type of sub-contraction because we implemented the models based on a semi realistic assumption.

From the results obtained from the implementation of the models the routing decisions were split among two out of the three available methods. At none of the three types of sub-contraction did we see both milk runs, indirect and direct transports to be performed. Additionally, the models were based on assumptions and constitute an abstract representation of the reality. Therefore it is logical to expect deviations between the scheduling as a result of modelling and the scheduling as could actually be decided by a management team.

Table 6.10: Summary of the results of the models for the different types of sub-contraction along with the current state of the system.

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A point that has to be highlighted is that because of the type of the material that transported, the waste, it is not possible to combine it in the same truck with other products. That means that if the truck is not utilised at its full capacity, the remaining space can not be exploited. Because of that, the way the carrier would charge the offered transport service could possibly be affected. Taking all the above into consideration we can conclude that the collection plan as obtained from the implementation of the models for the route based type of sub-contraction approaches the most real-life conditions.

Overall, with the results of the analysis presented in this section we can answer the last sub-question: ***"How would the different types of sub-contraction influence the logistical performance of the collection service in comparison with its current state?"***. From the problem description (see chapter 2) and the literature study (see chapter 3) we can conclude that there are two main perspectives that the logistical performance can be driven: the cost efficiency and the service performance. The service performance is reflected with the frequency of the pickups. This is because the frequent pickups help the waste generators to get rid of their waste and release space from their storage facilities.

From a cost perspective the results from the implementation of the models for the flow based type of sub-contraction has the lowest cost. We could name the rotation obtained from the flow based type of sub-contraction as the ***"least cost & maximum service performance"*** solution. The motivation behind is the very frequent pickups with low volumes that this solution demonstrates. Although, this is not the most efficient one because the filling rate of the trucks is low; below half of its available space. From a service performance perspective, it helps the waste generators to get rid of their waste and keep their storage facilities empty. The main flaw of this type of sub-contraction is the fact that it is not possible to transport waste combined with other items in the same truck. That being said, by transporting low quantities the remaining space of each truck will remain empty during transport. The literature that was researched was relevant to transport of regular gods and not specifically of waste therefore we can expect that most likely the actual cost of very frequent collections will be higher with the one that we present in this section.

Practically thinking, it is likely that this type of sub-contraction with this collection plan would not lead to such a high reduction in cost but it could bring an improvement. That is because the knowledge of the difference in the collections' cost could help the management team to negotiate with the carrier for a different pricing scheme that would depend on the quantities transported and the distance travelled.

The results from the implementation of the models for the route based type of sub-contraction show the highest trucks's filling rate and an average cost lower than the tour based and higher than the flow bases. The quantities are transported with direct transports or milk runs with less collections (in number) than in the flow based type of sub-contraction. Theoretically, from a cost perspective it is not the least costly type of sub-contraction but a ***"compromised"*** solution. Not very frequent pickups are scheduled but the pickups are combined in such a way that the trucks are utilised the most.

Practically, this type of sub-contraction approaches the problem in the most realistic way. The cost is dependent on the distance travelled and the use of trucks is compensated with in the sense that they are fully loaded. Thereby, at every collection scheduled as much waste as possible is transported to the recovery facility with respect to the truck's capacity.

With regards to the tour based type of sub-contraction, only seven days are required. In addition to this, milk runs are most frequently organised. From a perspective of transport efficiency, the resulting collection plan performs better than of the flow based and worse than of the route based type of sub-contraction. The total cost is the highest among all and the number of collections the lowest. This collection plan can be named as ***"compact"*** because of the frequency of the pickups in a low number of collections (19 pickups in 9 collections).

7

Analysis and implementation

This section contains the results of the implementation of the models that were presented in section 4 for several scenarios. The scope of the additional investigation is to confirm that the model requirements are met (see section 4.1) and to obtain more insights in what drives the cost. The structure of this chapter is as follows. First, we present in section 7.1 the results for the implementation of the models for five different capacities of the storage facilities (±50%, ± 25% of the current storage capacity, uncapacitated). Next, in section 7.2 we demonstrate the results for the implementation of the model for three different distributions of the demand. In section 7.3 we show the results of the implementation of the models for several instances. Following, in section 7.4 the solutions of the models for different network configurations are presented (±50%, ± 25% scale of the current). In sections 7.5 and 7.6 we present the solutions for the designs with multiple recovery facilities (2 recovery facilities) and multiple warehouses (2 warehouses). For simplicity, in this section we refer to the different types of sub-contraction as: route based (RB), flow based (FB), tour based (TB).

7.1. Capacity

The model was implemented for several instances of storage capacity: ±50%, ± 25% of the storage capacity and storage areas with unlimited capacity. For both three types of sub-contraction, when the storage capacities are the most limited (−50%) the average cost per pallet get its value [redacted]. Table 7.1 and figure 7.1 provide an overview of the results obtained for the several instances of storage capacities.

Table 7.1: Overview of the average cost per pallet for different values of storage capacity.

<*Removed due to confidentiality*>

The fact that there is a reduction in the average cost per pallet as the capacities increase is a common remark for all types of sub-contraction. However, the results for the route based of sub-contraction show a sharper increase in the cost for the smaller storage facilities; 57.2% higher than in the current state. With regards to the flow based type of sub-contraction the cost is not sensitive since it changes slightly (1.48%) for the lowest capacity. As for the tour based type of sub-contraction, the average cost per pallet increased

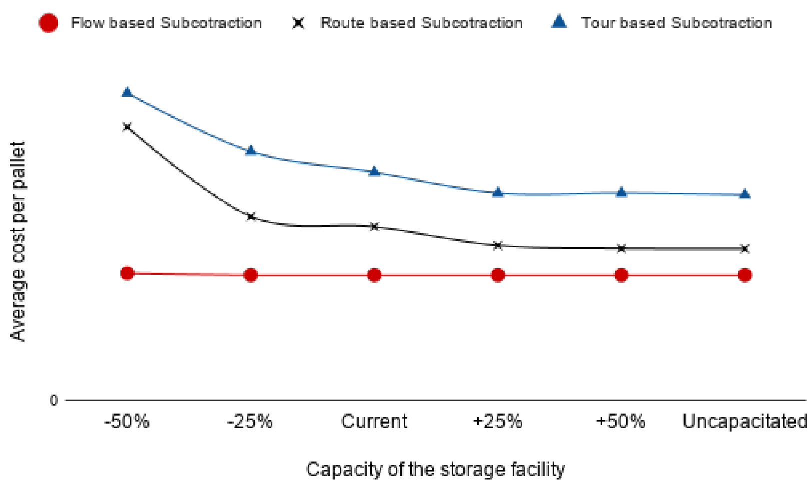

Figure 7.1: Change in the average cost per pallet (€) for different values of capacity.

by 34.62% when the capacity reduces at it half. A common remark for all types of sub-contraction is that the results showed little or no difference in the cost when the capacity increased by more than 50%.

Speaking of frequency of the collections, more collections are needed as the storage capacity gets more limited. The results obtained from the tour based type of sub-contraction and the route based type of sub-contraction are similar. The storage capacity slightly or not at all influence the frequency for these two types of sub-contraction. Figure E.4 shows the exact frequency of collections that are required for the examined instances. With regards to the routing decisions (transport methods), the results from the testings showed the following. Table E.1 (see appendix E.1) shows the results regarding the transport methods.

- With the flow based type of sub-contraction, the direct transport is mostly chosen.
- With the route based type of sub-contraction, the milk runs are mostly chosen.
- With the tour based type of sub-contraction, the milk runs are mostly chosen.

7.2. Demand

The model was implemented for three different distributions of demand. First, 50% less of the current state for the first three periods and 50% more for the rest (refer to hereon as scenario 1). Second, 50% additional for the first three periods and 50% less for the next three (refer to hereon as scenario 2). Third, that no quantities are generated during the first three periods while for the next three, the quantities were set equal to quantities at the actual state (refer to hereon as scenario 3). Figure 7.2 and table 7.2 show the results for the different types of sub-contraction.

Table 7.2: Percentage of change of the average cost per pallet for each type of sub-contraction with regards to different distribution in demands.

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The results show that the average cost per pallet for the flow type of sub-contraction does not change for the first two scenario and increases by 4.79% for the third one. The average cost for the tour based does not change for the first two scenarios by it increases drastically (145.51%) for the third one. The average cost per pallet increases by 22.05% for the first, by 32.49% for the second and by 76.84% for the third.

Regardless of the distribution of the demand there is no difference in the frequency of the collections for the route based and the tour based types of sub-contraction. The results show 8 collections for the first and the second case, and 5 collections for the third. The frequency is much higher for the flow based type of sub-contraction compared to the other types of sub-contraction. The results for the first case that was examined show 19 collections, for the second 19 and for the third 13 collections. Figure E.5 demonstrates the results. Some general remarks related to the transport methods are reported below. Table E.2 summarises the results with regards to the transport method.

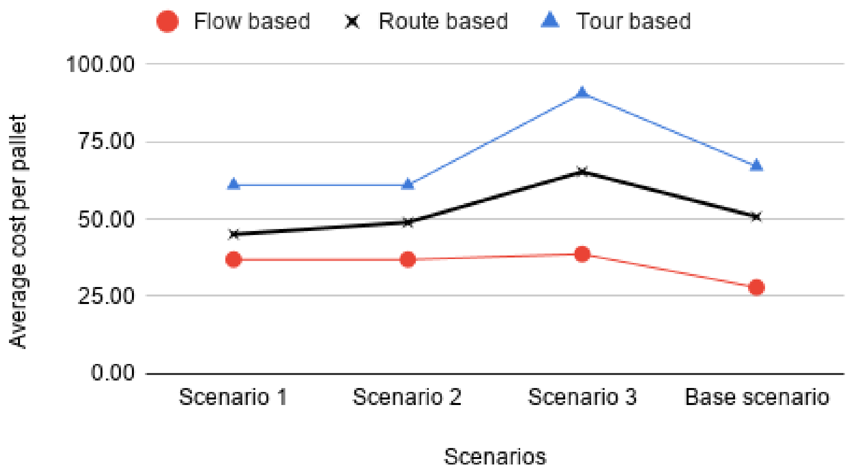

Figure 7.2: The average cost per pallet for different distributions of demand over the planning horizon.

- With the flow based type of sub-contraction, the direct transport is mostly preferred.
- With the route based type of sub-contraction, the milk runs are mostly selected.
- With the tour based type of sub-contraction, the milk runs are mostly preferred.

7.3. Computational time

To begin with, the implementation of the the models with long routes as inputs gave identical results. More specifically, the instances tested were: up to four and up to five waste generators be Incorporated in the same route. With these tests we can confirm that our assumption to consider only routes with up to three waste generators was valid (see chapter 5).

Thereafter, we performed several computational experiments to understand how efficient the models are (see section 4). In table 7.3 we present how much computational time several instances required. From the results we see that within two hours a problem with up to 20 waste generators and six periods of time can be solved. We investigated the route-based type of sub-contraction as we concluded that is the one closest to real life circumstances.

Table 7.3: Computational experiments with regards to the efficiency of the models.

Computation time (s)	1	2	3	4	5	6
10						95
15						186
20						4445
25				16432	Out of memory	Out of memory
26		478	2100	Out of memory	Out of memory	Out of memory
30		675	Out of memory	Out of memory	Out of memory	Out of memory

7.4. Alternative collection networks

The models were implemented with different collection networks to understand how the density of the waste generators would affect the cost of the waste collection service. First, the models were implemented with 13, 15, 17 ad 20 waste generators, randomly positioned around the recovery facility but within a range of 600km. Table E.5 shows the results. The reason for testing relatively random problems is that we wanted to investigate if the cost is influenced by the number of the sites where pallets have to be picked up. From the results obtained there is some evidence that the total distance travelled influences the cost. However, we can not conclude that the number of the waste generators or the travelled distance are responsible for the changes in the average cost per pallet.

Thereafter, in order to obtain a better understanding of what affects the cost we performed further experiments. We tested the uniform scale up and scale down of the network by considering different network alternatives. The instances regarding the scale up/down are mentioned below.

- Uniform scale down by 50%
- Uniform scale down by 25%
- Uniform scale up by 25%
- Uniform scale up by 50%

The tour based, the route based and the flow based type of sub-contraction were examined separately. We use the term "scale up/down" because with the uniform growth and drop at all distances of the network we wanted to demonstrate how dense or sparse the network is regarding the waste generators. The obtained results are presented in the appendix E.3.

A general remark from the obtained results is that there is a positive effect between the distance and the average cost per pallet (see table 7.4). The results show that the scale down of the network brings cost-savings. When the network is scaled up by 50% the cost is lower by 54.97% (RB), 27.27% (TB), and by 52.53% (FB). For a network scaled up by 25%, the average cost per pallet changes by -27.48% (RB), 27.27% (TB), and by 26.17% (FB). For a scale down by 25% the average cost per pallet changes by -25.65% (RB), 18.18% (TB), and by 40.02% (FB). For a scale down by 50% the average cost per pallet changes by -54.97% (RB), 36.36% (TB), and by 82.12% (FB). As for the different transport methods, the selection is not considerably affected (see appendix E.3).

Table 7.4: Overview of the average cost per pallet for alternative networks, scale up/down cases.

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7.5. Multiple recovery facilities

The results from the testings of alternative networks showed that that the average cost per pallet depends on the distance travelled to reach the recovery facility. In order to make this conclusion more concrete we implemented the models with the same network as in the case study but with two recovery facilities. Figure 7.3 depicts the network for which the model was implemented.The results from the implementation of these testings were compared with the results obtained from the case study. Table 7.5 shows the numerical results.

<*Removed due to confidentiality*>

Figure 7.3: The nodes of the service network when considering two recovery facilities.

With regards to the route based type of sub-contraction, 3.39% (8 pallets) more pallets were transported to a recovery facility. In total, one more collection with direct transport is scheduled (nine instead of eight). As for the required days of operation, seven days are needed instead of 12. The average cost per pallet is decreased by 40.09% and the average filling rate of the trucks is decreased by 8.10%. Considering the allocation of the waste generators to the recovery facilities, the results show some flexibility. Not all waste generators are assigned to a specific facility.

The results of the flow based type of sub-contraction for the same set of testings showed a slightly different sensitivity. The total quantity of the picked up waste is reduced by 2.54% and the average cost per pallet by 40.42%. The frequency of the collections did not change. There is no change in the milk runs as well. The results show that no milk runs are scheduled. The indirect transports are reduced by 83.33% and the direct transports have increased by 29.41%. In total five days less are needed for the operations and the average truck filling rate has dropped by 2.11%. Similarly to the route-based, there is a noticeable reduction in the cost with the same frequency of collections.

Table 7.5: Comparison of the results obtained from the implementation of the models for multiple recovery facilities

<*Removed due to confidentiality*>

Table 7.6: Percentage change between the results for the network with one facility and the network with two facilities

<*Removed due to confidentiality*>

The results of the tour based type of sub-contraction showed no sensitivity with regards to the number of pickups and a slight decrease of 11.11% in the frequency of the collections. The average cost per pallet drops by 29.18%. The quantity of the transported waste increased by 1.27%. The average cost per pallet reduced by 28.18% and only four days of operation are needed. Further, the average truck filling rate increased by 13.93%.

7.6. Multiple warehouses

After the testings for different number of recovery facilities, another set of testings was performed. The purpose was to obtain insights in how the test and the performance is influenced by the number of the warehouses. For that, we examined the case that two warehouses are available. For the sake of time we considered the geographical location of the hypothetical second recovery facility (see section 7.5). As in the case of multiple recovery facilities, both the three types of sub-contraction were tested and compared with the case with one warehouse. Table 7.7 shows the numerical results and table 7.8 shows the percentage change in comparison with the results from the implementation for the different types of sub-contraction.

The results of the route based type of sub-contraction show that 4.24% less quantity is picked up and the average cost per pallet drops by 34.21%. Opposed to the base case, the indirect transport method is more frequently chosen. Moreover, three days less are required for the operations and four out of ten collection are arranged with indirect transport. For these collections, the pallets from various waste generators were transported to the warehouse for consolidation. Thereafter, fully loaded trucks (100% filling rate) transported the waste to the recovery facility. Interestingly, the results showed that a few pallets are left in the warehouse after the end of the time horizon and that the frequency of the pickups was not affected. Another interesting result is that only the warehouse that was artificially placed is used. That implies that the location of the warehouse towards to the location of the waste generators influences the operations from a cost and a transport efficiency perspective .

Table 7.7: Comparison of the results for multiple warehouses

<*Removed due to confidentiality*>

Table 7.8: Percentage change of the results between the network with one warehouse and the network with two warehouses

<*Removed due to confidentiality*>

The results of the flow based type of sub-contraction demonstrate a reduction by 2.12% in the quantity of the transported waste and less frequent pickups (-4.35%). The average cost per pallet is lower by 13.37% than in the base case. The number of the indirect transports has been doubled and the average filling rate is increased by 20.21%. From an operational perspective, two days less are required. The presence of an additional warehouse affected the most the way the transports are arranged. The results indicate that when two warehouses are present in the network the waste is transported to the warehouse for consolidation (indirect transport).The frequency is slightly affected; one less pick up is performed.

The results of the tour based type of sub-contraction did not demonstrate considerable changes compared to the base case. The average cost per pallet was reduced by 1.39% and the frequency of the collections did not change (nine in total). The main difference is observed in the way that the collections are arranged. The waste is picked up only with milk runs while in the base case two direct transports are arranged.

7.7. Concluding remarks

Considering the case for the flow based and the route based type of sub-contraction, the capacity influences the cost of the operations (see section 7.1). The results from the implementation showed a reduction in the cost as the capacity was increasing. When the storage capacities are very limited, very frequent transports are required such that the storage capacities are respected. The obtained results showed that the flow based type of subcontraction could be the most profitable solution for the company for cases with very limited storage capacities. The unrestricted storage capacities do not influence the cost for none of the sub-contractions. A general conclusion is that the most frequently chosen transport method does not change with the different storage capacities.

The way the demand of waste is distributed over the time influences the cost (see section 7.2). Peak demands, affect negatively the average cost per pallet. As for the selection of the transport method, the most frequently chosen does not change for different distributions of the demand.

Another conclusion obtained from the implementation of the models is that the number of the waste generators -as a parameter- does not influence the decision making. The results presented in section 7.4 show that the relative 'size' of the network influence considerably the cost. Having said that, the more limited the area of operation the lower becomes the cost. More specifically, what influences the decisions is the distance of the pickup locations from the recovery facility and the warehouse (see sections 7.6, 7.5). The results demonstrated a remarkable reduction in the cost when adding a second warehouse and a second recovery facility closer to the waste generators.

8
Key findings

The structure of this chapter is as follows. In the section 8.1 the answers for the research question and sub-questions are provided. Next, in section 8.2 the scientific contribution of this thesis project is given. Following, in section 8.3 the contribution from a practical perspective is given. Lastly, in sections 8.4 and 8.5 the recommendations for the company and for further research are given.

8.1. Research objective and research questions

Looking at the beginning of this research, we stated that the objective this study seeks to meet is to understand what could be the impact of the different types of sub-contraction on the performance of a waste management service. In addition to this, we enlisted our main research question and six relevant sub-questions. Having completed the analysis and having demonstrated the results, it is essential to wrap up the conclusions and give an overview of the concluding remarks for every sub-question separately.

SQ1: Which are the entities involved in the waste collection service and how does it operate?

From the interview with the management team of the company we concluded that there are three main entities who are involved in the waste collection service: the waste generators, the waste carrier and the company. The objective of the service is to pick up waste from the sites of the waste generators and with the help of a waste carrier to transport it to recovery facilities in a cost efficient manner. There are two levels of decision making with regards to the management of the transport: the tactical and the operational level. At the tactical level, the decisions are related to how much, from which location, in what way and when waste should be transported to the recovery facilities. At the operational level, the days of operation during every period of the time horizon are decided (see chapter 2).

To explain better how the waste collection service operates the transport and legal constraints are provided (see chapter 2). With regards to the legal restrictions which were relevant to the transportation of the waste, some of them are explained. Though, the legal requirements are out of the scope of this study therefore no research was conducted for this category of requirements. The transport methods direct, indirect and milk run are those currently used for performing transports. Given the applicable transport methods, the collection network is shaped accordingly. Given the description as provided from the interviews the requirements of the system were taken into consideration in our analysis.

SQ2: How can we unify the different types of sub-contraction in a framework?

Thereafter, in order to make an overview of the different types of sub-contraction a selection of scientific articles was reviewed and their content was analysed. From the information gathered from the literature study (see section 3.6) the framework as depicted in the figure 3.1 was shaped.

A meaningful conclusion from the literature review (see section 3.6) is that three main types of sub-contraction are theoretically applicable at the waste collection service. Those are the: tour based, route based and flow based types of sub-contraction. The periodical services and the LTL[1] services were also met into the literature. However, because there is a slight overlap with the flow based type of sub-contraction and the tour based type of sub-contraction we did not focus on them.

SQ3: How can the decision making be optimised for this category of problems?

Another key information that was extracted from the literature was how this category of problems can be modelled. We met scientific studies that studied the vehicle routing problem, the inventory routing problem and the different types of sub-contraction. The scope, the methodology and they results of this studies are explained in chapter 3. The studied papers were classified based on the problem that was the subject of their research. Among the criteria for the classification were: the demand, the time horizon and the frequency. From this classification (see table 3.3) we draw the conclusion that this category of problems can be modelled as a multi-period inventory routing problem (see section 3.6).

SQ4: How can we assess the logistical performance of the waste collection service?

In order to understand the impact of the different types of sub-contraction in a waste collection service the results of the implementation of the models had to be interpreted. To do so, indicators were used. In that way, the comparison among the different types of sub-contraction was allowed and the comprehension of the results became easier. From the literature study many performance indicators were extracted; an overview of them is provided in table 3.2. Information from the problem analysis (see section 2) was also used. Finally, from the literature study and the problem description the indicators that are listed below were selected.

- Frequency of pickups
- Quantity of material collected within the time horizon
- The cost per unit of load
- Frequency of collections with direct/indirect/milk run transport method
- Total number of the days of operations

[1] LTL stands for less-than-truckload

- Filling rate in transport

SQ5: How can we develop a model that takes into account different types of sub-contraction regarding this system?

In order to model the system presented in the section 2.1 we looked into the literature to understand how this type of problem are modelled. A key conclusion from the previous research sub-question is that this type of problems can be classified as multi-period inventory routing problems.

Consequently, the base for the presented model was on the inventory routing problem as explained by Coelho et al. (2012). In order to include the different types of sub-contraction information from Kopfer and Krajewska (2007) was used. Eventually, two mathematical models were developed (see chapter 4). The reason for developing two models was that we wanted to model the different levels of decision making separately. Part of the results of the first model (tactical level) were used as input for the second (operational level) in order to keep the modelling procedure consistent (see chapter 4). Section 4.3 demonstrates which data from the results of the first model were used as inputs for the second model.

Next, to verify that the models were correct, we performed a number of verification tests. Thereby we confirmed that the models are solving what they are supposed to (see section 5.2).

SQ6: How would the different types of sub-contraction influence the logistical performance of the collection service in comparison with its current state?

In order to obtain insights in how the different types of sub-contraction would affect the collection of waste we implemented the model with real data provided by the company. The data of the case study are presented in section 6.1. Having incorporated the types of sub-contraction in the models (see sections 6.3.1, 6.3.2, 6.3.3) we implemented them with the case provided by the company which is a small instance problem. Thereafter, with performance indicators (see answer of SQ4), we interpreted the results of the implementation of the models. Table 6.10 and table 8.1 demonstrate the summary of the numerical results regarding the three types of sub-contraction.

Table 8.1: The influence of the sub-contraction on the performance of the waste collection service (percentage of change).)

<*Removed due to confidentiality*>

The results for the flow based type of sub-contraction showed the least cost and the most frequent collections. The average cost per pallet is 37.29% lower than as it is in the current state. In total, 23 collections are performed in 17 days while in the current state 14 in 20 days. We were critical regarding this type of sub-contraction because of the nature of the transported material. The waste as a material has different properties from the regular products. Because of that, it is not possible to combine the waste along with other products in the same truck. Considering the above, in terms of applicability the flow based type of sub-contraction does not approach real life conditions.

Although, we recognize that a transportation agreement according to which the compensation is based mainly on the quantities would result in cost savings. Another interesting finding is related to the frequency of the collections. The results illustrated that the collections are performed at every period with a repetitive pattern (see figures 6.4 - 6.9). By picking up frequently waste from the locations of the waste generators the service helps them to release space from their storage areas. By bringing together the key points of the results (see section 6.3.1), with this type of sub-contraction the service performance could be considerably improved. Theoretically thinking the cost could be reduced. From an operational perspective, almost (three days less) the same with the current state days of operation are required. Table 6.7 demonstrates the results.

The results from the implementation of the models for the route based type of sub-contraction showed cost-savings and an improvement in the efficiency of transportation with higher fulfillment rates of the trucks. The average cost per pallet is 13.17% less than in the current state. Within six periods, eight collections are performed; half of the collection as in the current state. From an operational perspective, the days required for the operations are considerably less than in the current state; 13 less. Another key point is that the collections are scheduled during the second, the third, the fourth and the sixth period (see figures 6.13 - 6.18). Therefore, collections are not scheduled during every period.

Because of the type of the material transported, it is more likely to 'book' a whole truck for one transport. Therefore, we consider this type of sub-contraction as the most realistic one. Table 6.8 demonstrates the results for the route based type of sub-contraction.

The results from the testing of the tour based type of sub-contraction demonstrated high transport costs and infrequent collections. The average cost per pallet is 13.91% higher than in the current state. Overall, the results show the most compact schedule of collections; in total only seven days of operations are needed. Same with the results from the implementation for the route based, in this type of sub-contraction the collections are scheduled during the second, the third, the fourth and the sixth period (see figures 6.22 - 6.22). We consider this type of sub-contraction a realistic one but not the most cost-efficient. Table 6.9 gives an overview of the numerical results.

Main RQ: How to improve the decision making given the different types of sub-contraction?

Taking into consideration the answers for the research sub-questions and the results of the implementation of the models (see chapter 7) we can answer the main research question.

Given the type of sub-contraction that may occur, the decision making may change.A general remark for the route based and the tour based is that the cost is distance driven (see chapter 7). Moreover, considering the flow based type of sub-contraction the key is to transport low quantities of waste for short distances regardless the transport method. Multiple warehouses or multiple recovery facilities allow for further reductions in the cost (see sections 7.6). With regards to the route based of sub-contraction, in order to enhance the cost efficiency it is important to schedule milk runs and take advantage the trucks' loading capacity (trucks' filling rate). Additional warehouses and recovery facilities contribute in achieving better transport/cost performance. The tour based type of sub-contraction is less sensitive to changes, compared to the other two. The collections become infrequent and compacted in a few days of operations. This type of sub-contraction leads to costly transports but efficient operations (fully loaded trucks and few days of operation).

8.2. Scientific contributions

To the best of our knowledge, the different types of sub-contraction in waste management with a special focus on industrial waste has little (or not at all) been researched. With this research we provided useful information with the intention to cover this knowledge gap.

A key scientific contribution comes from the framework of the different types of sub-contraction. Along with the analysis that followed, we concluded that the route based and the tour bases types could be applicable for a industrial waste management problem. Following, we classified the problem as multi-period inventory routing problem and we presented two mathematical formulations for modelling a waste collection system along with the sub-contraction. The approach that we presented for the implementation of the models can solve a problem that included 20 waste generators, one warehouse, one recovery facility and one depot within two hours. Besides the types of sub-contraction, while developing the mathematical formulations we incorporated practical constraints that are related to real life conditions such as the cost of waiting, the transport methods, the storage costs and the available days of operation. Moreover, the mathematical models are capable of being implemented with real data and examine different cases. Having said that, we believe that our models can be implemented with similar cases.

Another key scientific contribution is demonstrated by the results of the implementation of the models. The way the collections are organized for the different types of sub-contraction shows a typology of collection networks. The results demonstrated that there are different patterns of collections: "Least cost & maximum service performance", "Compromise" and "Compact". The additional implementations of the models showed that the cost is not sensitive to the storage capacity when the capacity increases by more than 25%. This remark is common for both three types of sub-contraction. The cost is sensitive to the distribution of the demand over the time; peak demands increase the cost. The main driver of the cost is the total distance travelled. More specifically, the density of the waste generators around the recovery facility and/or the warehouses is what affects the cost the most.

8.3. Practical contributions

The main practical contribution lies on the fact that the results obtained from the implementation of the models show that considerable cost savings could be accomplished. By arranging the collections with the route based type of sub-contraction the average cost per unit of load transported could be reduced by 13.17% and the filling rate of the trucks could be increased by 23.53%. Moreover, by looking at the collection plans as resulted from the analysis, we see that there is a lack of collections on specific periods of time. During the first and the fifth period, the results showed no activities. This is related to the low demand for collecting waste. The regularities that are observed in the results could provide significant help to the management team when planning the collections at the beginning of the planning horizon. For what concerns the cost, the density of the waste generators around the recovery facility leads to considerable cost reductions. The presence of multiple warehouses and/or multiple recovery facilities close to the locations of the waste generators could also bring considerable cost savings. Taking the above into consideration, the results obtained from the implementation of small-scaled problems with a rather simple mathematical model could help the management team to gain insights fast and with reasonable computational effort in how the cost, the logistics and the performance of the collection service would be formed under different conditions.

8.4. Recommendations for Avery Dennison

We made several assumptions while conducting this research project and the results have to be considered cautiously. Nonetheless, with the implementation of the models we obtained several insights that could be interesting for Avery Dennison. An overview of the concluding remarks is:

- *<Removed due to confidentiality>*

8.5. Limitations and recommendations for further research

For this research assumptions were made and we recognize several limitation which are discussed in the following paragraphs.

For what concerns the limitations of the models it is worth to mention that not all the available material is picked up within the specified planning horizon. To address this drawback another component could be added in the objective function that takes into account the value of the waste that is available for pick up. This problem could also be tackled by extending the planning horizon. As for the implementation approach, we were not capable of solving problems of large instances. To address this problem, we recommend for further research the development of more advanced solutions capable of solving larger problem.

Speaking of data availability, the results that were obtained from the models refer to a small instance problem provided by Avery Dennison. Several assumptions were made regarding the cost components for the different types of sub-contraction. To be exact, a piecewise linear cost function for the flow based type of sub-contraction could describe more precisely the reality. Other assumptions were made regarding the trucks. We considered that a truck can be available at any moment in time and we did not take into consideration any legal requirements that may should be respected. To overcome these limitations, we recommend further research in how the uncertain availability of trucks could be incorporated in a model for this type of problems. We also suggest further investigation on the legal requirements and how this type of requirements could affect the performance. Moreover, we did not consider any time related restrictions with regards to the operations. For that, we recommend further research on how time windows could be incorporated in the modelling of the decision making.

Lastly,in our study we considered the involvement of one transport operator. The "*cherry picking*" is a forwarding planning strategy according to which the requests are divided and assigned to different carriers (Wang et al., 2014). The investigation of the different types of sub-contraction in combination with the "*cherry picking*" could be a new topic for further research. This strategy has been studied for regular shipments however it has not been researched yet for the case of waste collection. the "*cherry picking*" is a forwarding planning strategy according to which the requests are divided and assigned to different parties (Wang et al., 2014). The investigation of the different types of sub-contraction in combination with the "*cherry picking*" could be a new topic for further research. This strategy has been studied for regular shipments however it has not been researched yet for the case of waste collection.

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A

Research paper

A short version of this thesis is provided in the pages that follow, with the form of research paper.

Sub-contraction in waste management.
Evaluation of the performance of a waste collection service.

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Abstract

The aim of this study is to investigate how the collection of industrial waste can be managed with different types of sub-contraction. Literature review was conducted in order to obtain knowledge about how this type of problems can be modelled, the types of sub-contraction and how the logistical performance could be assessed. Interviews with the management team of a company were performed to get a better understanding of the decision making for this type of problems. Thereafter, two mathematical models were formulated in order to model the decisions at tactical and operational level. In order to get more insights we implemented the developed models with a real-world case. We concluded that among the three types of sub-contraction that were examined, the results obtained from the route based and the tour based type give the most realistic solutions. Overall, the results indicate that the introduction of sub-contraction in waste collection brings considerable cost-savings. Following, we performed further testings to determine the efficiency of the developed models and to obtain managerial insights.

Keywords: waste collection, Inventory Routing Problem, sub-contraction, optimisation of decision making, industrial waste

1. Introduction

The collection of the domestic waste is one of the most important and expensive activity of the waste management [1]. Vecchi et al. [2] has reported that the collection and the transportation of the waste carry approximately half of the sanitary budget of the municipalities. A key challenge for the municipalities is the prediction of the required resources for collecting the waste. The reason for that is the lack of real time information regarding the quantity of waste at the collection spots [3]. Consequently, the steps of the collection and transportation have to be planned carefully to be cost-efficient. The collection process includes the routing, the idling time the availability and location of the disposal locations. Among all, the routing is what influences the most the cost of a collection [4].

Yeun et al. [5] researched how the Vehicle Routing Problem (VRP) and its variations can be modelled and solved. The authors provide useful information about the methods used for solving VRP but they do not examine a practical case study. Li et al. [6] proposed an algorithm that can solve the Vehicle Routing Problem with Time Windows (VRPTW) with high efficiency. In their research they highlighted the need for studying the routing problem with more realistic constraints. Sarmah et al. [4] studied the domestic waste collection and they implemented their model with a real case. The authors focused on how to solve the VRP on a daily basis but a time horizon was not included in their study. Kopfer and Wang [7] studied the vehicle routing problem with sub-contraction. The authors recommended further research on the impact of subcontracting on the operations' cost.

In this study we investigate how the collection of the waste of a specific type that is generated from businesses can be managed. This problem is different from the collection of domestic waste for three reasons. First, the waste is generated by businesses and not households. As a consequence the area of operations is different. Second, the demand is not daily but periodical while a time horizon applies. Third, we study the collection of one type of waste only. Because of that the quantities are much lower.

Taking the above into consideration, the novelty of this research paper lies in two parts. First, we consider a problem of collection of industrial waste of a specific type. The collection of industrial waste is different from the collection of the municipal waste with regards to the quantity and the frequency. Second, the waste is generated with a constant rate on a period basis during a predefined planning horizon. Third, we incorporate in our models the different types of sub-contraction. Our scope is twofold. To explore the different types of sub-contraction and to formulate a mathematical model for a waste collection problem that takes into consideration the different types of sub-contraction.

The results of this research will give insights to the decision makers in how the performance of the waste collection would change under different circumstances. Our research focuses on how the cost of collecting industrial waste would change when considering different types of sub-contraction. This knowledge would help the decision makers when negotiating with the organisations they would be working with. To this end, the main research question with regards to the collection of industrial waste that we will answer with this study is:

How to improve the decision making given the different types of sub-contraction?

The remainder of this paper is organised as follows. First, in section 1 we introduce the topic that this research focuses on. Following, in section 2 we provide information about the different types of sub-contraction. Next, in section 3 the indicators with which we will assess the results from our analysis are given. Thereafter, in section 4 the literature review is provided with regards to the vehicle routing problem, the inventory routing problem and their variations. In section 5 we report the research methodology. Then, in section 6 the problem description and the mathematical formulations are presented. The results of this research are discussed in sections 9 and 10.

2. Types of sub-contraction

Lundin and Hedberg [8] researched the different types of contracts between a shipper and a forwarder. They identified four different types of contracts: dedicated services, periodical services, truckload services and less-than-truckload services and they compared them on a basis of service costs, utilization and coordination costs. The authors classified the contracts as "behavior" and "outcome". The dedicated and periodical services fall under the former classification and the truckload service and less than truck load service under the latter. The main difference among the behavior oriented contracts is the length of the service commitment. For the dedicated service contracts the truck owner has to be compensated for the number of hours and distance travelled. However, the periodical service contracts dedicate the trucks for specific period(s) of time within the length of the contract. With regards to the outcome oriented contracts, the truck owners are compensated based on the number of hauls. Since the shipments can be either with fully loaded trucks or with less that fully loaded trucks, the type of contract is different in each case and the cost per haul varies accordingly.

Kopfer and Krajewska [9] studied the approaches that can be followed in order to integrate the sub-contraction in a transportation planning problem. They reported that in case of less than full truck load transport fixed tariffs are imposed and for full truck load transports two different types of sub-contraction are considered. First, complete tours are charged on a basis of fixed tariffs that depend on the distance to be driven. Second, the subcontractors charge the contractor on a daily basis with a flat rate. Moreover, Kopfer and Wang [7] studied how the different types of sub-contraction can integrated into the Vehicle Routing Problem. The authors developed a mixed integer linear programming model. Their findings showed a reduction in the total transportation cost. However, because of the complexity the size of the problem solved was very limited.

We gathered the aforementioned information in figure 1 where we unified the different types of sub-contraction with the shape of a framework. Even though we found in the literature several types of transport services we identify three main types: the tour based, the route based and the flow based type of sub-contraction. The compensation of the route based type of sub-contraction depends only on the distance. As for the tour based, the transport cost depends on the number of tours that are performed. For the flow based, the cost is a function of the transported quantity and the travelled distance [7, 10].

3. Performance indicators

Paddeu [11] mentioned that the assessment of the performance is necessary for planning the logistics activities. Caplice [12] reported that a performance measurement system can provide guidance to the decision makers for deciding which actions have to be taken. ODETTE [13] presented a list of key performance indicators for carriers and logistics service providers. The authors proposed the time, the security, the alert and the efficiency as the main criteria for assessing the logistical performance. As indicators they propose the arrival precision, pick up discrepancy alert, amount of accidents and late delivery alert.

Šimková and Konečný [14] studied the key performance indicators (KPIs) focused on logistics and on road transport. They mentioned that the KPIs could demonstrate how the logistics system evolves over time. They highlighted the importance of using clear and easy to understand indicators. The KPIs aim at helping the managers when making decisions at a strategic/tactical level. At operational level the performance indicators illustrate which areas have to be improved the most Šimková and Konečný [14]. The authors proposed the transport performance index for assessing the road transport. This index incorporates six core areas: the cost, the operations, the service, the compliance, the maintenance, and the environment. In order to select the most important indicators they conducted a questionnaire based study. Moreover, they provided a list of indicators that are measurable: the fuel efficiency, the transport performance [tons/km], the number of orders, the number of satisfied customers and the number of damaged goods.

Krauth et al. [15] conducted a literature review survey and formulated a framework that could capture the dynamic nature

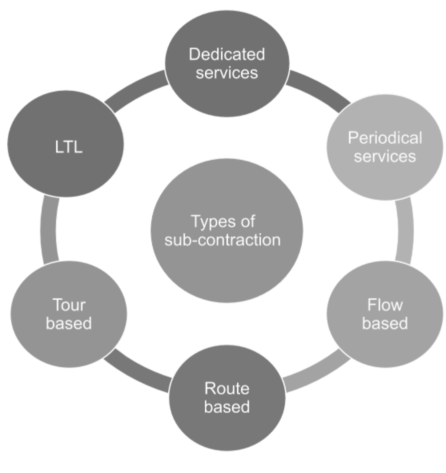

Figure 1: Framework of different types of sub-contraction

of the KPIs in logistics. To validate the framework an expert was interviewed. The number of trips per unit of time, the labour utilization and the on time deliveries are a few of the suggested indicators.

J. Liberatore [16] analyzed the performance metrics data from 247 manufacturing and service firms. The scope of the study was to cluster the firms based on their operational and planning priorities. The authors used the following metrics: Inventory carrying cost (% of revenue), warehouse management cost % of revenue), obsolete inventory (% of inventory value), transportation spend (% of revenue), supply chain planning cost, on-time delivery performance, forecast accuracy (%), days in inventory (number of days). Their analysis revealed four different types of firms. It was concluded that the logistics orientation of the firms did not influence the profitability. Limsomkiat and Vanichchinchai [17] investigated the satisfaction levels among shippers and international freight forwarders. The authors conducted a survey and they analysed statistically the collected data. The authors distinguished the performance in 6 dimensions: reliability, assurance, tangibles, empathy, responsiveness and service cost. The analysis showed that the service cost was the most important logistics service quality dimension for the shippers. Considering the aforementioned information, in order to understand how the different types of sub-contraction could affect the collections of waste, it is important to use performance indicators. Given the context of the problem we are focusing on we uses in our analysis the metrics that follow: the frequency of collections per transport method, the frequency of the pickups, the days of operation, the cost and the filling rate of the trucks.

4. Literature review

The decision making has been researched for various transport problems. For instance: the vehicle routing problem [5, 6, 18], the inventory routing problem, [19, 20, 21], the scheduling problem , the milk run problem [22]. Vecchi et al. [2] and Hannan et al. [3] studied the Vehicle Routing Problem (VRP) for the case of waste within an urban environment. Reihaneh and Ghoniem [23] examined the Vehicle Routing Allocation Problem. These studies examined the optimization of the routing of vehicles under conditions of static demand and infinite time horizon. Braekers et al. [24] and Yeun et al. [5] reviwed the literature and provided knowledge about how the VRP can be modelled and solved. Vecchi et al. [2] developed a three-phase sequential approach for optimizing the routes of trucks that collect solid waste. Heuristics are frequently used to solve the Vehicle Routing Problem problem more efficiently. However, this method was complex because of the formation of sub-routes, the number of which was increasing with the increasing number of nodes and arcs. The methodology that is presented by [2] allowed the extraction of solutions without the formation of sub-routes. At the first phase, an adapted version of the p-median problem was used to divide the area that has to be served by the vehicles. At the second phase the Capacitated Arc Routing Problem was used and at the third phase, an adapted version of the Hierholzer algorithm was applied to generate the routes of the trucks. Hannan et al. [3] researched the problem of the waste collection with the objective to minimize the financial and environmental impact. To solve the problem they proposed an adapted version of the Particle Swarm Optimization algorithm. In order to validate the model six different data sets were used for a hypothetical area with the same amount of identical vehicles with fixed capacities and static demand.

Reihaneh and Ghoniem [23] examined the Vehicle Routing Allocation Problem which is related to the decision making with regards to the allocation of goods and services to locations and the routing of the vehicles from the central depot to the customers locations. They introduced a branch-and-price algorithm to solve the problem. Sarmah et al. [4] presented a cost minimization model for a vehicle routing problem with periodic demand. They solved the problem with the Clark and Wright heuristic algorithm was applied. Li et al. [6] investigated the VRP with Time Windows and Synchronized visits. They proposed an improved ABC algorithm. Firstly, they modelled the dispatching problem with synchronized visits and thereafter they took into consideration the constraints derived from a practical application. The demand was considered as static. Chao et al. [25] studied the Periodic Vehicle Routing Problem (PVRP) where the planning period is M days instead of 1 day. In their study the authors considered that the frequency was predefined; the model determined the schedule.

Francis et al. [26] introduced the Periodic Routing Problem with Service choice (PVRP-SC). The PVRP is the generalization of the VRP. The difference is that the time horizon is incorporated: the vehicle routes are synthesized for a t-day period. In addition, the frequency is modelled as a decision variable. The authors developed an heuristic variation of the exact method that can solve large problems. They concluded that the introduction of the service choice improved the performance of the system. Hosseini et al. [27] reports that the milk run transportation method allows the reduction of holding costs and improves the efficiency. The model they proposed incorporated three transport methods: direct transportation, indirect transportation with cross-docking and milk run. They concluded that the proposed model can solve large problem instances.

We researched into the literature the vehicle routing problem and its variations. In order to summarize the literature we constructed table 1 where the reviewed articles are classified. This information was necessary to understand how our problem could be modeled. The studies that focus on modelling the decision-making, were classified based on four aspects: the demand (deterministic or stochastic), the time horizon (one day or t-day period), the inventory (storage cost are taken into account or not) and the frequency of service (parameter or decision variable). Table 1 shows how we categorized our problem. The problem that we analyze has deterministic demand, inventory cost and the service is offered periodically within a time horizon. From the literature review we understood that our problem has similarities with the Inventory Routing Problem and the Period-Vehicle Routing Problem. With the first one, the Inventory cost is taken into account at both cases. With

Table 1: Classification of reviewed studies

Problem	Author	Algorithm	Demand	Inventory	Time Horizon	Frequency	
						No/Yes	Decision variable or Parameter
VRP	Sarmah (2019)	Heuristic	Stochastic	No	No	No	-
VRP	Li (2020)	Heuristic Meta-heuristic	Deterministic	No	No	No	-
VRP	Yeun (2008)	Heuristic	Deterministic	No	No	No	-
Milk Run	Hosseini (2014)	Hybrid	Deterministic	Yes	Yes	Yes	Decision variable
PVRP	Chao (1995)	Heuristic	Deterministic	No	Yes	Yes	Parameter
PVRP-SC	Francis (2006)	Heuristic Exact	Deterministic	No	Yes	Yes	Decision variable
IRP	Coelho (2013)	Exact	Deterministic	Yes	Yes	No	-
IRP˜	Coelho (2012)	Heuristic	Deterministic	Yes	Yes	No	-
IRP	Archetti (2019)	Exact	Deterministic	Yes	Yes	No	-
IRP	Coelho (2014)	Heuristic	Deterministic Stochastic	Yes	Yes	No	-
MPIRP	Our problem	-	Deterministic	Yes	Yes	Yes	Parameter

the second one it is common the fact that the planning period is greater than one day. Taking the above into consideration, we can conclude that our problem falls into the category of the Multi-Period Inventory Routing Problem.

We found the most part of the decisions of the system can be modelled as a Multi-Period Inventory Routing Problem. That part of our problem is related to the decisions at tactical level. To model the decisions at operational level, the tactical level problem has to be firstly resolved. The study of the literature was addressed mainly on how to optimize the tactical level decision making.

5. Methodology

The scope of this paper is to understand how the decision making can be improved with regards to the collection of industrial waste.

Firstly, to gain knowledge about how the operations are managed and how the decisions are made we conducted interviews with two managers of the company and one transport operator. Moreover, the company gave access to numerical data related to the collections under strict confidentiality.

Secondly, in order to obtain insights in how the three types of sub-contraction could influence the collections of waste, two mathematical models were formulated. With these models, the decisions at tactical and at operational level are modelled separately. The decisions at tactical level are: the selection of the routes, the frequency and the quantities that are picked up per collection. The decisions at operational level are: the selection of days of operations and the allocation of routes to the available days of operation. The decisions at tactical level were modelled with a mathematical formulation inspired by the study of [20]. We modelled the decisions at operational level with a simplistic model, based on logical thinking, without consultation from the literature. The two models are connected in the sense that the decisions at tactical level influence the decisions at the operational level. To model this connection, the selection of the routes as decided by the first model (tactical level) is used as input for the second (operational level). As for the types of sub-contraction, we used information from the study of [7].

Thirdly, we implemented the models with data that was provided by the company. Data were also provided regarding the base case of the collection system. After the implementation of the models for every sub-contraction, we performed a comparative analysis with the results in order to understand which sub-contraction fits best for this type of problems. For better comprehension of the results, the following performance indicators were used.

- Frequency of collections
- Frequency of pickups
- Quantity of material collected within the time horizon
- The cost per unit of load [12, 15, 14]
- Frequency of collections with the direct, the indirect and the milk run transport method
- Days of operations
- Filling rate in transport [15, 13]

Last, we implemented the developed models for different cases of demand, storage capacity and different designs of collection networks with and without multiple warehouses/recovery facilities. The motivation behind this was to better understand what drives the cost.

6. Problem modelling

6.1. General problem description

The problem we are studying is the collection of industrial waste with different types of sub-contraction. The waste generators produce a known quantity of waste on a period basis. The waste is collected by trucks and transported to recovery facilities. The collections are planned during a predefined time horizon with multiple periods of activation. Moreover, in a day of operation the collections that can be performed are restricted.

The shipment of the waste to the recovery facilities can be arranged with three different transport methods: either directly or indirectly via a warehouse or via milk runs. With regards to the direct transportation a truck visits one waste generator at a time. At the indirect transportation multiple trucks visit multiple locations and deliver the material to a warehouse for consolidation. From there, transports to the recovery facilities are planned. With the milk run, multiple waste generators are traversed with the same route; the final destination is the recovery facility.

The transportation and the intermediate storage services are provided by an external organisation. The agreement that is in place makes sure that the external party provides the resources for the collection in terms of human resources and assets (trucks, warehouses) at any moment within the length of the agreement. The decisions related to the transportation (method of shipment, storage and routing decisions) are made by entity that arranges the transport.

The goal of the models is: to minimize the transport, the storage cost at tactical level and to minimize the days of operation at operational level. We incorporated in our models the different types of sub-contraction to understand how the performance of the collection service would be affected. In the following paragraphs we present the mathematical formulations for modelling the decisions.

6.2. *Modelling the decisions at tactical level*

In this section, we present the mathematical formulation for modelling the decisions at tactical level. As discussed in the paragraphs above, the problem of modelling these decisions has been categorized as multi-period inventory routing problem (refer to hereon as MP-IRP). The MP-IRP is defined on a graph $G(N, A)$. Let A be the arc set and $N = WG \cup W \cup F \cup D = \{0, ..., n\}$ the vertex set whereas WG represent the set of waste generators, F the set of recovery facilities, W the set of warehouses and D the depot. Let $T = \{1, ..., p\}$ be the set of periods of the time horizon. The storage capacities I_i^t of the waste generators are constrained by $IMax_i$ during the whole time horizon T. The warehouse is uncapacitated. The holding cost f_2 represents the storage cost when material is kept in the warehouse during a period of time. The cost f_4 represents the cost of waiting. Since a truck can travel a maximum number of kilometers in a day, a path may need more than one day in order to be completed. For every additional day required a cost f_5 for waiting is incurred. Additional costs H are incurred for transporting the waste to a warehouse $w \in W$.

At the first period of the time horizon, there is no stored material at the facilities of the waste generators and the warehouse. During the time horizon, v_i quantity of material is added at the storage facility I_i^t of the waste generators $i \in WG$ at every $t \in T$. Further, transports can be performed during every period $t \in T$. Nonetheless, arranging collection at every period is not considered as a hard constraint. All trucks start their trips from the depot D. The quantity of the material within one route has to be less than $QMax$ such that the trucks' capacities are respected. At the end of the planning horizon T, the material at the warehouse and the storage areas of the waste generators should not be higher than P units of load. Given the network of collections, a feasible set of routes $R = \{0, ..., r\}$ exists. The feasible routes apply on the directed graph $G(N, A)$.

The goal of this model is to minimize the cost. The cost of the waste collections has four main components: the transport cost, the storage cost of the waste generators, the additional cost incurred when waste is transported to the warehouse and the cost of waiting. The problem of the waste collections service is subject to the constraints mentioned below.

- The trucks' capacity should not be exceeded
- The storage facilities' capacities should not be exceeded
- The warehouses' capacities should not be exceeded
- All routes start from the depot
- The stored material at all storage facilities is always positive or zero
- The waste generators can be visited up to one time in a period $t \in T$
- The material at every storage facility at the end of the time horizon should be equal to or less than P units of load.

The model decides for the following:

- The quantity of material that is picked up from each waste generator and the warehouse at each period
- The quantity of the transported material to the warehouse at each period
- The activated routes at each period
- The quantity of material stored at the facilities of the waste generators and the warehouse at each period

We made the following assumptions:

- A truck is available at any period in time
- At the first period of the planning horizon there is no waste stored at the warehouse or the waste generators

In the mathematical formulation of the model for the waste collections the following decision variables have been introduced. Let y_r^t be a binary variable, equal to one if the route $r \in R$ is used at $t \in T$, q_i^{rt} be a continuous variable equal to the amount of material that is picked up from every waste generator $i \in WG$ and warehouse $w \in W$ during route $r \in R$ at period $t \in T$. Let x_{iw}^{rt} be a continuous variable equal to the quantity of the transported material from the waste generators $i \in WG$ to the warehouse $w \in W$ via the route $r \in R$ in period $t \in T$. Let I_i^t be a continuous variable that shows how much waste is stored at the facilities of the waste generators and the warehouse $i \in WG \cup W$ in period $t \in T$. We also denote a_i^r as the parameter that shows whether vertex $i \in N$ belongs or not to route $r \in R$ and the parameter $Waiting\ time_r$ that shows how many additional days are needed for a route in order to be completed. The objective function minimizes the cost:

Minimize :

$$\sum_{t\in T}\sum_{r\in R} c_r y_r^t + f_2 \sum_{t\in T}\sum_{w\in W} I_i^t + H \sum_{i\in WG}\sum_{r\in R}\sum_{t\in T}\sum_{w\in W} x_{iw}^{rt} + \\ + f_4 \sum_{r\in R}\sum_{t\in T} (Waiting\ Time_r) y_r^t \tag{1}$$

The transport is performed by an external organisation. As a result the routing cost depends on the type of sub-contraction. How this is incorporated in the mathematical formulation is specified in section 6.4. The storage cost and the additional costs depend on the quantity of the transported material. The notation used in the model is summarised in table 2 and the constraints are presented at the equations 2 to 19.

$$\sum_{r\in R} y_r^t a_i^r \ \leq\ 1 \quad \forall\ t \in T,\ i \in WG \tag{2}$$

$$q_i^{rt} - P \sum_{f\in F} y_r^t a_i^r a_f^r \ \geq\ 0 \quad \forall\ i \in WG \cup W,\ t \in T,\ r \in R \tag{3}$$

$$q_i^{rt} \ \leq\ M \sum_{f\in F} y_r^t a_i^r a_f^r \quad \forall\ r \in R,\ t \in T,\ i \in WG \cup W \tag{4}$$

$$\sum_{f\in F} y_r^t a_i^r a_f^r \ -\ q_i^{rt} \ \leq 0 \quad \forall\ r \in R,\ t \in T,\ i \in WG \cup W \tag{5}$$

$$q_w^{rt} \ \leq\ M \sum_{f\in F} y_r^t a_w^r a_f^r \quad \forall\ r \in R,\ t \in T,\ w \in W \tag{6}$$

$$x_{iw}^{rt} \ \leq\ M y_r^t a_i^r a_w^r \quad \forall\ t \in T,\ r \in R,\ i \in WG,\ w \in W \tag{7}$$

$$y_r^t a_i^r a_w^r \ -\ x_{iw}^{rt} \ \leq\ 0 \quad \forall\ t \in T,\ r \in R,\ i \in WG,\ w \in W \tag{8}$$

$$I_i^t \ =\ I_i^{t-1} + v_i - \sum_{r\in R} q_i^{rt} - \sum_{w\in W}\sum_{r\in R} x_{iw}^{rt} \quad \forall\ t \in T,\ i \in WG \tag{9}$$

$$I_w^t \ =\ I_w^{t-1} - \sum_{r\in R} q_w^{rt} + \sum_{i\in WG}\sum_{r\in R} x_{iw}^{rt} \quad \forall\ t \in T,\ w \in W \tag{10}$$

$$I_i^t \ \geq\ 0 \quad \forall\ i \in WG \cup W \tag{11}$$

$$I_i^{t=p} \ \leq\ P \quad \forall\ i \in WG \tag{12}$$

$$I_i^t \ \leq\ IMax_i \quad \forall\ i \in WG \cup W \tag{13}$$

$$\sum_{i\in WG\cup W} q_i^{rt} \ \leq\ QMax \quad \forall\ t \in T,\ r \in R \tag{14}$$

$$\sum_{i\in WG} x_{iw}^{rt} \ \leq\ QMax \quad \forall\ t \in T,\ r \in R,\ w \in W \tag{15}$$

$$y_r^t \in \{0, 1\} \quad \forall\ t \in T,\ r \in R \tag{16}$$

$$x_{iw}^{rt} \ \geq \quad \forall\ t \in T,\ r\ \in R,\ w \in W,\ i \in WG \tag{17}$$

$$I_i^t \ \geq\ 0 \quad \forall\ t \in T,\ i \in WG \cup W \tag{18}$$

$$q_i^{rt} \ \geq\ 0 \quad \forall\ t \in T \quad \forall\ i \in WG \cup W,\ r \in R \tag{19}$$

Equation 2 shows that at every period $t \in T$, all waste generators are visited up to one time. Equation 3 shows that in order for a pickup to be decided, at least P units of load have to be available at the locations of the waste generators and/or the warehouse. Equations 4 and 5 show that material is picked up from the waste generators only if the route that traverses the relevant location is selected. Equation 6 show that material is picked up from the warehouses only when the routes that traverse both the warehouse and the recovery facilities are activated. Equations 7 and 8 show that in each period t of the planning horizon material is transported to a warehouse only when the routes that traverse both a waste generator and a warehouse are activated. Equation 9 show that the stored material at each waste generator in period t is given by its previous state in period $t-1$ plus the material v_i that is generated at period t minus the quantity that is picked up at period t and minus the quantity transported to the warehouses at period t. Equation 10 show that the stored material at each warehouse in period t is given by its previous state in period $t-1$ plus the material v_i that is dropped off at period t minus the quantity that is picked up at period t. Equation 11 show that the stored material at each waste generator at each period t is positive or zero. Equation 12 show that the stored material at each waste generator and at each warehouse at the end of the planning horizon ($t = p$) is less than P. Equation 13 makes sure that the capacities of the storage areas of the waste generators are respected. Equations 14 and 15 show that the sum of the quantities transported either to the warehouse or to the recovery facility at each route $r \in R$ has to be less than $QMax$ in order to respect the capacity of the truck. The equations 16 to 19 represent the domain of variables.

6.3. Modelling decisions at operational level

In this section the mathematical formulation for the model with regards to the decisions at operational level is presented. We use the set of selected routes $ActR = \{ActR_1, ..., ActR_n\}$ that were obtained from the implementation of the model for the decisions at tactical level. Let $T = \{1, ..., p\}$ be the set of periods, same as in the model for the decisions at tactical level. A set of the available days of operation $D = \{1, ..., m\}$ for every period $t \in T$ is also used. We also denote Tw_{tr} as a parameter equal to one when material is transported to a warehouse during period $t \in T$ and zero otherwise. Tf_{tr} is a parameter equal to one when material is picked up from a warehouse during period $t \in T$, otherwise is equal to 0. Moreover, within a day of operations

Table 2: Notation used in the mathematical formulation of modelling the tactical level decisions

Symbol	Indices	Type	Meaning
WG		Set	Set of waste generators
R		Set	Set of feasible routes
T		Set	Set of periods
F		Set	Set of recovery facilities
W		Set	Set of warehouses
v_i	$i \in WG$	Parameter	Demand
f_2		Parameter	Holding costs
H		Parameter	Additional costs
f_4		Parameter	Cost of waiting one day
$Waiting\ Time_r$	$r \in R,\ t \in T$	Parameter	Waiting days per route r
$QMax$		Parameter	Capacity of vehicle
$IMax_i$	$i \in WG$	Parameter	Capacity of storage facilities
P		Parameter	Minimum quantity of P that can be picked up at the storage facilities of the waste generators
c_r	$r \in R$	Parameter	Cost of route r
a_i^r	$i \in WG \cup W \cup F\ r \in R$	Parameter	1 if i belongs to route r , 0 otherwise
M		Parameter	Big number
y_r^t	$r \in R, t \in T$	Decision variable	1 if route r is selected in period T, 0 otherwise.
q_i^{rt}	$i \in WG \cup W,\ r \in R$ $t \in T$	Decision variable	Quantity of the material that is picked up from the location i at period t.
x_{iw}^{rt}	$i \in WG,\ w \in W,\ r \in R,\ t \in T$	Decision variable	Quantity of the transported material from the waste generator i to the warehouse w at period t.
I_i^t	$i \in WG \cup W,$ $t \in T$	Decision variable	Quantity of waste stored at location i in period t.

up to $RMax$ routes can be performed. The goal of this model is to minimize the summation of the days of operation. The mathematical model of the operational level's decisions is subject to the following constraints:

- Up to $RMax$ transports per day can be activated.
- The routes in which material is transported to the warehouses can not be scheduled the same day with the routes in which material is picked up from there.
- If a route requires more than one day of operation in order to be completed, then it is allocated to more than one day.

This mathematical model decided for the following:

- Allocation of the activated routes to days of operation
- The activated days of operation per period

We made the following assumptions:

- A truck is available at any available day of operation
- There are no time related restrictions from the side of the waste generators, the warehouse or the recovery facility. Having said that, we assume that the operations (loading, unloading etc) take place always within working hours.

For the mathematical model we introduced two binary decision variables. Let z_d^t be equal to one if day $d \in D$ is activated at period $t \in T$ and l_d^{rt} equal to one if route $r \in ActR$ is allocated to day of operation $d \in D$ during period $t \in T$. The objective function minimizes the total number of days of operation within the planning horizon. Equation 20 shows the objective function and the equations 21 to 29 the constraints of the mathematical model. Table 3 presents the notation.

$$Minimize\ Z$$

$$Z = \sum_{d \in D} \sum_{t \in T} z_d^t \tag{20}$$

$$l_d^{rt} \leq z_d^t \quad \forall\ d \in D,\ t \in T,\ r \in ActR \tag{21}$$

$$z_d^t - z_{d+1}^t \leq 0 \quad \forall d \in D, t \in T \tag{22}$$

$$\sum_{r \in ActR} l_d^{rt} \leq RMax \quad \forall\ d \in D,\ t \in T \tag{23}$$

$$\sum_{t \in T} \sum_{d \in D} l_d^{rt} \geq 1 \quad \forall r \in ActR \tag{24}$$

$$\sum_{d \in D} l_d^{rt} - OD_r = 0 \quad \forall\ t \in T, \quad r \in ActR \tag{25}$$

$$\sum_{r \in ActR} I_d^{rt} T f_{tr} + \sum_{r \in ActR} l_d^{rt} T t_{tr} \leq 1 \quad \forall d \in D, t \in T \tag{26}$$

$$l_{d+1}^{rt} T t_{tr} - I_d^{rt} T f_{tr} \leq 0 \quad \forall\ t \in T,\ r \in ActR,\ d \in D \tag{27}$$

Table 3: Notation for the mathematical formulation of the model for the operational level's decisions.

Symbol	Indices	Type	Meaning
D		Set	Set of available days of operation
T		Set	Set of periods
$ActR$		Set	Set of activated routes
OD_r	$r \in ActR$	Parameter	Days of travelling per route r
Tf_{tr}	$t \in T$, $r \in ActR$	Parameter	1 if facility belongs to route r, 0 otherwise
Tt_{tr}	$t \in T$, $r \in ActR$	Parameter	1 if facility belongs to route r, 0 otherwise
$RMax$		Parameter	Maximum number of transports performed in a day of operation
l_d^{rt}	$t \in T$, $r \in ActR$, $d \in D$	Decision variable	1 if route $r \in ActR$ is activated in day d
z_d^t	$t \in T,\ d \in D$	Decision variable	1 if day d is activated during period t

$$l_d^{rt} \in \{0,1\} \quad \forall\, t \in T,\ r \in ActR,\ d \in D \tag{28}$$

$$z_d^t \in \{0,1\} \quad \forall\, t \in T,\ d \in D \tag{29}$$

Equation 21 shows that a route can be activated only if it is assigned to an day of operation. Equation 22 makes sure that the days of operation are ordered. Equation 23 shows that within one day of operation up to $RMax$ routes can be activated. Equation 24 shows that all routes that belong to the solution of the mathematical problem of the model for the tactical level's decisions have to be allocated to one day (at least). A route may need for more than one day to be completed. Equation 25 shows that every route has to be allocated to as many days as required in order to be completed. Equation 26 shows that the routes via which material is transported to the warehouse and the routes via which the material is transported to the facility cannot be allocated to the same day. Equation 27 makes sure that the routes via which material is dropped off at the warehouse have to scheduled before the deliveries to the recovery facilities.The equation 28 and 29 define the domain of the variables.

6.4. Modelling sub-contraction

The types of sub-contraction: flow based, route based and toured based are incorporated in the objective function of the modes for the decision making at tactical level. The mathematical formulation proposed by [7] is used. The notation is included in table 2

For the first type of sub-contraction (flow basis), the transport cost depends on the distance c_r travelled and the quantity of the transported material q_i^{rt}, x_{iw}^{rt} [7]. The parameter $Rate_1$ represents how the sub-contracted organisation charges the contractor for the offered services per unit of load and unit of distance travelled. The transported quantity is given by the decision variables q_i^{rt} and x_{iw}^{rt}. We assume a linear rate function that depends on the quantity transported within a single route. The objective function is shown in equation 30.

$Minimize$:

$$\sum_{i \in WG \cup W} \sum_{r \in R} \sum_{t \in T} \sum_{w \in W} Rate_1 \cdot c_r(q_i^{rt} + x_{iw}^{rt}) \ +\ f_2 \sum_{t \in T} \sum_{i \in W} I_i^t \ + \\ +H \sum_{i \in WG} \sum_{r \in R} \sum_{t \in T} \sum_{w \in W} x_{iw}^{rt} \ +\ f_4 \sum_{r \in R} \sum_{t \in T} (Waiting\ Time_r) y_r^t \tag{30}$$

For the route based type of sub-contraction the transport cost depends only on the distance travelled [7]. We use the parameter $Rate_2$ to present how much the sub-contracted organisation charges the contractor per unit of distance travelled. In this case the objective function becomes as shown in equation 31.

$Minimize$:

$$\sum_{r \in R} \sum_{t \in T} Rate_2 c_r y_r^t + f_2 \sum_{t \in T} \sum_{i \in W} I_i^t + H \sum_{i \in WG} \sum_{r \in R} \sum_{t \in T} \sum_{w \in W} x_{iw}^{rt} + \\ + f_4 \sum_{r \in R} \sum_{t \in T} (Waiting\ Time_r) y_r^t \tag{31}$$

For the tour based type of sub-contraction the transport cost depends only on the days of travelling [7]. With the parameter $Rate_3$ we show how much the sub-contracted organisation charges the contractor per day of travelling. In this case the objective function becomes as shown in equation 32. The cost of waiting is not included in this cost function.

$Minimize$:

$$\sum_{r \in R} \sum_{t \in T} Rate_3 OD_r y_r^t \ +\ f_2 \sum_{t \in T} \sum_{i \in W} I_i^t + H \sum_{i \in WG} \sum_{r \in R} \sum_{t \in T} \sum_{w \in W} x_{iw}^{rt} \tag{32}$$

7. Implementation

For the implementation we used a laptop computer with a processor Intel i5, CPU running at 2.5GHz with 8.00 GB of

RAM. We used python as the modelling programming language and solved the problem with the help of the solver Gurobi. The models were verified with balance tests, input tests, consistency tests and manual tests. Following, we implemented the models with a small instance case provided by the company. This data was used as our base case with which we compared the results that came out from our models. The collection network that we examine, consists of nine waste generators, one warehouse , one recovery facility one entity that arranges the transport and one transport operator. Not all the nodes of the collection network and interconnected but the following conditions apply:

- The paths connecting the warehouse and the facility should not traverse the location of a waste generator.
- The warehouse, the waste generators and the recovery facilities should not be traversed by the same path.
- The paths connecting the waste generators and the warehouses should not traverse the recovery facilities.
- In order to limit the computational time we made the assumption that up to three waste generators can be incorporated in the same collection.

The time horizon consists of six periods and every period consists of 20 available days of operation. Within an available day of operation, up to two transports can be performed.

8. Results

In this section we present the results of the implementation of the developed models. First in subsection 8.1 we describe the results with regards to the implementation with the real data. Thereafter, in sections 8.2-8.7 we present the results of the implementation with different instances.

8.1. Types of sub-contraction

Table 4 shows the most interesting results from the implementation of the models with the case that was provided by the company. The results obtained from the implementation of the models show the lowest average cost in the case of the flow based type of sub-contraction (reduction by 37.29%). With regards to the quantity of the waste transported to the recovery facility, there was no difference between the different types of sub-contractions. The total quantity transported was lower than in the base case by 9.92% . For what concerns the days of operations, at both three types of sub-contraction they are less than in the base case.

More specifically, comparing the results for the flow based type of sub-contraction with the base case the frequency of the collections has increased by 64.29%. On average, the cost per pallet transported has been reduced by 37.29% . The results for the flow based type of sub-contraction show that the majority of the collections are planned with direct transport. In total, 23 pickups are incorporated in 23 collections. The transports were performed directly (17 pickups) and indirectly (six pickups) For the collections to be performed three days less are needed. The filling rate of the truck is 57.04% lower than the base case.

By comparing the results from the implementation of the model for the route based type of sub-contraction the average cost per pallet has reduced by 13.17%. The average truck's fulfilment rate is increased by 23.53%. In order for the waste to be transported, 16 pickups are incorporated in eight collections. The transports are performed with milk runs (six pickups) and indirect transport (two pickups) In addition to the above, the days of operation decreased by 13 days.

Regarding the tour based type of sub-contraction we see that the truck's fulfilment ratio is higher by 9.81%. The days of operation have been decreased by 13 and the average cost per pallet transported has increased by 13.91%. In total, 16 pick ups are incorporated in nine collections. The collections are performed at their majority with milk runs. Seven out of the nine collections were performed with milk runs and two with direct transport.

8.2. Capacity

The model was implemented for several instances of storage capacity: ±50%, ± 25% of the storage capacities of the storage areas of the waste generators and with unlimited capacity. Figure 2 shows how the cost changes for the different instances. For both three types of sub-contraction, when the storage capacities are the most limited (−50%) the average cost per pallet get its lowest value.

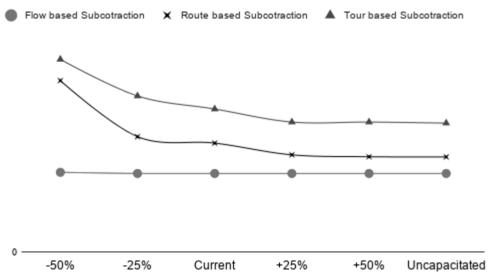

Figure 2: Change in the average cost per unit of load for different capacities of the storage areas of the waste generators.

The fact that there is a reduction in the average cost per pallet as the capacities increase is a common remark for all types of sub-contraction. However, the results for the route based of sub-contraction show a sharper increase in the cost for the smaller storage facilities; 57.2% higher than in the base case. With regards to the flow based type of sub-contraction the cost is not sensitive since it changes slightly (1.48% increase) for the lowest capacity. As for the tour based type of sub-contraction, the average cost per pallet increases by 34.62% when the capacity reduces at it half. A common remark for all types of sub-contraction is that the results showed little or no difference in the cost when the capacity increases for more than 25%.

8.3. Demand

The model was implemented for three different distributions of demand. First, 50% less of the base case for the first three

Table 4: The impact of the sub-contraction on the performance (percentage of change)

Sub-contraction	Frequency of pickups	Quantity picked up	Average cost per unit of load	Frequency of collections	Filling rate
Route based	-20%	-9.92%	-13.17%	-42.86%	+23.53%
Flow based	+15%	-9.92%	-37.29%	+64.29%	-57.04%
Tour based	-5%	-9.92%	+13.91%	-35.71	+9.81%

periods and 50% more for the rest (scenario 1). Second, 50% additional for the first three periods and 50% less for the next three (scenario 2). Third, that no quantities are generated during the first three periods while for the next three, the quantities were set equal to quantities at the actual state (scenario 3).

The results (see figure 3) show that the average cost per unit of load for the flow type of sub-contraction does not change for the first two scenario and increases by 4.79% for the third one. The average cost for the tour based does not change for the first two scenarios by it increases drastically (145.51%) for the third one. The average cost per pallet increases by 22.05% for the first, by 32.49% for the second and by 76.84% for the third.

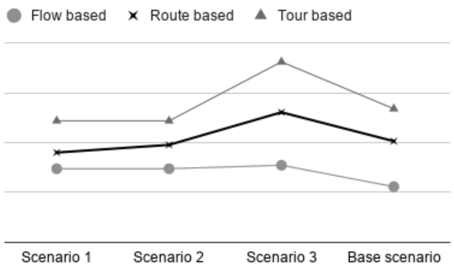

Figure 3: The average cost per pallet for different distributions of demand over the planning horizon.

8.4. Computational experiments

To begin with, the implementation of the models with long routes as inputs gave identical results. More specifically, the instances tested were: up to four and up to five waste generators be Incorporated in the same route. With these tests we can confirm that our assumption to consider only routes with up to three waste generators was valid.

The implementation of the the models with long routes as inputs gave identical results. More specifically, the instances tested were: up to four and up to five waste generators be Incorporated in the same route. With these tests we can confirm that our assumption to consider only routes with up to three waste generators was valid. Thereafter, we performed several computational experiments to understand how efficient the models are.

Thereafter, we performed several computational experiments to understand how efficient the models are. In table 5 we present how much computational time several instances required. From the results we see that within two hours a problem with up to 20 waste generators and six periods of time can be solved.

8.5. Alternative networks

The models were implemented with different collection networks to understand how the density of the waste generators would affect the cost of the waste collection service. First, the models were implemented with 13, 15, 17 ad 20 waste generators, randomly positioned within a range of 600km around the recovery facility. The reason for testing relatively random problems is that we wanted to investigate if the cost is influenced by the number of the sites where pallets have to be picked up. From the results obtained there is some evidence that the total distance travelled influence the cost. However, we can not conclude the number of the waste generators or travelled distance was responsible for the changes in the average cost per pallet.

Then, in order to obtain a better understanding of what affects the cost we performed further experiments. We tested the uniform scale up and scale down of the network by considering different network alternatives. The instances regarding the scale up/down are mentioned below.

- Uniform scale down by 50%
- Uniform scale down by 25%
- Uniform scale up by 25%
- Uniform scale up by 50%

The tour based, the route based and the flow based type of sub-contraction were examined separately. We use the term "density" because with the uniform growth and drop at all distances of the network we wanted to demonstrate how dense the network. We consider as 'density' the number of the waste generators within a specific geographical area of operation. We kept the number of waste generators constant and we scaled the area.

A general remark from the obtained results is that there is a positive effect between the distance and the average cost per pallet. The results show that the denser the network is the lower becomes the average cost per pallet. When the network is denser by 50% the cost is lower by 54.97% (RB), 27.27% (TB), and by 52.53% (FB). For a network denser by 25%, the average cost per pallet changes by -27.48% (RB), 27.27% (TB), and by 26.17% (FB). For a less by 25% network the average cost per pallet changes by -25.65% (RB), 18.18% (TB), and by 40.02% (FB). For a less by 50% network the average cost per pallet changes by -54.97% (RB), 36.36% (TB), and by 82.12% (FB).

8.6. Multiple recovery facilities

The results from the testings of alternative networks showed that that the average cost per pallet depends on the distance travelled to reach the recovery facility. In order to make this conclusion more concrete we implemented the models with the same network as in the case study but with two recovery facilities. Table 6 demonstrates the results.

Table 5: Computational experiments with regards to the efficiency of the models.

Computation time (s)	1	2	3	4	5	6
10						95
15						186
20						4445
25				16432	Out of memory	Out of memory
26		478	2100	Out of memory	Out of memory	Out of memory
30		675	Out of memory	Out of memory	Out of memory	Out of memory

With regards to the route based type of sub-contraction, 3.39% more units of load were transported to a recovery facility. The average cost per pallet is decreased by 40.09% and the average fulfilment ratio of the trucks is decreased by 8.10%. Considering the allocation of the waste generators to the recovery facilities, the results show some flexibility. Not all waste generators are assigned to a specific facility.

The results of the flow based type of sub-contraction for the same set of testings showed a slightly different sensitivity. The total quantity of the picked up waste is reduced by 2.54% and the average cost per unit of load by 40.42%. The frequency of the collections did not change. There is no change in the milk runs as well. The results show that no milk runs are scheduled. The indirect transports are reduced by 83.33% and the direct transports have increased by 29.41%. In total five days less are needed for the operations and the average truck fulfilment rate has dropped by 2.11%. Similarly to the route-based, there is a noticeable reduction in the cost with the same frequency of collections.

The results of the tour based type of sub-contraction showed no sensitivity with regards to the number of pickups and a slight decrease of 11.11% in the frequency of the collections. The average cost per pallet drops by 29.18%. The quantity of the transported waste increased by 1.27%. The average cost per pallet reduced by 28.18% and only four days of operation are needed. Further, the average truck fulfilment increased by 13.93%.

8.7. Multiple warehouses

After the testings for different number of recovery facilities, another set of testings was performed. The purpose was to obtain insights in how the test and the performance is influenced by the number of the warehouses. For that, we examined the case that two warehouses exist in the collection network. For the sake of time we considered the geographical location of the warehouse the same with the one of the hypothetical second recovery facility. As in the case of multiple recovery facilities, both the three types of sub-contraction were tested and compared with the case with one warehouse.

The results of the route based type of sub-contraction show that 4.24% less quantity is picked up and the average cost per pallet drops by 34.21%. Opposed to the base case, the indirect transport method is more frequently chosen. Moreover, three days less are required for the operations and four out of ten collection are arranged with indirect transport. For these collections, the pallets from various waste generators were transported to the warehouse for consolidation. Thereafter, fully loaded trucks (100% fulfillment rate) transported the waste to the recovery facility. An interesting result is that a few units of load are left in the warehouse after the end of the time horizon and that the frequency of the pickups was not affected. The results show that only the warehouse that was artificially placed is used. That implies that the location of the warehouse towards to the location of the waste generators influences the operations from a cost and a transport efficiency perspective.

The results of the flow based type of sub-contraction demonstrate a reduction by 2.12% in the quantity of the transported waste and less frequent pickups (-4.35%). The average cost per pallet is lower by 13.37% than in the base case. The number of the indirect transports has been doubled and the average fulfillment ratio is increased by 20.21%. From an operational perspective, two days less are required. The additional warehouse affected the most the way the transports are arranged. The waste is transported to the warehouse from the sites of the waste generators for consolidation. Because of that, the average trucks' fulfillment rates are also higher. The frequency is slightly affected; one less pick up is performed.

The results of the tour based type of sub-contraction did not demonstrate significant changes compared to the base case. The average cost per pallet was reduced by 1.39%. The frequency of the collections did not change. The main difference is observed in the way that the collections are arranged. The waste is picked up only with milk runs while in the base case two direct transports are arranged.

9. Conclusion

We classified the problem as multi-period inventory routing problem and we presented two mathematical formulations for modelling a waste collection system along with the subcontraction. The approach that we presented for the implementation of the models can solve a problem that included 20 waste generators, one warehouse, one recovery facility and one depot within two hours. Besides the types of sub-contraction, while developing the mathematical formulations we incorporated practical constraints that are related to real life conditions such as the cost of waiting, the transport methods, the storage costs and the available days of operation. Moreover, the mathematical models are capable of being implemented with real data and examine different cases. Having said that, we believe that our models can be implemented with similar cases.

Furthermore, the results of this study indicate which types of sub-contraction could be applicable for a waste management

Table 6: Percentage change between the results for the network with one facility and the network with two facilities

	Facilities	Frequency of pickups	Quantity picked up	Average cost/pallet	Frequency of collections	Frequency of milk Runs	Frequency of indirect	Frequency of direct	Days of operation	Average truck filling rate
Route based	2	6.25%	3.39%	-40.09%	12.50%	0.00%	0.00%	50.00%	0.00%	-8.10%
Flow based	2	43.75%	-2.54%	-40.42%	0.00%	0.00%	-83.33%	29.41%	-29.41%	-2.11%
Tour based	2	18.75%	1.27%	-28.18%	-11.11%	14.29%	0.00%	-100.00%	-42.86%	13.93%

Table 7: Percentage change of the results between the network with one warehouse and the network with two warehouses

	Facilities	Warehouses	Frequency of pickups	Quantity picked up	Average cost/pallet	Frequency of collections	Frequency of milk Runs	Frequency of indirect	Frequency of direct	Days of operation	Average truck filling rate
Route based	1	2	0.00%	-4.24%	-34.21%	25.00%	-50.00%	100.00%	50.00%	28.57%	-17.80%
Flow based	1	2	-4.35%	-2.12%	-13.37%	-4.35%	0.00%	116.67%	-47.06%	-11.76%	20.21%
Tour based	1	2	5.26%	0.42%	1.39%	0.00%	28.57%	0.00%	-100.00%	0.00%	0.42%

service. Another point that the results demonstrate is that every type of sub-contraction influences in a different way the decision making.

The results for the flow based type of sub-contraction showed the least cost and the most frequent collections. The average cost per pallet is 37.29% lower than as it is in the base case. We were critical regarding this type of sub-contraction because of the nature of the transported material. The waste as a material has different properties from the regular products. Because of that, it is not possible to combine the waste along with other products in the same truck. Considering the above, we concluded that in terms of applicability the flow based type of sub-contraction does not approach real life conditions.

The results from the implementation of the models for the route based type of sub-contraction showed cost-savings and an improvement in the efficiency of transportation with higher fulfillment rates of the trucks. The average cost per pallet is 13.17% less than in the base case. Because of the type of the material transported, it is more likely to 'book' a whole truck for one transport. Therefore, we consider this type of sub-contraction as the most realistic one.

The results from the testing of the tour based type of sub-contraction demonstrated high transport costs and infrequent collections. The average cost per pallet is 13.91% higher than in the base case. We consider this type of sub-contraction an applicable one but not the most cost-efficient.

Given the type of sub-contraction that may occur, the decision making may change. A general remark for the route based and the tour based is that the cost is distance driven. Multiple warehouses or multiple recovery facilities allow for further reductions in the cost. With regards to the route based of sub-contraction, in order to enhance the cost efficiency it is important to schedule milk runs and take advantage the trucks' loading capacity (trucks' filling rate). Additional warehouses and recovery facilities contribute in achieving better transport/cost performance. The tour based type of sub-contraction is less sensitive to changes, compared to the other two. The collections become infrequent and compacted in a few days of operations. This type of sub-contraction leads to costly transports but efficient operations.

10. Discussion

For this research assumptions were made and we recognize several limitation which we discuss in the following paragraphs.

For what concerns the limitations of the models it is worth to mention that not all the available material is picked up within the specified planning horizon. To address this drawback another component could be added in the objective function that takes into account the value of the waste that is available for pick up. This problem could also be tackled by extending the planning horizon. As for the implementation approach, we were not capable of solving problems of large instances. To address this problem, we recommend for further research the development of more advanced solutions capable of solving larger problem.

Speaking of data availability, the results that were obtained from the models refer to a small instance problem provided by a company. Several assumptions were made regarding the cost components for the different types of sub-contraction. To be exact, a piecewise linear cost function for the flow based type of sub-contraction could describe more precisely the reality. Other assumptions were made regarding the trucks. We considered that a truck can be available at any moment in time and we did not take into consideration any legal requirements that may should be respected. To overcome these limitations, we recommend further research in how the uncertain availability of trucks could be incorporated in a model for this type of problems. We also suggest further investigation on the legal requirements and how this type of requirements could affect the performance.

Moreover, we did not consider any time related restrictions with regards to the operations. For that, we recommend further research on how time windows could be incorporated in the modelling of the decision making.

Lastly, in our study we considered the involvement of one transport operator. The "*cherry picking*" is a forwarding planning strategy according to which the requests are divided and assigned to different carriers [28]. The investigation of the different types of sub-contraction in combination with the "*cherry picking*" could be a new topic for further research. This strategy has been studied for regular shipments however it has not been researched yet for the case of waste collection.

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B

Semi-structured interviews

B.1. Interview with the transport manager

<Removed due to confidentiality>

B.2. Interview with the project manager

<Removed due to confidentiality>

B.3. Interview with the waste carrier

<Removed due to confidentiality>

C

Inventory routing problem

In order to model the decision making at tactical level we used the formulation of Coelho et al. (2012). The author presented the mathematical formulation for the problem: Inventory Routing Problem with Transshipment. Below, the equations C.1 to C.12 we provide the formulation of Coelho et al. (2012). We initially considered that the term transshipment could be used for describing our system. However, the term "transshipment" implies that the material can be kept at a warehouse for up to 24 hours. In our problem, we wanted to examine the case where waste could be stored for at least a period in a warehouse (see appendix B.1).

$Minimize\ Z$

$$Z = \sum_{i\in V}\sum_{t\in T} h_i I_i^t + \sum_{i\in V}\sum_{j\in V, i<j}\sum_{k\in K}\sum_{t\in T} c_{ij} x_{ij}^{kt} \tag{C.1}$$

$$subject\ to\ I_0^t = I_0^{t-1} + r^t - \sum_{k\in K}\sum_{i\in V} q_i^{kt} \quad t\in T \tag{C.2}$$

$$I_0^t \geq 0, \quad t\in T \tag{C.3}$$

$$I_i^t = I_i^{t-1} + \sum_{k\in K} q_i^{kt} - d_i^t, \quad i\in V,\ t\in T \tag{C.4}$$

$$I_i^t \geq 0, \quad i\in V,\ t\in T \tag{C.5}$$

$$I_i^t \leq C_i, \quad i\in V,\ t\in T \tag{C.6}$$

$$\sum_{k\in K} q_i^{kt} \leq C_i - I_i^{t-1}, \quad i\in V,\ t\in T \tag{C.7}$$

$$q_i^{kt} \leq C_i y_i^{kt}, \quad i\in V,\ k\in K,\ t\in T \tag{C.8}$$

$$\sum_{j\in V, i<j} x_{ij}^{kt} + \sum_{j\in V, j<i} x_{ji}^{kt} = 2y_m^{kt}, \quad i\in V,\ k\in K,\ t\in T,\ for\ some\ m\in S \tag{C.9}$$

$$q_i^{kt} \geq 0, \quad i\in V, k\in K, t\in T \tag{C.10}$$

$$x_{i0}^{kt} \in \{0,1,2\}, \quad i\in V, k\in K, t\in T \tag{C.11}$$

$$x_{ij}^{kt} \in \{0,1\}, \quad i,j\in V, k\in K, t\in T \tag{C.12}$$

$$y_i^{kt} \in \{0,1\}, \quad i\in V, k\in K, t\in T \tag{C.13}$$

D
Verification

In this section we present the results of the verification tests. We implemented a small instance problem to verify that the models that we developed are providing the expected output. To begin with, figure D.1 shows the arcs and the vertices of the small case in a compact ed form and figure D.2 illustrates the depot, number of the waste generators, the warehouse, the recovery facility and the connecting arcs. Following, figure D.3 illustrates part of the output of the implementation. A key observation is that a solution is found.

```
Depot: [WasteGenerators[0], WasteGenerators[1], WasteGenerators[2],
                     "W"],
WasteGenerators[0] : [WasteGenerators[1], WasteGenerators[2],
                               "facility", "W"],
WasteGenerators[1] : [WasteGenerators[0], WasteGenerators[2],
                               "facility", "W"],
WasteGenerators[2] : [WasteGenerators[0], WasteGenerators[1],
                               "facility", "W"],
  W : ["facility"],
 facility : []
```

Figure D.1: The list of adjacent vertices for the examined case

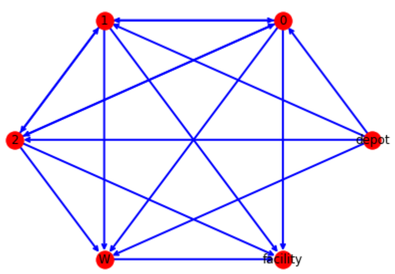

Figure D.2: The generated graph for the small instance problem

Figure D.3: Part of the output of the verification test.

```
Found heuristic solution: objective 14056.200000→ This shows that the

Gurobi heuristics found two integer feasible solutions before the root
relaxation was solved.

Root relaxation: objective 1.202724e+04, 95 iterations, 0.00 seconds


Nodes    |    Current Node    |     Objective Bounds      |     Work
 Expl Unexpl |  Obj  Depth IntInf | Incumbent    BestBd   Gap | It/Node Time
0     0 12764.2154    0   22 14056.2000 12764.2154  9.19%     -    0s
     0     0 12827.9628    0   25 14056.2000 12827.9628  8.74%     -    0s
     0     0 12827.9628    0   20 14056.2000 12827.9628  8.74%     -    0s
     0     2 12827.9628    0   20 14056.2000 12827.9628  8.74%     -    0s

Cutting planes:
  Cover: 1
  MIR: 4
  Flow cover: 3

Explored 95 nodes (520 simplex iterations) in 0.18 seconds
Thread count was 4 (of 4 available processors)

Solution count 2: 14056.2 14056.2

Optimal solution found (tolerance 1.00e-04)
Best objective 1.405620000000e+04, best bound 1.405620000000e+04, gap 0.0000%

Variable types: 0 continuous, 3960 integer (3960 binary)
Coefficient statistics:
  Matrix range     [1e+00, 1e+00]
  Objective range  [1e+00, 1e+00]
  Bounds range     [1e+00, 1e+00]
  RHS range        [1e+00, 2e+00]
Found heuristic solution: objective 11.0000000
Presolve removed 4086 rows and 3960 columns
Presolve time: 0.02s
Presolve: All rows and columns removed

Explored 0 nodes (0 simplex iterations) in 0.02 seconds
Thread count was 1 (of 4 available processors)

Solution count 2: 9

Optimal solution found (tolerance 1.00e-04)
Best objective 9.000000000000e+00, best bound 9.000000000000e+00, gap 0.0000%
```

Next, tables D.1, 6.8, 6.9 shows the results of the balance tests 2 and 3 for both three types of sub-contraction. The results showed that the material transported, picked up and stored was consistent. In that way, we could confirm that there is a balance in the flow of the waste in the system. In addition, when "injecting" a non-logical value in the model we received an error output as demonstrated in figure D.4. As far as consistency is concerned for the modelling of the decisions at tactical level, tables D.4 to D.9 demonstrate the results of the tests that we examined for all types of sub-contraction.

As for the decisions at operational level, tables D.10 to D.12 show the chosen routes and how they were allocated to the available days of operation. From all these testings, we concluded that the models are verified. Therefore, we could implement them with the case study in order to get the insights we intended to.

Table D.1: Results of balance checks 2 and 3, flow based type of sub-contraction.

Node	Period	Inventory[t]	Inventory[t]-Inventory[t-1]	Manual Check	Check	Waste Generated	Waste delivered to recovery facility	Waste transported to the warehouse
0	1	9	9	9	TRUE	9	0	0
0	2	18	9	9	TRUE	9	0	0
0	3	0	-18	-18	TRUE	9	0	27
0	4	9	9	9	TRUE	9	0	0
0	5	18	9	9	TRUE	9	0	0
0	6	6	-12	-12	TRUE	9	0	21
1	1	4	4	4	TRUE	4	0	0
1	2	8	4	4	TRUE	4	0	0
1	3	12	4	4	TRUE	4	0	0
1	4	0	-12	-12	TRUE	4	0	16
1	5	4	4	4	TRUE	4	0	0
1	6	6	2	2	TRUE	4	0	2
2	1	0	0	0	TRUE	30	30	0
2	2	0	0	0	TRUE	30	30	0
2	3	0	0	0	TRUE	30	30	0
2	4	0	0	0	TRUE	30	30	0
2	5	6	6	6	TRUE	30	24	0
2	6	6	0	0	TRUE	30	30	0
W	1	0	0	0	TRUE	0	0	
W	2	0	0	0	TRUE	0	0	
W	3	0	0	0	TRUE	0	27	
W	4	0	0	0	TRUE	0	16	
W	5	0	0	0	TRUE	0	0	
W	6	0	0	0	TRUE	0	23	

Table D.2: Results of balance checks 2 and 3, route based type of sub-contraction.

Node	Period	Inventory[t]	Inventory[t]-Inventory[t-1]	Manual Check	Check	Waste Generated	Waste delivered to recovery facility	Waste transported to warehouse
0	1	9	9	9	TRUE	9	0	0
0	2	18	9	9	TRUE	9	0	0
0	3	27	9	9	TRUE	9	0	0
0	4	36	9	9	TRUE	9	0	0
0	5	15	-21	-21	TRUE	9	0	30
0	6	6	-9	-9	TRUE	9	0	18
1	1	4	4	4	TRUE	4	0	0
1	2	8	4	4	TRUE	4	0	0
1	3	12	4	4	TRUE	4	0	0
1	4	16	4	4	TRUE	4	0	0
1	5	20	4	4	TRUE	4	0	0
1	6	6	-14	-14	TRUE	4	0	18
2	1	6	6	6	TRUE	30	24	0
2	2	6	0	0	TRUE	30	30	0
2	3	6	0	0	TRUE	30	30	0
2	4	6	0	0	TRUE	30	30	0
2	5	6	0	0	TRUE	30	30	0
2	6	6	0	0	TRUE	30	30	0
W	1	0	0	0	TRUE	0	0	
W	2	0	0	0	TRUE	0	0	
W	3	0	0	0	TRUE	0	0	
W	4	0	0	0	TRUE	0	0	
W	5	0	0	0	TRUE	0	30	
W	6	6	6	6	TRUE	0	30	

Figure D.4: Results for the verification test: 'Fault injection'.

```
        Explored 0 nodes (0 simplex iterations) in 0.01 seconds
Thread count was 1 (of 4 available processors)

Solution count 0

Model is infeasible
Best objective -, best bound -, gap -
```

Table D.3: Results of balance checks 2 and 3, tour based type of sub-contraction

Node	Period	Inventory[t]	Inventory[t]-Inventory[t-1]	Manual Check	Check	Waste Generated	Waste delivered to recovery facility	Waste transported to warehouse
0	1	3	3	3	TRUE	9	6	0
0	2	12	9	9	TRUE	9	0	0
0	3	21	9	9	TRUE	9	0	0
0	4	30	9	9	TRUE	9	0	0
0	5	27	-3	-3	TRUE	9	12	0
0	6	6	-21	-21	TRUE	9	30	0
1	1	4	4	4	TRUE	4	0	0
1	2	8	4	4	TRUE	4	0	0
1	3	12	4	4	TRUE	4	0	0
1	4	16	4	4	TRUE	4	0	0
1	5	2	-14	-14	TRUE	4	18	0
1	6	6	4	4	TRUE	4	0	0
2	1	6	6	0	FALSE	30	30	0
2	2	6	0	0	TRUE	30	30	0
2	3	6	0	0	TRUE	30	30	0
2	4	6	0	0	TRUE	30	30	0
2	5	6	0	0	TRUE	30	30	0
2	6	6	0	0	TRUE	30	30	0
W	1	0	0	0	TRUE	0	0	
W	2	0	0	0	TRUE	0	0	
W	3	0	0	0	TRUE	0	0	
W	4	0	0	0	TRUE	0	0	
W	5	0	0	0	TRUE	0	0	
W	6	0	0	0	TRUE	0	0	

Table D.4: Results for consistency check, flow based type of sub-contraction

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Table D.5: Results for consistency check, route based type of sub-contraction

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Table D.6: Results for consistency check, tour based type of sub-contraction

<Removed due to confidentiality>

Table D.7: Consistency tests, flow based type of sub-contraction

<Removed due to confidentiality>

Table D.8: Consistency tests, route based type of sub-contraction

<Removed due to confidentiality>

Table D.9: Consistency tests, tour based type of sub-contraction

<Removed due to confidentiality>

Table D.10: Schedule for collections, flow based type of sub-contraction.

<Removed due to confidentiality>

Table D.11: Schedule for collections, route based type of sub-contraction.

<Removed due to confidentiality>

Table D.12: Schedule for collections, tour based type of sub-contraction.

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E

Results of implementation and analysis

In this appendix we present the results obtained from the implementation of the models. In section E.1 we show the results with regards the testings for several instances of storage capacities. Then, in section E.2 we present the results with regards to the testings for different cases of demand. In section E.3 we present the results for the implementation for the different cases of collection network.

E.1. Capacity

Table E.1: The transport methods with regards to the different storage capacities.

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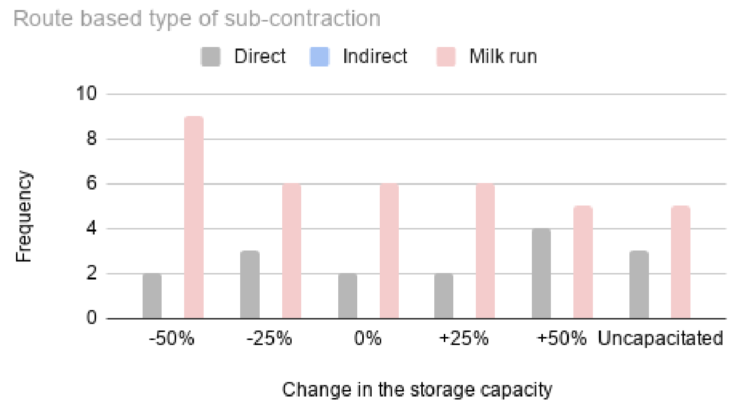

Figure E.1: The results obtained for the hypothetical instances of storage capacities, route based type of sub-contraction

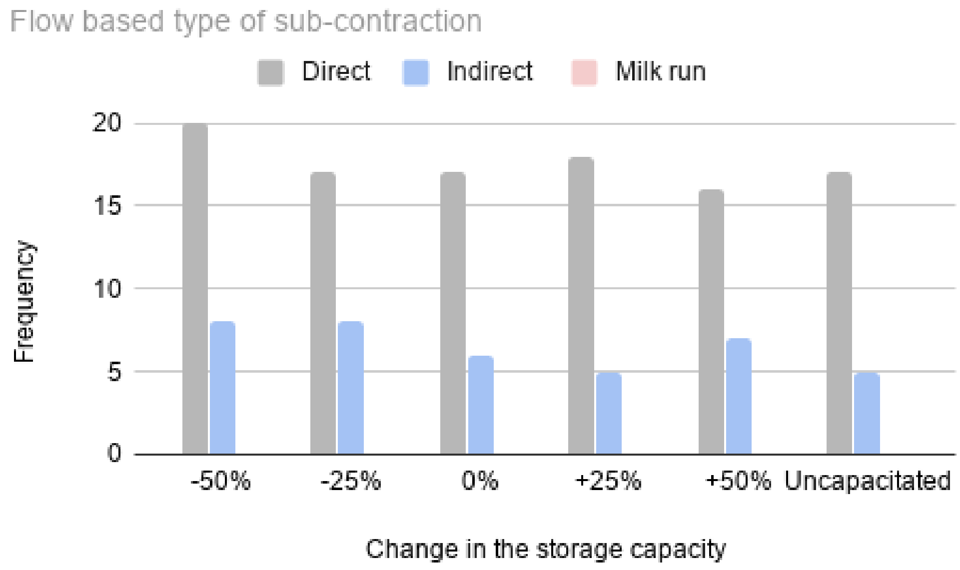

Figure E.2: The results obtained for the hypothetical instances of storage capacities, flow based type of sub-contraction

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Figure E.3: The results obtained for different of storage capacities, tour based type of sub-contraction

<Removed due to confidentiality>

Figure E.4: The frequency of the collections for different cases of storage capacities.

E.2. Demand

<Removed due to confidentiality>

Figure E.5: The frequency of the collections for hypothetical instances of demand's distribution.

Table E.2: The transport methods with regards to the different distributions of demand over the time horizon.

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E.3. Alternative networks

Table E.3: Results for different network alternative with regards to the route based type of sub-contraction

<Removed due to confidentiality>

Table E.4: Results for different network alternative with regards to the tour based type of sub-contraction

<Removed due to confidentiality>

Table E.5: Testings on the number of waste generators would affect the cost efficiency.

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Table E.6: Results for different network alternative with regards to the flow based type of sub-contraction

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