Consolidation of commercial waste collection

A case study of the urban area of the Municipality of Rotterdam

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by

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Preface

This thesis presents the work I have done over the course of several months as part of the conclusion of the Mechanical Engineering master here at the TU Delft. I am grateful for the opportunities the TU Delft has provided me and for the knowledge that I have obtained in both my bachelor and master courses.

I would like to thank Jos Streng from the Municipality of Rotterdam for his guidance and participation in my work. I am thankful for his trust in me. Jos has provided me with important contacts in the waste collection world and a beautiful work environment in the office building at Kop van Zuid.

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I am grateful for the meetings I had with Jos, Bilge and Michiel which have always been incredible useful, encouraging, and kept me on the right track.

Third, I am grateful to my girlfriend Joanne for her never ending support. Although we went (and are still going) through a turbulent time with respect to her health during my work on this thesis, she has always been incredible supportive and selfless.

Finally, I am thankful for my parents and parents-in-law for their support and I thank God for holding my hand along the way.

A.P.J. van Zwienen
Delft, March 2025

Executive summary

Densely populated urban areas feature many forms of logistics, one of which is waste collection. While domestic waste collection in Dutch cities is generally the responsibility of the local authorities, commercial waste collection is a free market in which there are many different services and waste collectors available. Collaboration between waste collectors is still in its infancy, and there is limited information about the precise benefits.

The Municipality of Rotterdam has the ambition to create a realistic tool for simulation of urban freight transport at city level and is looking to improve the way in which waste from companies is simulated. Specifically, it is relevant to assess the impact of collaborations between waste collectors.

The goal of this research is to develop and implement a simulation model for commercial waste collection, specifically focusing on the simulation of collaboration between waste collectors and quantifying the benefits of these partnerships. The methodology is shown in Figure 1.

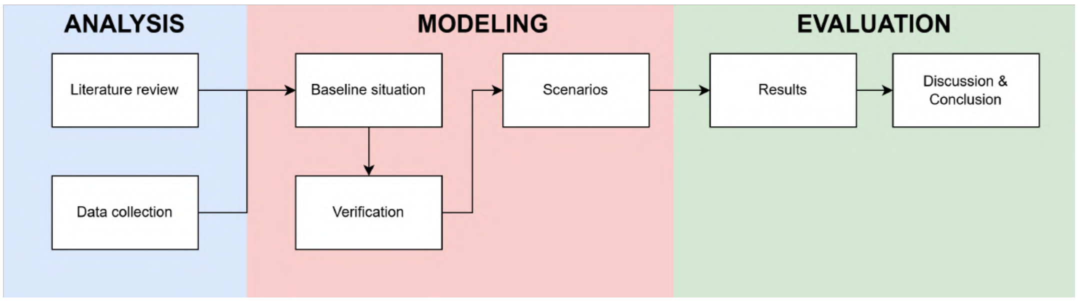


Figure 1: Proposed methodology

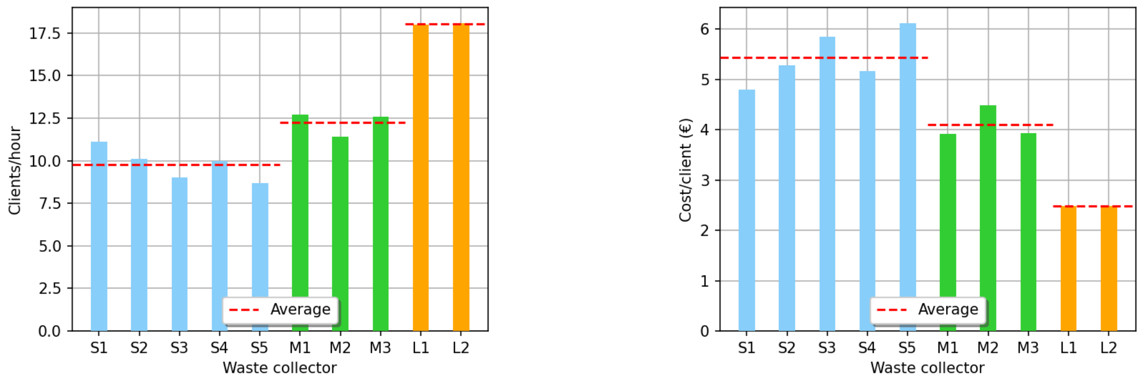
The modeling of the problem is performed in Python, making use of two libraries: OSMnx and OR-tools. OSMnx is used for retrieving and visualizing geospatial features such as street networks, pickup locations and routes. OR-tools is used to solve the vehicle routing problem associated with commercial waste collection. Input data such as container distributions, service times and average weight is based on real data from a commercial waste collector in Rotterdam. The number of waste collectors active in the study area is set at 10. There are three distinct sizes in market share: small waste collectors (50 daily clients), medium waste collectors (100 daily clients) and large waste collectors (500 daily clients). With 5 small waste collectors, 3 medium waste collectors and 2 large waste collectors, the total daily clients served is 1550.

The simulation model is then applied to the urban area of Rotterdam. In this area, many shops and offices are located which generate commercial waste, which is collected by means of rolling containers. First, all waste collectors are individually simulated without collaboration. This is scenario 1. Secondly, collaboration without constraints is simulated. Lastly, two additional collaborative scenarios with balancing are simulated. The scenarios are as follows:

- Scenario 1: no collaboration;
- Scenario 2: full collaboration (no constraints);
- Scenario 3: collaboration with client balancing. Here, the number of clients of a waste collector in a collaborative partnership is equal to the number of clients before joining the collaboration;
- Scenario 4: collaboration with revenue balancing. Here, the revenue of a waste collector in a collaborative partnership is equal to the revenue before joining the collaboration.

Three groups of waste collectors with the same market share are formed . The scenarios are then simulated for each group. For the group containing the large waste collectors, scenario 3 and 4 are omitted.

First, the results in case of absence of collaboration (scenario 1) are shown. It is clear that small waste collectors operate less efficient than large waste collectors. Figure 2 shows statistics for the number of clients serviced per hour (left) and the average cost per client (right).



(a) Clients per hour

(b) Cost per client

Figure 2: KPIs cost and cost/client

The low efficiency of small waste collectors is related to their scale and, generally related to this, the low client density. Larger waste collectors have the advantage of scale and can serve more clients per hour, resulting in more efficient operations and a lower cost per client.

When simulating collaboration, this produced a significant reduction in traveled distance for all groups: a reduction in traveled distance of 60%, 45% and 27% for the small, medium and large collaborative partnership, respectively. Associated cost also decreased significantly, 47%, 30% and 14%. The results are shown in Figure 3.

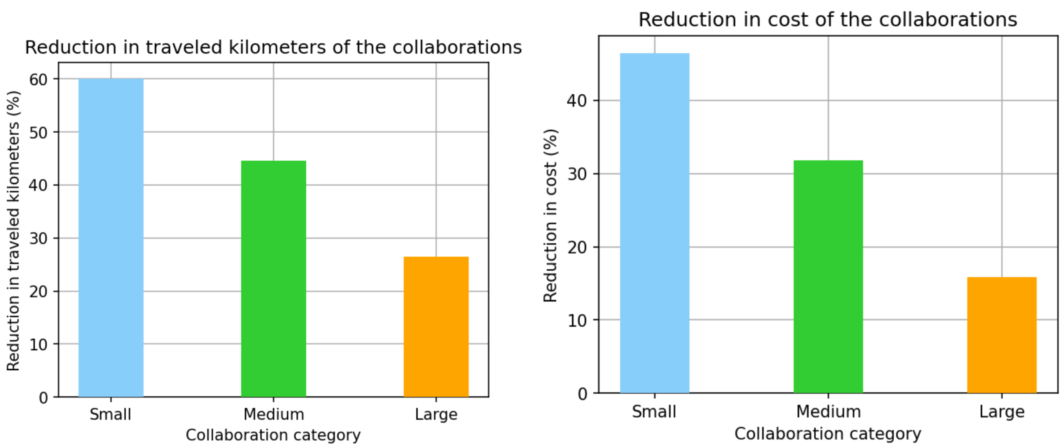


Figure 3: Savings in traveled kilometers (left) and cost (right). Data is the percentage decrease of scenario 2 (full collaboration) with respect to scenario 1 (no collaboration)

While collaboration without constraints provided most benefits and the greatest reduction in distance, the collaborative scenarios with constraint performed similar and did not produce significantly worse solutions. Although every group benefits from collaboration, small waste collectors benefit the most. This is because they can greatly improve their efficiency by combining operations. The large waste collectors already perform well individually due to their scale. However, collaboration still provides significant benefits.

While generally every waste collector experiences benefits of collaboration, still, profit sharing mechanism should be used to fairly allocate the benefits over all members of the collaboration.

This study has shown how collaborative partnerships in waste collection logistics can have a significant impact on operational efficiency and decrease traveled distance and costs of waste collectors. Because less vehicles are needed and there is better coordination between vehicles, this will also avoid multiple vehicles traveling through the same area at the same time, resulting in less inconvenience for residents and overall a better environment.

Although many authors have developed own algorithms for solving various VRPs, it is important to acknowledge the potential of open-source tools like OR-tools and OSMnx in simulating logistics. To increase problem scale however, some form of clustering is recommended. This will allow to generate better solutions for the same computational time. Furthermore, more data is required from smaller waste collectors about client distribution and operational efficiency, since this study has used mostly data from a larger waste collector.

Finally, more research is required as to how client overlap, efficiency and operational scale of individual waste collectors impacts the benefits that can be achieved through collaboration.

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Nomenclature

Abbreviations

Abbreviation	Definition
CWC	Commercial Waste Collector
VRP	Vehicle Routing Problem
MoR	Municipality of Rotterdam
OSM	OpenStreetMap

1
Introduction

1.1. Research motivation

Many cities in The Netherlands are expected to keep growing the coming decade. This growth puts increasing strain on city logistics. Traffic caused by logistics is expected to grow by 19% by 2035 due to an increase of parcel delivery, construction and other logistic streams [44]. The growth of the city also results in increasing population density, resulting in more commuting traffic and less space. In order to facilitate an increasingly developing city, logistics will have to keep developing as well and increase its efficiency.

One of the aspects in this logistical puzzle is the waste collection process. This process consists of trucks navigating through the city to collect waste from containers and transport the waste to depots. In Dutch municipalities, local authorities are responsible for the collection of domestic waste. Because this type of waste collection is done by one party, the process is often relatively efficient due to the consolidated nature of the service.

Commercial waste generated by the the office, retail and service sector is often collected by private waste collection services and features many clients in the city center, which results in a lot of freight movements in a dense urban space. When these private actors operate individually, this results in an efficiency loss: trucks from different operators will travel through the same streets, serving clients close to each other. In the Netherlands, this inefficiency has recently been acknowledged and has resulted in collaboration between several waste collectors. Two of the major collection services, Renewi and PreZero, have started a partnership under the name 'Green Collective'. This partnership strives to bring together waste collection services in order to create one consolidated service for the collection of commercial waste. Within Green Collective, clients of multiple waste collectors are combined and serviced by one operator. This requires less trucks, resulting in less trips which consequently makes for decreased emissions, less transport activities and in general a much more efficient waste collection. A second partnership is OpenWaste, consisting of smaller waste collectors. While these collaborations between waste collectors are often still limited to small areas in few cities, they are appearing at more municipalities and aiming to increase the area of collaboration.

In the quest for efficient city logistics, the Municipality of Rotterdam has the ambition to create a realistic tool for the simulation of urban freight transport at city level. The Tactical Freight Simulator (developed within the EU-project HARMONY on the basis of MASS-GT) contains a general approach of freight simulation and parcel delivery. Waste collection is much less understood.

The Municipality of Rotterdam is looking to improve the way in which waste from companies is simulated, using local information. This would help them develop and analyze policies in the area of urban waste collection, and determine the effect of measures to be taken either by the local government or by the companies/organizations collecting waste.

Specifically, it is relevant to assess the impact of collaborations between waste collectors (such as Green Collective) to determine how the implementation of such partnerships impact efficiency of the commercial waste collection process. In order to analyze this efficiency, a quantitative output is required, expressing waste collection in terms of number of trips, distance traveled by trucks, etc. In addition, the model developed by this study can be used by the MoR for further studies on waste collection, including other waste segments.

1.2. Research goal and scope

The goal of this research is to develop and implement a simulation model for commercial waste collection, focusing specifically on the simulation of collaboration between waste collectors and quantifying the benefits of these partnerships.

Because residual waste is the waste segment responsible for the most trips [5] and is the main focus of collaboration partnerships like Green Collective and OpenWaste, this study is limited to commercial residual waste. Waste containers are limited to container sizes of 240-1100 liters, which are used by most businesses and can all be served by the same truck.

In this study, the developed model will be used in a case study of the city of Rotterdam. The study area is limited to the urban part of the city, with port areas falling outside the scope of this study. The study area is presented in Figure 1.1. Most of the waste generation in the study area (urban environment) is produced by the office, retail and service sector.

Figure 1.1: Study area

1.3. Research questions

How can the commercial waste collection process for residual waste be modeled and potential benefits of collaboration between waste collectors quantitatively be assessed?

- What is the state-of-the-art in literature regarding waste collection in urban environments and collaboration in logistic environments, specifically waste collection?
- What is the current situation regarding commercial waste collection in the city of Rotterdam?
- How to approach the modeling of collaborative commercial waste collection based on available data?
- Which relevant waste collection collaborative scenarios can be simulated and how do they perform compared to the current situation?

1.4. Methodology

To answer the research questions, the following approach is proposed. First, available literature on similar subjects will be reviewed (Chapter 2). Parallel to the literature review, the current status quo of waste collection in the city of Rotterdam is analyzed. Chapter 3 discusses the proposed model. In Chapter 4, relevant data is collected from OpenStreetMap, a commercial waste collector operating in Rotterdam and the Municipality of Rotterdam. This data is used as input for the model. Chapter 5 applies the model and analyzes the results of multiple collaborative scenarios. The results are discussed in the same chapter. Finally, Chapter 6 concludes the research and gives recommendations for future research. The methodology is illustrated in Figure 1.2.

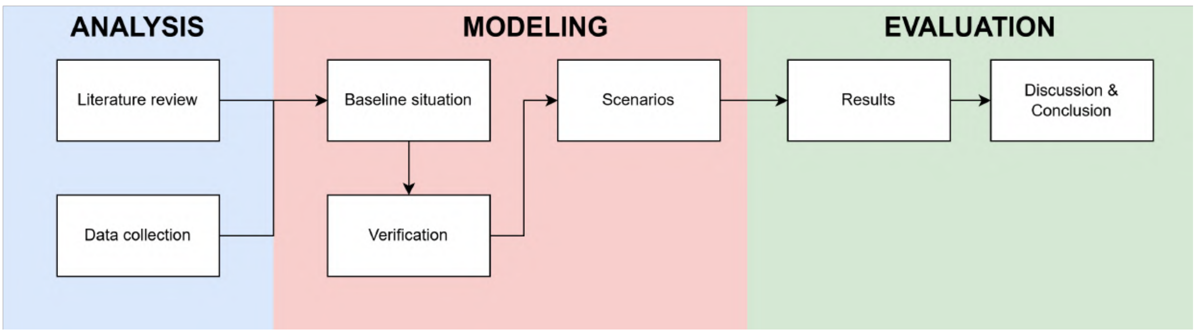


Figure 1.2: Proposed methodology

2

Literature review and state-of-the-practice

In this chapter, relevant literature is discussed and the state-of-the-art of commercial waste collection is studied. In section 2.1, literature on waste collection modeling is reviewed. In section 2.2, available literature on collaborative routing is discussed. Section 2.3 reviews open-source VRP solvers. The literature gap is discussed in section 2.4. Section 2.6 and the consecutive sections discuss the state-of-the-art of waste collection in the city of Rotterdam. The information about client scheduling, trucks and shift times are provided by a waste collector operating in Rotterdam.

2.1. Waste collection modeling in literature

The waste collection problem can be defined as a reverse logistics problem [22]. In a regular logistics problem, goods are transported from depots to clients with vehicles. In reverse logistics problems, the flow of products is reversed. In the case of waste collection, the products (waste) are generated by the client and collected by the transporter. There is extensive literature on waste collection. Most studies on waste collection focus on optimization by improving routes or minimizing the number of vehicles used [22]. Various studies focus on developing heuristic algorithms for the WCVRP [4][9][12].

The waste collection logistics problem can be studied on multiple layers or echelons [59]. The first echelon is defined as the collection of waste from customers and the disposal of waste at a depot. The second echelon is taking the waste from the depot to a treatment facility for further processing.

The approach most often used in literature to model the waste collection process, is to define waste collection as a Vehicle Routing Problem (VRP) [24]. The VRP is basically a traveling salesman problem (TSP) with multiple vehicles visiting clients [23]. The VRP is based on a network of nodes connected by edges. In general, one of the nodes is designated as a depot, and the other nodes are designated as clients. The aim of a VRP is to visit these clients and find the optimal solution based on the objective. The objective function can take various forms. However, distance or travel time are most often included in research [8] and can be combined with other objectives, for example the number of vehicles used. In logistic problems, the capacitated VRP (CVRP) appears most often due to its relative simplicity and its use as a base scenario for implementing other variants [28]. Other most studied variants are VRPTW (time windows), VRPPD (pickup and delivery), and HFVRP (heterogeneous fleet) [28].

Within waste collection, specialized versions of the VRP appear. One of which is 'multi-trip'. In [56], vehicles start and end their shift at a depot. When capacity is reached, vehicles can visit a disposal site to empty their vehicle. The disposal site is at a different location from the depot. A different approach is used by [36]. In this case, there are no intermediate facilities but a vehicle is allowed to travel back to the depot in between visiting clients. This is made possible by cloning the depot at the same location. With this method, an important constraint of the VRP problem (nodes can only be visited once) is technically not violated even though vehicles are able to visit the same location twice.

Another variant is multi-depot. Here, there are multiple vehicles, each starting and ending at its own depot. An example of this is [20], where cooperation is studied to optimally make use of different depots. In the paper, [20] notes that although multi-depot has been often studied, application within a waste collection context is rare.

When studying larger number of clients in VRP modeling, a cluster-first route-second approach is sometimes used. For example, [17] studied municipal waste collection in Rotterdam and used a clustering algorithm to optimize daily waste collection routes. Using this approach, the VRP is split into multiple smaller VRPs, reducing the complexity of the problem.

2.2. Collaborative routing

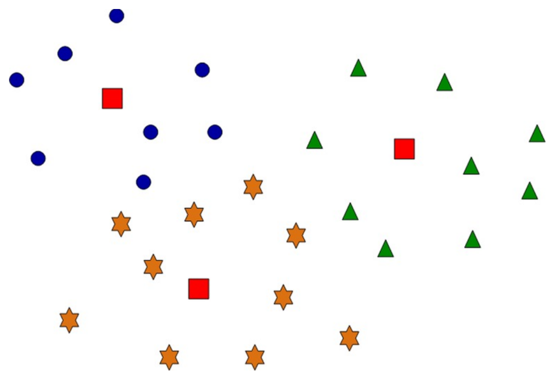
Gansterer et al. [16] has studied literature on collaborative vehicle routing and identifies two main participants in transportation: shippers and carriers. Carriers are responsible for the transportation process (including trucks and routes) and shippers supply the shipments. In some applications, the moment of pickup/delivery can be specified by means of time windows that serve as input for the routing problem (see previous section). In waste collection, shippers are the waste collectors. Instead of delivering goods, waste collectors are collecting goods (waste) by means of carriers. Therefore, waste collection is a reverse logistics problem.

Collaboration in vehicle routing can significantly reduce costs, according to many studies [16]. Collaboration has the potential to mitigate transportation costs [25] mainly because the distance and duration of routes can be reduced. [54] has also shown that horizontal collaboration can significantly reduce emissions. This is a logical result considering that emissions are closely related to the distance driven by vehicles.

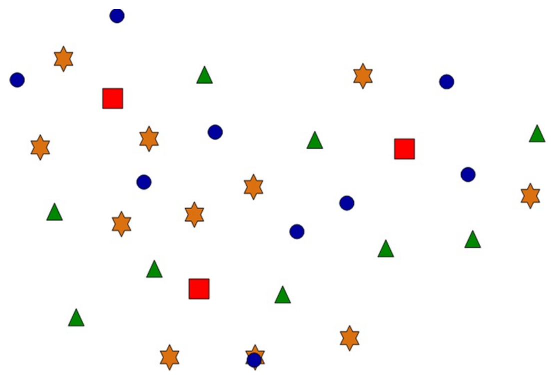
A study by [32] defines two main types of collaboration between carrier alliances. The first is order sharing, in which customer requests are exchanged. By merging customer requests of several carriers, joint route planning can be used to efficiently redistribute clients and decrease travel distance and/or the number of vehicles.

The second type of collaboration is capacity sharing, in which vehicle capacities are shared. Capacity sharing requires a pool of available vehicles (from other carriers) that a carrier can use to compensate for the limited capacity of its own fleet. However, when not combined with some form of client sharing, capacity sharing will not decrease route distances. However, capacity sharing can prevent idle vehicles and increase utilization rate.

A study by [41] studies horizontal collaboration in road transportation with multiple depots, and considers three scenarios. The first scenario is maximum collaboration. This is the ideal scenario, and allows for assigning any customer to any operator. Scenario two and three assume that there is no collaboration. Scenario two considers the case where customers are clustered around depots. Scenario three considers the case where customers are dispersed. Scenario two and three are illustrated in Figure 2.1. In the case of commercial waste collection, scenario three is more likely if there is no coordination between individual waste collectors. In a competitive environment such as commercial waste collection, the operational areas of waste collectors overlap resulting in clients of various waste collectors residing in the same area.



(a) Clustered clients (ideal case)



(b) Scattered clients (realistic case)

Figure 2.1: Client distribution from [41]. Red squares: carrier depots. Blue, green and orange symbols represent clients belonging to a specific carrier.

In an analysis of various works from literature, [32] found collaborative benefits from order sharing range between 13 and 30%. In a study on the collaborative CVRP, [62] found cost savings of 21 and 49.6% for an asymmetric and symmetric CVRP, respectively.

2.2.1. Workload balancing

In VRPs, workload balancing (or workload equity) is the fair distribution of workload and/or resources between different actors.

Workload can be expressed as the number of clients per truck, the distance traveled and various other metrics [35]. In a survey on workload equity in VRPs, [34] has analyzed studies on the subject, reviewing variations of workload balance. These studies do not include workload balance in collaborative scenarios. The literature works above consider workload balance between different vehicles. Sometimes balance is considered over an extended planning horizon, allowing for imbalance in a given interval in that period [37] [33].

Mancini et al. [33] introduced workload balance and consistency in a collaborative scenario. First, a set of carriers and respective clients is defined, and costs are calculated in a non-collaborative scenario. Then, a collaborative scenario is simulated, with added constraints to ensure workload balance and consistency. Notable constraints are:

- Carriers profits must be equal to or greater than in the non-collaborative scenario
- The number of customers assigned to a carrier must be equal to the value in the non-collaborative scenario - or can not be less than a given percentage of the original value

Dropping (combinations of) constraints was found to only slightly impact solution quality. Therefore, in the studied case, workload balance could be implemented without a significant decrease of the solution with respect to the optimal solution (collaboration without balance constraints).

2.2.2. Collaboration within a waste collection context

[20] studied horizontal collaboration as defined by [2]. In the study, horizontal collaboration within the waste collection context is defined as the sharing of containers (or clients), depots and landfills. The advantages of horizontal collaboration are quantified using benchmarks by Kim et al [26], adopted to a scenario with multiple depots. Results presented a 12 percent reduction in cost on average.

[31] studies collaboration in a two-echelon waste collection problem. In the collaborative network, clients, trucks and waste transfer stations are shared. The collaboration between different operators is found to significantly reduce costs and emissions.

Van den Berg et al. [5] studied commercial waste collection in 4 major cities in The Netherlands, one of which is Rotterdam. The study focus is on the office, retail and service sector (ORS), since this sector generates mostly waste inside the urban environment. From a 2019 data set of waste produced by this sector, [5] found that residual waste is the greatest waste segment in terms of weight with a relative weight of 77,7 %. The average weight per stop was found to be about 50 kg. The number of trips for residual waste collection was found to be 39,6 % of total trips. The deviation in these percentages can be explained by the fact that different waste segments can significantly vary in density [55]. Collaboration pilots in The Netherlands showed the potential to significantly decrease the required number of trips, up to 53% [5].

2.3. VRP solvers

Waste collection as a vehicle routing problem has been the topic of various studies, with many of these studies focusing on optimization based on KPIs like distance or number of vehicles used [22]. Many solution methods have been developed in literature and as a result, many VRP solvers exist, either open-source or licensed. For accessibility reasons and to ease reproducibility, this paper will utilize an open-source VRP tool for constructing the routes. However, not all are equipped with a Python interface. Open-source solvers suitable for use in Python are Google OR-tools, PyVRP, VRPSolverEasy and vrp-cli.

- Google OR-Tools is a well-known combinatorial optimization package and is able to solve various problems, including constraint programming, MIP problems, and vehicle routing problems [19].
- PyVRP [42] is a relatively new VRP solver using hybrid genetic search. It ranked first in the 2021 DIMACS VRPTW challenge. The solver is partly implemented in C++ to improve performance [60].
- VRPSolverEasy is a Python interface to VRPSolver, an exact solver using the branch-cut-and-price algorithm to solve various variants of the VRP [13].
- vrp-cli is a one-man project by Ilya Builuk and is aimed at supporting a wide range of VRP variants [10].

In Table 2.1, an overview is given of available open source VRP solvers for Python. Search hits on Google Scholar were counted to give an indication of its use in academics. Because OR-Tools can also be used for many other mathematical problems, an extra search term was added for a fair comparison. Google OR results in most hits. While a search hit does not necessarily equal its use in an academic paper, these numbers give an indication to the popularity of these tools in academic research. Note that the lack of results for PyVRP, VRPSolverEasy and vrp-cli might also be caused by the fact that they are still in their infancy.

Table 2.1: VRP Solvers and search hits on Google Scholar (H = Heuristic, E = Exact)

	Google OR-Tools	PyVRP	VRPSolverEasy	vrp-cli
Solving method	H	H	E	H
Search term	”google or-tools” ”vrp”	”pyvrp”	”vrpsolvereasy”	”vrp-cli”
Results	546	24	14	4

2.4. Literature gap

Although waste collection has been the subject of various studies, mainly using VRP optimization models, there is little research on the topic of collaboration within a waste collection context [31]. While [31] studies collaboration on a two-echelon level, the Euclidean distance is used between customers. Euclidean distance is an approximation, since vehicles do not travel in a straight line to their clients. Furthermore, obstacles such as water bodies may have a significant impact on the distance, which is not taken into account with the Euclidean approximation. In the case of a real-world situation like waste collection, the nodes (clients) are located in a road network. Therefore, the real distance is not equal to the Euclidean distance, because trucks can only use the road network to reach their clients. [7] found that in cases where only a small portion of the total number of network nodes is visited, using Euclidean distance to solve a capacitated VRP gives 'acceptable' results. However, this was only found to be the case when solving a VRP without time windows. Although the VRP might be solved with reasonable performance, calculated route distances are unlikely to be accurate [29]. Especially in cities where the road network can not be approximated by a grid.

In waste collection research, most research handles relatively small data sets [24][29]. Furthermore, [20] notes that although multi-depot has been often studied, application within a waste collection context is rare.

In conclusion, there is a gap in research that focuses on the quantitative performance of collaborative frameworks within a large-scale waste collection context. This study is proposed to bridge this gap.

2.5. Summary

Waste collection in literature is a subject that has been studied by many authors and is often formulated as a CVRP. Many studies have developed methods or heuristics to solve waste collection problems. Collaborative routing is being actively researched, and various studies have shown its benefits, mostly in the form of order sharing. Cost savings from collaboration may vary significantly per study, depending on the characteristics and scale of the studied problem. Some authors have studied different forms of balancing in collaborative routing. Balancing can be understood in two ways: balancing of certain route properties (like the number of served clients) before and during collaboration, or balancing the workload over multiple vehicles in a single VRP.

To solve VRPS, there are multiple open-source VRP solvers available, with Google OR-tools appearing most often in literature.

Although waste collection VRPs (and VRPs in general) is an active topic of research, most research uses Euclidean distances and small-scale problems. Collaboration within waste collection is rare.

This research will focus on order sharing as mechanism of collaboration, since this will result in most benefits regarding the reduction of distance and duration of routes.

2.6. Waste collection in the city of Rotterdam: status quo

In the following (sub)sections, the status quo of commercial waste collection in the MoR is reviewed. Specific information about the commercial waste collection procedure is obtained by means of an interview with experts from a commercial waste collector in Rotterdam. In this section, only qualitative information is presented. Data collection is performed in the next chapter.

The waste collection in the city of Rotterdam is divided into two major flows: domestic waste and commercial waste. In The Netherlands, municipalities are required to collect domestic waste at least once a week [40]. It is up to the municipality how they perform this task. They can utilize a third party or collect the waste themselves. In the city of Rotterdam, residential waste is collected by the Municipality of Rotterdam (MoR). The MoR is equipped with its own vehicle fleet and therefore performs all tasks related to residential waste collection in-house. In most urban zones, residential waste is collected by means of underground containers. These containers are equipped with sensors measuring the amount of waste per container every hour, and this data is used to determine appropriate emptying moment [52]. In parts of Rotterdam without underground containers, waste is deposited in regular 240L rolling containers without sensors.

2.6.1. Commercial waste collection

For commercial entities (like retail, restaurants, offices), there are two options for waste disposal. The first option for a business is to make use of the ”bedrijfsreinigingsrecht”, disposing waste at the underground containers for residential waste. The second option is to sign a contract with a certified waste collection service (CWC). To use the first option, a business needs to meet certain requirements. These requirements prescribe:

- a maximum surface area of the business premises (this area restriction is dependent on the business category);
- a restriction to the waste being disposed at underground containers (the waste needs to be similar to residential waste in terms of type and composition) [51]

If a business cannot meet these requirements, it needs to select option 2, which is to sign a contract with a CWC. When a business has signed a contract with a CWC, it is not allowed to use underground containers to dispose of waste. For a business to prove that it has signed a contract with a CWC to dispose of waste, it is required to share this contract with the MoR.

Many municipalities (including Rotterdam) have underground containers equipped with sensors [21][15][57] as mentioned earlier. Containers are incorporated into routes when reaching a certain percentage of their maximum capacity, causing irregular emptying times. While commercial and municipal waste collection is based on the same principle, commercial waste collection follows a more regular pattern, as customers generally maintain the same service interval [22] because commercial bins generally do not have waste level sensors.

A CWC, as specified in the above section, is a commercial entity specialized in the collection of waste. A CWC provides (rolling) containers to a client. Clients can use the containers to dispose of their waste, and have the CWC empty the containers. Clients can sign up for a subscription to have their waste collected on a certain day of the week, at given intervals. This subscription features a day of the week (optionally with a time window) as the collection date. The interval time between collection dates is defined in (one or more) weeks. It is also possible for a business to sign a contract without a subscription. In this case, the client can contact the CWC at will. This is useful when a client requires waste disposal at irregular and long intervals, which is sometimes the case for smaller businesses.

In order for a CWC to operate, it requires vehicles used to transport waste, a location to store the vehicles when not in use, and a location (depot) to dispose of the collected waste. In general, the depot is used to temporarily store waste. Since residual waste cannot be reused, it is then transported to a waste incineration plant, where it is incinerated [47]. The Netherlands has 12 of these waste incineration facilities [30], one of which is located in Rotterdam [61]. Most of the smaller CWCs in Rotterdam only have waste transfer locations and do not have facilities for waste processing.

There are many CWCs operating in the city, often involved in the collection of waste in multiple waste segments. See chapter 4 for an estimate of the number of CWCs collecting residual waste.

2.6.2. Client scheduling

In general, waste collection service offered is as follows. Businesses can sign up for a subscription to have their waste collected on a certain day of the week, at given intervals. This subscription features a day of the week with an interval as the collection date. The interval time between collection dates is defined in (one or more) weeks. It is also possible for a business to sign a contract without a subscription. In this case, a business can contact the CWC at will. This is useful when a business requires waste disposal at irregular intervals, which is usually the case for smaller businesses.

At the start of a given working day, orders are collected. These orders are both subscription-based orders and 'random' orders, as explained in Section 2.6.2. The orders are then fed into the internal route planning software, which creates routes serving all clients on that day; see Figure 2.2. The number of routes (trucks) depends on the number of clients to be served. Small CWCs might require one truck, while larger CWCs will have multiple vehicles driving different routes through the city at the same time in order to be able to serve all daily clients.

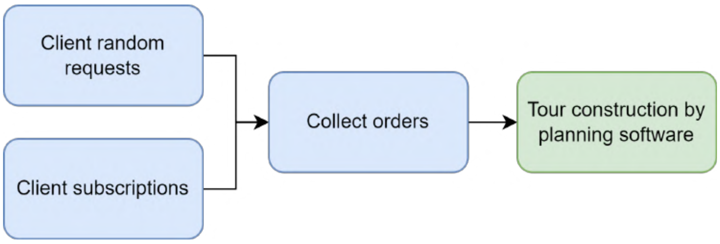


Figure 2.2: Order collection

In the residual waste segment, the majority of clients (>99%) have a subscription, and random requests are rare. Therefore, the number of clients served is easily predictable.

2.6.3. Waste containers

Containers come in various sizes. The sizes range from 120 liters to 1700 liters, with some CWCs offering containers with a size of 2500 liter. The construction of the containers is such that they can all be emptied by the same garbage truck. In Table 2.2, examples of available container sizes of 4 large CWCs are shown. Containers with a volume of 240, 660, 1300 or 1600 liters are commonly available sizes. They are equipped with wheels to ease movement. Waste containers of up to 660 liters fit through doors.

Table 2.2: Available containers per CWCS

	120	240	360	500	660	750	770	1000	1100	1300	1600	2500
Omega [38]	x	x		x	x	x		x		x	x	
Renewi [48]		x			x				x			x
Bedrijfsafval Nederland [3]		x	x	x	x	x	x		x	x		x
Renes [45]		x			x				x	x	x	

A second category of containers are large steel containers. These containers are static (without wheels) and are generally used only for a large amount of waste. A client (business or individual) can order a container and use it to dispose of waste. Once full, the CWC will retrieve the container. These containers are usually static for a long period of time (without intermediate emptying) and are generally not used in urban environments by typical businesses. Secondly, they can only be collected in a single pick-up trip, without the possibility of collecting multiple of these containers in a single tour. Therefore, these containers are omitted in this research.

Containers of businesses are required to be positioned close to the road and easily accessible. Because waste collection employees have to push the container to the truck and (after emptying) push it back to its original spot, easy access to the container will minimize the time spent moving the container to the truck and vice versa.

2.6.4. Trucks

Waste collection trucks feature back-loaders with a modular design, allowing for the handling of various container sizes. Trucks handling residual waste are equipped with waste compactors to reduce the volume of collected waste. Due to the compressibility of residual waste, this frees up significant space in the vehicle and increases its volumetric capacity. The load capacity in tons depends on the truck used. A capacity of 11-12 ton is used by [5]. In accordance with the data provided by a waste collector, a regular waste collection truck capacity of approximately is set at 11 tons.

In general, there are two employees per vehicle, both involved in driving the truck and handling the containers. The reason for this is that heavy containers of 1600L size also need to be handled during shifts, which is done by two employees.

2.6.5. Durations and regulations

European regulations prescribe truck drivers a 45 minute break after 4,5 hours of driving. It is also possible to divide this break into one 15 minute and one 30 minute break [49]. Usually, drivers start their shift early in the morning at 06:00-07:00 and end their shift after 8 hours. Of course, shift times can vary per CWC. Most CWCs visit clients between 06:00-17:00.

Route duration is dependent on three factors: time spent driving, time spent at each client (emptying the container) and break duration. Relevant data will be discussed in chapter 4.

2.6.6. Locations for storing trucks and disposing waste

A CWC needs a location to store its vehicles in a parking lot and needs a waste transfer station (WTS) to dump collected waste. When a truck is serving clients on a given day, the parking lot is the start and end point of the route. Some CWCs have a parking lot (PL) and waste depot/transfer location on the same location, others do not. The following combinations are possible:

- Combined PL and depot
- Combined PL and depot plus additional depots
- PL and depot on separate locations

These parking lots and depots can be located in the city itself or elsewhere. Renewi is the only known residual CWC with a WTS inside the study area. All other depots are stationed outside or at the edge of the study area. This makes sense since waste depots in urban environments are undesirable.

For example, the case for Renewi is the second combination: a combined parking lot and depot in Vlaardingen and an additional depot in Rotterdam-South. Other CWCs also adhere to one of these combinations. Some of these local CWCs have depots/parking lots in the outskirts of Rotterdam, others have their locations elsewhere in the Province of South-Holland.

For an illustration of route examples for different PL and depot locations, see Figure 2.3. In this instance, a truck only visits the depot at the end of the route.

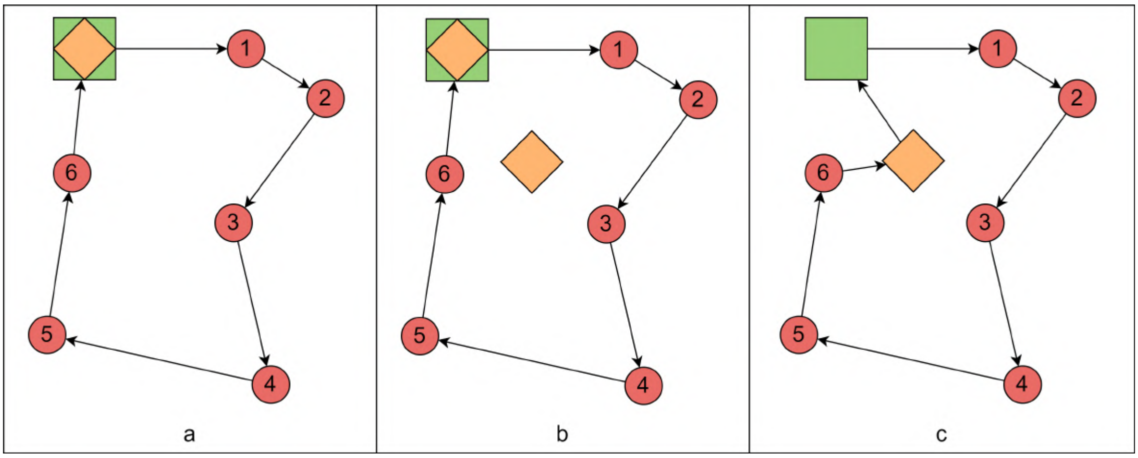


Figure 2.3: Route examples for different PL/WTS configurations with unloading at end of route. **(a)** Combined PL and WTS **(b)** Combined PL and WTS plus additional WTSs **(c)** PL and WTS on separate locations

In Figure 2.4, route examples are shown for the same configurations, however, in this instance trucks visit depots during a route. This happens when the capacity of a truck is reached before all clients are visited. Consequently, a truck must be unloaded during its route in order to be able to serve the rest of the clients. In Figure 2.4 only one intermediate visit to a depot is illustrated. In theory, this can happen an indefinite number of times, although intermediate visits to depots are only required when the capacity of a truck is reached. This will depend on the average quantity of waste collected per stop, the capacity of a truck and the density/volumetric properties of the waste. For residual commercial waste collection in the office, retail and service sector, intermediate trips to the depot to dump the waste do not appear often, since the main bottleneck is time.

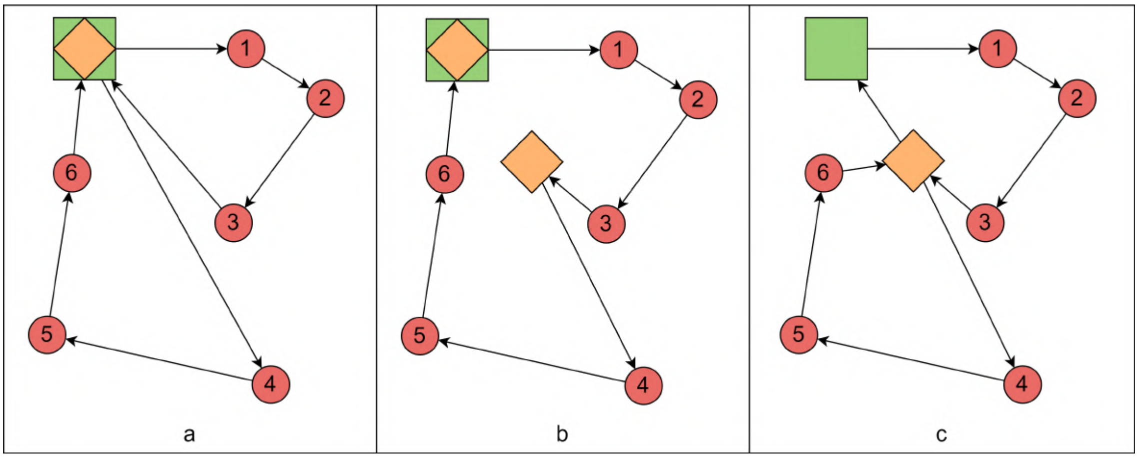


Figure 2.4: Route examples for different PL/WTS configurations with intermediate unloading. **(a)** Combined PL and WTS **(b)** Combined PL and WTS plus additional WTSs **(c)** PL and WTS on separate locations

2.7. Existing collaborative partnerships

2.7.1. Green Collective

In 2021, Green Collective [46] was founded. Green Collective (GC) is an initiative of waste collectors Renewi and PreZero. The goal of Green Collective is to combine routes and share trucks between different CWCs. In this way, clients of multiple CWCs can be served by the same truck. This can significantly reduce total truck trips, since fewer trucks are needed to serve multiple businesses in a given area.

Green Collective is currently operating in more than 30 municipalities in The Netherlands, one of which is the MoR. Currently, the Green Collective partnership in Rotterdam is only active in the residual waste segment and serves clients in two postal codes.

The goal of Green Collective is to combine the routes of different waste collectors. In this way, clients of multiple waste collectors can be served by the same truck. The type of collaboration introduced by Green Collective is based on the concept of centralized collaborative planning [16], which is equivalent to order sharing. In this type of collaboration, all client contracts from different waste collectors are combined to form an aggregate client contract base. The routes are then planned to serve this client base, and one party is responsible for waste collection. Since this type of coordination features a central coordination, it is expected that it is the most efficient way to decrease time and distance, resulting in decreased costs. The precise revenue-sharing mechanism is not publicly shared, but in general the CWC responsible for the collection within the partnership receives a sum for every additional client, based on the amount of waste. The advantage of the waste collecting party within the partnership is increased revenue (and profit) due to the extra clients, and the parties 'lending' the clients will see their operational costs dropping. Although operational costs are not shared, joint collecting pilots in Dutch cities Gouda and Haarlem indicated a decrease in number of trips of 53 percent, and a 16 percent increase in the number of stops per hour [5].

2.7.2. OpenWaste

OpenWaste [39] is a similar collaboration between smaller waste collectors in multiple municipalities of The Netherlands. As of the start of this study, OpenWaste was not yet operating in the MoR. OpenWaste uses the same collaborative approach as Green Collective, serving clients of multiple CWC's with one vehicle.

Besides Green Collective, there are no other collaborative partnerships in the city.

3

Modeling

This chapter describes the setup of the simulation model. In Section 3.1, the conceptual model is proposed and elaborated on. In Section 3.2, an appropriate VRP solver is selected and the constraints are formulated.

3.1. Conceptual model

The simulation model is implemented in Python. The first step is the creation of the input files. The input is then fed into the VRP Solver, which solves the routing problem and outputs routes with the respective distance and duration. The initialization of the input data is illustrated in Figure 3.1. The VRP solver and I/O are illustrated in Figure 3.2.

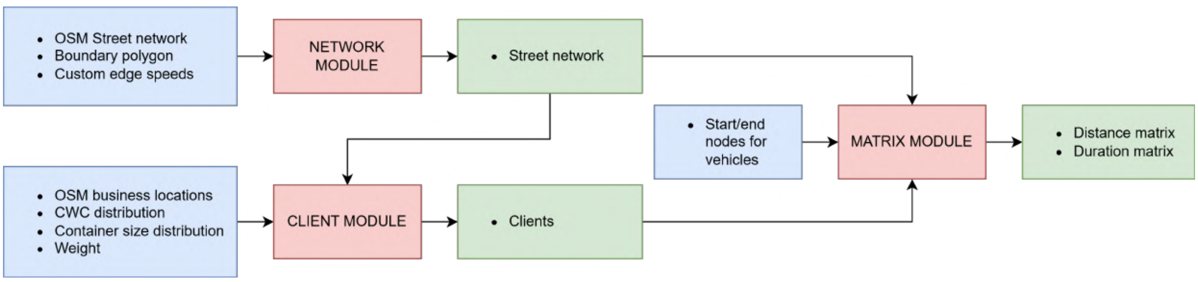


Figure 3.1: First phase: input data initialization

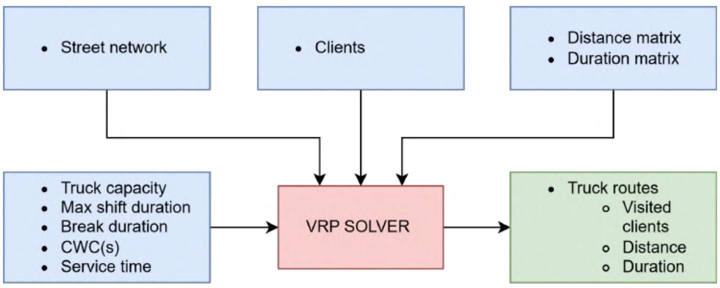


Figure 3.2: VRP solver input and output

The purpose of the network module is to provide a node/edge street network of the city. The network is loaded by means of OSMnx. OSMnx is an open-source Python package built on NetworkX and GeoPandas and can be used to download and process street network data from Open Street Maps (OSM) [6]. The OSM street network is represented by nodes and edges. Nodes are represented by a unique id and a pair of coordinates. The OSM street network features various attributes describing its properties. Examples of this are maximum speeds, road type (highway, residential, etc.) and one-way constraints.

The purpose of the client module is to generate clients that will be served by the CWCs.

The matrix module collects all street nodes from the clients and creates a distance/time matrix. To calculate the matrices, the *shortest_path_length* algorithm from the NetworkX package is used. This calculates the shortest path between two nodes using the Dijkstra algorithm. The edge weight used for the calculation can be specified as distance or time, which are properties of the street network's edges. In the matrix module, the Python multiprocessing pool is used to allow for parallel execution, decreasing the calculation time.

The output of the matrix module consists of a distance matrix and a time matrix, which are used as input for the VRP solver. The VRP solver uses this information to construct routes on the road network.

3.2. VRP solver

In section 2.3, four open-source solvers were introduced. Because this study handles a large number of clients and finding optimal solutions is not a necessity, a heuristic solver is found to be the most convenient. Therefore, VRPSolverEasy is excluded, since this is an exact solver. At the time of writing, the Python interface of vrp-cli was not functioning correctly, so it was also excluded. Choosing between OR-Tools and PyVRP, they both offer good solutions, although PyVRP offers better optimality gaps with respect to OR-tools [43]. Although PyVRP and (some other VRP solvers) are capable of generating better solutions [58], OR-tools was found to be the most versatile option since it currently supports many variants of the VRP, including custom constraints. Its Python wrapper makes it easy to use. Therefore, OR-tools was chosen as the VRP-solver.

3.2.1. Model formulation

OR-tools has a dedicated RoutingModel specifically designed for VRPs in which trivial VRP constraints such as ensuring that all nodes are visited only once are already implemented by default. Therefore, they are not listed here. To make the VRP model suitable for this study, several constraints are added. Their mathematical formulation is as follows:

The binary variable x_{ijk} has a value of 1 if the arc from node i to node j is in the optimal route and 0 zero otherwise. A vehicle is indicated as k, and there are p vehicles.

$$x_{ijk} \in \{0,1\} \quad \forall k \in \{1,\ldots,p\}, \quad i,j \in \{1,\ldots,n\}$$

The travel cost from node i to node j is defined as c_{ij}.

The objective function can be formulated as follows:

$$\text{Minimize} \sum_{k=1}^{p} \sum_{i=1}^{n} \sum_{j=1}^{n} c_{ij} x_{ijk}$$

It describes that the sum of the added costs c_{ij} of all p vehicles should be minimized. The cost can be expressed in time t or distance d. In this study, every VRP is solved for distance and time individually.

Capacity constraint
The total pickup $\boldsymbol{q_j}$ of the nodes served by a vehicle $\boldsymbol{k}$ should be equal to or less than its capacity $\boldsymbol{Q}$.

$$\sum_{i=1}^{n}\sum_{j=1}^{n} q_j x_{ijk} \leq Q \quad \forall k \in \{1, \ldots, p\}$$

Time constraint
First, the allowed time of a route is defined. The allowed time is equal to the shift time $\boldsymbol{T_{shift}}$, which is set at 8 hours:

$$T_{allowed} = T_{shift} = 8$$

The total duration $\boldsymbol{t_k}$ of a vehicles route consists of the sum of the travel time $\boldsymbol{tt_{ij}}$ from node $\boldsymbol{i}$ to node $\boldsymbol{j}$ plus the sum of the service time $\boldsymbol{ts_i}$ of the departure node $\boldsymbol{i}$:

$$t_k = \sum_{i=1}^{n}\sum_{j=1}^{n} tt_{ij} x_{ijk} + \sum_{i=1}^{n} ts_j x_{ijk} \quad \forall k \in \{1, \ldots, p\}$$

The total duration $\boldsymbol{t_k}$ of a route driven by a vehicle $\boldsymbol{k}$ should be equal to or less than the allowed time $\boldsymbol{T_{allowed}}$:

$$t_k \leq T_{allowed} \quad \forall k \in \{1, \ldots, p\}$$

Time starts when a vehicle leaves its starting node and ends when the allowed time is reached or when the vehicle visits its last node. The allowed time is the same for each vehicle. There are no time windows in the VRP model because the order in which clients are served is based on the optimal route for a vehicle. By regulation, a 45 minute break is mandatory after at most 4.5 hours of driving (see section 2.6.5). Thus, after 45 minutes of work, a driver will stop along the route and take a break. This break is performed not at a specific location, but along the route when 4.5 hours have passed. After the break, the driver will continue with the planned route.

Because realistic implementation of such breaks is unlikely to impact results in a significant way, if at all, they are added after the VRP has been solved and are not part of the objective function. If the route of a truck exceeds 4.5 hours, a 45 minute break (0.75 hours) is added to the total duration $\boldsymbol{k}$ of the respective route. Otherwise, the time of a route is equal to the time found by the solver.

$$T_{total} = \begin{cases} t_k & t_k < 4.5 \\ t_k + T_{break} & t_k \geq 4.5 \end{cases} \quad \forall k \in \{1, \ldots, p\}$$

Both break duration and shift duration are inputs to the solver (see Figure 3.2) and can be altered if necessary. $\boldsymbol{T_{shift}}$ and $\boldsymbol{T_{break}}$ are set at 8 hours and 45 minutes, respectively. The parameters and variables are listed in Table 3.1 and 3.2.

Table 3.1: The parameters of the CVRP model

Parameters		
Symbol	**Definition**	**Value**
Q	Capacity	11000 kg
T_{shift}	Shift duration	8 hours
T_{break}	Break duration	0.75 hours

Table 3.2: The variables of the CVRP model

Variables	
Symbol	**Definition**
x_{ijk}	Binary variable
c_{ij}	Cost of travel between client i and j (distance or time depending on objective)
q_i	Waste pickup of client i
tt_{ij}	Travel time between client i and j
ts_i	Service time of client i
t_k	Route duration of vehicle k
T_{total}	Total route duration of vehicle k

3.2.2. Implementation in the solver

The OR-tools solver takes the input as shown in Figure 3.2. The service time and weight are properties of a client.

Accumulating variables like distance, time and collected waste (demand) of routes are dimensional objects and registered in OR-tools by means of callbacks, which are functions to keep track of these variables. When traveling from node i to node j, the distance between them is returned by the callback function by searching for the corresponding index in the distance matrix. The time registration is performed the same, but with the service time of node i added. The demand callback returns the demand of node i.

In order to minimize the number of vehicles used, a penalty per used vehicle is introduced. These penalties consist of an arbitrary large number that is added to the objective function for every used vehicle.

The OR-tools suite offers several heuristics to find initial solutions. Parallel cheapest insertion is found to be most reliable. Other heuristics either provided worse solutions or did not find initial solutions at all for problems with multiple constraints (capacity and time). Guided local search is selected as metaheuristic. This metaheuristic uses penalties to escape local minima and, as a result, is able to find better solutions. Guided local search is the recommended local search strategy for routing problems, according to the OR-tools documentation.

4

Rotterdam case study

In this chapter, data is collected to implement the proposed methodology. The data is collected from OSM, the anonymous commercial waste collector in Rotterdam and the MoR.

4.1. Data Collection

In order to simulate a representative situation for the study case, the following data is required:

- The number of waste collectors active in the city and their market share
- The number and distribution of clients served on a given weekday
- The characteristics of driven routes
  - Service time per container size
  - Weight per container size
  - Cost and revenue of daily operation

4.1.1. Waste collectors and clients

From the MoR, an incomplete list of CWCs was collected. This list is composed of registered CWCs 2.6.1. It is difficult to get an overview of all CWCs involved in commercial waste collection in the city of Rotterdam, and estimate their market share.

The reasons for this are:

- In general, CWCs do not share sensitive commercial data like their number of clients;
- Some businesses have signed a contract with a intermediary instead of directly with a CWC. Therefore, the actual CWC serving the client does not become clear from the list;
- Many CWCs on the list are specialized in waste segments not relevant for this research (for example, swill, construction waste, paper);
- Most CWCs are active not only in Rotterdam, but several other surrounding cities. Some CWCs even have national coverage.

The list was filtered based on the following two criteria:

- The CWC needs to collect (among other segments) residual waste
- The CWC needs to utilize rolling containers (so no roll-on/roll-of container)

The filtering was done by manually looking up websites of CWCs. Finally, an estimation was made of about 10-15 CWCs in the study area.

Route data is analyzed from the waste collector in a part of the Centrum district of the city. It is estimated that the number of clients served on an average weekday is 40% of the total (unique) number of customers. The reason for this is that different clients might have different collection intervals (e.g. once per day, once per week, once per two weeks, etc.). Therefore, not all clients with a contract are serviced daily. The number of unique clients found in the dataset is 100 for the given area. The number of clients in this small sample is used to estimate the number of clients of the respective CWC in the study area.

To extrapolate the number of 100 clients to the rest of the city, the interactive map of *Bedrijven op de kaart* ('Businesses mapped out') was used [14]. This website collects data from the Chamber of Commerce (KvK), BAG (Registration of addresses and buildings in The Netherlands) and other sources. From data scraping the number of businesses per district in the city, a quantitative indication of business density per district can be calculated.

In Table B.1 (see Appendix B), the number of businesses per suburb of the Centrum district is displayed. In Table 4.1, the business distribution per district in the city is shown. The percentage of each suburb/district with respect to the total is included in the table.

With the CWC serving 100 clients in a part of the Centrum district, Table B.1 is used to estimate the total number of clients in this district at 163 clients.

Table 4.1: Business distribution in the study area from [14]

	Districts	**Business distribution (%)**
North	Noord	9.0
	Kralingen-Crooswijk	12.2
	Delfshaven	12.4
	Centrum	33.0
South	Charlois	10.3
	Feijenoord	14.2
	IJsselmonde	8.9
	Total	100

With Table 4.1, using the same approach as before, the number of clients for a large CWC in the study area is calculated using table 4.1. With the Centrum district covering 163 clients which is equal to 33 % of total businesses in the study area, the number of clients for a large CWC is estimated to be $163/33 * 100 = 493$. A noteworthy observation is that a third of all businesses in the city are concentrated in the relatively small Centrum district. The rest of the districts have roughly the same number of businesses, with all of the districts located in the 8.9-14.2 % range.

An estimate of the characteristics of smaller CWCs is made based on information provided by a representative of OpenWaste. The representative also confirmed the number of 10-15 CWCs as being realistic. Based on the information, an estimate was made of 5 small CWCs (50 customers) and 3 medium CWCs (100 customers).

Thus, to create a distinction in market share, the CWC market is assumed to be divided into three categories: small, medium and large CWCs. Each CWC is assigned an estimated market share. The results are presented in Table 4.2. The third column represents the number of waste collectors of the respective category in the study area. The market share of medium and small clients is confirmed by the OpenWaste representative to be a reasonable approximation.

Table 4.2: CWC with respective market share

Category	Clients	Number
Large	500	2
Medium	100	3
Small	50	5

Adding up the clients of each CWC, a total of 1550 clients is found. This is the number of clients served daily. As stated in the beginning of this section, the true number of unique clients is estimated at 3875. However, not every client is serviced daily, hence the number of 1550.

The distribution from Table 4.1 is used to distribute the found number of 1550 clients over the districts. The result is shown in table 4.3.

Table 4.3: Estimated clients served daily in the study area

	Districts	Number of registered businesses	Percentage
	Noord	140	9.0
North	Kralingen-Crooswijk	189	12.2
	Delfshaven	192	12.4
	Centrum	512	33.0
	Charlois	160	10.3
South	Feijenoord	220	14.2
	IJsselmonde	138	8.9
	Total	1550	100

4.1.2. Routing

Using data from the waste collector, truck tours were analyzed in a small and dense part of the city center. The dataset is composed of truck trips in a given area in the month August. More details about these routes can be found in Section 4.2. The data comprises routes with:

- Start and end times
- Emptied containers: size and weight
- Break duration

The main observation was that for residual waste, intermediate trips to a depot are generally not necessary because the capacity limit is not reached. The volume capacity is generally not reached because the compactor in the truck is able to compress the waste, which has a relatively low density. When the number of clients cannot be serviced by one truck, multiple trucks will operate on the same day, each driving their own collection route.

Time seems to be the main bottleneck for the collection of residual waste, especially when clients are spread over a large area. In dense urban environments, trip duration is also impacted by road congestion and generally low speed limits.

As mentioned in 2.6.1, contrary to municipal waste collection, containers in the commercial sector are generally not equipped with sensors. Therefore, the amount of waste in client's containers can not be monitored. Customers with empty containers will be scheduled regardless. On inspecting the routes, it appears 25% of customers are not serviced for various reasons. Most often, containers have not been properly positioned as agreed with, are empty, or they cannot be retrieved due to obstructions like closed gates.

4.1.3. Containers: size, service time and weight

A distribution of container sizes is created from data provided by the waste collector. The data is slightly altered. The sizes and frequencies of containers used by clients are presented in Table 4.4.

Table 4.4: Container sizes

Container	240	360	660	770	1100
Percentage	30	10	21	17	22

From the data it appears the smallest format, 240L, occurs frequently. 1100L and 660L take second and third place, respectively.

Service time is defined as the time required to empty a container. Service times depend on the container size. For example, smaller containers are usually lighter and easier to move. They take up less space, allowing for a close placement near the road. Heavier containers, however, are harder to move and more time-consuming. In literature, the following estimates are found. [53] estimates an average of 54 seconds per stop for household waste collection, including extra time spent due to decelerating/accelerating at a stop. The research assumes small household bins along the road. In a Spanish study case on waste collection, [11] studied average stop duration. For rolling containers, an average between 42-74 seconds was found depending on the number of containers per stop. Data used by [18] from household waste collection with back-loaded garbage trucks averages at about 128 seconds per stop. The authors note that determining the time spent at a stop is hard to estimate and correctly predicting individual service times requires knowledge of many variables, such as surface type (paved/unpaved), truck distance from the container and the location of a container.

The CWC provided data on the average service time per container size. Averaging this data, a service time of 97 seconds is found. This result is similar compared to the numbers used in literature. The service time of each client will be implemented based on the size of the used container.

Lastly, the weight per container is provided by the waste collector. The average weight depends on container size. Averaging over all container sizes, a weight of 49.6 kg is found. This corresponds to the number found by [5].

4.1.4. Network module

The OSM street network is imported with a high density node/edge geometry in order to generate a detailed street network. This allows for many options for trucks to stop and the simulation of clients close to each other. Each edge in the graph has several attributes describing its properties, one of which is *travel_time*. The travel time is calculated by dividing the length of an edge by its *max_speed* (speed limit) property. However, it is unlikely that vehicles navigating through a dense city will drive at the speed limit. On average, speeds are lower due to traffic (lights) and constant acceleration/deceleration. To achieve a more realistic travel time, several route travel times are calculated in Google Maps, on 30 km/h and 50 km/h roads in the city. The average speeds are calculated to be 14,5 and 23,5 km/h, respectively (see Table 4.5 and 4.6). The maximum speeds are replaced with these values and the travel times are recalculated.

Table 4.5: Average speed 30 km/h sections

Time (minutes)	2	3	6	7	
Distance (km)	0.4	0.8	1.3	2	**Average**
Speed (km/h)	12	16	13	17	**14.5**

Table 4.6: Average speed 50 km/h sections

Time (minutes)	12	17	14	9	
Distance (km)	4.6	7	5.9	3.3	**Average**
Speed (km/h)	23	24	25	22	**23.5**

The street network is used as input for the following tasks:

- Calculating the nearest street network node to a business in the client module;
- Creating the distance and duration matrices in the matrix module by calculating distance/durations of routes between nodes on the network;
- Plotting the routes in the VRP solver

4.1.5. Client module

To generate client locations, it is possible to use the *osmnx.utils_geo.sample_points()* function. This function generates points on the street network, for which the nearest node can be found using the *osmnx.distance.nearest_nodes()* function. Sampling points this way yields a uniform distribution over the study area, see Figure 4.1.

Figure 4.1: Uniformly distributed clients

This distribution is not realistic, since true distributions of businesses are rarely uniform. They are often clustered, especially in city centers, shopping malls and shopping streets. To achieve more realism and generate clients according to the distribution found in Table 4.3, OSM data was used as a source for the locations of clients. Since typical clients in city are businesses in the KWD sector, the following keys and values were used in OSM to find related businesses (see Table 4.7:

Table 4.7: OSM keys and values used to identify clients

Key	Value
Office	All
Shop	All
Amenity	Restaurant, bar, cafe, fast_food, food_court, pub, school

Using the OSMnx features module, all entities with the tags from Table 4.7 are collected, resulting in 3565 potential clients. The result is shown in Figure 4.2. The client distribution is much more realistic, with clusters and shopping streets easily identifiable. The Centrum district features the greatest business density, with some well known shopping districts visible: the Nieuwe Binnenweg west of the city center, and the shopping centers in Zuidplein and Keizerswaard (Rotterdam south).

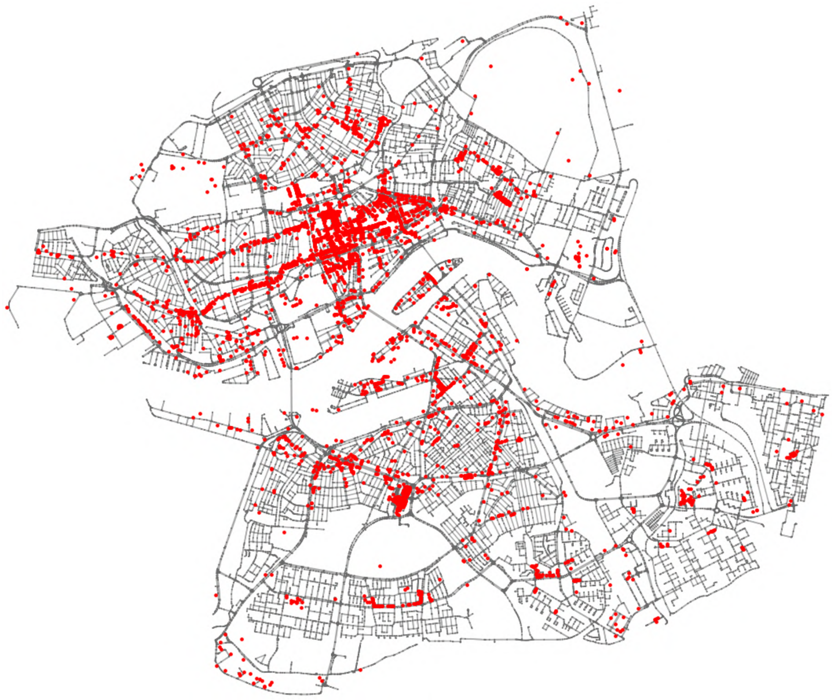


Figure 4.2: Realistically distributed clients

Subdividing into districts, the following distribution is found (Table 4.8):

Table 4.8: Distribution of clients among the city, extracted from OSM

	District	Number	Percentage
North	Noord	290	8.1
	Kralingen-Crooswijk	285	8.0
	Delfshaven	384	10.8
	Centrum	1414	39.7
South	Charlois	475	13.3
	Feijenoord	479	13.4
	IJsselmonde	238	6.7
	Total	3565	100

The data from OSM correspond adequately to the distribution found in chapter 4 (see Table 4.1). Compared with the data by [14], the Centrum district again is found to be housing the majority of the city's businesses. Other districts are located in the range of 8.0-13.4 %, with the exception of IJsselmonde featuring 6.7 % of businesses. Due to the similarities between the dataset from [14] and OSM, this dataset is considered a realistic approximation of the distribution of businesses over the city.

After locating clients, *np.random.choice* is used to uniformly remove clients from the dataframe to achieve the number of clients agreed on in Section 4.1.1. This is done to decrease the number of clients without degrading the quality of the overall distribution. Using *osmnx.distance.nearest_nodes()*, the nearest nodes on the road network are generated, representing the containers. In three instances, this results in nodes placed on the highway. These clients are filtered out from the dataset.

Lastly, CWCs and containers are assigned randomly to clients according to the distributions in Section 4.1.1 (see Table 4.2). This results in the distribution as shown in Table 4.9. The entry point is defined as the starting point where vehicles enter the study area. They represent CWCs entering the city based on their geographical location.

The entry points of the CWCs are shown in Figure 4.3.

Table 4.9: Distribution of clients over waste collectors. L = large, M = medium, S = small.

CWC	S1	S2	S3	S4	S5	M1	M2	M3	L1	L2
Daily clients	47	55	47	54	48	103	98	90	504	504
Entry point (north/south)	N	N	N	S	S	N	N	S	N	N

Figure 4.3: Entry points of the study area

The collected data and used sources is summarized in Table 4.10.

Table 4.10: Collected data and associated sources

Source	**Data**
Waste collector in the study area	- Container size distribution - Average weight per container size - Service time per container size - Route data from city center
OpenStreetMap	- Street network - Client distribution over the study area
MoR, OpenWaste, Waste collector	- CWCs in the study area and market share
Google Maps	- Average edge speeds

4.1.6. Cost and revenue

Cost is difficult to implement and can vary significantly per waste collector. To estimate the cost, the following approach was used. From [27], the wage costs relative to vehicle costs for waste collection is extracted. This ratio is equal to 1.44 (53.8 % wage cost, 37.4 % vehicle cost). The wage costs are set to € 34 per hour. The routes of the small waste collectors (solved for time) are used as a reference. Multiplying the total route durations (working hours) of all small waste collectors (22.6) by 34 gives total wage costs of € 767. Dividing by the found ratio yields vehicle costs of € 532. This is equal to € 1.56 per kilometer. Therefore, costs are set at € 34/hour and € 1.56/km.

Although wage costs might differ from real operations (drivers are often paid per month instead of per hour), the ratio between wage costs and vehicle costs is more important and is considered appropriate with this approach. Because costs are based on a combination of distance and duration of a route, costs will allow for additional comparison between waste collectors and assess the financial benefits of collaboration for (groups of) waste collectors.

Secondly, revenue is implemented. It is estimated that waste collection accounts for 30% of the costs [1]. Therefore, the revenue of the containers are based on the prices used by Renewi [48] multiplied by 0.3. This results in the revenue per container as shown in Table 4.11:

Table 4.11: Revenue per container

Container size (L)	240	360	660	770	1100
Revenue (€)	6.52	8.64	13.1	14.4	17.5

Because the ratio between operational revenue and operational costs is not known and will likely be different for each waste collector, revenue and costs are listed separately.

In Table 4.12, the CWCs are shown with calculated daily revenue.

Table 4.12: Distribution of clients over waste collectors. L = large, M = medium, S = small.

CWC	S1	S2	S3	S4	S5	M1	M2	M3	L1	L2
Daily clients	47	55	47	54	48	103	98	90	504	504
Revenue (€)	509.0	632.1	500.7	574.4	532.6	1164.4	1047.5	977.4	5299.0	5391.7

4.2. Verification and validation of the model

To verify the routes generated by the solver, a part of the operational area of the waste collector is used as study area. This area is covered by 1 truck.

From the waste collectors data, the average route distance on a weekday (183 clients) is 29.55 kilometers, and the average time is 7.93 hours. To calibrate the model, a corrected service time of 110 seconds per client is used. This also includes the time 'lost' when decelerating/accelerating from a stop.

Using the OSM data to generate 183 clients in the same area as the waste collector, the routes are constructed using both time and distance as objective, see Table 4.13.

Table 4.13: Simulating a real-life scenario

	Distance	**Time**
Objective: distance	29.5	7.96
Objective: time	29.0	7.91

Solving for time or distance yields very similar results. This is likely caused by the extreme density of clients, resulting in many solutions with approximately the same performance and distance/time solutions being closely related. Also, there are limited options for the truck in choosing which roads to use and which not, since most of them will have to be visited anyway because there are clients along the road. When observing the results, they agree with the average numbers from the waste collector with about a 1.9% deviation in distance and 0.4% in time. Because the waste collectors data features some slight variation, the performance of the model is considered realistic.

When simulating the route of a small waste collector with 47 clients throughout the city, the difference in distance and time for both objectives is more pronounced (see Table 4.14). This is caused by the opportunity to use the highway. In this example of CWC 6S, the results are logical taking into account the objective.

Table 4.14: Simulation of a small waste collector

	Distance	**Time**
Objective: distance	52.3	4.23
Objective: time	56.4	4.06

The routes of this CWC are illustrated in Appendix A.

Lastly, CWC 6S is used as benchmark to test the constraints. The results are shown in Table 4.15.

Table 4.15: Validation checks to test the constraints

Hypothesis	Meets requirements?
Decreasing the capacity to 1500 will result in two routes	✓
Decreasing the shift time to 3 hours will result in two routes	✓

5 Application of the model

In this chapter, the model is applied and results are presented. The routes of every CWC are optimized based on two objective functions: distance and time. In real operations, a combined objective of time and distance is used. However, by optimizing for both objectives separately, the difference in route formation is more clearly visible, hence why a combined time and distance objective is not studied. All the resulting route(s) for every CWC are included in Appendix A. Section 5.1 discusses the scenarios. In Section 5.3, the results are shown in case there is no collaboration. Section 5.4, 5.5 and 5.6 cover the results of the collaborative scenarios for the small, medium and large waste collectors, respectively.

5.1. Overview of scenarios

In this section, the scenarios that are simulated will be explained. For multiple commercial reasons, a CWC might be hesitant to completely hand over the servicing of clients to other CWSs in a collaboration. Therefore, two workload balancing scenarios have been implemented, ensuring equal workload before and after the implementation of the collaborative framework. The workload is defined in two different ways in scenario 3 and 4.

The total operational costs of a waste collector depend on total duration of the route (working hours) and the distance traveled. The profit depends on the type of clients served (larger containers have more expensive contracts). Further complicating the matter, the cost reductions caused by collaboration will not be equal for each waste collector. Because no scenario guarantees perfect cost balancing, after implementation of collaboration (even with balancing constraints) CWCs will always need to agree on a profit sharing mechanism which fairly distributes the cost savings and revenue over the CWCs.

Scenario 1: No collaboration
In this scenario, all waste collectors will operate independently from each other. There is no collaboration or any form of sharing of clients.

Scenario 2: Full collaboration (no constraints)
In the second scenario, the focus is on collaboration by consolidation of clients. All clients of collaborating partners are fed into the solver, which solves for time or distance. No extra constraints or restrictions are imposed. This scenario is likely to perform the best of all scenarios in minimizing both the objective (time/distance) and the number of vehicles used, because it efficiently reshapes routes and drops redundant vehicles, without being bound by additional constraints.

Scenario 3: Client balancing
In this scenario, clients are shared between the CWCs. A new route is then constructed combining the client base for an improved solution (decreased total time/distance). To maintain self-sufficiency, the number of clients served by each CWC before and after implementation of the collaboration is required to be equal:

$$\sum_{i=1}^{n}\sum_{j=1}^{n} x1_{ijk} = \sum_{i=1}^{n}\sum_{j=1}^{n} x2_{ijk}$$

Like in section 3.2.1, $x1_{ijk}$ has a value of 1 if the arc from node i to node j is in the optimal route and 0 otherwise. In this equation, the subscript $_1$ denotes the case of no collaboration, and the subscript $_2$ denotes collaboration.

The constraint is implemented in the solver as a second demand dimension, with its own capacity. Every client has a pickup value of 1, and the capacity of the trucks is set to the number of clients they serve in the non-collaborative scenario. This is basically the same as x_{ijk}, but with capacity added. For example, in scenario 3 for the small CWCs, the total demand is equal to the number of clients (251). The virtual capacity of each truck is set to the number of clients served in scenario 1, resulting in the capacities $[47, 55, 47, 54, 48]$.

When solving the VRP problem however, such a hard constraint makes it hard for the solver to find feasible solutions. Since the summed capacities of the trucks are exactly equal to the clients served, there is zero slack, and the feasible solution space is significantly reduced. In the case of scenario 3 for the medium CWCs, no initial solution is found. To mitigate this, some 'slack' is introduced. The client capacity of each truck is removed, and a soft bound is implemented. This soft constraint provides some slack in the number of clients served by a vehicle which allows it to deviate from its initial number of clients. Violating the soft bound is allowed, but this generates a penalty:

$$penalty = \alpha * |x1_{ijk} - x2_{ijk}|$$

The penalty is equal to the absolute deviation from the soft bound multiplied by a large coefficient α. Therefore, violating the constraint will yield a penalty proportional to the violation. The sum of the penalties over all vehicles will be added to the objective function:

$$\text{Minimize}(\sum_{k=1}^{p}\sum_{i=1}^{n}\sum_{j=1}^{n} c_{ij}x_{ijk} + \sum_{k=1}^{p} penalty_k)$$

This will discourage the solver from violating the constraint. By formulating the constraint this way, the solver performs better and finds more solutions. In fact, it is able to find solutions without violating the constraint at all.

Scenario 4: Client sharing - revenue balancing
In scenario 4, clients are again shared between CWCs and new routes are generated. This time, the revenue of a CWC is required to be equal before and after implementation of the collaboration. The income generated by a CWCs client is related to its container size. The constraint is implemented similarly to the constraint from scenario 3.

5.2. Implementation and KPIs

The collaboration is implemented as follows. First, groups are formed of CWCs with similar numbers of daily clients (market share). This imitates similar real-world collaborations like Green Collective and OpenWaste, which also exist of waste collectors with comparable market shares. For each group, the four scenarios are simulated. This allows for assessing the benefits of collaboration between CWCs and comparing collaborations of different scales.

In section 5.3, scenario 1 (no collaboration) is simulated for all CWCs. The results of this section show how individual CWCs perform and will later be used to assess the benefits of collaboration. Section 5.4, 5.5, 5.6 cover all scenarios (as explained in section 5.1) for the small, medium and large CWCs, respectively. The results of the collaborative scenarios (2,3,4) are grouped together per CWC size category to allow for comparison between different forms of collaboration in the same size category.

As part of the results, several KPIs are calculated:

- **Costs**
  These are the costs associated with the truck routes. They are calculated as explained in 4.1.6;
- **Cost per client**
  The cost per client is defined as the daily cost of a CWC divided by the number of clients served by all vehicles combined;
- **Clients per hour**
  The number of clients per hour is defined as the number of clients served by a CWC divided by the total number of hours of all vehicles combined;
- **Clients per kilometer**
  The number of clients per kilometer is defined as the number of clients served by a CWC divided by the total number of traveled kilometers of all vehicles combined;
- **$T_{service}/T_{total}$**
  The ratio $T_{service}/T_{total}$ is defined as the service time divided by the total time of all vehicles excluding breaks;
- **Speed**
  The speed is defined as the average speed, which is the number of kilometers traveled by all vehicles divided by the total time spent on the road.
- **Vehicle utilization rate (VUR)**
  The vehicle utilization rate is the vehicle use divided by the maximum use of a vehicle. Vehicle use is defined as the time spent driving, and the maximum use of a vehicle is 8 hours. The VUR is expressed as a percentage (%).

5.3. Scenario 1: No collaboration

In this scenario, the CWC's operate independently from each other. The results are illustrated in the following subsections. To calculate the routes of the small CWCs, the solver is given a runtime of 60 seconds. Medium and large CWCs are allowed a longer runtime of 300 s and 3600 s, respectively, since the computational complexity is greater due to the larger number of clients. The following subsections show the results for each CWC group. The end of this section, subsection 5.3.4, compares how the CWC relate to one another.

5.3.1. Small CWCs

The small CWCs feature a small number of clients (~ 50) throughout the city. Therefore, every CWC is able to satisfy daily demand with one truck and one tour. For illustration purposes, the routes of CWC S1 are shown in Figures 5.1 and 5.2. The routes of S2, S3, S4 and S5 are shown in Appendix A.

Figure 5.1: Collection route for CWC S1 (objective = distance)

Figure 5.2: Collection route for CWC S1 (objective = time)

The quantitative results for every CWC are illustrated in Figure 5.3, 5.4 and 5.5. Both objectives are shown. First, a route is formed based on the shortest distance. This is shown at the left of each diagram. Then, the simulation is run again and a route is formed based on the shortest time. This is shown at the right of each diagram. The number of trucks used is shown in the title of the diagram. An important remark is that the difference in total time for both objectives is sometimes caused by the 45 minute breaks, which are mandatory after 4.5 hours of driving. When solving for distance, route durations just surpass 4.5 hours for S1 - S5, resulting in an additional break added to the route duration. When this is the case, the time without a break is shown in red. This allows for a more fair comparison.

It is observed that for some small CWCs, there is a relatively large difference in route distance when solving for time vs distance. This is caused by the tendency of the solver to (not) use the highway. For example, CWC S5 shows a large difference in highway use as shown by its routes (see Appendix A). Highway use generally results in a larger distance but in a shorter time, due to the high travel speed. This is why the highway is more often included in routes when time minimization is the objective. Whether the solver uses the highway or not is related to the positioning of the clients; the solver only uses the highway when it makes sense to do so (e.g. when it results in a shorter time/distance), which is more likely when clients are located closely to freeway ramps and exits. In Figures 5.1 and 5.2 the difference in highway use is also clearly visible between the two objectives. Using the highway is beneficial in two ways: it reduces travel time and results in less distance traveled in the urban environment. Therefore, it is also assumed to happen in real-world operations for smaller waste collectors.

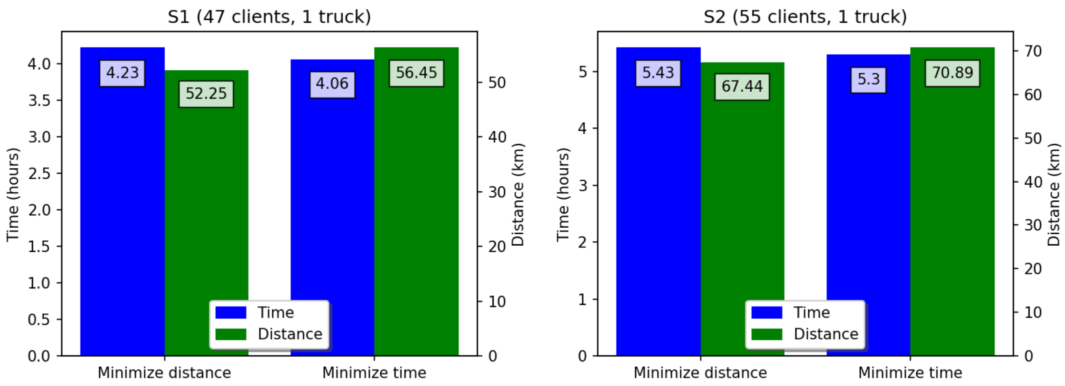


Figure 5.3: Time/distance statistics of the daily collection routes for CWC S1 and S2

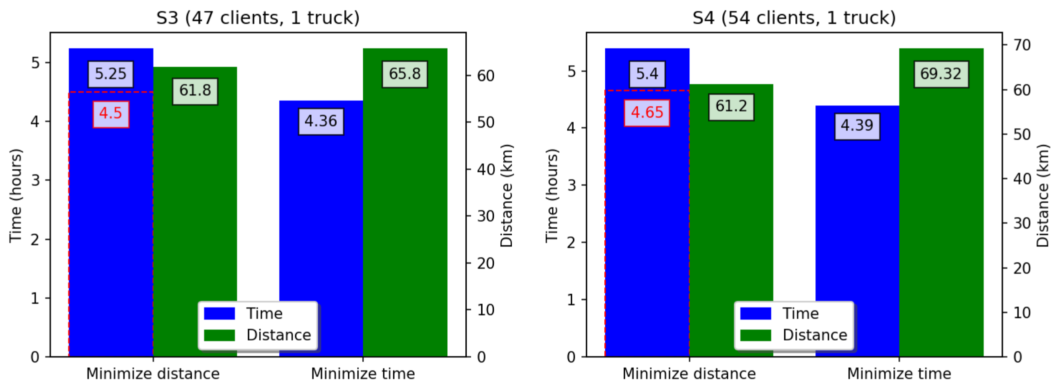


Figure 5.4: Time/distance statistics of the daily collection routes for CWC S3 and S4

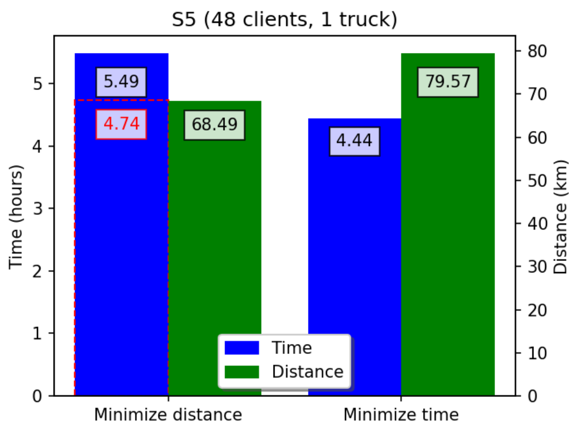


Figure 5.5: Time/distance statistics of the daily collection routes for CWC S5

5.3.2. Medium CWCs

In the figures below, distance and time results of the medium sized CWCs are shown in the same manner as the previous section. For illustration, the routes of M1 are shown in Figures 5.7 and 5.6. The routes for M2 and M3 can be found in Appendix A.

Figure 5.6: Collection route for CWC M1 (objective = distance)

Figure 5.7: Collection route for CWC M1 (objective = time)

The distance and duration of the routes of M2 are relatively short compared to the other medium CWCs. This is caused by the distribution of its clients; M2 features less outliers near the edges of the study area in the north/east/south (see Appendix A). Because clients are spread out over a smaller area, it is possible to serve all clients in a shorter route compared to 3M and 4M. An additional reason for the short distance and time is that M2 serves less clients.

Compared with small CWCs, medium-sized CWCs spend significantly more time collecting waste, because they have more clients.

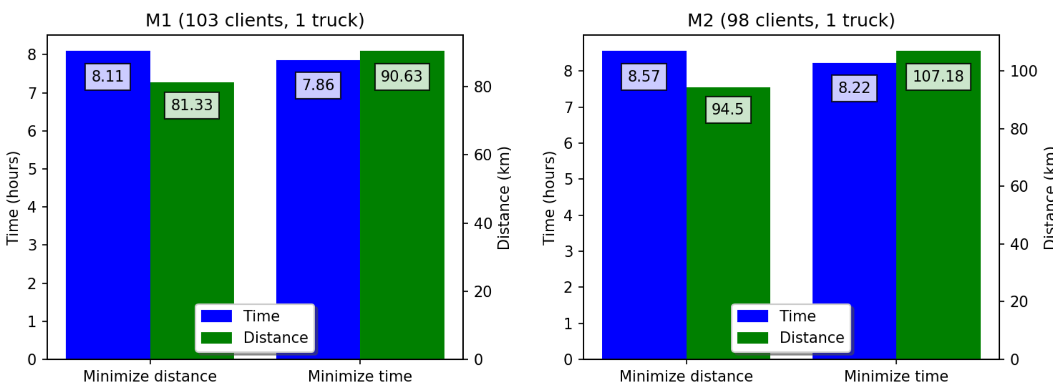


Figure 5.8: Time/distance statistics of the daily collection routes for CWC M1 and M2

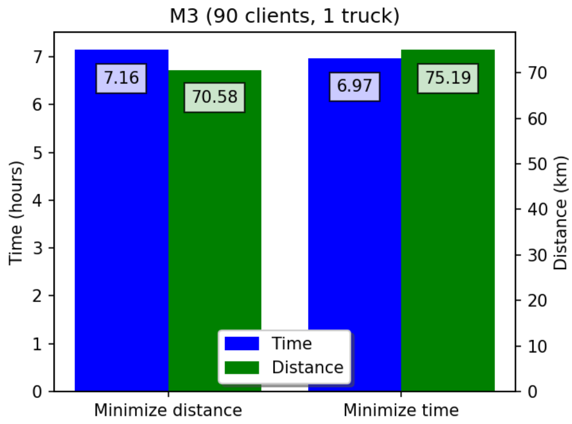


Figure 5.9: Time/distance statistics of the daily collection routes for CWC M3

5.3.3. Large CWCs

Figure 5.12 shows the results for the large CWCs. The large CWCs both require 4 trucks to serve all daily clients, resulting in 4 routes. The routes are shown in Figures 5.10 and 5.11. Every color represents a route. The routes for CWC L2 can be found in Appendix A.

Figure 5.10: Collection route for CWC L1 (objective = distance)

Figure 5.11: Collection route for CWC L1 (objective = time)

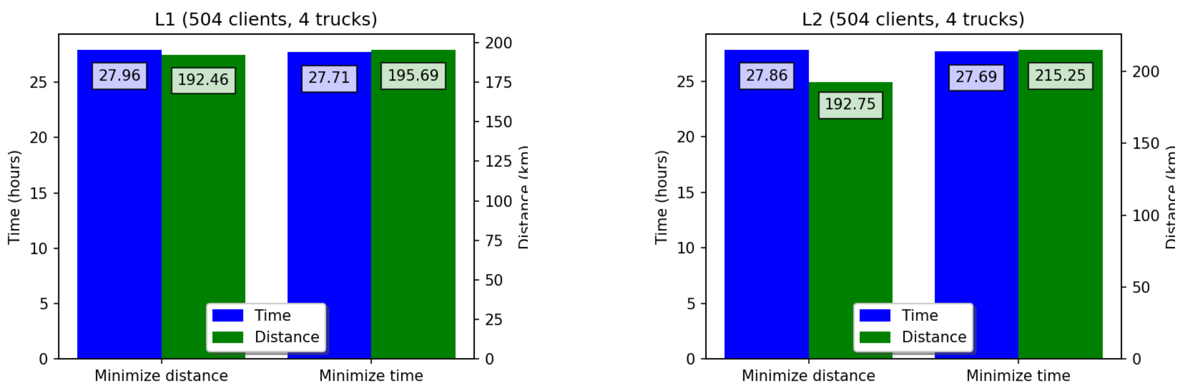


Figure 5.12: Time/distance statistics of the daily collection routes for CWC L1 and L2

As shown in Table 5.1 and 5.2, there is one truck driving considerably shorter routes. This is related to the fact that 3 vehicles is just not enough to serve all daily clients. Increasing the shift time will result in the usage of 3 vehicles. However, since the shift duration is already considered on the long side, this is not considered.

Table 5.1: Statistics per vehicle for CWC L1

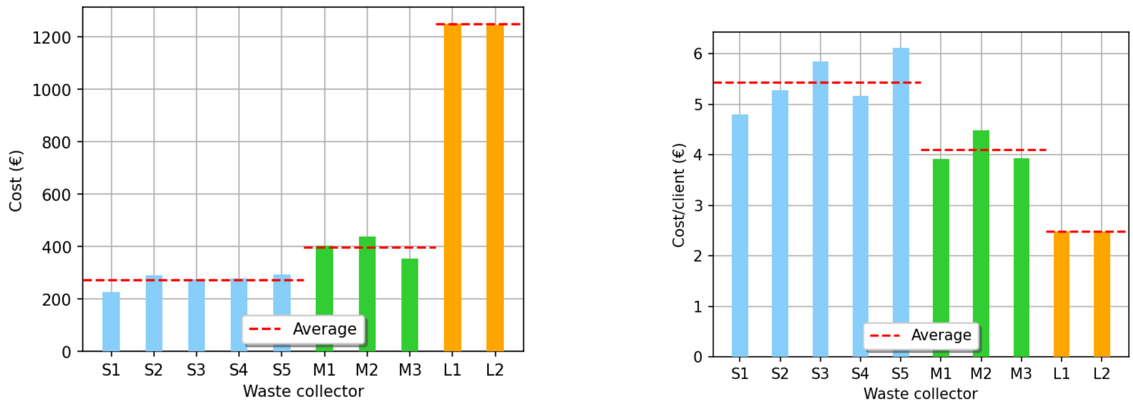
	Objective: distance		**Objective: time**	
Vehicle	**Time (hour)**	**Distance (km)**	**Time (hour)**	**Distance (km)**
1	8.4	70.9	3.2	21.0
2	8.4	54.6	8.4	74.8
3	3.5	17.9	8.3	51.5
4	7.6	49.0	7.8	48.4

Table 5.2: Statistics per vehicle for CWC L2

	Objective: distance		**Objective: time**	
Vehicle	**Time (hour)**	**Distance (km)**	**Time (hour)**	**Distance (km)**
1	8.8	63.0	8.8	87.7
2	6.4	39.9	2.9	21.4
3	8.6	66.7	7.7	48.1
4	4.2	23.2	8.4	58.0

5.3.4. Summary

To assess the differences between the CWCs, their KPIs are compared. This section shows bar plots of all KPIs for every CWC. Every CWC size category is assigned a color. The average KPI per group is shown with a red dotted line. The bar plots in this section only show results for the distance objective. The complete results are shown in Table 5.4.

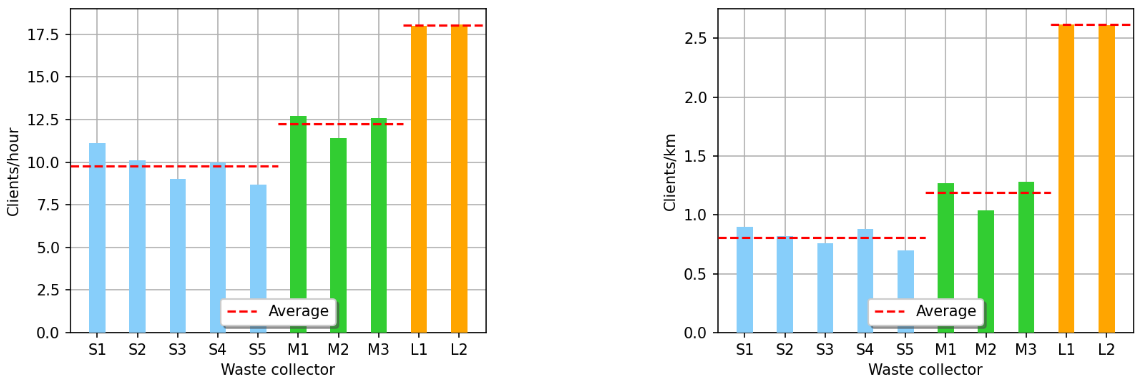


(a) Total cost

(b) Cost per client

Figure 5.13: KPIs cost and cost/client

In Figure 5.13 the results for cost are shown. The cost depends on the distance and time, which are related to the number of clients served. Large CWCs have a cost of about €1250, medium CWCs €400, and small CWCs €270. Although the larger CWCs feature 10 times as many clients as smaller CWCs, the cost is only 4.6 times as high. The cost per client is shown in Figure 5.13b.

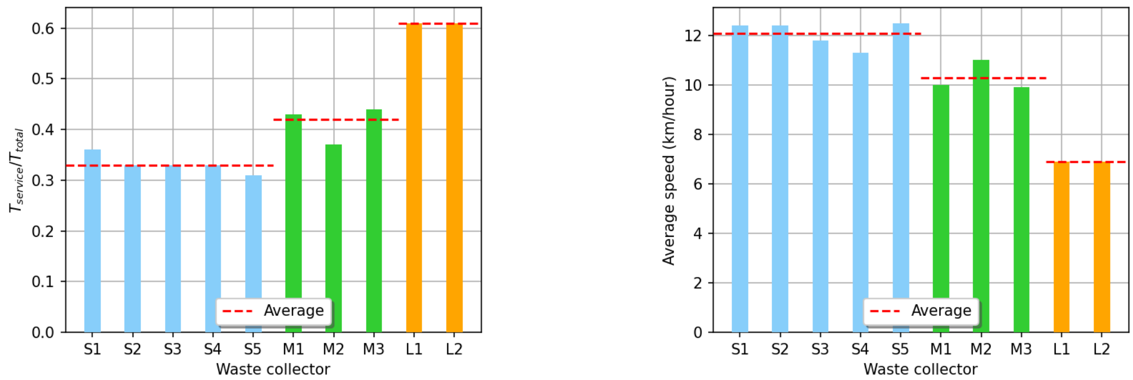


(a) client/hour

(b) client/km

Figure 5.14: KPIs client/hour and client/km

Figure 5.14 shows the number of clients per hour and the number of clients per kilometer. The average client/hour ratio for small, medium and large CWCs is respectively 9.79, 12.24 and 18.06. The average client/km ratio for small, medium and large CWCs is respectively 0.81, 1.19 and 2.62. The relative difference in clients/km for different CWC groups is more pronounced than the client/hour ratio.



(a) $T_{service}/T_{total}$ **(b)** Average speed

Figure 5.15: KPI $T_{service}/T_{total}$ and average speed

Figure 5.15 shows the KPIs $T_{service}/T_{total}$ and average speed. The $T_{service}/T_{total}$ ratio for small, medium and large CWCs is respectively 0.33, 0.42 and 0.61. This shows that the large CWCs spend more time servicing clients than they are driving. The opposite is true for small and medium CWCs: they spend more time driving than servicing clients.

The average speed for small, medium and large CWCs is respectively 12.07, 10.30 and 6.90 km/h.

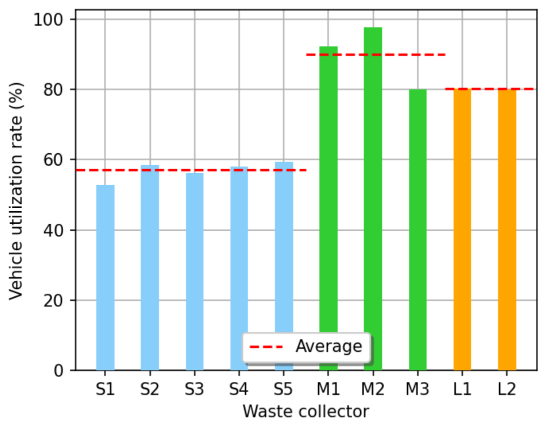


Figure 5.16: KPI Vehicle utilization ratio

The last KPI shows the vehicle utilization ratio (VUR). The VUR is largest for medium CWCs, with 90.1 %. The small and large CWCs have a VUR of respectively 57 and 80 %.

The complete results are shown in Table 5.3 and 5.4. Table 5.3 shows the time/distance statistics of the CWCs, and Table 5.4 shows the KPIs for both distance and time.

Table 5.3: Time/distance statistics of the daily collection routes for all CWCs

			Objective: distance		Objective: time	
CWC	**Revenue (€)**	**Clients**	Time (hour)	Distance (km)	Time (hour)	Distance (km)
S1	509	47	4.2	52.3	4.1	56.4
S2	632	55	5.4	67.4	5.3	70.9
S3	501	47	5.3	61.8	4.4	65.8
S4	574	54	5.4	61.2	4.4	69.3
S5	533	48	5.5	68.5	4.4	79.6
M1	1164	103	8.1	81.3	7.9	90.6
M2	1047	98	8.6	94.5	8.2	107.2
M3	977	90	7.2	70.6	7.0	75.2
L1	5299	504	28.0	192.5	27.7	195.7
L2	5392	504	27.9	192.8	27.7	215.2
Total	16629	1550	106	943	101	1026

Table 5.4: KPI's for all CWCs

	CWC	**S1**	**S2**	**S3**	**S4**	**S5**	**M1**	**M2**	**M3**	**L1**	**L2**
	Revenue (€)	509	632	501	574	533	1164	1047	977	5299	5392
Objective: distance	**Vehicles**	1	1	1	1	1	1	1	1	4	4
	Costs (€)	225	290	275	279	294	403	439	354	1251	1248
	Costs/client (€)	4.80	5.27	5.85	5.17	6.12	3.91	4.48	3.93	2.48	2.48
	Clients/hour	11.1	10.1	9.0	10.0	8.7	12.7	11.4	12.6	18.0	18.1
	Clients/km	0.90	0.82	0.76	0.88	0.70	1.27	1.04	1.28	2.62	2.61
	$T_{service}/T_{total}$	0.36	0.33	0.33	0.33	0.31	0.43	0.37	0.44	0.61	0.61
	Speed (km/h)	12.4	12.4	11.8	11.3	12.5	10.0	11.0	9.9	6.9	6.9
	VUR (%)	52.9	58.5	56.3	58.1	59.3	92.3	97.8	80.1	80.3	80.0
Objective: time	**Vehicles**	1	1	1	1	1	1	1	1	4	4
	Costs (€)	226	291	251	257	275	409	447	354	1247	1277
	Costs/client (€)	4.81	5.29	5.34	4.77	5.73	3.97	4.56	3.94	2.48	2.53
	Clients/hour	11.6	10.4	10.8	12.3	10.8	13.1	11.9	12.9	18.2	18.2
	Clients/km	0.83	0.78	0.71	0.78	0.60	1.14	0.91	1.20	2.58	2.34
	$T_{service}/T_{total}$	0.38	0.34	0.34	0.35	0.34	0.45	0.39	0.46	0.61	0.61
	Speed (km/h)	13.9	13.4	15.1	15.8	17.9	11.5	13.0	10.8	7.1	7.8
	VUR (%)	50.8	56.9	54.5	54.9	55.5	88.9	93.3	77.8	79.6	79.5

5.4. Collaborative scenarios: small waste collectors

5.4.1. Combined results

To assess the benefits of collaboration, the sum of the time and distance in Scenario 1 (no collaboration) of the small waste collectors is used for comparison. The results are shown in Figure 5.17 and Figure 5.18 for the distance and time objective, respectively.

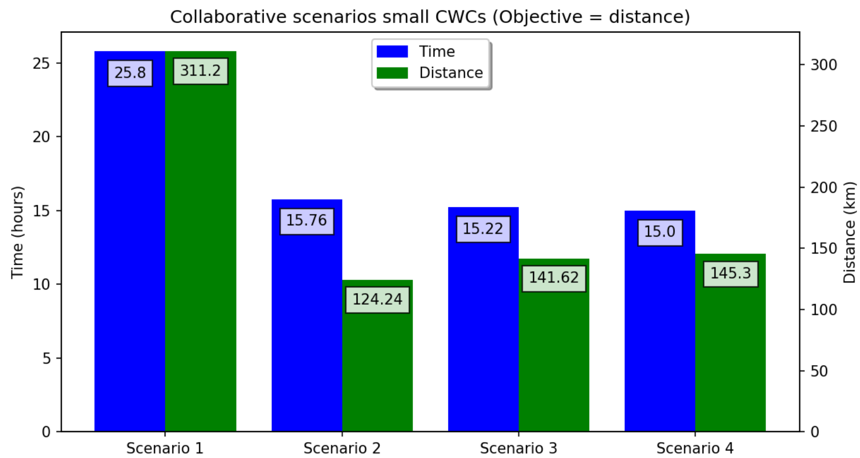


Figure 5.17: Results for the collaborations with objective = distance. Scenario 1 (no collaboration), Scenario 2 (full collaboration, no constraints), Scenario 3 (client balancing), Scenario 4 (revenue balancing). Results shown are summed over the small CWCs for Scenario 1,3 and 4.

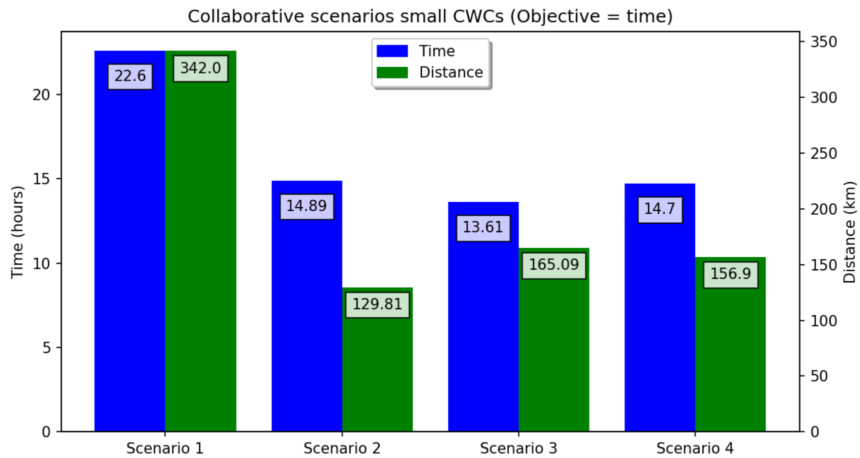


Figure 5.18: Results for the collaborations with objective = time. Scenario 1 (no collaboration), Scenario 2 (full collaboration, no constraints), Scenario 3 (client balancing), Scenario 4 (revenue balancing). Results shown are summed over the small CWCs for Scenario 1,3 and 4.

The results show how the combined distance and duration of the small CWCs decreases due to collaboration. The results are also shown in Table 5.5. In case of scenario 2 (full collaboration), the total duration decreases with 34-38.9% and the distance decreases with 60.1-62.0%. Scenario 3 and 4 also show a large decrease in combined distance and time, although less pronounced than scenario 2. Scenario 3 and 4 show similar reductions in time and distance. Although scenario 2 yields the best results since it features the least constraints, the total duration is longer compared to scenario 3 and 4. This is because scenario 2 uses two vehicles (including two breaks), and scenario 3 and 4 use five vehicles but end their shift before the mandatory break time.

Table 5.5: Time/distance statistics of the scenarios

		Objective: distance		Objective: time	
		Time (hour)	Distance (km)	Time (hour)	Distance (km)
Scenario 1	Total	25.8	311.2	22.55	342.0
Scenario 2	Total	15.76	124.24	14.89	129.81
	Difference (%)	-38.9	-60.1	-34.0	-62.0
Scenario 3	Total	15.2	141.6	13.6	165.1
	Difference (%)	-41.0	-54.5	-39.6	-51.7
Scenario 4	Total	15.0	145.3	14.7	156.9
	Difference (%)	-41.7	-53.3	-34.8	-54.1

Table 5.6 shows the combined KPIs of the collaborative scenarios. The costs for each scenario is summed over all CWCs, and for the other KPIs, the average over the CWC is taken. Because scenario 2 is full collaboration and scenario 3 and 4 demand every CWC to keep operating, there is only a reduction in vehicle use in scenario 2. Besides a decrease in distance and time, there is a savings in costs of 43-47%. In terms of cost decrease, the results for the time and distance objective are similar.

Table 5.6: KPIs for the different scenarios of the small CWCs.

		Scenario 1	Scenario 2		Scenario 3		Scenario 4	
		Total	Total	Diff. (%)	Total	Diff. (%)	Total	Diff. (%)
Objective: distance	Vehicles	5	2	-60.0	5	0.0	5	0.0
	Costs (€)	1363	730	-46.5	738	-45.8	738	-45.9
	Costs/client (€)	5.44	2.91	-46.6	2.94	-45.9	2.94	-46.0
	Clients/hour	9.79	15.93	+63	16.49	+69	16.70	+71
	Clients/km	0.81	2.02	+148.9	1.77	+118.4	1.73	+112.9
	$T_{service}/T_{total}$	0.33	0.53	+59.7	0.50	+49.7	0.51	+51.5
	Speed (km/h)	12.1	7.9	-34.7	9.3	-22.9	9.7	-19.9
	VUR (%)	57	89		38		38	
Objective: time	Vehicles	5	2	-60.0	5	0.0	5	0.0
	Costs (€)	1300	709	-45.5	720	-44.6	745	-42.7
	Costs/client (€)	5.19	2.82	-45.6	2.87	-44.7	2.97	-42.8
	Clients/hour	11.17	16.86	+50.9	18.44	+65.1	17.07	+52.9
	Clients/km	0.74	1.93	+160.9	1.52	+105.1	1.60	+115.8
	$T_{service}/T_{total}$	0.35	0.57	+62.6	0.56	+59.9	0.52	+48.1
	Speed (km/h)	15.2	8.7	-42.7	12.1	-20.3	10.7	-29.8
	VUR (%)	55	84		34		37	

5.4.2. Individual results

In Table 5.7, the cost savings for individual CWCs are shown. Scenario 2 is omitted because not all CWCs are operating.

Table 5.7: Cost per client for scenario 1,3,4 for every small CWC (objective = distance).

		CWC S1	CWC S2	CWC S3	CWC S4	CWC S5
Scenario 1	**Costs/client (€)**	4.80	5.27	5.85	5.17	6.12
Scenario 3	**Costs/client (€)**	2.78	2.73	2.32	3.73	3.07
	Difference (%)	-42.1	-48.2	-60.3	-27.7	-49.9
	Clients serviced	47	55	47	54	48
Scenario 4	**Costs/client (€)**	2.05	2.42	2.84	3.54	3.90
	Difference (%)	-57.3	-54.0	-51.5	-31.5	-36.3
	Clients serviced	50	54	47	52	48

Although the cost decrease is not evenly divided among CWCs, Table 5.7 shows that every CWC experiences a decrease in operational costs and therefore a decrease in costs per client. The cost decrease per CWC is very much dependent on its assigned route, and may vary significantly between objectives or scenarios. When comparing the number of clients per CWCs in scenario 4 with the original numbers (shown in row 3 of scenario 3), it can be concluded that revenue sharing also keeps the number of clients relatively stable, since revenue is related to the number of clients served.

5.5. Collaborative scenarios: medium waste collectors

5.5.1. Combined results

The results for the collaborative scenarios for the medium CWCs are shown in Figure 5.19 and Figure 5.20.

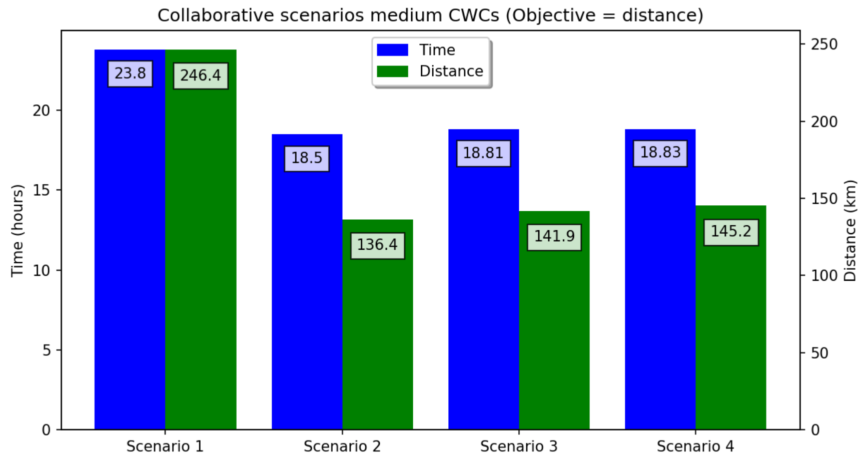


Figure 5.19: Results for the collaborations with objective = distance. Scenario 1 (no collaboration), Scenario 2 (full collaboration, no constraints), Scenario 3 (client balancing), Scenario 4 (revenue balancing). Results shown are summed over the medium CWCs for Scenario 1,3 and 4.

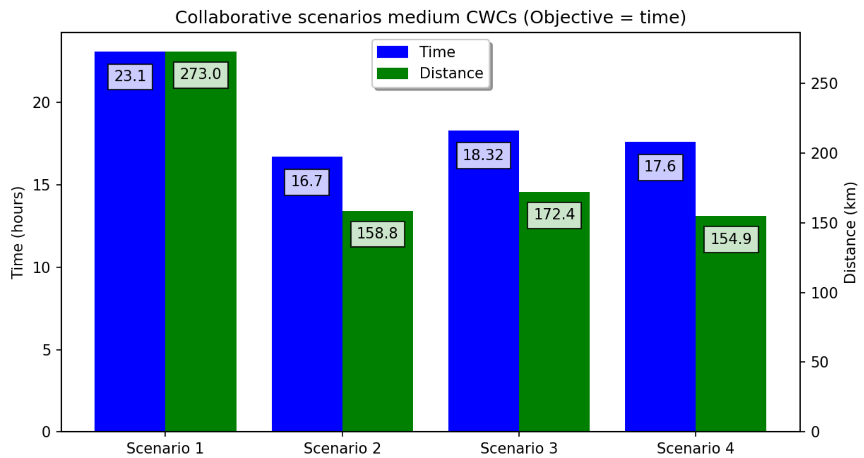


Figure 5.20: Results for the collaborations with objective = time. Scenario 1 (no collaboration), Scenario 2 (full collaboration, no constraints), Scenario 3 (client balancing), Scenario 4 (revenue balancing). Results shown are summed over the medium CWCs for Scenario 1,3 and 4.

Again, a significant decrease in combined distance and duration is shown. The results are also shown in Table 5.8. In case of scenario 2 (full collaboration), the total duration decreases with 23-28% and the distance drops with 42-45%. Like with the small CWCS, scenario 3 and 4 show similar reductions in time and distance.

Table 5.9 shows the combined KPIs of the collaborative scenarios. Note that even in scenario 2, there is no vehicle reduction, because it is not feasible to serve all clients in a day with less than 3 vehicles, unless shift time is significantly increased. Solving for time results in slightly lower costs compared to distance.

Table 5.8: Time/distance statistics of the scenarios

		Objective: distance		Objective: time	
		Time (hour)	Distance (km)	Time (hour)	Distance (km)
Scenario 1	**Total**	23.84	246.401	23.05	273.0
Scenario 2	**Total**	18.46	136.44	16.70	158.78
	Difference (%)	-22.6	-44.6	-27.5	-41.8
Scenario 3	**Total**	18.8	141.9	18.3	172.4
	Difference (%)	-21.1	-42.4	-20.5	-36.8
Scenario 4	**Total**	18.8	145.2	17.6	154.9
	Difference (%)	-21.0	-41.1	-23.6	-43.3

Table 5.9: KPIs of the different scenarios for the medium CWCs

		Scenario 1	Scenario 2		Scenario 3		Scenario 4	
		Total	Total	Diff. (%)	Total	Diff. (%)	Total	Diff. (%)
Objective: distance	**Vehicles**	3	3	0.0	3	0.0	3	0.0
	Costs (€)	1195	840	-29.7	861	-28.0	867	-27.5
	Costs/client (€)	4.10	2.89	-29.6	2.96	-27.9	2.98	-27.4
	Clients/hour	12.24	15.76	+29	15.47	+26	15.45	+26
	Clients/km	1.19	2.13	+78.8	2.05	+72.0	2.00	+68.0
	$T_{service}/T_{total}$	0.42	0.55	+32.6	0.54	+29.9	0.54	+29.7
	Speed (km/h)	10.3	7.4	-28.3	7.5	-26.8	7.7	-25.2
	VUR (%)	90	68		69	0.0	69	0.0
Objective: time	**Vehicles**	3	3	0.0	3	0.0	3	0.0
	Costs (€)	1195	816	-31.8	892	-25.4	840	-29.7
	Costs/client (€)	4.15	2.80	-32.5	3.06	-26.2	2.89	-30.5
	Clients/hour	12.65	17.43	+37.8	15.88	+25.6	16.53	+30.7
	Clients/km	1.08	1.83	+69.3	1.69	+55.9	1.88	+73.6
	$T_{service}/T_{total}$	0.43	0.59	+36.9	0.56	+29.5	0.56	+29.2
	Speed (km/h)	11.8	9.5	-19.3	9.4	-20.1	8.8	-25.3
	VUR (%)	87	63		67		67	

5.5.2. Individual results

The cost savings for the individual CWS are displayed in Table 5.10. Although in this case the costs per client have decreased for each CWC in the collaboration, there are large differences in cost savings. CWC M3 gains only small benefits from the collaboration and saves 10.7% costs per client in scenario 3 and only 3.8% in scenario 4. This can be attributed to the fact that the route length of CWC M3 in the collaborative scenarios is very long. Since CWC M3 starts at the south of the study area, it handles most of the clients of the southern part of the city. These clients are spread out and require a long route to service.

Table 5.10: Cost per client for all scenarios (objective = distance)

		CWC M1	CWC M2	CWC M3
Scenario 1	**Costs/client (€)**	3.91	4.48	3.93
Scenario 3	**Costs/client (€)**	2.10	3.36	3.51
	Difference (%)	-46.4	-25.0	-10.7
	Clients serviced	103	98	90
Scenario 4	**Costs/client (€)**	2.14	3.08	3.78
	Difference (%)	-45.3	-31.2	-3.8
	Clients serviced	102	94	95

5.6. Collaborative scenarios: large waste collectors

Lastly, the results are shown for collaboration between the large CWCs. Unfortunately, implementing the balancing constraints over multiple vehicles did not work, since the soft constraint used in OR-tools can only be implemented on individual vehicles. When using a hard constraint instead, this did not produce feasible solutions. The hard constraint is likely to severely restrict the solver in finding solutions.

Because no constraint could be implemented to simulate scenario 3 and 4, only collaborative scenario 2 is simulated. The results are shown in Figure 5.21 and Figure 5.22.

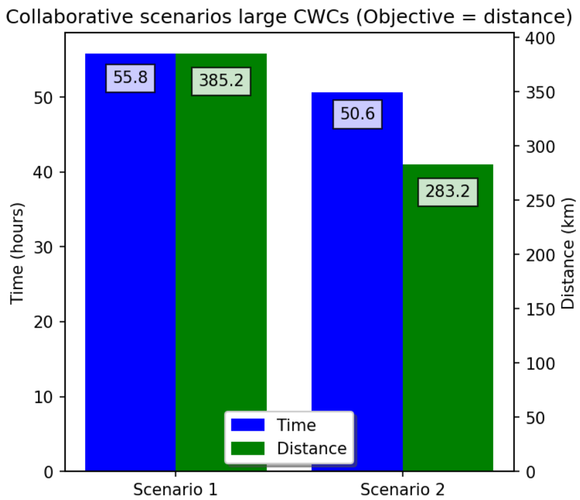


Figure 5.21: Results for the collaborations with objective = distance. Scenario 1 (no collaboration), Scenario 2 (full collaboration).

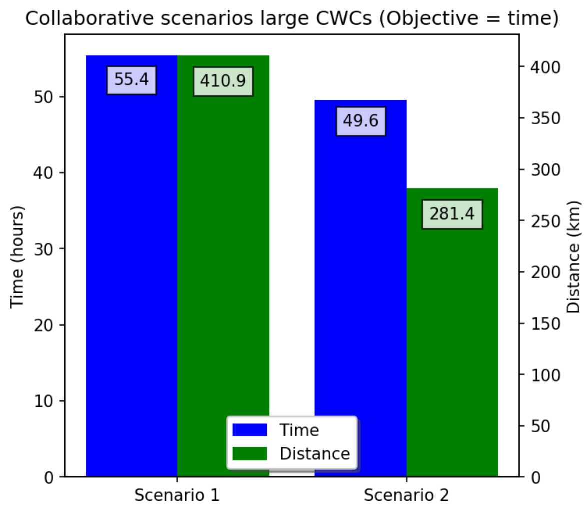


Figure 5.22: Results for the collaborations with objective = time. Scenario 1 (no collaboration), Scenario 2 (full collaboration).

For the large CWCs, the reduction in distance ranges from 27-32% and the reduction in time ranges from 9-11% (see Table 5.11). The collaboration also allows for two vehicles to be dropped, resulting in the usage of six vehicles.

Table 5.11: Time/distance statistics of collaboration between the large CWCs

		Objective: distance		Objective: time	
		Time (hour)	Distance (km)	Time (hour)	Distance (km)
Scenario 1	**Total**	55.8	385.2	55.4	410.9
Scenario 2	**Total**	50.6	283.2	49.6	281.4
	Difference (%)	-9.4	-26.5	-10.5	-31.5

When solving for time, the solver produces a result in which the route distance is shorter than when solved for distance. It is likely that the solver was stuck in a local minimum when solving for distance and was not able to escape. When comparing the routes in (Appendix A, Figure A.33 and A.34), the solution for time minimization also appears slightly more clustered, indicating a better solution. The solution for distance minimization features many vehicles using the same bridge in the middle of the study area, and some overlapping routes at the north-west direction. More computational time would likely enhance the solvers ability to escape the local minimum and find better solutions for the distance objective.

The KPIs of scenario 1 and 2 for the large CWCs are shown in Table 5.12. The KPIs in scenario 2 show the highest efficiency out of all collaborations due to the benefit of scale. However, the relative difference between no collaboration and collaboration is the smallest compared with the small and medium CWCs. When solving for time, the cost decrease for the CWCs is larger than when solving for distance.

Table 5.12: KPI of the different scenarios for the medium CWCs

		Scenario 1	Scenario 2	
		Total	Total	Diff. (%)
Objective: distance	**Vehicles**	8	6	-25.0
	Costs (€)	2499	2161	-13.5
	Costs/client (€)	2.48	2.15	-13.2
	Clients/hour	18.06	19.85	+10
	Clients/km	2.62	3.54	+35.5
	$T_{service}/T_{total}$	0.61	0.67	+11.0
	Speed (km/h)	6.9	5.6	-18.8
	VUR (%)	80	96	
Objective: time	**Vehicles**	8	6	-25.0
	Costs (€)	2525	2125	-15.8
	Costs/client (€)	2.50	2.12	-15.5
	Clients/hour	18.19	20.25	+11
	Clients/km	2.46	3.57	+45.1
	$T_{service}/T_{total}$	0.61	0.69	+12.5
	Speed (km/h)	7.4	5.7	-23.5
	VUR (%)	80	94	

5.7. Discussion of the results

In this section, the results are discussed in more detail. Section 5.7.1 discusses the individual CWCs, section 5.7.2 discusses the benefits of collaboration and section 5.7.5 discusses the visual atractiveness of the routes.

5.7.1. Performance of individual CWCs

The results for the routes of individual CWCs without collaboration are mostly trivial. Useful information on the efficiency of individual CWCs can be extracted from the KPIs. All KPIs show how larger CWCs operate more efficiently: the cost per client is the smallest, and large CWCs serve the most clients per hour and kilometer. Another indicator of their efficiency is the $T_{service}/T_{total}$. The time spent driving from client a to client b should be minimized, since the goal is the collection of waste. Larger CWCs operate on a larger scale and have a high client density. This results in a $T_{service}/T_{total}$ ratio of 0.6, which means that employees spend more time emptying containers than driving. Due to this fact, the average speed of larger CWCs is the lowest.

The vehicle utilization ratio can serve as an indicator of efficiency in some cases, but should be approached with care. A large VUR may indicate that vehicles are efficiently utilized, but may also indicate that the routes are inefficient, resulting in more vehicle usage than required. The VUR of small CWCs is the lowest, because they end their shift after $\sim$ 5 hours, utilizing only 5 out of 8 hours available for a vehicle. The medium CWCs use >80%, because they use one vehicle for more clients. The large CWCs feature one truck with a relatively short shift, because 3 vehicles are not sufficient to serve all daily clients. This results in a relatively low VUR.

For the large CWCs, optimizing for time/distance produces similar results for route duration. Due to the large number of clients in the city, highway use is minimal since it will not give any advantages in terms of route duration. Secondly, the CWCs already operate at a high efficiency level, resulting in a $T_{service}/T_{total}$ ratio of 0.61. This means that a relatively small part of a route is spent actually driving, and a significant part of the route can be linked to servicing clients and the usual break. Therefore, optimizing for time will not have great impact on the total duration of daily collection.

5.7.2. Benefits of collaboration and impact of constraints

In all CWC size categories, collaboration offers significant benefits over individual operation. Figure 5.23 shows the decrease in traveled kilometers and cost of scenario 2 with respect to scenario 1 for all collaboration categories (small, medium and large).

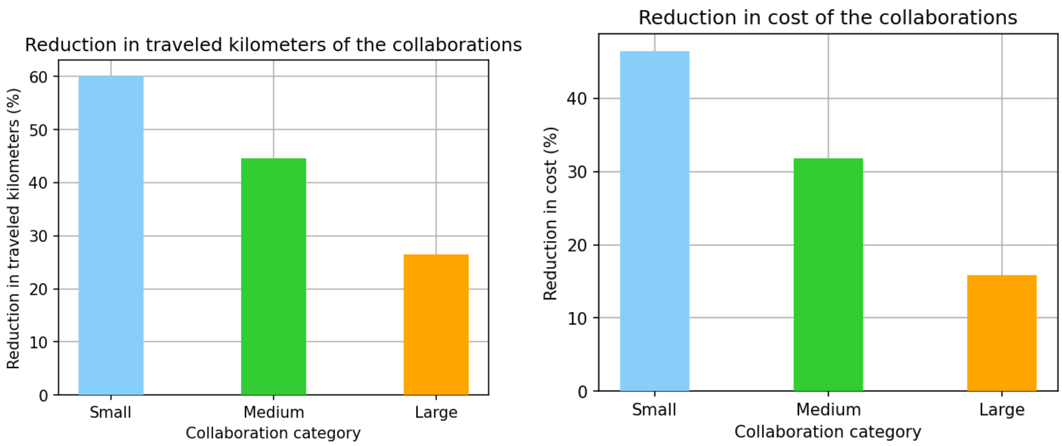


Figure 5.23: Savings in traveled kilometers (left) and cost (right). Data is the percentage decrease of scenario 2 (full collaboration) with respect to scenario 1 (no collaboration)

The reduction in traveled distance is 60%, 45% and 27% for the small, medium and large collaborative partnership, respectively. The reduction in cost is 47%, 30% and 14%, respectively. The benefits are most clearly present in the collaboration of the small CWCs. Since the small CWCs operate relatively inefficient (see section 5.7.1), they will profit the most from collaboration. This provides not only a decrease in traveled kilometers and hours of work time, but also frees up vehicles. In some cases, like the collaboration between medium CWCs, there is no decrease in the number of vehicles used, because serving all clients with 3 vehicles is still not feasible even in a collaboration. The potential benefits of collaboration are therefore very much related to the characteristics of the joining parties, and their operational efficiency.

As shown in the results it appears that imposing constraints in the form of scenario 3 (fixed number of clients) or scenario 4 (fixed revenue) slightly decreases solution quality and results in a higher distance and time compared to collaboration without constraints. This makes sense, since the solution space is decreased by the constraints. However, the resulting solutions are still very acceptable. Therefore, given appropriate scale of the problem, imposing constraints is possible without (significantly) sacrificing the solution. However, since this will not decrease the number of vehicles used, this may not be the right approach in some cases.

Because all CWCs have roughly the same container size distribution in their client base, revenue is very much related to the number of clients serviced. This is reflected by the individual results in the small and medium collaborations (Figure 5.7 and 5.10). Smaller number of daily clients will likely cause more pronounced differences between CWCs and reduce the link between revenue and number of clients serviced.

An important note is that it is best to avoid constraints altogether. Although the constraints used in this study may give a CWC the same number of clients or the same amount of revenue compared with the situation prior to collaboration, the costs may not be fairly distributed among individual CWCs as shown in the individual results. Therefore, there still need to exist mechanisms to equally share the benefits of collaboration among its participants. Although technically, the individual CWCs can be balanced based on cost in a collaboration, this will severely decrease solution space and produce less feasible solutions. Balancing based on cost will also result in technical difficulties; CWCs entering a collaboration may have different costs and therefore cost balancing would still not be fair.

When reviewing the benefits of all collaborations, the distance is decreased from 943 daily kilometers to 544 daily kilometers, resulting in a 58% decrease. Table 5.13 shows how each CWC contributes to the traveled distance.

Table 5.13: Daily distance traveled by all CWCs

	Percentage of total daily clients	**Combined distance traveled (km)**	**Percentage of total daily distance**
Small CWCs	16.2	311	33.0
Medium CWCs	18.8	246	26.1
Large CWCs	65.0	385	40.8
Total	100	943	100

Although small waste collectors serve only 16.2% of total daily clients, the daily distance traveled is 33% of the total. Therefore, the impact of collaboration for small waste collectors should not be underestimated.

5.7.3. Comparison with experience from the Green Collective collaboration

The results of the large waste collectors have been compared with real-world results from Green Collective, which has expanded its operational area to the study area used in this study as of January first, 2025. The size of the collectors expected to be roughly similar to the two main parties of the Green Collective in Rotterdam: PreZero and Renewi. A representative found the model used by this study to be accurate. Although specific efficiency numbers can not shared in this report due to it being confidential information, the decrease in the number of trucks from 8-6 and the decrease in traveled kilometers of 27.5 % are found to be reasonable, although the benefits of collaboration in the model used by this study are a bit conservative. This may be caused by the fact that the collaboration between the large waste collectors in this study does not completely reflect the situation of Green Collective, since Green Collective features one more smaller partner (the MoR) and features a depot in the study area, both contributing to a higher efficiency. In addition, the problem solved by the model features 1008 nodes, which requires a lot of computing time to solve. A longer solve time would likely increase the solution. Finally, although the client distribution in the model used by this study is deemed accurate, it will be different from the real client distribution which could also impact results.

5.7.4. Client distribution and collaborative benefits

The distribution of clients (see Figure 2.1) plays a role in the benefits of collaboration. If clients are clustered and there is few overlap between the operational areas of CWCs, collaboration between CWCs will likely increase vehicle utilization, but not decrease distance or duration of routes. However, a clustered client group for every CWC is not realistic and would indicate that there already is collaboration/coordination between CWCs.

Commercial waste collection in Rotterdam features many overlapping clients from several CWCs. This is caused by the fact that shops and stores are often clustered in the form of shopping centers and shopping streets. This contributes to the potential benefits of collaboration. Less overlapping clients would result in less benefits when joining collaboration.

5.7.5. Visual attractiveness of routes

OR-tools generally forms 'clustered' routes without intersections. However, sometimes it produces results with some intersections of routes. An example is shown in Figure 5.24. The figures are also shown in Appendix A (see Figure A.27 and A.28). The routes in the left figure intersect partially, while the routes in the right figure are more clustered.

Figure 5.24: Different route formations: the right figure features more clustered routes, while in the left figure, some routes intersect

Although visually attractive route formations are often interpreted by humans as more optimal, it is not generally true that solutions with a high visual attractiveness are objectively better solutions [50]. Of course, intersection within a single route (which is basically a traveling salesman problem) does indicate non-optimality. However, intersection between routes in a VRP may still yield an optimal solution. In real operations however, it is preferred to avoid intersections and assign a specific area per driver. This avoids trucks traveling through the same streets multiple times, and allows for a driver to gain experience in his own part of the city and thus increase his efficiency.

5.7.6. Translation of results to other forms of collaboration

In this study, collaborative partnerships between partners with market shares of the same size have been modeled. The reasoning for this is that it reflects the two partnerships in Rotterdam, Green Collective and OpenWaste. These partnerships also feature CWCs with comparable market shares. Smaller waste collectors are hesitant to join forces with large waste collectors out of fear of losing control over their own operations.

The benefit of the simulated partnerships is that it shows how collaborative benefits are strongly related to the market shares of CWCs. CWCs with a smaller market share operate less efficient and benefit more from collaboration than larger waste collectors. When reviewing the results, it is likely that large waste collectors have enough 'slack' to completely take over daily clients of a small waste collector without adding vehicles to its fleet.

The collaboration between the large waste collectors has a large benefit of scale. Therefore KPIs like the number of clients serviced per hour will not increase much more when considering greater scale problems (e.g. larger collaborative partnerships). In case of a single, consolidated commercial waste collection in the study area, is therefore expected that KPIs will be only slightly better than those of the collaboration between the large waste collectors.

6 Conclusions and recommendations

This chapter presents the main conclusions of the research carried out. In Section 6.1, the research questions are addressed. In Section 6.2, suggestions are discussed to improve the accuracy of the model. Finally, Section 6.3 discusses recommendations for future research and the adaptability of the model.

6.1. Research questions revisited

How can the commercial waste collection process for residual waste be modeled and potential benefits of collaboration between waste collectors quantitatively be assessed?

- **What is the state-of-the-art in literature regarding waste collection in urban environments and collaboration in logistic environments, specifically waste collection?**
  Although waste collection is a subject that has been researched by many studies, the combination of collaboration in a waste collection context has been less studied. Specifically, the use of a real-life study case with realistic, non-Euclidean distances and a large scale problem is a niche. This study has filled the gap by simulating collaboration in commercial waste collection by means of a realistic, large scale study case on a real life street network.
- **What is the current situation regarding commercial waste collection in the city of Rotterdam?**
  Commercial waste collection in Rotterdam is performed by many individual waste collectors and involves many different waste segments, with some waste collectors specializing in certain waste segments. The collection of commercial waste is performed by about 10 waste collectors. A significant market share is covered by two parties. In addition, there are smaller waste collectors active in the city. Clients of these collectors are spread over the city and there are no specific 'districts' per waste collector. There are two known collaborative partnerships for commercial waste collection, OpenWaste and Green Collective. However, their operational area is relatively limited and there is little publicly known available information on the quantitative benefits of collaboration in commercial waste collection.
- **How to approach the modeling of collaborative commercial waste collection based on available data?**
  To model the collection of residual commercial waste in an urban environment, Python is used in combination with two packages: OSMnx and OR-tools. OSMnx is used for retrieving and visualizing geospatial features such as street networks, pickup locations and routes. OR-tools is used to solve the vehicle routing problem associated with commercial waste collection. Input data such as container distribution, service times and average weight is based on real data from a commercial waste collector in Rotterdam.

- **Which relevant waste collection collaborative scenarios can be simulated and how do they perform compared to the current situation?**
  Three partnerships of waste collectors have been simulated, ranging from a group of 5 small waste collectors (50 daily clients per waste collector), three medium-sizes waste collectors (100 daily clients per waste collector) and two large waste collectors (500 daily clients per waste collector). Full collaboration has been studied, and two additional collaborative scenarios have been studied in which constraints are imposed. All collaborative scenarios provided significant advantages and resulted in a decrease in traveled distance and work hours. Full collaboration produced a reduction in traveled distance of respectively 60%, 45% and 27% for the small, medium and large collaborative partnership, respectively. The reduction in cost is 47%, 30% and 14%, respectively. Imposing constraints to collaborations may still result in good solutions. However, profit sharing mechanisms will still be required to fairly allocate the benefits resulting from collaboration.

6.2. Potential for model improvement

In rare cases, the shift-time constraint is slightly violated by the solver. When solving for distance, the VRP uses the distance matrix as input for a vehicle's arc cost, which is consequently used by the objective function to minimize total distance. Parallel to this, the solver is also keeping track of the accumulating time due to the shift-time constraint. This is done with the time matrix. For VRPs with Euclidean distance between nodes, this does not pose a problem. However, for nodes located in a street network, finding a route from node A to node B based on time or distance will sometimes result in different routes. When using the time matrix to keep track of time when solving for distance, this will result in a shorter route duration than in reality. Although both distance and duration variables are outputs of the solver, due to this inaccuracy, only the variable that is used in the objective function is used. The other output is calculated by selecting the appropriate edge weight and using the approach as discussed in 3. This results in a route duration that sometimes slightly violates the shift-time constraint. However, since the overshoot is small and might occur similarly in real-life operations, this is considered a minor inaccuracy.

There is no restriction that prevents vehicles turning on undirected edges. This results in vehicles sometimes making a 'u-turn' on a road. Although this might also sometimes happen in reality (on intersections, empty roads or dead ends), it is generally not allowed/possible to do this on busy or small streets. The impact on overall route length/duration is considered small since this does not happen very frequently.

As mentioned in chapter 4, the driving speed (and consequently, travel time) on edges is based on Google Maps data with average traffic density. Ideally, travel time should depend on the time of day, since there is rush hour traffic at the morning and evening. Since the travel time matrix is static in itself, a possible approach for this could be to multiply the time matrix by a constant which depends on time of day. However, it is not known whether OR-tools supports this, and what the impact would be on performance since an extra calculation is required to be made. A second challenge with this approach is that OR-tools only supports integer values as input. Therefore, this multiplication would also have to be rounded to integers.

To reduce computational time of large scale problems in OR-tools (500+ nodes), clustering may be useful. This will also prevent overlapping routes, and result in a greater visual attractiveness. For large-scale problems, it might give better results for the same computational time, since the problem scale is reduced. However, clustering may be a difficult task due to the capacity and time constraints, especially when considering clustering with soft boundaries.

6.3. Recommendations and directions for future research

As with any model, this model would benefit from more accurate input data and model improvements. Below, some recommendations are made to improve accuracy of the model.

- **More data from other waste collectors**
  Because the data in this study was provided by a relatively large waste collector, it would be appropriate to study the operations of other (smaller) waste collectors. This way, more accurate data can be obtained about containers used, service times per container, client distributions, operational procedures and depot locations.
- **Other VRP solvers**
  While Google OR-tools was used in this study, PyVRP could potentially be a good candidate, given it is still in development and new features are still being implemented. Since PyVRP performs better in benchmarks than OR-tools, it might provide useful advantages in solution quality or computational time.
- **Vehicle properties**
  This study used homogeneous vehicles. Future research could study what the effect would be of collaborations between waste collectors with heterogeneous fleets.
- **Service time based on client properties**
  The service time in this study is directly related to container size. There has been few research on how to approach accurately modeling service times. Especially for smaller scale problems, service time should be approached more detailed and be based on proximity to other containers.
- **Soft boundary clustering**
  The implementation of soft boundary clustering will reduce the required computational time by splitting the VRP into multiple smaller VRPs. The soft boundary will allow vehicles to visit clients of neighboring clusters if this improves the solution. However, more research is needed on how to integrate this clustering technique in VRP solvers.
- **Indicators of the potential of collaboration**
  The previous chapter discussed how client overlap impacts collaborative benefits. The overlap of clients and individual operational efficiencies of waste collectors in a collaboration are important indicators as to how collaboration will perform. It should be studied how client overlap, carrier efficiency and scale of the studied problem impacts collaborative benefits.

The model presented in this study can be adapted for use in other forms of waste collections, such as glass, paper or other waste segments. However, it is important that the model is adapted appropriately. As previously mentioned, return trips are omitted in this study since they are considered an anomaly in average operations. However, with high-density materials like glass, or large-volume materials, return trips may be necessary provided enough clients due to volume or weight constraints of the vehicles. OR-tools does support return-trips using virtual depots, which are nodes at the same location as the start depot. These virtual nodes are assigned a demand equal to the negative capacity of a truck, and can be dropped from the route at no cost. This allows for disposing waste and multi-trip functionality. Therefore, if required, multi-trip can be implemented in further research. Finally, the model in this study can potentially be integrated in MASS-GT and provide a more detailed logistics model for waste collection in the city of Rotterdam or on a greater scale. However, more research is required to reduce computational time to more acceptable standards. While the distance matrix and time matrix can be precomputed, the VRP solver still needs computational time to find routes, which can increase significantly with larger problems.

6.3.1. Recommendations for policy makers

This study has clearly indicated the quantitative benefits of collaboration between waste collectors in the commercial waste collection market. Collaboration will not only result in cost savings for the waste collectors, but will also significantly reduce traffic in the city due to the reduced logistical kilometers and the reduction in vehicles. Collaboration should therefore be stimulated and encouraged. Stimulating collaboration could also be done in other forms of logistics if collaborative benefits are expected (see Section 5.7 for indicators of potential collaborative benefits).

In case CWCs want to keep serving the same number of clients in a collaboration (scenario 3), a platform should be created to only share the relevant data of daily clients/orders (like time and location) without sharing sensitive data. This platform will then calculate the most efficient routes and returns these daily routes to individual waste collectors. Preferably, a neutral third party should be responsible for this platform. This construction will make collaboration more accessible and does not require a CWC to share sensitive data with other CWCs.

Theoretically, a joint collection could be set up, combining domestic waste and commercial waste collection. Domestic waste is distinctive in the fact that it mostly uses underground containers with sensors. Therefore, it should be investigated whether combining rolling containers with underground containers in a single route is beneficial. An alternative is to have two separate fleets: one for the underground containers, and one for the rolling containers. Incorporating rolling containers from the domestic waste sector into collection routes for commercial waste should be feasible, since they can both be emptied by the same truck. However, since the scope of this study is limited to commercial waste collection, there is limited information about the location and distribution of these rolling containers for domestic waste.

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A

Routes

A.1. Routes individual CWCs

Figure A.1: Route data of CWC S1 (objective = distance)

Figure A.2: Route data of CWC S1 (objective = time)

Figure A.3: Route data of CWC S2 (objective = distance)

Figure A.4: Route data of CWC S2 (objective = time)

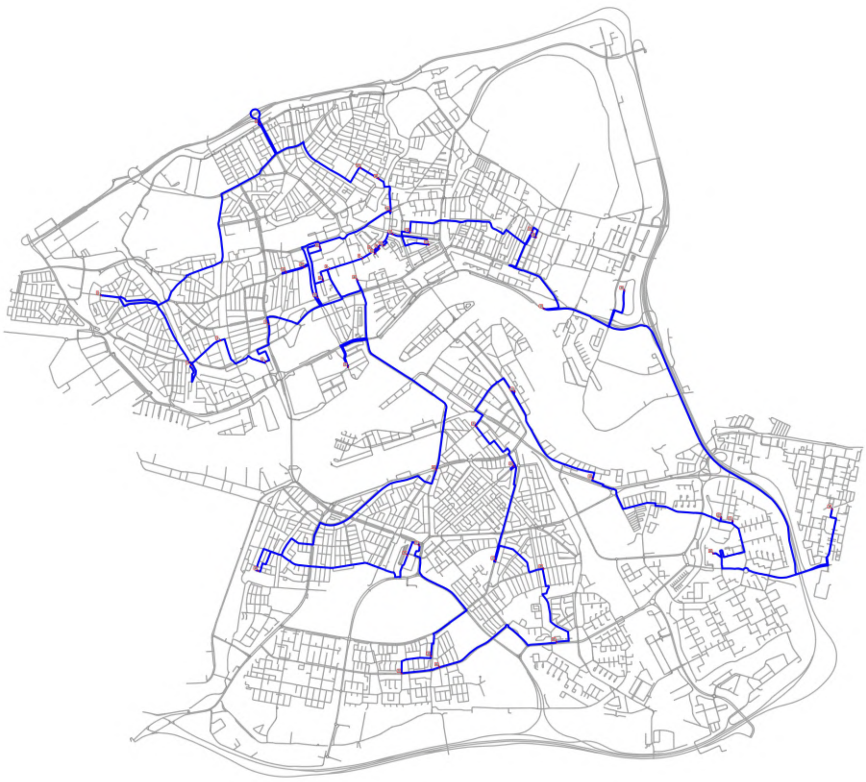

Figure A.5: Route data of CWC S3 (objective = distance)

Figure A.6: Route data of CWC S3 (objective = time)

Figure A.7: Route data of CWC S4 (objective = distance)

Figure A.8: Route data of CWC S4 (objective = time)

Figure A.9: Route data of CWC S5 (objective = distance)

Figure A.10: Route data of CWC S5 (objective = time)

Figure A.11: Route data of CWC M1 (objective = distance)

Figure A.12: Route data of CWC M1 (objective = time)

Figure A.13: Route data of CWC M2 (objective = distance)

Figure A.14: Route data of CWC M2 (objective = time)

Figure A.15: Route data of CWC M3 (objective = distance)

Figure A.16: Route data of CWC M3 (objective = time)

Figure A.17: Route data of CWC 1L (objective = distance)

Figure A.18: Route data of CWC 1L (objective = time)

Figure A.19: Route data of CWC 2L (objective = distance)

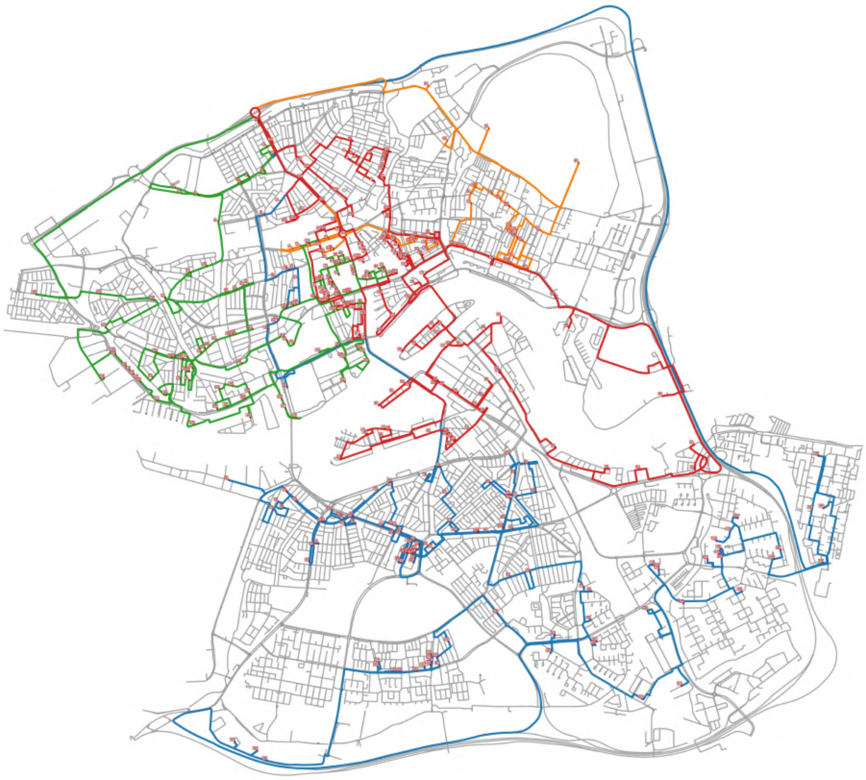

Figure A.20: Route data of CWC 2L (objective = time)

A.2. Routes collaboration small CWCs

Figure A.21: Route data of Scenario 2 (objective = distance)

Figure A.22: Route data of Scenario 2 (objective = time)

Figure A.23: Route data of Scenario 3 (objective = distance)

Figure A.24: Route data of Scenario 3 (objective = time)

Figure A.25: Route data of Scenario 4 (objective = distance)

Figure A.26: Route data of Scenario 4 (objective = time)

A.3. Routes collaboration medium CWCs

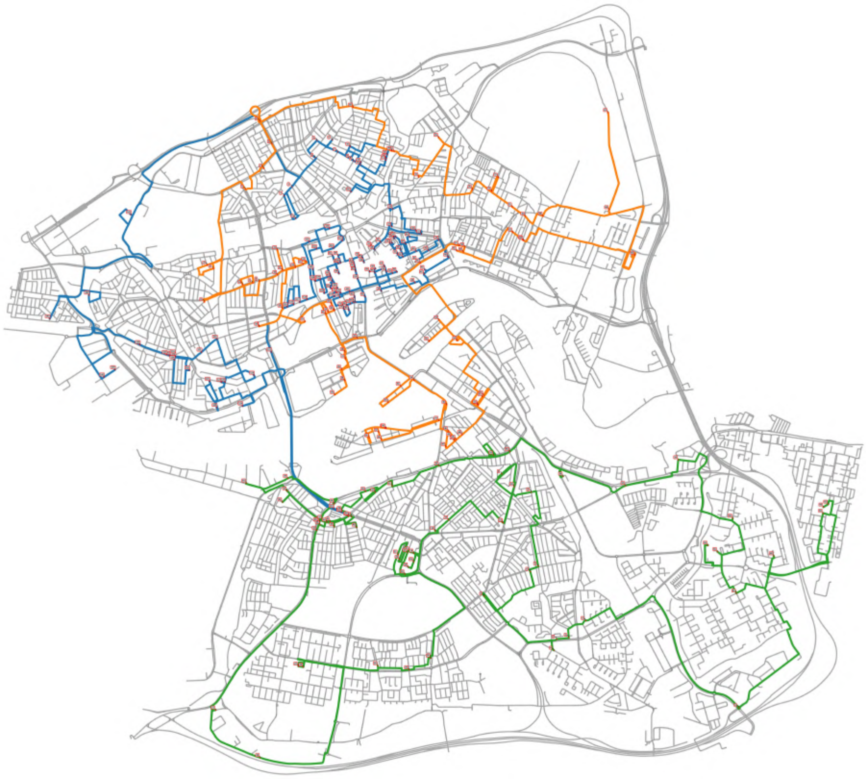

Figure A.27: Route data of Scenario 2 (objective = distance)

Figure A.28: Route data of Scenario 2 (objective = time)

Figure A.29: Route data of Scenario 3 (objective = distance)

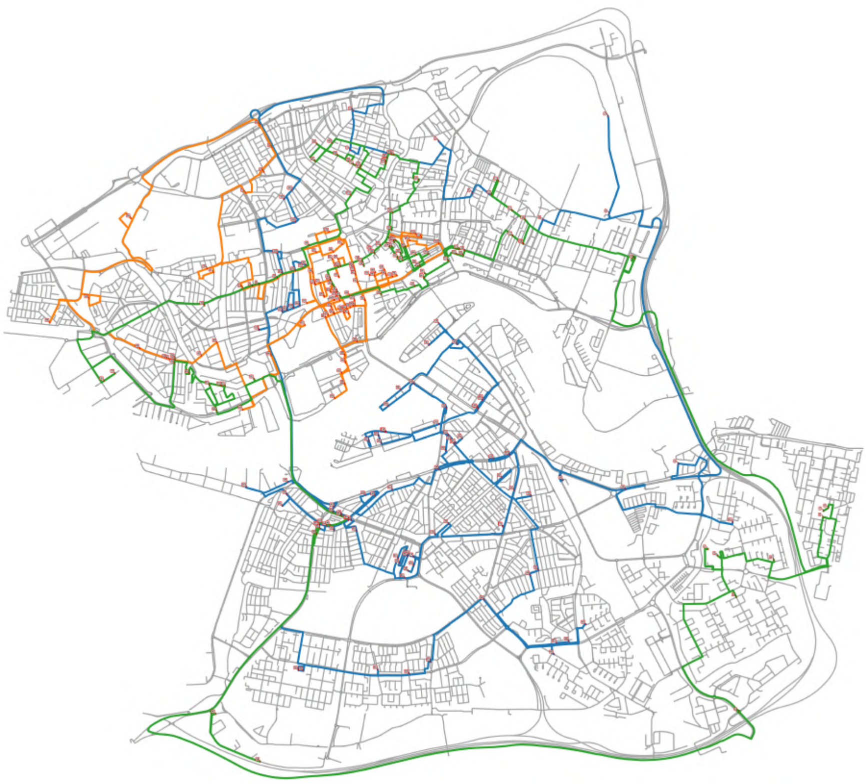

Figure A.30: Route data of Scenario 3 (objective = time)

Figure A.31: Route data of Scenario 4 (objective = distance)

Figure A.32: Route data of Scenario 4 (objective = time)

A.4. Routes collaboration large CWCs

Figure A.33: Route data of Scenario 2 (objective = distance)

Figure A.34: Route data of Scenario 2 (objective = time)

B

Figures and tables

Table B.1: Business distribution in the Centrum district [14]

Suburb	**Number of registered businesses**	**Percentage**
Stadsdriehoek	2130	39.0
CS-kwartier	615	11.2
Cool	1224	22.4
Oude Westen	535	9.8
Dijkzigt	132	2.4
Nieuwe Werk	831	15.2
Total	5467	100

C

Paper

Consolidation of commercial waste collection: A case study of the urban area of the Municipality of Rotterdam

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Commercial waste collection in Dutch cities is a free market in which many waste collectors operate independently. Collaboration among waste collectors is a relatively recent phenomenon that is still in its infancy. This study develops a Python-based simulation model using OSMnx and Google OR-tools to assess the potential benefits of collaboration in waste collection in Rotterdam. Four collaborative scenarios are simulated, three of them in a collaborative setting. Results show that collaboration can significantly reduce the distance traveled by vehicles and the costs for waste collectors, with smaller waste collectors benefiting the most. While full collaboration offers the greatest efficiency gains, even constrained partnerships improve operations. These findings highlight the potential for collaboration to enhance urban logistics and sustainability.

I. Nomenclature

CWC	=	Commercial Waste Collector
VRP	=	Vehicle Routing Problem
MoR	=	Municipality of Rotterdam
OSM	=	OpenStreetMap

II. Introduction

Many cities in The Netherlands are expected to continue growing the coming decade. This growth puts increasing strain on city logistics. Traffic caused by logistics is expected to grow by 19% by 2035 due to an increase of parcel delivery, construction and other logistic streams [1]. One of the logistical streams is the waste collection process. This process consists of trucks navigating through the city to collect waste from containers and transport the waste to depots. In Dutch municipalities, commercial waste generated by the the office, retail and service sector is often collected by private waste collection services. The Municipality of Rotterdam has the ambition to create a realistic tool for the simulation of urban freight transport at city level and is looking to improve the way in which waste from companies is simulated, using local information. Specifically, it is relevant to assess the impact of collaborations between waste collectors to determine how the implementation of such partnerships impact efficiency of the commercial waste collection process. The goal of this research is to develop and implement a simulation model for commercial waste collection, focusing specifically on the simulation of collaboration between waste collectors and quantifying the benefits of these partnerships. This research will therefore answer the following research question:

How can the commercial waste collection process for residual waste be modeled and potential benefits of collaboration between waste collectors quantitatively be assessed?

III. Methodology

IV. Literature review and state of the art

A. Literature review

The waste collection problem can be defined as a reverse logistics problem [2]. In a regular logistics problem, goods are transported from depots to clients with vehicles. In reverse logistics problems, the flow of products is reversed. In the case of waste collection, the products (waste) are generated by the client and collected by the transporter. There is extensive literature on waste collection. Most studies on waste collection focus on optimization by improving routes or minimizing the number of vehicles used [2]. Various studies focus on developing heuristic algorithms for the WCVRP [3][4][5]. The approach most often used in literature to model the waste collection process, is to define waste collection as a Vehicle Routing Problem (VRP) [6].

Collaboration in vehicle routing can significantly reduce costs, according to many studies [7]. Collaboration has the potential to mitigate transportation costs [8] mainly because the distance and duration of routes can be reduced. [9] has also shown that horizontal collaboration can significantly reduce emissions.

In an analysis of various works from literature, [10] found collaborative benefits from order sharing range between 13 and 30%. In a study on the collaborative CVRP, [11] found cost savings of 21 and 49.6% for an asymmetric and symmetric CVRP, respectively.

In a survey on workload equity in VRPs, [12] has analyzed studies on the workload, reviewing variations of workload balance. These studies do not include workload balance in collaborative scenarios. The literature works above consider workload balance between different vehicles. Sometimes balance is considered over an extended planning horizon, allowing for imbalance in a given interval in that period [13] [14]. Mancini et al. [14] introduced workload balance and consistency in a collaborative scenario. Dropping (combinations of) constraints was found to only slightly impact solution quality. Therefore, in the studied case, workload balance could be implemented without a significant decrease of the solution with respect to the optimal solution (collaboration without balance constraints).

Not much is known in the academic field about collaborative benefits in waste collection, however, collaboration pilots in The Netherlands showed the potential to significantly decrease the required number of trips, up to 53% .

Although waste collection has been the subject of various studies, mainly using VRP optimization models, there is little research on the topic of collaboration within a waste collection context [15]. Many studies use Euclidean distance instead of real-world routes. Although the VRP might be solved with reasonable performance, calculated route distances are unlikely to be accurate [16]. In addition most research handles relatively small data sets [6][16]. Furthermore, [17] notes that although multi-depot has been often studied, application within a waste collection context is rare.

In conclusion, there is a gap in research that focuses on the quantitative performance of collaborative frameworks within a large-scale waste collection context.

V. Modeling and data collection

The simulation model is implemented in Python, and uses the Python packages OSMnx and Google OR-tools. OSMnx is an open-source Python package that can be used to download and process street network data from Open Street Maps (OSM) [18]. OR-tools is an open-source combinatorial optimization package specialized in VRP modeling [19]. A conceptual illustration of the input and output of the VRP solver is shown in Figure 1.

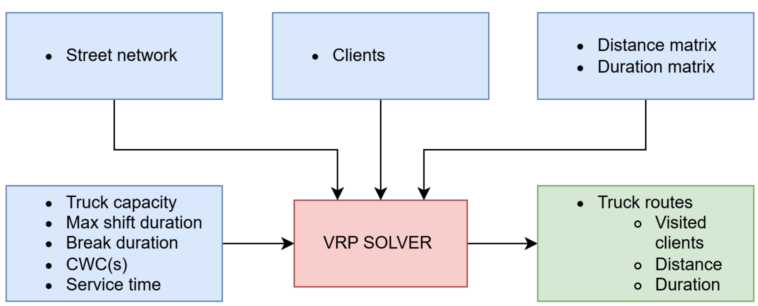


Fig. 1 VRP solver input and output

OR-tools has a dedicated RoutingModel specifically designed for VRPs in which trivial VRP constraints such as ensuring that all nodes are visited only once are already implemented by default. Therefore, they are not listed here. To make the VRP model suitable for this study, several constraints are added. The mathematical formulation is as follows.

The binary variable $\boldsymbol{x_{ijk}}$ has a value of **1** if the arc from node $\boldsymbol{i}$ to node $\boldsymbol{j}$ is in the optimal route and **0** zero otherwise. A vehicle is indicated as $\boldsymbol{k}$, and there are $\boldsymbol{p}$ vehicles.

$$x_{ijk} \in \{0, 1\} \quad \forall k \in \{1, \ldots, p\}, \quad i, j \in \{1, \ldots, n\}$$

The travel cost from node $\boldsymbol{i}$ to node $\boldsymbol{j}$ is defined as $\boldsymbol{c}_{ij}$.

The objective function can be formulated as follows:

$$\text{Minimize} \sum_{k=1}^{p} \sum_{i=1}^{n} \sum_{j=1}^{n} c_{ij} x_{ijk}$$

It describes that the sum of the added costs $\boldsymbol{c}_{ij}$ of all $\boldsymbol{p}$ vehicles should be minimized. The cost can be expressed in time $\boldsymbol{t}$ or distance $\boldsymbol{d}$. In this study, every VRP is solved for distance and time individually.

Capacity constraint
The total pickup $\boldsymbol{q}_j$ of the nodes served by a vehicle $\boldsymbol{k}$ should be equal to or less than its capacity $\boldsymbol{Q}$.

$$\sum_{i=1}^{n} \sum_{j=1}^{n} q_j x_{ijk} \leq Q \quad \forall k \in \{1, \ldots, p\}$$

Time constraint
First, the allowed time of a route is defined. The allowed time is equal to the shift time $\boldsymbol{T}_{shift}$, which is set at 8 hours:

$$T_{allowed} = T_{shift} = 8$$

The total duration $\boldsymbol{t}_k$ of a vehicles route consists of the sum of the travel time $\boldsymbol{tt}_{ij}$ from node $\boldsymbol{i}$ to node $\boldsymbol{j}$ plus the sum of the service time $\boldsymbol{ts}_i$ of the departure node $\boldsymbol{i}$:

$$t_k = \sum_{i=1}^{n} \sum_{j=1}^{n} tt_{ij} x_{ijk} + \sum_{i=1}^{n} ts_j x_{ijk} \quad \forall k \in \{1, \ldots, p\}$$

The total duration $\boldsymbol{t_k}$ of a route driven by a vehicle $\boldsymbol{k}$ should be equal to or less than the allowed time $\boldsymbol{T_{allowed}}$:

$$t_k \leq T_{allowed} \quad \forall k \in \{1, \ldots, p\}$$

Because realistic implementation of such breaks is unlikely to impact results in a significant way, if at all, they are added after the VRP has been solved and are not part of the objective function. If the route of a truck exceeds 4.5 hours, a 45 minute break (0.75 hours) is added to the total duration $\boldsymbol{k}$ of the respective route. Otherwise, the time of a route is equal to the time found by the solver.

$$T_{total} = \begin{cases} t_k & t_k < 4.5 \\ t_k + T_{break} & t_k \geq 4.5 \end{cases} \quad \forall k \in \{1, \ldots, p\}$$

Both break duration and shift duration are inputs to the solver (see Figure 1) and can be altered if necessary. $\boldsymbol{T}_{shift}$ and $\boldsymbol{T}_{break}$ are set at 8 hours and 45 minutes, respectively. The variables and parameters are listed in Tables 1 and 2.

Table 1 The variables of the CVRP model

Variables	
Symbol	**Definition**
x_{ijk}	Binary variable
c_{ij}	Cost of travel between client i and j (distance or time depending on objective)
q_i	Waste pickup of client i
tt_{ij}	Travel time between client i and j
ts_i	Service time of client i
t_k	Route duration of vehicle k
T_{total}	Total route duration of vehicle k

Table 2 The parameters of the CVRP model

Parameters		
Symbol	**Definition**	**Value**
Q	Capacity	11000 kg
T_{shift}	Shift duration	8 hours
T_{break}	Break duration	0.75 hours

There are 10 CWCs operating in the study area. Every CWC has its own market share: small (~ 50 daily clients), medium (~ 100 daily clients) and large (~ 500 daily clients). An overview of the CWCs is shown in Table 7 (see Appendix).

Using the OSMnx features module, 1550 clients are generated and attributed to CWCs according to Table 7. These clients are found by selecting office, shop and amenity tags. The resulting clients are uniformly decreased to 1550. Secondly, using OSMnx, a detailed street network of the study area is imported. The results are shown in Figure 2.

Fig. 2 Client distribution in the study case

Additional data is provided by a waste collector in Rotterdam. This data is comes from real-world operations and is used to complete the model. The data covers container size distributions among clients and weight and service time per container size. The collected data is summarized in Table 8 (see Appendix).

A distance matrix and travel time matrix is generated featuring distance and travel times between every client by means of the *shortest_path_length* algorithm from the NetworkX package. This results in realistic distance/time calculations.

VI. Application of the model and results

A. Scenarios

The proposed model is used to simulate the four scenarios. In the first scenario, there is no collaboration. Scenario 2, 3 and 4 are collaborative scenarios. The scenarios are defined as follows:

Scenario 1: No collaboration: All waste collectors will operate independently from each other. There is no collaboration or any form of sharing of clients.

Scenario 2: Full collaboration (no constraints): All clients of collaborating partners are fed into the solver, which solves for time or distance. No extra constraints or restrictions are imposed.

Scenario 3: Client balancing: Clients are shared between the CWCs. A new route is then constructed combining the client base for an improved solution (decreased total time/distance). To maintain self-sufficiency, the number of clients served by each CWC before and after implementation of the collaboration is required to be equal:

$$\sum_{i=1}^{n}\sum_{j=1}^{n} x1_{ijk} = \sum_{i=1}^{n}\sum_{j=1}^{n} x2_{ijk}$$

Like in Section V, $x1_{ijk}$ has a value of 1 if the arc from node i to node j is in the optimal route and 0 otherwise. In this equation, the subscript $_1$ denotes the case of no collaboration, and the subscript $_2$ denotes collaboration.

Scenario 4: Client sharing - revenue balancing: Clients are again shared between CWCs and new routes are generated. This time, the revenue of a CWC is required to be equal before and after implementation of the collaboration. The income generated by a CWCs client is related to its container size. The constraint is implemented similarly to the constraint from scenario 3.

Three groups of CWCs are formed, each group composed of CWCs with the same market share. The scenarios are then simulated for each separate group. All scenarios are simulated with two objectives: distance and time. The results are shown in the next section.

B. Results

First, the CWCs are simulated in case there is no collaboration. The results are shown in Table 3. The small and medium CWCs are able to serve all daily clients with one vehicle. The large CWCs require 4 vehicles to serve all their daily clients due to the large client base. The *VUR* is the vehicle utilization rate, indicating how much percentage vehicles are used with respect to full utilization (8 hours per vehicle, or a full shift). Useful information on the efficiency of individual CWCs can be extracted from the KPIs. All KPIs show how larger CWCs operate more efficiently: the cost per client is the smallest, and large CWCs serve the most clients per hour and kilometer. Another indicator of their efficiency is the $T_{service}/T_{total}$. The time spent driving from client a to client b should be minimized, since the goal is the collection of waste. Larger CWCs operate on a larger scale and have a high client density. This results in a $T_{service}/T_{total}$ ratio of 0.6, which means that employees spend more time emptying containers than driving. Due to this fact, the average speed of larger CWCs is the lowest.

Table 3 KPI's for all CWCs in case of no collaboration

	CWC	S1	S2	S3	S4	S5	M1	M2	M3	L1	L2
	Revenue (€)	509	632	501	574	533	1164	1047	977	5299	5392
Objective: distance	**Vehicles**	1	1	1	1	1	1	1	1	4	4
	Costs (€)	225	290	275	279	294	403	439	354	1251	1248
	Costs/client (€)	4.80	5.27	5.85	5.17	6.12	3.91	4.48	3.93	2.48	2.48
	Clients/hour	11.1	10.1	9.0	10.0	8.7	12.7	11.4	12.6	18.0	18.1
	Clients/km	0.90	0.82	0.76	0.88	0.70	1.27	1.04	1.28	2.62	2.61
	$T_{service}/T_{total}$	0.36	0.33	0.33	0.33	0.31	0.43	0.37	0.44	0.61	0.61
	Speed (km/h)	12.4	12.4	11.8	11.3	12.5	10.0	11.0	9.9	6.9	6.9
	VUR (%)	52.9	58.5	56.3	58.1	59.3	92.3	97.8	80.1	80.3	80.0
Objective: time	**Vehicles**	1	1	1	1	1	1	1	1	4	4
	Costs (€)	226	291	251	257	275	409	447	354	1247	1277
	Costs/client (€)	4.81	5.29	5.34	4.77	5.73	3.97	4.56	3.94	2.48	2.53
	Clients/hour	11.6	10.4	10.8	12.3	10.8	13.1	11.9	12.9	18.2	18.2
	Clients/km	0.83	0.78	0.71	0.78	0.60	1.14	0.91	1.20	2.58	2.34
	$T_{service}/T_{total}$	0.38	0.34	0.34	0.35	0.34	0.45	0.39	0.46	0.61	0.61
	Speed (km/h)	13.9	13.4	15.1	15.8	17.9	11.5	13.0	10.8	7.1	7.8
	VUR (%)	50.8	56.9	54.5	54.9	55.5	88.9	93.3	77.8	79.6	79.5

Tables 4, 5 and 6 show the results of the collaborations. The statistics of scenario 1 are summed over the CWCs. In all CWC size categories, collaboration offers significant benefits over individual operation. Figure 3 shows the decrease in traveled kilometers and cost of scenario 2 with respect to scenario 1 for all collaboration categories (small, medium and large). Scenario 3 and 4 are only simulated for the small and medium CWCs. Solving for time and distance produces different results, although there is not a large difference. This is because apart from the highway, there is no large difference in travel speed on the roads. Many roads feature clients along the way, forcing vehicles to visit regardless. Therefore, when there is a high client density, vehicles do not have a great variety of options to adjust their route, resulting in small differences between solving for time or distance.

Table 4 Time/distance statistics of the scenarios for the small CWCs

		Objective: distance		Objective: time	
		Time (hour)	**Distance (km)**	**Time (hour)**	**Distance (km)**
Scenario 1	**Total**	25.8	311.2	22.55	342.0
Scenario 2	**Total**	15.76	124.24	14.89	129.81
	Difference (%)	-38.9	-60.1	-34.0	-62.0
Scenario 3	**Total**	15.2	141.6	13.6	165.1
	Difference (%)	-41.0	-54.5	-39.6	-51.7
Scenario 4	**Total**	15.0	145.3	14.7	156.9
	Difference (%)	-41.7	-53.3	-34.8	-54.1

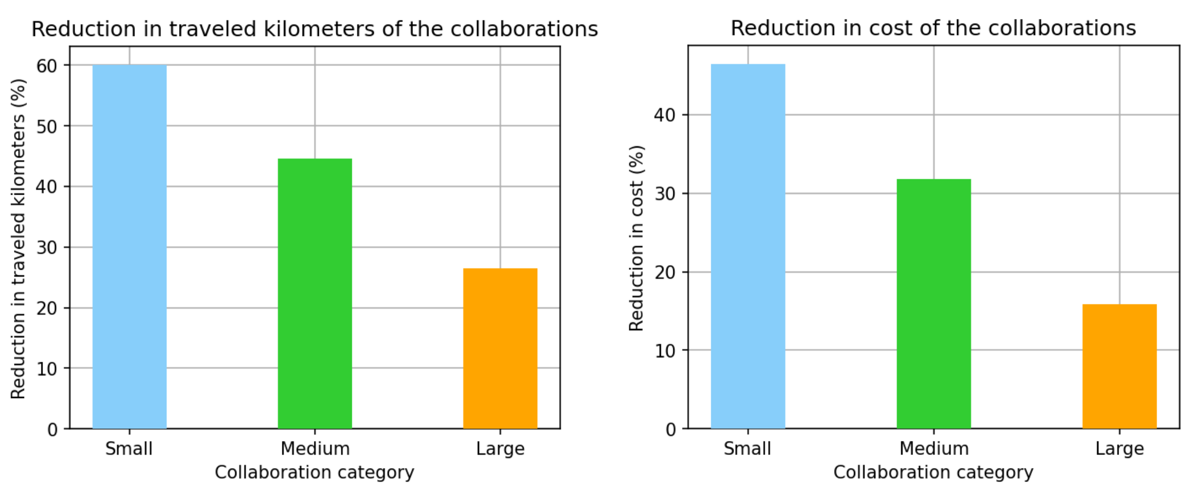
Table 5 Time/distance statistics of the scenarios for the medium CWCs

		Objective: distance		Objective: time	
		Time (hour)	Distance (km)	Time (hour)	Distance (km)
Scenario 1	Total	23.84	246.401	23.05	273.0
Scenario 2	Total	18.46	136.44	16.70	158.78
	Difference (%)	-22.6	-44.6	-27.5	-41.8
Scenario 3	Total	18.8	141.9	18.3	172.4
	Difference (%)	-21.1	-42.4	-20.5	-36.8
Scenario 4	Total	18.8	145.2	17.6	154.9
	Difference (%)	-21.0	-41.1	-23.6	-43.3

Table 6 Time/distance statistics of the scenarios for the large CWCs

		Objective: distance		Objective: time	
		Time (hour)	Distance (km)	Time (hour)	Distance (km)
Scenario 1	Total	55.8	385.2	55.4	410.9
Scenario 2	Total	50.6	283.2	49.6	281.4
	Difference (%)	-9.4	-26.5	-10.5	-31.5

The results show that the small collaboration shows the greatest reduction in traveled distance and time. This can be attributed to the fact that small CWCs operate relatively inefficiently. Therefore, they will benefit the most from collaboration. Although scenario 3 and 4 impose constraints on collaboration and therefore make the VRP harder to solve, they still provide similar results compared to scenario 2.



(a) Savings in traveled kilometers

(b) Savings in cost

Fig. 3 Savings in distance and cost

Concluding, the reduction in traveled distance is 60%, 45% and 27% for the small, medium and large collaborative partnership, respectively. The reduction in cost is 47%, 30% and 14%, respectively. The results are shown in Figure 3. While large CWCs already operate very efficiently, there is still a serious decrease in traveled distance and cost possible if they decide to collaborate. A second important benefit is the decrease in the number of vehicles used. While scenario 3 and 4 do not decrease the number of vehicles because each CWC stays operational, scenario 2 results in a reduction from 5 to 2 vehicles for the medium CWCs and a reduction from 8 to 6 vehicles for the large CWCs. For the collaboration of the medium CWCs, there is no reduction. This is caused by the fact that they already have a high vehicle utilization ratio when operating individually, and collaboration is not sufficient to increase vehicle utilization to the point where vehicles can be dropped.

VII. Discussion and conclusion

This study has shown how collaborative partnerships in waste collection logistics can have a significant impact on operational efficiency and decrease traveled distance and costs of waste collectors. Because less vehicles are needed and there is better coordination between vehicles, this will also avoid multiple vehicles traveling through the same area at the same time, resulting in less inconvenience for residents and overall a better environment. While collaboration provides significant cost savings, it is important to use a profit-sharing mechanism to equally divide the benefits of collaboration over all members of the collaboration.

Although many authors have developed their own algorithms for solving various VRPs, it is important to acknowledge the potential of open-source tools like OR-tools and OSMnx in simulating logistics. It is useful to study what other VRP solvers can be used for implementation in the model. Secondly, for larger problem scales, the possibility of integrating clustering technique should be studied to reduce the required computational time by splitting the VRP into multiple smaller VRPs.

Because the data in this study was provided by a relatively large waste collector, it would be appropriate to study the operations of other (smaller) waste collectors. This way, more accurate data can be obtained about containers used, service times per container, client distributions, operational procedures and depot locations.

The overlap of clients and individual operational efficiencies of waste collectors in a collaboration are important indicators as to how collaboration will perform. It should be studied how client overlap, carrier efficiency and scale of the studied problem impacts collaborative benefits.

This study has clearly indicated the quantitative benefits of collaboration between waste collectors in the commercial waste collection market. Collaboration will not only result in cost savings for waste collectors, but will also significantly reduce traffic in the city due to the reduced logistical kilometers and the reduction in vehicles. Collaboration should therefore be stimulated and encouraged. Stimulating collaboration could also be done in other forms of logistics if collaborative benefits are expected.

Appendix

Table 7 Distribution of clients over waste collectors. L = large, M = medium, S = small.

CWC	S1	S2	S3	S4	S5	M1	M2	M3	L1	L2
Daily clients	47	55	47	54	48	103	98	90	504	504

Table 8 Collected data and associated sources

Source	**Data**
Waste collector in the study area	- Container size distribution - Average weight per container size - Service time per container size - Route data from city center
OpenStreetMap	- Street network - Client distribution over the study area
MoR, OpenWaste, Waste collector	- CWCs in the study area and market share
Google Maps	- Average edge speeds

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