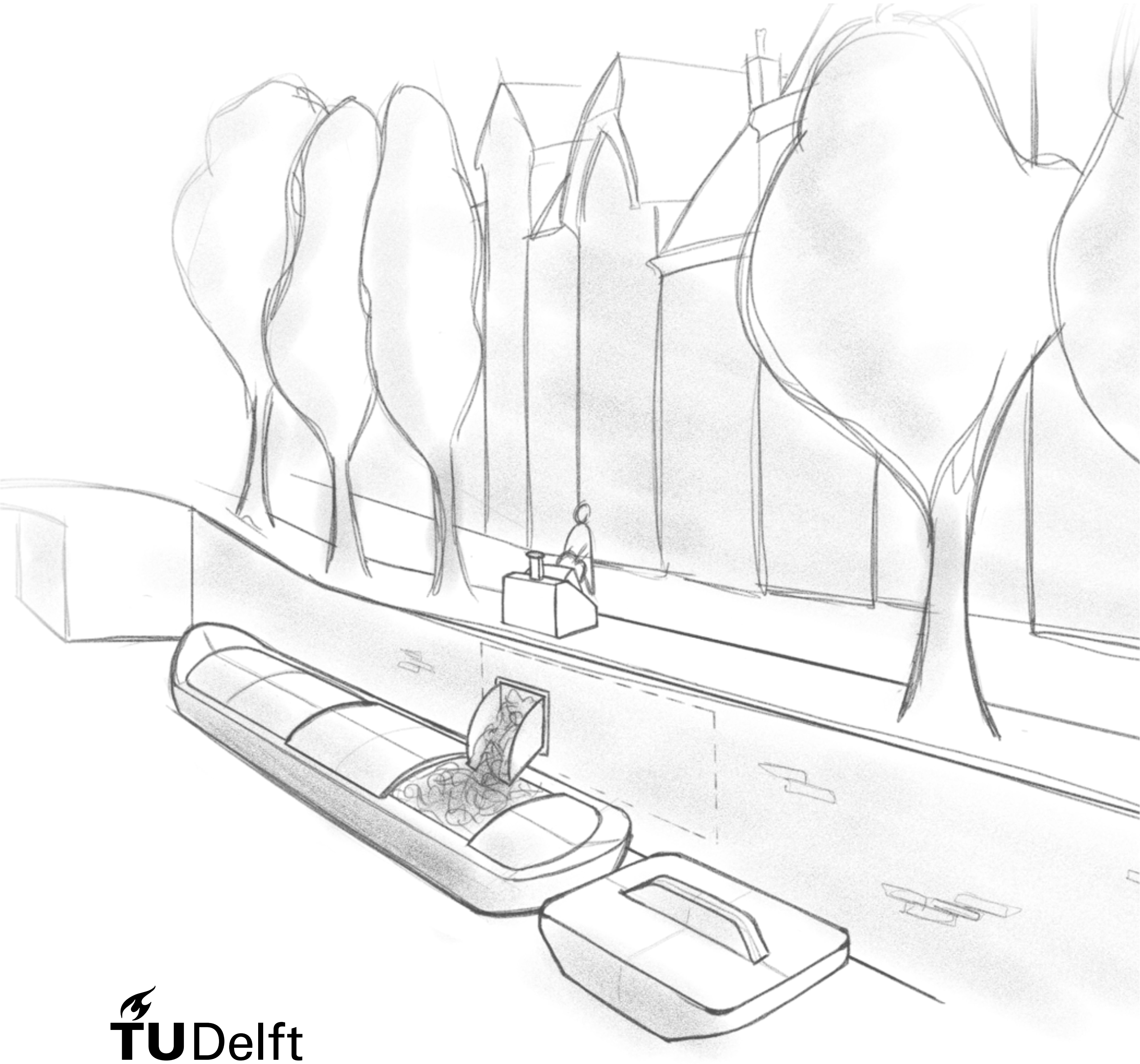
H.J. van Toor

Waste Collection in Amsterdam Centrum using Autonomous Vessels (Roboats)



TU Delft

Waste Collection in Amsterdam Centrum Using Autonomous Vessels (Roboats)

By

H.J. van Toor

Master Thesis

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Preface

This Master thesis describes the optimization of the container type selection and location for a household waste collection system in Amsterdam Centrum. The research is done as part of the graduation during the second year of the track 'Transport Engineering and Logistics' in the MSc 'Mechanical Engineering'. The research is executed in collaboration with the Amsterdam Institute for Advanced Metropolitan Solutions and the municipality of Amsterdam. I am thankful for the unique opportunity they gave me to work on a project that is involved in either Roboats as well as waste collection in Amsterdam. After my literature assignment in 2019 with the title: 'The potential of autonomous vessels in Amsterdam', I was very enthusiastic about the innovative Roboat project. Also, the waste collection system in Amsterdam Centrum has my interests since that is the city where I currently live, and I think a better solution could be found. Therefore, I am very proud to have been a part of this research.

First of all, I would like to thank Dr. Bilge Atasoy for her supervision and guidance during this research. It was a pleasure to work with her through excellent communication. Secondly, I want to thank the chair of my committee Prof. Dr. Rudy Negenborn for his accurate feedback, which was very useful during the whole process.

Furthermore, I would like to thank all my colleagues at AMS Institute for providing me with a great workspace with friendly people and helping me when needed for the past months. Especially, a big thanks to Ynse Deinema for his supervision, but mostly the fun times together is was kept me energetic throughout the research. Finally, I would like to thank Anita Numan for providing me with the required data and for connecting me to the right people within the municipality. This collaboration made the research an efficient and fluent process.

H.J. van Toor
August 12, 2020, Delft

Summary

In the current situation, the household waste of almost all 86.862 residents (OIS Amsterdam, 2019) in the Centrum area is located on the sidewalk within specific time-slots twice a week. The smelly garbage bags attract unpleasant animals such as mice, rats and seagulls. However, the heavy trucks do even more harm to the city; they destroy the fragile and poorly maintained quay walls. The restoring costs of these quay walls are estimated to be several billion euros. During this restoring process, there is a possibility to implement containers in the quay walls, which was not everywhere possible before due to tree roots, cables or pipes. The collected household waste within these build-in containers could be collected by Roboats, small autonomous vessels developed for the canals of Amsterdam. This will reduce the stress on the quay walls and follows the restrictions of the city centre to be a combustion engine free area in 2025.
This research investigates the possibilities of a new household waste collection system and its corresponding container locations, taking these problems into account. Based on the current problems, upcoming restrictions, and the municipality's preferences, a list of requirements has been developed. The goal of the new waste collection system is to serve as many as possible residents in the Centrum area with the least amount of containers or the lowest costs. All produced waste from one household belongs to one container, and the containers require a specific capacity. Next, it should be possible to define a maximum number of containers for one specific container type. Finally, a short walking distance is preferred, and the maximum walking distance is defined as 150 meters. This results in a system were autonomous vessels (Roboats) will be applied to collect waste from the build-in containers in the quay walls.

Literature review

There are multiple modalities applicable to collect all household waste in Amsterdam Centrum. The first possible solution is the application of autonomous Roboats, which will collect and transport the waste via the canals. This could either be done as a tugboat or as a waste vessel itself. The heavy trucks will not be allowed to drive over the quays anymore soon. However, the main roads through the city centre are strong enough to carry these heavy loads. A possibility is to collect waste from the households near these main roads by installing underground containers. This will probably be the cheapest method in the short term. The third possible modality is

a small electric vehicle (EV) that could collect portable containers. These containers will be smaller than the underground containers and will be located on parking lots, for example. The next modality taken into account is the self-driving drone, which is currently tested with package delivery in the United States. These drones could also work the other way around; collecting bags on appointment. The final possibility is the application of an underground vacuum network. These pipes could be located in the canals to save costs. This system is already in use in Stockholm and the Sluispoort in Amsterdam.

A common problem with great practical importance is to choose the location of facilities, such as fire departments or warehouses, in order to achieve a specific objective while satisfying the demand for some commodity (Cornuéjols, Nemhauser, and Wolsey, 1983). Depending on the specific problem to be tackled, costs, travel distance or market share could be one of the objectives. These problems are called facility location problems (FLPs). If a demand point is covered by two or more facilities, such that each facility covers a percentage of the demand, it is called an implicit approach (Qian, 2012). Other variations of the FLP could be assigning a capacity (CFLP) (Sridharan, 1995)(Verter, 2011), multi-objectives (MOFLP) (Matai, 2015), multi-level (MLFLP) (Rodriguez and Doria, 1996), multi-echelon (MEFLP) (Gao and Robinson Jr, 1992)(Tragantalerngsak, Holt, and Rönnqvist, 2000)(Li, Chu, Prins, and Zhu, 2014), multi-facility (MFLP) (Farahani and Hekmatfar, 2009), or hierarchical (HFLP) (Farahani, Fallah, Ruiz, Hosseini, and Asgari, 2019)(Şahin and Süral, 2007)(Böttcher and Rembold, 1977)(Demir et al., 2001)(Barros, Dekker, and Scholten, 1998).

These problems could be solved in several ways. The most common method is to use mixed integer programming (MIP) or linear programming (LP). These MIP or LP packages could be added to a programming language such as Python. The advantage of using these programs is that the algorithm is build from scratch and relatively easy to make adjustments within the code. At the same time, that is a disadvantage: it is relatively time-consuming to build the whole algorithm, and it could be harder to validate the model.

A different and relatively new method is solving these type of problems with Geographical Information Systems (GIS). One of the reasons for the success of GIS is their capacity to generate visualizations of data, which greatly assist in such a complex decision-making process as retail site or container location (Hernandez, 2007)(Musyoka, Mutyauvyu, Kiema, Karanja, and Siriba, 2007). An advantage of using GIS is that the software itself quickly generates large data sets. For example, the origin-destination cost matrix, which calculates all walking distances between the possible facility and demand points using the road network. Using GIS software makes it easy to check if the output makes sense due to the visualizations. Finally, it is possible to give demands to the system with integrated buttons as well as with Python commands.

Solution approach

First of all, the given requirements of the new system are translated into a integer programming model. With this model, combined with the provided data, it is possible to define the solution method for this research. After the pros and cons of both solution methods are weighted, GIS software is selected to solve the problem. Between the different GIS applications, ArcGIS Pro 2.5 is chosen based on the advanced network analysis tools. Then, with the provided data, calculations are made to define the capacity of the possible container types. With this calculated demand, the simulation strategies could be defined for ArcGIS Pro. The first strategy is to solve the location-allocation with a serial approach for the 12.250 buildings containing at least one household. This means that the problem is solved for every modality one by one. Method 1 assigns buildings first to Roboat containers until they are not efficient anymore, which means that they are filled for less than 66,7%. Next, truck containers are assigned to the buildings that were not assigned to Roboat containers until they are not efficient anymore. Finally, EV containers will assign the rest of the buildings. Method two uses the same strategy but varies the order. First, the trucks containers will be located, then the Roboat containers and finally the EV containers. Method 3 leaves the trucks out of the simulations. This results in assigning Roboat containers before the EV containers are assigned.
Methods 4 and 5 use the parallel approach to assign the containers to the 12.250 buildings containing at least one household. These methods assign facilities to demand points next to each other, not taking a lower bound into account. The container that could assign the most buildings will assign them. Method 4 uses the three discussed modalities to solve the problem for the Centrum area. Method 5 does the same calculations, but this time without the truck containers.

Results

These described calculations result in a set of located containers per modality for all methods. Method 1, 2 and 3 require more containers to serve the total demand of the Centrum area than the parallel approach. Every simulation has assigned 100% of the total demand to a specific container with a given geographical location, all within 150 meters walking distance. Based on the formulated objective function, the parallel approach provides a more favourable result. Therefore, the parallel approach is recalculated with an update of the input data. The 12.250 buildings are replaced by the location of all 51.132 households. This new set of demand points result in a different capacity of the containers as well. After defining the new capacity, the set of located containers is defined, combined with the corresponding walking distances. The average walking distances per modality vary between the 67 and 79 meters, for method 3 and 6 respectively. Finally, an efficiency score is calculated by the average number of buildings assigned to a container per container type, divided by the capacity of that container type. These scores confirm that the parallel approach is more efficient than the serial approach.

Conclusion and Recommendations

First of all, it can be concluded that the parallel approach is more efficient than the serial approach based on the number of located containers and the calculated efficiency score. Secondly, methods 6 and 7 have higher accuracy than methods 4 and 5. However, methods 4 and 5 are useful to compare the serial approach with the parallel approach. Methods 4 and 5 assume that the households are equally distributed over the buildings, which mean that on average 7.09 residents live in one building. However, this is not true since some buildings are apartment blocks and some buildings are small houses.

Depending on the preferences of the municipality, a decision can be made to transform method 6 or 7 into reality. If the municipality decides to use different modalities, a vacuum system or drones, this framework is still useful for the container location definition. With the Matlab file, the parameters are easily recalculated, which could afterwards be implemented in ArcGIS Pro.

It would be recommended to develop more strategies for the calculation methods based on the costs of the implementation of the containers. Therefore, a financial overview of the costs must be developed, and the financial acceptance of the municipality have to be investigated. With that information, the parameters can be chosen to achieve the objective for the container locations and the financial objective. This could also lead to a new multi-objective facility location problem where the costs are taken into account.

Secondly, the vessel design needs further research. The suggestion of this research is to apply large engine-less barges which will be tugged by Roboat tugboats. In this case, a minimum number of Roboats is required, which could save costs. Next, the container design should be taken into account. Currently, AMS Institute is researching the possibilities of these build-in containers and the possible emptying systems. If these containers are developed, the noise should be measured during the emptying process to check if the operations could be executed in the night. This will define the number of required vessels.

Another essential factor is the quay wall height. The height of the quay walls vary through the city and affect the possible container size. Currently, there is no accurate data on the quay wall height. Soon tests will be performed with Roboats to scan the surroundings with LiDAR. This data could be useful for container location decisions. Also, the restoring locations of the quay walls should be taken into account. If a quay wall will not be restored, it is essential to check if it is possible to build a container on that location.

The final recommendation is to take a closer look at small areas just outside the service area of 150 meters. By assigning a few households to a specific container with a slightly larger walking distance than 150 meters, it could save some extra located containers.

List of Abbreviations

Abbreviation	Description
ASV	Autonomous Surface Vehicles
AEB	Afval Energie Bedrijf (Waste Energy Company)
AMS	Amsterdam Institute for Advanced Metropolitan Solutions
CFLP	Capacitated Facility Location Problem
DifTar	Differntiated Prices
EV	Electric Vehilce
FLP	Facility Location Problem
GIS	Geographical Information System
HFLP	Hierarchcal Facility Location Problem
KPI	Key Performance Indicator
LiDAR	Light Detection and Ranging
LP	Linear Programming
MEFLP	Multi-Echelon Facility Location Problem
MFLP	Multi-Facility Location Problem
MIP	Mixed Integer Programming
MIT	Massachusetts Institute of Technology
MLFLP	Multi-Level Facility Location Problem
MOFLP	Multi-Objective Facility Location Problem
MSW	Municipal Solid Waste
NFC	Near Field Communication
NP	Non-deterministic Polynomial-time
OR	Operational Research
PMP	P-Median Problem
SFLP	Single-Facility Location Problem
SHP	Shape file
UFLP	Uncapacitated Facility Location Problem
WFS	Web Feature Service
WMS	Web Map Service

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Chapter 1

Introduction

The last decade has been a revolution for digitization, which affects various industries. In many sectors people are replaced by machines, robots or computers, which results in a world where your order is picked by a machine, stocks are traded by algorithms, and even your coffee is brought to you by a robot to keep distance between human beings. The reason why companies are switching towards a more autonomous world is apparent; autonomy could provide costs savings, is not dependent on time, it reduces the number of errors and most of all it should be an improvement in safety. One of the industries where autonomy starts to grow is the maritime industry. An era of intelligent vessels has begun where shipowners, captains and control posts will be able to use the new technologies and their developments to manage assets, optimize decisions, and deploy remote and autonomous operations.

1.1 Background information

This research strives to contribute to the solution of the Amsterdam waste problem by improving the location determination of the various container types within the Centrum area. In order to have satisfactory background information to understand the entire problem and circumscribe the fields that require more research, this section provides context on various elements of the problem and solution. First of all, autonomous shipping will be addressed. Secondly, the current waste collection system in the Centrum area will be discussed. Then background information on the Amsterdam Institute for Advanced Metropolitan Solutions is provided. Next, an introduction is given on the Roboat project, followed by the planned quay wall renovations. Finally, background information is provided on facility location problems and their corresponding solution methods.

1.1.1 Autonomous shipping

The digital revolution creates many new possibilities. One of these exciting possibilities is developing autonomous or uncrewed vessels. This development starts with a low autonomy level and is focused on gaining complete autonomous vehicles. The development of autonomous vessels has reached the point where complete autonomy is possible, but not proven to be flawless. Electric autonomous vessels will provide a more sustainable transport industry by improving the safety, efficiency and reducing the carbon dioxide emission. They would also solve anticipated crew shortages, improve the working conditions and will better integrate shipping in the transport system[1]. Full autonomous vessels do not require a steering wheel and throttle, so vessels could become smaller with the same capacity or could carry more cargo with the same size. This leads to lower power demand and could lower the cost of shipping.

Furthermore, computers and robots work more consistent than humans and could operate non-stop. If the sensors work properly and the software is correct, no collisions would occur anymore. The human error is cancelled out, and the number of dangerous situations will reduce due to better anticipation and communication (Levander, 2016).

Since the development of the first computer, ideas raised about self-thinking and -deciding machines. These ideas came alive in movies but were always related to futuristic scenarios. However, the reality of fully autonomous vehicles has begun. The development of the first autonomous vehicles was mainly focused on operating on land. In the following years, air, space and sea surface became interesting as well. Vehicles that are operating on the water surface are called autonomous surface vehicles (ASVs) and have started being developed at an academic level since 1993 when MIT presented its first ASV called Artemis (Rodriguez and Doria, 1996). Now that a basic ASV is developed, many new applications are possible. For each different application, a combination of various sensors, communication, and navigation systems is required to obtain full autonomy. An autonomous vehicle follows a predefined trajectory with certain degrees of freedom, which allows adjustments in the route according to legislation, or the arising dangerous situations[2]. An ASV relies on the combination of a proper working positioning system in combination with various sensors. With the information of these systems, a 3D mapping of the surroundings can be created. Accurate sensors and a precise positioning system are required to obtain full safety.

The different application possibilities require their combination of sensors and positioning system to obtain full autonomy. Each application has its requirements and restrictions. For example, cameras and LiDAR systems can scan the surroundings and create a 3D mapping. Google's self-driving car relies on LiDAR[3] and Elon Musk relies on high fidelity cameras to create full safety for his Teslas (Jayaweera, Rajatheva, and Latva-aho, 2019). Another advantage of these cameras and LiDAR systems is that you gain information about your surroundings, which could be useful to monitor the quay wall quality, for example, or cracks under a bridge.

[1] https://www.tudelft.nl/technology-transfer/development-innovation/research-exhibition-projects/autonomous-shipping

[2] http://www.unmanned-ship.org/munin/wp-content/uploads/2016/02/MUNIN-final-brochure.pdf

[3] https://www.kurzweilai.net/googles-self-driving-car-gathers-nearly-1-gbsec

1.1.2 Waste collection in Amsterdam's city centre

Currently, almost all residents in Amsterdam Centrum have to drop their waste on the sidewalk. However, they are only allowed to do so twice a week. The specific day depends on the area where their house is located. The residents in the Centrum area produce on average 281.9 kg municipal solid waste (MSW) per year (Reeze, 2020), excluding bulky household waste, coarse garden waste and wood waste. With 86.862 residents (OIS Amsterdam, 2019) living in the city centre, this means that every year about 24.486 MT of household waste is being collected. Which is equal to an average of 471 MT each week, similar to almost 100.000 garbage bags of 5 kg. The garbage collectors will pick up the garbage bags by hand and throw them in the garbage trucks. The rest of the week, people have to collect their waste at home. This waste causes a problem for many households; it attracts mice and rats. The garbage bags outside attract seagulls as well, which will destroy the bags and spread the waste through the streets. This system ruins the historical centre through the uninvited animals, the way it looks and the bad smell.
There are two different waste management systems in Amsterdam; the collection of household waste and a separate collection for commercial waste. The municipality, Suez and Renewi collect the major part of the commercial waste, but there are many smaller (also called pirate) parties which have contracts with companies as well. Due to this competition and separated system, 9,1 trucks will drive through the 9-straatjes (Gemeente Amsterdam, 2020a) on average, an area in the canal district. The current quay walls of Amsterdam Centrum are not able to carry that amount of weight and are therefore rapidly decreasing in quality. The current waste collection system and its problems will be further explained in section 2.1.

1.1.3 AMS Institute

The Amsterdam Institute for Advanced Metropolitan Solutions (AMS Institute) is an internationally leading institute where talent is educated and engineers, designers and both natural and social scientists jointly develop and valorize integrated metropolitan solutions for the capital of the Netherlands. Their mission is to develop a deep understanding of the city, design solutions for its challenges and integrate these in Amsterdam. One of their focus areas is mobility; moving towards a combustion engine free city centre with the least as possible transport moves using the street network. Resulting in a situation where transport via the canals becomes interesting, again. Until 1992 the transport of waste from the city centre to the incinerator was done via the waterways. From that moment the municipality decided to move to the roads due to financial reasons. However, the quality of the quay walls is rapidly decreasing because of the heavy trucks and will cost even more. Therefore, the municipality started a tender in 2015 for autonomous vessels which could operate in the narrow and busy canals in Amsterdam. Massachusetts Institute of Technology (MIT) and AMS Institute became the winner of that tender, so they started the Roboat project together in September 2016.

1.1.4 Roboat Project

Roboat is a five-year research project and collaboration between the Amsterdam Institute for Advanced Metropolitan Solutions and the Massachusetts Institute of Technology. The goal of this research is to develop the world's first fleet of autonomous vessels for the city of Amsterdam and to investigate the potential of self-driving technology to change our cities and their waterways. The AMS Institute possesses one full-scale Roboat, one half-scale and four quarter-scale Roboat units. The quarter-scale units are used for multi-vessel formation control and have a dimension of 1 by 0,5 meters. The sensors of the half-scale unit, with a dimension of 2 by 1 meter, are only tested for a short period. In April 2020 the full-scale Roboat arrived at AMS Institute, and after installing all technological parts, the goal is to start with the tests in July 2020. The quarter-scale is shown in figure 1.1a, and the concept of the full scale is shown in figure 1.1b.

The Roboats will be a new kind of on-demand infrastructure and logistics. These multi-purpose vessels could behave as autonomous platforms to create floating bridges and stages. Other purposes are delivering goods, transport people or collecting waste as a waste-vessel or tugboat pushing or pulling floating containers. During these operations, they continuously collect data about the city. Previous research about the waste collection with Roboats assumes that 96 floating dumpsters could serve around 87% of the Centrum area (Zhang et al., 2018). Therefore, around 10 Roboat tugboats should be sufficient (Daub, 2019). The first cost estimation states that collecting waste with floating dumpsters could save up to almost 2.5 million euros per year (van Pampus, 2020).

(a) Quarter scale Roboat at AMS

(b) Full scale Roboat with passengers module

Figure 1.1: Two different Roboat concepts

1.1.5 Quay wall renovations

There is a reason why the municipality relies on the current waste system since 1992; it was cheaper and faster than collecting waste with vessels. Furthermore, it was hard to build underground container is the narrow streets of the Centrum area. Other reasons why these underground containers were not installed in the late '90s was because it was unknown what was actually under the surface of the streets. There was no clear overview of all pipes, cables and tree roots. Furthermore, the canals are part of the UNESCO world heritage, and containers would ruin the view of these canals. Deferred maintenance has led to a situation where kilometres of quays are in critical condition as well as several bridges. Therefore, the municipality starts in 2020 with three different groups of companies who will start renovating these quay walls. The group who renovates the quickest and cheapest with the least impact will do the rest of the quay walls. During this renovation period, which will take many years and billions of euros, there is a possibility to integrate an underground container. This concept is further explained in figure 1.2.

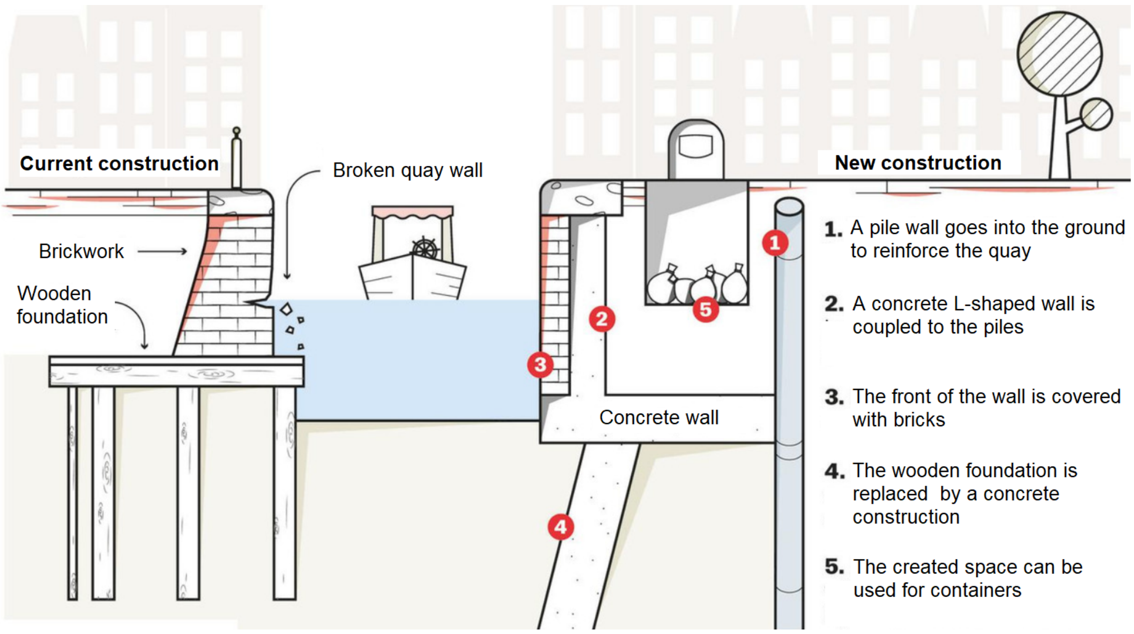


Figure 1.2: Quay wall renovation

1.1.6 Facility location problem

The facility location problem (FLP) is an optimization problem to determine the number and locations of a set of facilities (warehouses, hospitals, containers) and assign a set of demand points (customers, clients, residents) to these in such a way that a certain objective is achieved (minimum costs, minimum distance, maximum attendance) (Wu, Zhang, and Zhang, 2006). FLPs are a well-known subject within operational research (OR) and are a commonly faced problem in practice. There is a wide range of varieties of FLPs, varying in objectives, hierarchy, number of facility layers, capacity, and others. FLPs are categorized as a non-deterministic polynomial-time (NP)-hard problem (Mirchandani and Francis, 1990).

1.1.7 Solution methods

There are several possibilities to solve the FLP. The most common method in literature is the application of programming languages such as Python, Matlab, R or others. There are different application methods within these software programs such as linear integer programming, mixed integer programming, Branch-and-Bound method or a Lagrangian relaxation and decomposition (Farahani, Hekmatfar, Fahimnia, and Kazemzadeh, 2014). Other software possibilities are Geographical information systems (GIS). The most popular GIS-software applications are ArcGIS and the open-source Q-GIS program. GIS software provides the ability to capture and analyze spatial and geographical data. With this tool, it is possible to create interactive queries, edit data points on a visual map, analyze spatial information output, and visually share the results of the calculations.

1.2 Problem statement

As described in section 1.1.2, almost all residents of the Centrum area have to drop their waste on the sidewalk. The garbage bags are collected twice a week by garbage collectors with a large truck. The garbage bags waiting in the open air to be collected are not the only problem; garbage trucks cause even more problems. First of all, trucks cause congestion in the inner city, resulting in a multitude of mobility problems. Secondly, these trucks are diesel-powered, and so they add to the problem of emissions and noise in a densely populated area. Next, the truck drivers cause dangerous situations from time to time and are sporadically involved in accidents. The most critical problem that is caused by the trucks is that they are too heavy for most of the quay walls and bridges. The lack of maintenance in the past decades has led to frail quay walls. The weight of the trucks causes cracks in the bridges, roads, quay walls and houses, which will be expensive to restore.
Furthermore, the current waste collection system is divided into two different flows: commercial waste and household waste. There are several companies involved in collecting commercial waste, which has lead to a situation where multiple different trucks are driving through the same street. In the 9-straatjes area in Centrum, this is on average 9,1 truck on the same road every day (Gemeente Amsterdam, 2020a). The number of trucks could be reduced by combining the systems. Another problem is the piles of garbage bags on the streets. This leads to many problems with mice, rats and seagulls. Furthermore, the smell of the waste is unattractive for more than nine million tourists every year and the residents itself. Also, the view of the canals is ruined by these bags, and these canals are part of the UNESCO-world-heritage. On the other

hand, that was one of the reasons why build-in containers were not possible a couple of years ago. Also, the roots of trees, cables and pipes could appear during the installation of these build-in containers, since there is not much information about the underground infrastructure. However, during the quay wall renovations, it becomes possible to implement containers, and UNSECO is nowadays positive about build-in containers (P. Rosenberg, 2020).
The municipality of Amsterdam will ban combustion engine vehicles in the city centre from 2025, including all trucks and cars (Bork, 2020). This means that electric and hydrogen trucks will be allowed. The only problem is that the electric trucks are even more onerous than the current trucks due to the large battery package. A solution to this problem could be implementing autonomous vessels in the waste collection system, which will collect the waste from containers along the canals. From 2025 all commercial ships need to be zero-emission (Mensch and Verbeek, 2015), so electric autonomous sailing is in line with the plans of the city.

1.3 Research objective

The goal of this research is to design a new household waste collection system for Amsterdam Centrum using autonomous vessels and is applicable in the upcoming years. In other words, the applicable waste collection modalities with their corresponding container types have to be investigated. Next, the container locations for the selected types have to be defined. This research will not go into detail for the container design, which will be done by a colleague at AMS Institute. Different solving strategies will be compared with each other to find the ideal container locations. The objectives of the research can be formulated into a main and several sub research questions:

Main research question

'How to optimize the container type selection and location for a new household waste collection system in Amsterdam Centrum using autonomous vessels (Roboats)?'

Sub-research questions

- What are the municipality's requirements and preferences for the new waste collection system, and how are these implemented in the model?
- What are the possible waste collection concepts for water or land application, and which combination is the most efficient?
- Which methods could be used for solving the facility location problem, and how does this method contribute to the current research field?

- Which different strategies could be applied to the solution method and which obtains a more favourable result on the objective?
- Which method would be recommended for Amsterdam Centrum based on the approach and results?

1.4 Research scope

The scope of this research is to define a set of container locations in the centre of Amsterdam (Stadsdeel Centrum), shown in figure 1.3. The problems related to waste collection in the other parts of the city have different reasons, and it is not possible to collect waste with vessels in those areas. Furthermore, this research is limited to the collection of household waste. However, the developed framework could easily be adjusted to take commercial waste into account as well. Also, the design of the required container and its corresponding emptying system will not be investigated.

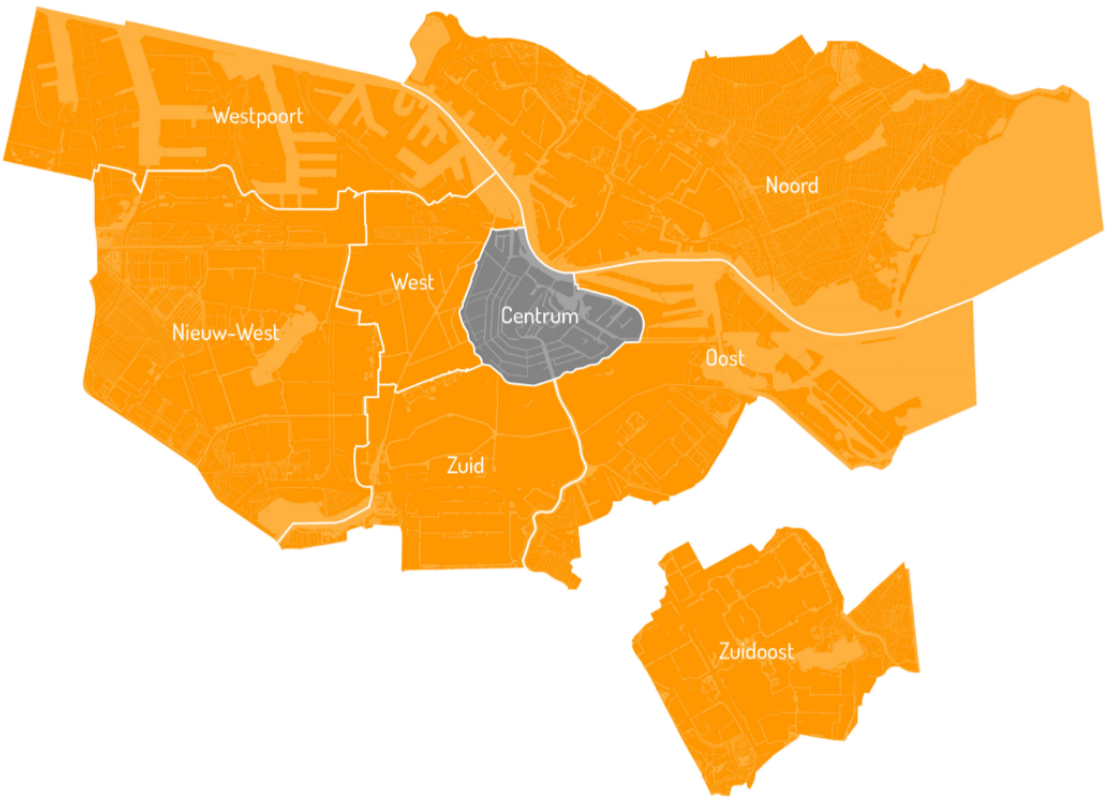


Figure 1.3: The focus of this research is only on the Centrum area of Amsterdam (Zhang et al., 2018)

1.5 Research approach

This section provides the applied approaches that are used to address the earlier mentioned research questions. First of all, the current situation will be investigated, and the objectives of the municipality will be identified. Secondly, the possible waste collection modalities and their corresponding container types are investigated. Next, the requirements by the municipality are translated into a mathematical model, and the different container types are taken into account. However, the designed model could be applied to all modalities in the end. Next, the solving methods will be discussed, and the used software will be selected. Different strategies and methods will be applied to get insight into the quality of the calculations. Since this is not done before in literature, the strategies have to be defined beforehand. After calculating all parameters, the calculations can be set up and start. Finally, the calculations will be evaluated, and conclusions can be drawn.

1.6 Thesis outline

This section describes the organization of the remaining part of this thesis. Chapter 2 contains the literature review about facility location problems, describes the context of the current situation in Amsterdam Centrum and the possible modalities with their corresponding containers. Chapter 2 end with the proposed system to be researched. Next, chapter 3 starts with the description of basic mathematical models that are commonly used for different facility location problems, followed by an advanced model that describes the waste collection objective with corresponding constraints, based on the requirements given by the municipality. Then, Chapter 4 describes the applied data for the model and explains the experimental setup, which includes the generation of all used data points. Also, the solution method is selected based on the developed mathematical model and provided data. Chapter 5 contains the calculation methodology and how it is applied within the solution method. At the end of the chapter, there is an overview of the applied and investigated methods. The results and evaluation of the calculations are described and discussed in Chapter 6. Finally, Chapter 7 provides a conclusion on the research question and delivers the recommendations for further research.

Chapter 2

Context and literature review

2.1 Current situation in Amsterdam

In the current situation, inhabitants of the centre of Amsterdam have to drop their waste on the sidewalk. This is only allowed twice a week. The specific day depends on the area where their house is located. The garbage collectors will pick up the garbage bags by hand and throw them in the garbage trucks. These garbage trucks are mostly diesel-driven and could weight up to 25 metric ton when they are fully loaded. According to S. Bork (2020), the municipality is considering a new rule for the maximum weight of road transport in the centre of Amsterdam, where the maximum weight would become 7,5 ton, or even less.
In the peripheral area, underground containers are used. Different experiments have shown that around 40% of the waste in these containers originates from companies (E. Almer, 2020). Most of these companies do not pay to use these containers. Companies have their commercial waste management system and have to use it by signing a contract with one of the waste collecting companies. It is hard to control the behaviour of companies and to prevent them from using the private waste system. A possible solution could be merging private and commercial waste into one system; urban waste management system. Currently, a pilot is going on in the 9-straatjes where different tests are done with urban waste, according to A. Numan (2020). The municipality wants to keep control over this system, but companies will carry out the task. Another possibility to solve this problem is by using DifTar (differentiated prices), where users of the waste collection system pay for everything they throw away. Containers could be opened with an NFC chip and reader, charging a standard price per bag, for example. There are only two disadvantages: first of all, the municipality prefers to use an open system, according to E. Almer (2020) where everybody can use the waste-collecting system. The second disadvantage is that probably more waste will end next to these containers. He also states that the cheapest and most efficient way to handle the waste is to separate it at the end of the chain, so at the AEB (Afval Energie Bedrijf, translated: Waste Energy Company) for example. Where others are focusing on improving the separation of waste at the source during the 9-straatjes pilot, they

both conclude that the separation of fruit, vegetable and other food waste (organic waste) is the most important. Organic waste is wet and makes it impossible to recycle the rest of the waste. The most recent plan of the municipality is to stop the separation of plastic waste and to start the separation of organic waste (Gemeente Amsterdam, 2020b). However, these plans are still with reservation and could become definitive in September 2020.
The regulations on the Amsterdam waterways were a frequently discussed topic in the past few years. Since May 2019 it is not allowed to sail with more than thirteen people on one boat. Also, the allowed sailing times were discussed. Currently, it is still allowed to sail during the whole day and night, but the municipality has the right to close the canals between midnight and 7:00 a.m. if they think it is necessary. So, it could be a solution to collect waste during the night (Bork, 2020). However, it is only permitted to produce industrial noise from 7:00 a.m. until 11:00 p.m. with a maximum of 70 dB (APV Amsterdam, 2008). Another law that could make waste-collecting with autonomous vessels hard on the short term is the law that every ship has to be crewed by at least one captain (v.d. Broek, 2020). In the meantime, it could be a solution to provide every garbage vessel with a captain. Another operation window could be between 7:00–10:00 a.m. since most commercial tourist vessels do not operate before 10:00 a.m. and the canals of Amsterdam are almost empty within that window (Nepveu, 2020). So, these three hours could become the ideal operation time.

2.2 System requirements

During the first weeks of this research, the problems of the current waste collection system became clear. Based on the current problems, upcoming restrictions, and the municipality's preference, a list of requirements has been developed which will be taken into account during the development of the framework in the following chapters. The goal of the new waste collection system is to serve as many as possible residents in the Centrum area with the least amount of containers or the lowest costs. The requirements are as follows:

- Limit the total costs or use the least amount of containers, maximize the number of assigned buildings to one container
- The total waste production from one household belongs all to one container
- Do not exceed a certain number of located containers
- No more waste on the streets, do not exceed the capacity
- The maximum walking distance from a household to a container is 150 meters
- Preferably a short walking distance

Furthermore, the are restrictions and requirements for the new waste collection system which affect the appearance of the containers but not directly the mathematical formulation of the problem. These restrictions and requirements are as follows:

- No more heavy loads on the quay walls
- No more combustion engines from 2025
- System should work for upcoming decades
- The system should be in line with UNESCO-world heritage

Since it is not allowed to have heavy loads on the quay walls, a system has to be found that uses the canals or air, or lightweight vehicles might solve the problem. All solutions should be powered by electricity, either from a battery or hydrogen tank. The solutions should work for the upcoming decades and should be approved by UNESCO-world heritage. Possible solutions will be discussed in the following paragraphs.

2.3 Possible waste systems

There are several possibilities to collect the waste in the centre of Amsterdam that causes less damage to the quay walls compared to the current system. The different possible modalities with their corresponding containers will be discussed in the following subsections. Each system has its advantages and disadvantages, while they are all tackling the problem with heavy trucks which reduce the lifetime of the quay-walls.

2.3.1 Vessels

Until 1992 the canals were, among other things, used for collecting all household waste in the Centrum area. The main advantage of using vessels is that no harm will be done to the quay walls; the water will carry the weight of the vessels. During the morning hours, there are almost no other water users, while the streets are already crowded. By using autonomous vessels, it would even be possible to operate during the night without making it a costly system. The negative side of using vessels is that they are slower than using trucks or other road vehicles. The possible container types for the vessels will be discussed in the following sections.

Floating dumpsters

One of the possible container types for using vessels could be floating dumpsters, which will be stationed next to the quay walls. These dumpsters will be collected with tugboats and brought to the AEB. An advantage of this dumpster is that no weight is resting on the quay walls. To reduce the movements of the vessels and to reduce the amount of change of the street view, the dumpster will only be there twice a week. The residents are already used to that frequency, so that is an advantage as well. Fundamental research for this application is already done by S. Zhang et al. (2018). However, the chance that waste will get into the water is plausible, and the capacity of these containers is relatively small as well. Therefore, some adjustments have to be made to make this a realistic applicable system. The design of this concept is already drawn for the Roboat project and shown in figure 2.1.

Figure 2.1: Floating dumpster in the Centrum area of Amsterdam [1]

Build-in containers

The other considered container possibility is located in the quay walls. The municipality of Amsterdam will restore many quay walls in the city centre, and the new quays could be equipped with build-in container. These containers could be emptied in a garbage vessel or a barge which will be guided by a tugboat. Therefore, people can throw away their waste each day of the week. However, there is not much research done for emptying containers in floating objects.

Design possibilities

There are several ways to design a floating dumpster or a build-in container. Although the focus of this research is not on the container design, it is important to consider the possibilities to

[1] http://senseable.mit.edu/waste-streams/household/

check if the proposed method is even realistic in the future. In figure 2.2, nine different container types are drawn to create an overview of the possibilities.

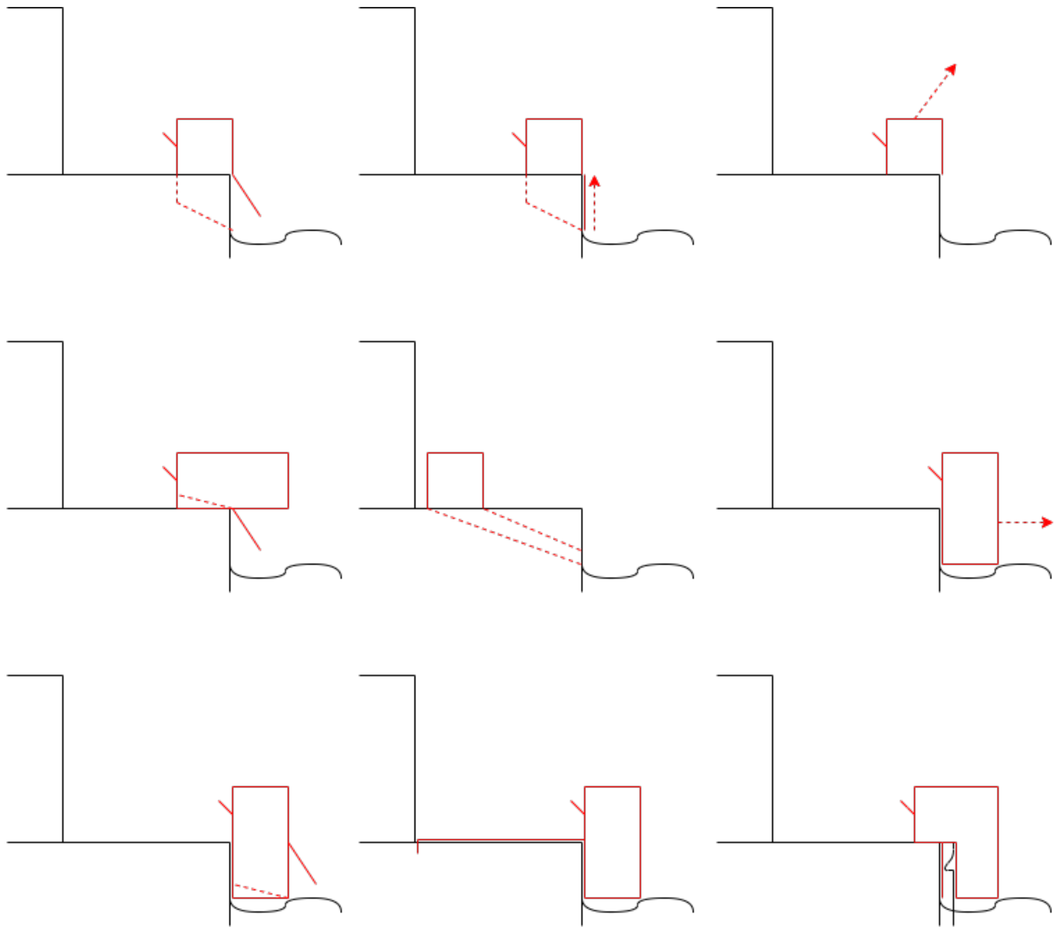


Figure 2.2: Nine different container possibilities

From left to right, and from top to bottom, the different sketches represent the following types of containers:
1) Build-in container with opening door with waste collection vessel or barge
2) Build-in container with sliding door with waste collection vessel or barge
3) Container on quay will be picked up by container vessel with crane
4) Large container on the quay, waste will drop into the waste collection vessel or barge
5) Build-in container with pipe to the waste collection vessel or barge
6) A floating container combined with a tug boat
7) A floating container which will be emptied by a waste collection vessel or barge
8) Flying container resting on the road combined with waste collection vessel or barge
9) Container resting on quay support combined with waste collection vessel or barge
Although no decision has to be made during this research, it is assumed that container type 1

or 2 will be used in the future. Both types would be equipped with a connector on top in case the container must be emptied with a crane, suggested in concept 3. AMS Institute is currently researching the possibilities for developing these containers.

2.3.2 Trucks

Although the combustion and hybrid trucks, figure 2.3a, will be banned in Centrum from 2025 (Gemeente Amsterdam, 2015), it would still be possible to use electric trucks on a few roads which can handle the heavy load. This is the case for the main roads of Centrum, which are defined as 'Hoofdroutes' by the municipality. The use of garbage trucks is a proven concept, they are relatively cheap, and the inhabitants are used to this method. Nevertheless, they are too heavy for the quays, and the electric trucks are even more onerous than the combustion engine trucks. Therefore, the trucks cannot operate alone to collect all the municipal waste in the Centrum area, but they are a considered candidate for a partial role in the future waste collection system.

Underground containers

Each district in Amsterdam is accommodated with underground containers, except the Centrum area. The trucks can easily lift the large containers with a grabber and empty them in the truck. In some areas there are already smart containers, which are able to communicate with the municipality if they are almost full. This smart container is currently the best solution for waste collection with trucks and is shown in figure 2.3b.

(a) A garbage truck from the municipality of Amsterdam

(b) An underground smart container [2]

Figure 2.3: Truck and container

[2]https://sidcon.nl/restafval/

2.3.3 Small electric vehicles

One of the possible solutions for a new waste management system could be replacing the heavy trucks with smaller electric vehicles (EVs), shown in figure 2.4a. This could be done with one person who picks up the garbage bags from the ground or by collecting containers which are located on the ground. The latter situation is already considered in the area around the 9-straatjes and the Central Station of Amsterdam by Zoev-City (Verweijen, 2020). These EVs are significantly lighter than the currently used trucks.

Dynamic container

These EVs are designed for specific portable containers with a volume of 3 m^3, the so-called EcoCassette. The small electric vehicle picks up the containers and replaces them with empty ones. These containers are a good solution for a dynamic system since they could be located on demand and are not assigned to one specific location. Due to their relatively small size, they could be located on parking spots, for example. Therefore, no structural adjustment have to be made, which saves costs. The main disadvantage is that they cause theoretically more movements per street due to the smaller size of the containers, while the municipality prefers fewer road movements and vehicles. However, by combining household waste and commercial waste into one system, the number of movements will significantly be decreased.

(a) An electric vehicle picking up an EcoCassette

(b) The EcoCassette, a dynamic portable container

Figure 2.4: The solution with EVs and EcoCassettes

2.3.4 Drones

In the last couple of years, many experiments are done with self-driving autonomous drones. The first prototype was launched in 2015, and since 2016 companies such as FedEx and Amazon are testing these drones in specific areas. Instead of delivering packages, they could also work the other way around: collecting garbage bags on appointment at your front door. An ideal scenario would be that these drones would be a multi-purpose vehicle which could deliver packages and collect waste at the same time. However, conflicting interests between companies would become an obstacle.

Figure 2.5: A self-driving drone designed for package delivery [3]

2.3.5 Underground vacuum system

Another serious possibility is a vacuum pipe system underground, or in the water, to collect the garbage bags. The new housing project in the Sluispoort area[4] will be equipped with such an underground vacuum system. Also, parts of Stockholm are already using this system, and it works properly[5]. This could be an uncapacitated waste collection system in the centre of Amsterdam. By building this pipe network under the water surface, it would be easier to repair or replace the pipes than if they are built in the quays. Disadvantages could be the high energy consumption of the vacuum pumps or the threat of a terrorist attack due to the large open network. This static system could look like figure 2.6

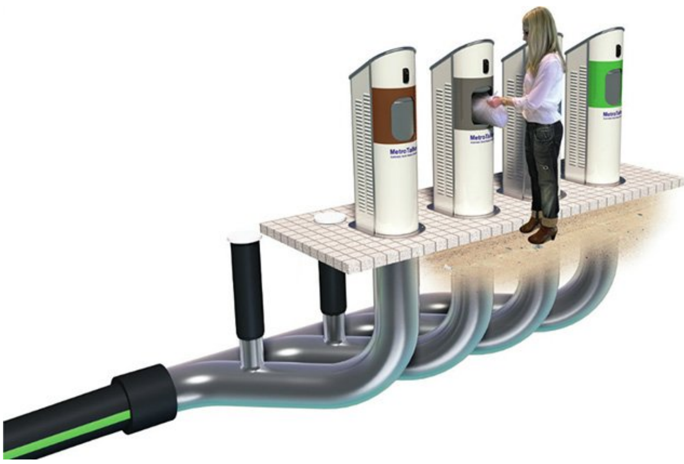


Figure 2.6: A vacuum waste system[6]

[3]https://tech.eu/brief/starship-launches-rollout-autonomous-delivery-services-plans-deploy-1000-robots-2018/
[4]https://www.parool.nl/nieuws/afval-in-de-sluisbuurt-straks-afgevoerd-via-buizen b1564a73/
[5]https://www.envacgroup.com/waste-collection-reimagined/

2.4 Facility location problems

A common problem with great practical importance is to choose the location of facilities, such as fire departments or warehouses, in order to achieve a specific objective while satisfying the demand for some commodity (Cornuéjols et al., 1983). Depending on the specific problem to be tackled, costs, travel distance, or market share could be one of the objectives. This method could be applied for a wide range of situations, as long as there is a set of possible facility locations and a certain demand on the other side. If each demand area can be covered by two or more facilities that each covers a percentage of demand, it is called an implicit approach. If that demand point is covered by one specific facility, it is an explicit problem (Qian, 2012). The set of demand points is described as set I, and the possible facility locations are described as set J. The specific costs between the sets I and J are generated in Matrix d $[I\text{x}J]$, where d_{ij} is the cost between point $i \in I$ and $j \in J$. The goal of a facility location problem is to find a set S of facilities i to serve the (partial) demand of set J. Since the situations could vary from locating supermarkets to define container locations for a district, it is understandable that the objectives of set S vary as well. For example, supermarkets are not limited by a certain capacity, but containers are filled after a while. Examples of different objectives of set S could be (Farahani, SteadieSeifi, and Asgari, 2010):

- Minimizing total cost
- Minimizing average travelling time/distance
- Maximizing coverage
- Maximizing capacitated coverage
- Maximizing coverage and minimize facilities
- Maximizing market share

The corresponding objective functions of these objectives could be assigned to the following types of FLPs shown in table 2.1. The type of FLP defines the corresponding name of the problem and the variations will be discussed in the following paragraphs.

[6] http://www.metrotaifun.com/

Common approach	Variation
Uncapacitated	Capacitated
Single-objective	Multi-objective
Single-level	Multi-level
No echelons	Multi-echelons
Single-facility	Multi-facility
Exact	Heuristic
Discrete	Continuous
Non-hierarchical	Hierarchical

Table 2.1: Different types of facility location problems

2.4.1 Capacitated Facility location problem

An FLP without any comments is usually an uncapacitated FLP (UFLP). Once the facilities are limited in assigning demand points due to a given capacity, the FLP is called a Capacitated Facility Location Problem (CFLP). Most of the waste management systems are a typical example of a CFLP, where their size and pick-up frequency, combined with waste production, determine the container capacity. There is plenty of research done in CFLP and listed in reviews (Sridharan, 1995),(Verter, 2011).

2.4.2 Multi-objective facility location problem

A multi-objective facility location problem (MOFLP) consists of two or more objective functions. A popular MOFLP is a maximization of the attendance while minimizing the costs. By assigning weight to the different objectives, a priority of the objectives can be assigned (Matai, 2015).

2.4.3 Multi-level facility location problem

The multi-level facility location problem (MLFLP) consists of two or more layers of facilities, which means that the selection of the closest facilities for the first layer is not always the best selection for the entire problem. Therefore, this FLP is a computational power consuming method and well-known in supply-chain. Possible solutions for an MLFLP are shown in figure 2.7.

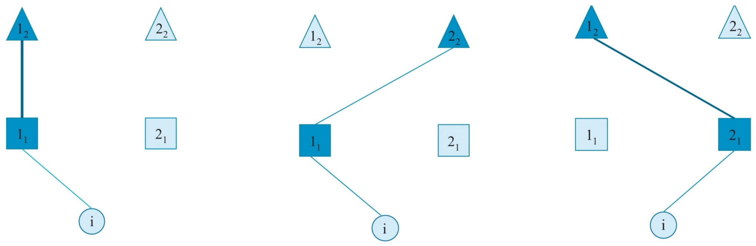


Figure 2.7: Solution possibilities for a Two-level facility location problem (Rodriguez and Doria, 1996)

2.4.4 Multi-echelon facility location problem

The term echelon is generally associated with distribution networks where products are transported between each pair of levels. Such pairs are called echelons. The multi-echelon FLP (MEFLP) is well known in the telecommunication sector and often applied for multi-depot problems such as mail and boxes delivery (Gao and Robinson Jr, 1992), (Tragantalerngsak et al., 2000), (Li et al., 2014).

2.4.5 Multi-facility location problem

In some situations, it is interesting to define the most efficient location for a specific store, warehouse or hospital. In that case, the focus is on a set of demand points and only one facility point, a so-called single-facility location problem (SFLP). The multi-facility location problem (MFLP) focuses on a set of facilities to locate (Farahani and Hekmatfar, 2009). Most often, the goal is to locate a set of new facilities such that the transportation cost from facilities to customers is minimized and an optimal number of facilities is found to satisfy the customer demand.

2.4.6 Heuristic facility location problem

Heuristics are needed to solve large problems quickly and to provide good initial solutions for algorithms (Azarmand and Neishabouri, 2009). These heuristics generates subsets to improve the calculation speed, and within these subsets, an exact approach could be used. The first time heuristics were applied for a FLP was in 1964, and many heuristics have been proposed for classic FLP since then (Cooper, 1964). Examples of this approximate method are the Lagrangian heuristics (Caprara, Fischetti, and Toth, 1999), Greedy heuristics (Jain, Mahdian, and Saberi, 2002) and Local search heuristics (Yagiura, Kishida, and Ibaraki, 2006). An even rougher method is applying meta-heuristics, which include simulated annealing (Vincent, Lin, Lee, and Ting, 2010), genetic algorithm (Solar, Parada, and Urrutia, 2002) and tabu search (Sun, 2006). For the exact method, a branch and bound algorithms (Fisher and Kedia, 1990) or Lagrangian relaxation (Balas and Carrera, 1996) could be applied, for example.

2.4.7 Continuous facility location problem

Within a continuous FLP, the selection of the new facility locations can be anywhere within the specified space (Wong and Sun, 2001). For the location of containers along streets, this means that the street could be defined as a continuous line where containers could be located. A discrete FLP would generate points along the same street. These points become possible container locations. A continuous FLP is more accurate than the discrete FLP. However, the calculation time will be improved by using a discrete approach.

2.4.8 Hierarchical facility location problem

A popular MLFLP is the hierarchical FLP (HFLP). HFLP models are commonly used for healthcare systems and waste management systems, which are summed up in the different literature reviews (Farahani et al., 2019)(Şahin and Süral, 2007). According to Sahin et al., hierarchical systems have to decide about the locations of their interacting facilities within a multiple layer configuration. Within waste management systems, this means mostly that the multiple facility layers represent pick-up, drop-off and storing points. The system needs to follow the path from the first facility layer to the second facility layer. No decisions have to be made to chose between one of the layers. Therefore, these methods are not comparable to the problem described in section 1.2. There are multiple HFLPs focusing on waste management systems (Böttcher and Rembold, 1977), (Demir et al., 2001) and (Barros et al., 1998).

2.5 Solution methods

There are several possibilities to solve the described problems with either exact methods and approximate algorithms (heuristics and meta-heuristics). The most common method is to use mixed integer programming (MIP) or linear programming (LP). These MIP or LP packages could be added to programming software such as Python, Matlab or Java. The advantage of using these programs is that the algorithm is build from scratch and relatively easy to make adjustments within the code. At the same time, that is a disadvantage: it is relatively time-consuming to build the whole algorithm, and it is harder to validate the model. A different and relatively new method is solving these kinds of problems with Geographical Information Systems (GIS). Gu et al. stated in 2009 that solving the location-allocation problem with geographical software is a new problem in facility location research. Location-allocation generally refers to FLP algorithms within GIS software to determine the optimal location of facilities. Since 2009 it became a more popular method to solve these complex problems, especially on larger scales were road or water networks are time-consuming to regenerate. One of the reasons for the success of GIS is their capacity to generate visualizations of data, which greatly assist in such a complex decision-making process as retail site or container location (Hernandez, 2007)(Musyoka et al.,

2007)(Gu, Wang, and Geng, 2009). An advantage of using GIS is that the software itself easily generates large data sets. For example, the origin-destination cost matrix, which calculates all walking distances between the possible facility and demand points using the road network. Using GIS software makes it easy to check if the output makes sense due to the visualizations. Also, the interface is user friendly, and it is possible to give demands to the system with build-in buttons as well as Python.
Especially for time-limited projects, it is profitable to use GIS software instead of any programming language. GIS software is developed to solve FLPs and other problems in an easier way than it was before. Therefore, it is usually less time consuming than developing the model completely from scratch with any programming language. GIS software is a proven success for accurate outcomes within municipal solid waste management systems (Rathore and Sarmah, 2019),(Tirkolaee, Mahdavi, Esfahani, and Weber, 2020) and (Garcia-Palomares, Gutiérrez, and Latorre, 2012). The visual output creates a direct confirmation of the quality and reliability of the simulation. Finally, once all required shapefiles are uploaded, and the calculation settings are set, it is easy to compare calculations by adjusting the parameters.
The possible location-allocation objectives are described in the following paragraphs, which could be solved with either GIS software or a programming language.

2.5.1 Minimize Weighted Impedance

The minimize weighted impedance method is commonly used for a warehouse problem, and it minimizes the walking distance in the container location case. This method is also known as the P-Median method (or K-Median in some research). Facilities are located such that the sum of all weighted costs between demand points and solution facilities is minimized for the given number of located facilities, which will be the walking distance in this research. This optimization method does not take any cut-off distance into account, neither capacity for each facility point (Mladenović, Brimberg, Hansen, and Moreno-Pérez, 2007)(Karatas, Razi, and Tozan, 2016).

2.5.2 Maximize Coverage

The maximize coverage method is a calculation method for the uncapacitated facility location problem, which aims to find a set of facilities that serve the maximum possible number of demand points within the impedance cut-off. The number of located facilities could be defined in advance to solve the problem for a certain price, for example, or iterations could obtain the optimal number of located facilities.

2.5.3 Maximize Capacitated Coverage

This solution method has the same objectives as the maximize coverage method in section 2.5.2, this time with a capacity assigned to the facilities (Chauhan, Unnikrishnan, and Figliozzi, 2019).

Therefore, this solution method is applied to capacitated FLPs. Again, facilities are located to maximize the coverage within the impedance cut-off. The number of located facilities could be defined in advanced or could be found by iterations.

2.5.4 Maximize Coverage and Minimize Facilities

The maximize coverage and minimize facilities approach is a variation on the maximize coverage method (Trilling, Guinet, and Le Magny, 2006). The solution methods are both applied to uncapacitated FLPs, possibly restricted to a certain impedance cut-off. The difference between the two approaches is that the maximize coverage and minimize facilities method calculates the minimum required number of facilities to serve the total possible demand, where the maximize coverage method calculates the maximum number of demand points that could be assigned to the defined number of facilities.

2.5.5 Maximize Attendance

This method is based on the likeliness a demand point will be served by a facility, specially developed for locating supermarkets or other stores with a competitive behaviour (Hillsman, 1984). The facilities are chosen such that as much demand weight as possible is allocated to facilities while assuming the demand weight decreases with the distance between the facility and the demand points.

2.5.6 Maximize Market Share

The maximize market share method focuses on assigning as much demand points around the possible facility points based on competition between facilities. A specific number of facilities is chosen such that the allocated demand is maximized in the presence of competitors. The goal is to capture as much of the total market share as possible with a given number of facilities, which is defined in advance. The total market share is the sum of all demand weight for valid demand points.

2.5.7 Target Market Share

The target market share method based on the same principle as the maximize market share approach but works the other way around. The target market share objective chooses the minimum number of facilities necessary to capture a specified percentage of the total market share in the presence of competitors. The total market share is the sum of all demand weight for valid demand points. The percentage of the market share could be defined in advanced; the objective defines the minimum number of required facilities to meet that threshold.

2.6 Previous research for Roboat project

The most recent research for waste collection in Amsterdam with Roboats is done by Zhang et al. (2018) and Daub et al. (2019) in order of MIT. Zhang researched the location and number of required containers, while Daub researched the routing for the waste collection, assuming the locations of Zhang. Their research assumed that floating dumpsters would be used as containers, with a capacity of one ton, which will be collected with tugboats and brought to the AEB. The floating dumpsters will be located throughout the city and are assigned to residents within 120 meters, based on the average maximum walking distances of the other districts. The dumpsters will be located and collected twice per week and follow the current pick-up schedule for each neighbourhood. However, this research does not take commercial waste into account that will be dumped in these containers as well. Also, no restrictions were applied to the possible container locations except for the area around bridges. This research gave a good insight into the possibilities of waste collection in Amsterdam with autonomous vessels, but some calculations and assumptions should be redefined. After personal communication with P. Rosenburg (2020), which is responsible for the spatial quality in the city and the UNESCO-world-heritage canals appearance, it became clear that build-in containers are preferred over the proposed floating dumpsters. The dumpsters could be a cheaper solution since they are dynamic and reused in different locations all the time. Therefore, around 95 dumpsters would be necessary to serve the selected 283 container locations. The results of the research are shown in table 2.2.

Neighborhood	Density (Household/bin)	% within 97.6 m	% within 120 m	% within 150 m
Nieuw-West	14	91%	94%	95%
Noord	68	78%	87%	93%
Oost	40	91%	94%	95%
West	290	21%	23%	26%
Zuid	49	55%	57%	61%
Average	**92**	**67%**	**71%**	**74%**
Centrum	**1106**	**87%**	**100%**	**100%**

Table 2.2: Results of the research on floating dumpsters (Zhang et al., 2018)

2.7 Decision possibilities

During the qualitative research in the beginning of this scientific research, several decisions and assumptions were made to define a solution approach. These decisions vary from the scope to pick-up times of the containers. In the beginning of the research it was unclear if the Roboat and container design would be included. Due to the limited time range only suggestions were made for the design. Important decisions towards waste collection with autonomous vessels are listed in table 2.3, based on the personal talks with stakeholders.

Operational decisions			Decision
	Scope	Centrum	Selected
		Part of Centrum	
		Zoev city's locations	
		Jetties	
	Drop-off location	AEB	Assumed, no effect
		Incinerator	
		Semi-Hubs	
	Pick-up times	Daytime	
		7 - 10 a.m.	Suggested, no effect
		Nighttime	
	Pick-up frequency	Twice a week	Truck containers
		Three times per week	Roboat/EV containers
		Everyday	
	Max. walking distance	150 meters	Selected
		Same as other districts	
	Container location restrictions	Bridges	Selected
		Houseboats	Selected
		Buildings and gardens	Selected
		Trees	
		Parking spaces	
		Underground infrastructure	
Waste decisions			
	Container types	Build-in container	Assumed, no effect
		Floating	
	Waste transport	Pushed into vessel	Assumed, no effect
		Lifted with crane	Optional
	Waste types	All waste	
		Household waste	Selected
		Commercial waste	
Roboat decisions			
	Roboat type	Waste collection vessel	
		Tug boat	Suggested, no effect
		Container collector	
	Roboat size	Current size (4x2x1m)	
		Ideal for tug	Suggested, no effect
		Ideal for waste collection	

Table 2.3: Decision possibilities

As described in section 1.4, the scope is the whole Centrum area of Amsterdam. This contains a large data-set, which results in time-consuming calculations. However, the results will be more accurate than splitting the Centrum area into smaller parts or only use specified locations. The previous research for the Roboat project assumed that there could be an incinerator at the edge of the Centrum area where the Roboats could drop the collected floating dumpsters (Zhang et al., 2018)(Daub, 2019). However, this is not plausible due to the high number of buildings around that location. It could be possible to create semi-hubs where the floating dumpsters or only the waste will be transported from one small vessel to another larger one. This research assumes that large barges without propulsion systems will be used to collect the waste from the build-in quay wall containers and will be guided by Roboat tugboats. As long as the waste collection could be done quietly, it is allowed to do so during the night. However, it is expected that it will make too much noise. Since the canals are relatively empty between 7 and 10 a.m., this time slot is suggested. The rest of the decisions will be elaborated in chapter 4.

2.8 Proposed system

This research focuses on a household waste collection system in the Centrum area with Roboats in combination with trucks and EVs. The municipality does not want to focus yet on one specific system before all possibilities, costs and effects are elaborated. Therefore, both a system with and without trucks will be taken into account. Although it is still unknown if the EVs will be the future of waste collection, it is the solution which is the closest to reality and a better-tested system than the drones. However, if the municipality of Amsterdam decides to collect waste with Roboats and drones, this research is still applicable. The drones could serve the households which are not assigned to a Roboat container. No specific locations have to be defined for the containers since drones are a dynamic solution. Only the number of applied drones should be calculated based on their capacity and operational speed. Furthermore, the model could be used for floating dumpsters as well as build-in containers. Only the capacity should be adjusted. This is also true for a vacuum waste system; only an uncapacitated solver would be used since the capacity of that system is infinite.

So, there are two proposed systems which will be compared with each other; Collecting waste in the centre of Amsterdam with Roboats, trucks and EVs, and the second waste collection system only consists of Roboats and EVs. The Roboats will use the canals to collect the waste from the build-in containers in the quay walls. There is no container prototype yet, but AMS Institute is currently designing a suitable container concept. Most likely the container will empty the waste in a large barge which will be guided by one or two Roboat tugboats. The trucks will lift-up underground containers to collect the waste, similar to the way they do so in the other areas of Amsterdam. Finally, the EVs will collect the EcoCassettes, or other dynamic containers, and change them with empty and clean containers. The EVs bring the filled containers to a barge which can carry multiple EcoCassettes. Both Roboats combined with a barge and the barge with the EcoCassettes will sail to the AEB, where the waste can be separated and incinerated. The route from the Centrum area to the AEB is over ten kilometres and is shown in figure 2.8. The trucks will use the road network to visit the AEB.

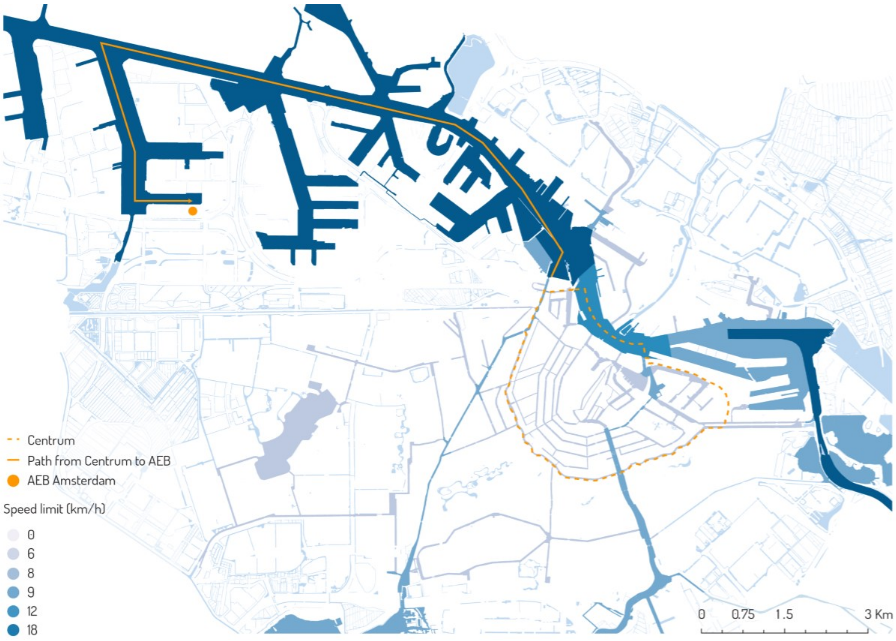


Figure 2.8: Roboat collecting waste in Centrum and dropping it at the AEB (Zhang et al., 2018)

Chapter 3

Mathematical modelling

This chapter starts with the basic mathematical models that are commonly used for different facility location problems. These objective functions with corresponding constraints could be used to solve the FLP. These models assume a single set of demand points and a single set of facility points. Since this research focuses on three different sets of facilities, an advanced MIP model is provided in section 3.2. The objective and constraints of this model correspond with the described system requirements described in section 2.2. Several model descriptions discussed in chapter 2.5 are useful for FLPs but not relevant for the container problem in the Amsterdam Centrum area. The maximize attendance model, described in section 2.5.5, aims to assign as much demand as possible to a facility point, based on the likeliness that the demand will visit the facility. The objective is based on competition, where the container location in Amsterdam aims to be not competitive at all. It could cause problems if people started using other containers than the one they are assigned to. The two other models that will be left out from this point are the maximize market share and target market share models, described in section 2.5.6 and 2.5.7, respectively. Those models are also based on competition and on (a percentage of) the market share, which is not preferred.

3.1 Basic models

The integer programming models in the following sections are described by the following sets, indices, parameters and decision variables. Consider a set of demand points $i \in I$ and a set of possible facility locations $j \in J$, with a distance $d_{i,j} \geq 0$ between demand point $i \in I$ and facility $j \in J$. The first objective $x_{i,j}$ describes if demand node $i \in I$ is assigned to a specific facility $j \in J$. The following decision variable is y_j, which describes if a facility is located at $j \in J$.

Sets

I	Set of all demand points [Households]
J	Set of all possible facility points [Containers]

Indices

$i \in I$	Demand point in the set of demand points
$j \in J$	Facility point in the set of facility points

Parameters

$d_{i,j}$	Travel distance [m] between demand point $i \in I$ to facility $j \in J$
d_{max}	Maximum walking distance [m]
p	Maximum number of facilities
C	Capacity of each located facility

Decision variables

$x_{i,j} =$	1,	if demand node $i \in I$ is assigned to facility located at $j \in J$
	0,	otherwise
$y_j =$	1,	if facility is located at $j \in J$
	0,	otherwise

3.1.1 Minimize weighted Impedance

This location-allocation model is also known as the P-median problem (PMP) or the warehouse problem and is described in section 2.5.1. The PMP chooses facilities such that the sum of the walking distances between the demand points and facilities is minimized for a given amount of facilities. With the described sets, indices, parameters and decision variables, the formulation of the PMP method is as follows (Mladenović et al., 2007),(Karatas et al., 2016):

$$\min \sum_{j \in J} \sum_{i \in I} d_{i,j} x_{i,j} \tag{3.1}$$

Subject to:

$$\sum_{j \in J} x_{i,j} \leq 1, \forall i \in I \tag{3.2}$$

$$x_{i,j} - y_j \leq 0, \forall i \in I, j \in J \tag{3.3}$$

$$\sum_{j \in J} y_j \leq p \tag{3.4}$$

$$x_{i,j} d_{i,j} \leq x_{i,j} d_{max}, \forall i \in I, j \in J \tag{3.5}$$

$$x_{i,j} \in \{0, 1\}, \forall i \in I, j \in J \tag{3.6}$$

$$y_j \in \{0, 1\}, \forall j \in J \tag{3.7}$$

The objective function in (3.1) describes the minimization of distance $d_{i,j}$ summed over all facilities and demand nodes. The first constraint in (3.2) states that a demand point i can only be assigned to one facility j. The next constraint, described in (3.3), states that demand node i can be served by a facility at j only if there is a facility at j, because if $y_j = 0$ then we must have that $x_{i,j} = 0$. The constraint (3.4) means that we must place exactly p facilities. Lastly, the constraints (3.6) and (3.7) force the decision variables to be binary.

3.1.2 Maximize Coverage

For the maximize coverage model the walking distance is not involved in the objective. The maximize coverage model aims to cover as many demand points as possible with a given number of facilities. The number of facilities is defined in advance. Therefore, this model could be used as an iteration tool. The objective is described in equation 3.8.

$$\max \sum_{i \in I} x_{i,j} \tag{3.8}$$

Subject to:

$$\sum_{j \in J} x_{i,j} \leq 1, \forall i \in I \tag{3.9}$$

$$\sum_{j \in J} y_j \leq p \tag{3.10}$$

$$x_{i,j} - y_j \leq 0, \forall i \in I, j \in J \tag{3.11}$$

$$x_{i,j} d_{i,j} \leq x_{i,j} d_{max}, \forall i \in I, j \in J \tag{3.12}$$

$$X_{i,j} \in \{0, 1\}, \forall i \in I, j \in J \tag{3.13}$$

$$Y_j \in \{0,1\}, \forall j \in J \tag{3.14}$$

3.1.3 Maximize Capacitated Coverage

The maximize capacitated coverage model has the same objective as the maximize coverage model. However, this model is limited by a given capacity. Consider a set of demand points $i \in I$ and a set of possible facility locations $j \in J$, with a distance $d_{i,j} \geq 0$ between demand point $i \in I$ and facility $j \in J$. Other parameters are p for the maximum number of facilities and C for the capacity of each located facility. The formulation of the maximized capacitated coverage problem is as follows (Chauhan et al., 2019):

$$\max \sum_{i \in I} x_{i,j} \tag{3.15}$$

Subject to:

$$\sum_{j \in J} x_{i,j} \leq 1, \forall i \in I \tag{3.16}$$

$$\sum_{j \in J} y_j \leq p \tag{3.17}$$

$$\sum_{i \in I} x_{i,j} \leq C y_j, \forall j \in J \tag{3.18}$$

$$x_{i,j} - y_j \leq 0, \forall i \in I, j \in J \tag{3.19}$$

$$x_{i,j} d_{i,j} \leq x_{i,j} d_{max}, \forall i \in I, j \in J \tag{3.20}$$

$$X_{i,j} \in \{0,1\}, \forall i \in I, j \in J \tag{3.21}$$

$$Y_j \in \{0,1\}, \forall j \in J \tag{3.22}$$

The maximize capacitated coverage model does not require an impedance cutoff. However, when an impedance cutoff is specified, any demand point outside all the facilities' impedance cutoffs is not allocated. If the total demand within the impedance cutoff of a facility is greater than the capacity of the facility, only the demand points that maximize total captured demand and minimize the total weighted impedance are allocated. An allocated demand point has all or none of its demand weight assigned to a facility; that is, demand is not apportioned with this problem type.

3.1.4 Maximize coverage and minimize facilities

For the maximize coverage and minimize facilities method, no specified number of located containers is predefined. Therefore, this model can not be used as an iteration tool. Usually, this method is used without an assigned capacity. The objective of the model is to assign as much demand points to the least possible facility points. The objective is described in equation 3.23 (Trilling et al., 2006).

$$\max \sum_{i \in I} x_{i,j} - \sum_{j \in J} y_j \tag{3.23}$$

Subject to:

$$\sum_{j \in J} x_{i,j} \leq 1, \forall i \in I \tag{3.24}$$

$$x_{i,j} - y_j \leq 0, \forall i \in I, j \in J \tag{3.25}$$

$$x_{i,j} d_{i,j} \leq x_{i,j} d_{max}, \forall i \in I, j \in J \tag{3.26}$$

$$X_{i,j} \in \{0, 1\}, \forall i \in I, j \in J \tag{3.27}$$

$$Y_j \in \{0, 1\}, \forall j \in J \tag{3.28}$$

3.2 Advanced model

The following advanced model is developed to describe the objective and constraints of the waste collection problem in Amsterdam Centrum, based on the given requirements by the municipality, described in section 2.2. The model contains the three containers types, collected by the different modalities. These are the Roboat, truck and EV containers. This model could be described as a capacitated multi-facility location problem. The model is described as follows:

Sets

I	Set of all demand points [Households]
J	Set of all possible Roboat container points
K	Set of all possible truck container points
L	Set of all possible EV containers points

Indices

$i \in I$	Demand point in the set of demand points
$j \in J$	Roboat container point in the set of Roboat container points
$k \in K$	Truck container point in the set of truck container points
$l \in L$	EV container point in the set of EV container points

Parameters

$d_{i,j,k,l}$	Travel distance [m] from demand point $i \in I$ to facility $j \in J$, $k \in K$ or $l \in L$	
d_{max}	Maximum walking distance [m]	
$p_{j,k,l}$	Maximum number of facilities j, k or l	
$C_{j,k,l}$	Capacity of facility j, k or l	
$\boldsymbol{w_m} =$	Weighting factors (w_1, w_2, w_3)	$w_m \in \{0, 1\}$

Decision variables

$r_{i,j} =$	1,	if demand node $i \in I$ is assigned to a Roboat container located at $j \in J$
	0,	otherwise
$s_{i,k} =$	1,	if demand node $i \in I$ is assigned to a truck container located at $k \in K$
	0,	otherwise
$t_{i,l} =$	1,	if demand node $i \in I$ is assigned to an EV container located at $l \in L$
	0,	otherwise
$y_{j,k,l} =$	1,	if facility is located at $j \in J, k \in K$ or $l \in L$
	0,	otherwise

$$\max \sum_{i \in I} (w_1 r_{i,j} + w_2 s_{i,k} + w_3 t_{i,l}) - \sum_{j \in J} \sum_{k \in K} \sum_{l \in L} y_{j,k,l} \tag{3.29}$$

Subject to:

$$\sum_{j \in J} r_{i,j}, \sum_{k \in K} s_{i,k}, \sum_{l \in L} t_{i,l} \leq 1, \forall i \in I \tag{3.30}$$

$$\sum_{j \in J} y_j \leq p_j, \sum_{k \in K} y_k \leq p_k, \sum_{l \in L} y_l \leq p_l \tag{3.31}$$

$$\sum_{i \in I} r_{i,j} \leq C_j y_j, \sum_{i \in I} s_{i,k} \leq C_k y_k, \sum_{i \in I} t_{i,l} \leq C_l y_l, \forall j \in J, k \in K, l \in L \tag{3.32}$$

$$r_{i,j} d_{i,j} \leq d_{max}, s_{i,k} d_{i,k} \leq d_{max}, t_{i,l} d_{i,l} \leq d_{max}, \forall i \in I, j \in J, k \in K, l \in L \tag{3.33}$$

$$r_{i,j} d_{i,j} \leq d_{i+1,j}, s_{i,k} d_{i,k} \leq d_{i+1,k}, t_{i,l} d_{i,l} \leq d_{i+1,l}, \forall i \in I, j \in J, k \in K, l \in L \tag{3.34}$$

$$r_{i,j}, s_{i,k}, t_{i,l}, y_{j,k,l} \in \{0, 1\}, \forall i \in I, j \in J, k \in K, l \in L \tag{3.35}$$

The given requirements by the municipality are already discussed in section 2.2 and could be summarized by the following list:

1. Limit the total costs or use the least amount of containers, maximize the number of assigned buildings to one container
2. The total waste production from one household belongs all to one container
3. Do not exceed a certain number of located containers
4. No more waste on the streets, do not exceed the capacity
5. The maximum walking distance from a household to a container is 150 meters
6. Preferably a short walking distance

Each system requirement is translated to the model objective and its corresponding constraints. Starting with requirement 1, translated into the objective to maximize the number of assigned demand points for the three different container types and minimize the number of required containers to do so, described in equation 3.29. The first constraint, equation 3.30, states that at most one facility point is assigned to the demand of a certain demand point, either a Roboat, truck or EV container. The following constraint in 3.31 states the number of located containers may not exceed a given maximum number of containers, which creates to possibility to limit the costs if there will be a price difference between the containers. Requirement 4 aims to prevent waste ending up next to a filled container by defining a specific container capacity.

This requirement is translated to equation 3.32, which limits the assigned facility point by its capacity. Next, constraint 3.33 makes sure that facility points could only be assigned to demand points within the maximum walking distance, which is 150 meters in this particular case. The final requirement prefers a short walking distance, but is submissive to the objective. Constraint 3.34 is added to meet this requirement, which states that the shortest walking distance will be assigned before a demand point that is further away. Finally, the last constraints makes sure that the decision variables are binary.
Now, the system requirements are translated to a mathematical model. This means that from this point the solution method could be defined, based on this model and the provided data. This will be explained in the following chapter.

Chapter 4

Data and Experimental Setup

This chapter provides the obtained and applied data during this research. These data will be processed, combined with assumptions, into useful parameters. The selection of the used software will be discussed in section 4.4. Next, the experimental setup of the framework is provided in section 4.5 and 4.6, which describe the demand and facility points, respectively.

4.1 Provided data

The municipality of Amsterdam has a well-ordered open-source database[1] with over 300 data-sets that could directly be uploaded into GIS software, containing the registration of all households, houseboat permits, and speed limits on the water, for example. These data-sets are packed within shapefiles (SHP), Web Feature Service (WFS) or Web Map Service. The latter two are both connectable to the GIS software with a web link. So, if changes will be made within the data-sets, they could update the GIS model as well. It is possible to use the features of the WFS in commands. This means that it is possible to, for example, give a command to delete all possible containers outside 150 meters walking distance from all households, where the households are within the WFS. Unfortunately, this is not possible for the WMS files; these layers are only visible on the map but are not applicable within commands. It is also possible to link WFS and WMS files to a programming language with corresponding packages. However, this is more cumbersome than using GIS software. The final data-sets are provided in Excel files, which are processed with a programming language as well as GIS software.

4.1.1 Constructions and residents

The data about all buildings, households and residents are all provided by the municipality itself. These files about the buildings and households contain information about their geographical position, address, building date, if it is bought or rented, number of households per building, and

[1] https://data.amsterdam.nl/

others. This data is provided within shapefiles, which are geographical files containing points, lines or polygons with x- and y-coordinates. In table 4.1 the number of buildings, households and residents are shown, combined with the ratio of residents per building, and residents per households.

Layer	**Number**	**Residents per -**	**Source**
Buildings	12.250	7,09	(Gemeente Amsterdam, 2019a)
Households	51.132	1,70	(Gemeente Amsterdam, 2019a)
Residents	86.862	-	(Gemeente Amsterdam, 2019b)

Table 4.1: Number of residents, household and buildings in Centrum

An objective from the municipality is that the residents are not allowed to walk more than 150 meters towards a containers (Numan, 2020). The 150 meters have to be calculated along the shortest possible route from their house towards their assigned container. This 150 meters exceed the average maximum walking distance of the other districts in Amsterdam, which is calculated to be 97.6 meters (Zhang et al., 2018). Table 4.2 shows the maximum walking distance per district.

District	**Max. distance [m]**
Nieuw-West	53
Noord	132
Oost	71
West	150
Westpoort	N/A
Zuid	82
Zuid-Oost	N/A
Average	**97.6**

Table 4.2: Maximum walking distance per district

The walking distance between the demand points and facility points will be measured along the streets. The data website from the municipality also provided the road network file. Using the road network provides a much more accurate result than using the Euclidean distance.

4.1.2 Waste

The following data is also provided by the municipality and based on the household waste throughout the whole city (Reeze, 2020). Bulky household waste, coarse garden waste, and wood waste are not taken into account. Currently, these types of waste have a different collection flow and will be recycled or incinerated in different places. In table 4.3 the density, amount and

volume of the produced waste are shown per waste type. In this table, also organic waste is taken into account, which means all vegetable, fruit and other food waste. The municipality has made plans to start with collecting this organic waste separately from the other types. Organic waste causes a drop in the recycling rate due to the wet substance. It is not possible in Amsterdam to throw the organic waste in a grinder in the sink, what for example, happens in the United States. The sewer system in the Netherlands is not under pressure by which bacteria and fungus will affect the water recycling systems (E. Almer, 2020).
The calculated volumes of the different fractions are based on the provided density. However, these density values are clearly rounded. Therefore, the exact volume of the total produced waste could vary in practice.

Fraction	**Density [kg/m3]**	**Produced [kg]**	**Volume [m3]**
Rest	100	219	2,19
Paper	50	19	0,38
Glass	300	18,3	0,061
Textile	25	3,5	0,14
Plastic	150	4,2	0,028
Organic	400	17,9	0,045
Annually	99.13 (Average)	281,9	2,8438
Daily	99.13 (Average)	0,7723	0,0078

Table 4.3: Waste density and production per resident of Amsterdam

The municipality prefers a new MSW system, but they want to be sure that this system will work for the upcoming decades. Therefore, it is interesting to follow the growth of the waste production, shown in figure 4.4. In the past three years the total waste production per resident has decreased 30,1 kg which means an average of 10 kg per year. Between 2018 and 2019 this production has dropped by 6,7 kg. However, the number of residents are increasing every year. Comparing the 86.442 residents in 2018 with the 86.862 resident in 2019, it is still an annual decrease of almost 462 metric ton of household waste. The prediction of the municipality is that there will be 90.416 resident in 2025 and 86.515 in 2050[2]. If the waste production keeps decreasing, it is expected that the designed waste collection system will be able to serve all residents until at least 2050.

[2]https://data.amsterdam.nl/datasets/Q1fjq8zfXdlChA/bevolking-stadsdelen/

Fraction	2016	2017	2018	2019	Difference
Rest	248	242	226	219	-7
Paper	22,4	21,3	19,6	19	-0,6
Glass	17,7	17,5	18	18,3	+0,3
Textile	3,4	3,5	3,6	3,5	-0,1
Plastic	2,6	3,1	3,5	4,2	+0,7
Organic	-	-	-	17,9	
Total	294,1	287,4	270,7	264 (+17,9)	-6,7

Table 4.4: Overview of the annually produced waste per resident

Table 4.5 presents the waste collection per day in Amsterdam. On Monday and Tuesday the collection is higher than the rest of the week. During the weekend the collection is the lowest due to the reduction of shifts. Usually, there is no waste collected on Sunday, but exceptions are made from time to time. With this information it is not possible to say that the production of waste is the same as the amount of collected waste. From practical experience it can be concluded that containers are always overfull on Sunday which cause waste on the streets. This table is also graphically displayed in figure 4.1.

Day	MT/year
Monday	44.512
Tuesday	46.335
Wednesday	37.758
Thursday	39.358
Friday	42.394
Saterday	11.986
Sunday	865
Total	223.207

Table 4.5: Annually collected waste per day in Amsterdam

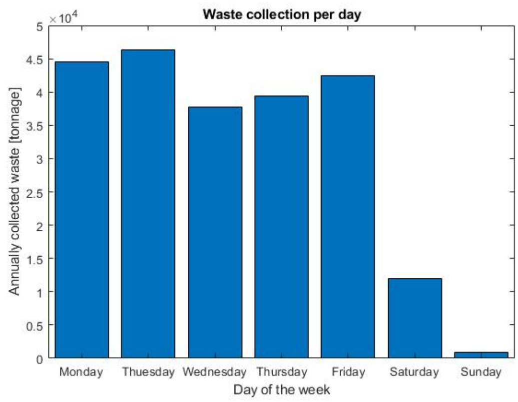


Figure 4.1: Waste collection per day in Amsterdam [MT]

The final data about waste collection in Amsterdam has a significant impact on the calculations. According to Numan (2020) and Almer (2020), two different experiments within the Centrum area have shown that circa 40% of the waste in a container originates from companies, which means that the residents itself can use only 60% of the container. A solution would be to apply DifTar (differentiated prices), where people get a (pre-paid) card and pay per bag with an easily integrated NFC system. The disadvantage could be that more waste will end up on the streets. The municipality prefers a so-called 'open' system, which would not be the case with DifTar. Therefore, the chance that this system will be implemented is relatively small.

4.2 Assumptions

During this research, the following assumptions have been made. First of all, this research assumes that walking distance does not vary over time. Which means that the containers and households are static objects that do not move, or that the route between the containers and households do not change. During road works, it could be possible that some containers are harder to reach, but this is neglected in the model. Another assumption is that waste production is constant over time. There is only data available on the waste collection over the week, but this does not give insight into the production of waste. However, it is plausible that waste production does vary over time. Due to the smart containers that communicate with the municipality about the filling rate of the container, it is possible to adapt to variations over time. Therefore, the total number of waste collection moments per container will not vary much from the first calculated number of pick-up moments. However, one of the advantages of using autonomous vessels and smart containers is that it is possible to scale up the waste collection frequency for unusual moments such as Kingsday, Christmas or new years day, where waste production is above average. Next, it is assumed that during the calculations, only 60% of the container space is available for residents, since companies will use 40% of the container. This directly assumes that this ratio is constant over all containers in Amsterdam Centrum.

The next assumption that has been made is that the build-in containers in the quay walls will have the same specifications as the underground containers. Currently, there is no container designed for waste collection via the canals yet. Plausible is that it will be developed with the company that already installed almost all smart containers in Amsterdam, which is Sidcon. The installed container will probably have the same grinder system in it and requires the same feature on top of the container to lift it with the garbage truck cranes. Therefore, the build-in container will have the same press ratio as well. The press ratio of the containers is also an estimation. The specifications on the website of the container supplier state that their container can compress residual waste up to six times[3]. However, practical experience points out that the average density of the compressed waste is around three times higher than before it was compressed. The trucks can even double that density again with their build-in compression system. The EV containers are based on the specifications of an EcoCassette, which are currently used during a pilot in Amsterdam (Gemeente Amsterdam, 2020a). The supplier of the EcoCassette states that the capacity of the container is at least five times higher than the actual volume of the waste[4]. However, practical experience has learned that the weight of a full EcoCassette will not exceed one metric ton, which means that the waste is only compressed around three times. The ratios are rounded to the lower integer due to the uncertainty of the assumptions.

The final assumption is that the Roboat and EV containers will be collected at most three times per week. Currently, every time waste is dropped at the AEB costs are taken into account.

[3] https://sidcon.nl/product/presstation-pro-voor-restafval/

[4] http://www.ecovision.nl/web/Products/EcoCassette.htm

Therefore, it is preferred to visit as least as possible with as many as possible waste. Since the trucks are estimated to have the largest capacity of the three modalities, it is accepted to collect the waste twice per week. The results of the container settings are shown in figure 4.6.

Modality	**Container volume [m^3]**	**Press ratio**	**Max. pick-up [$week^{-1}$]**
Roboat	5	3	3
Truck	5	3	2
EVs	3	3	3

Table 4.6: Applied container details

The final assumption that has been made is that each container has to be emptied at least one per week. This is done to prevent containers from an unacceptable and unpleasant smell.

4.3 Calculated parameters

With the previous describes data-sets and assumptions, it is possible to calculate the rest of the required parameters. First the capacity of the different container types will be calculated, either calculated in buildings per container as in households per container. The calculation requires the defined pick-up frequency, compression ratio, assumed volume share for household waste, container volume, the produced waste volume per day and finally the average number of resident per building or household. This results in the following equations:

$$\text{Buildings: } \mathrm{C}_{\text{Modality}} = \frac{\frac{\text{pick-up freq}}{\text{7 days}} * \text{ press ratio } * \text{ assumed share } * \text{ container volume}}{\text{waste volume per day } * \text{ resident per building}} \tag{4.1}$$

$$\text{Households: } \mathrm{C}_{\text{Modality}} = \frac{\frac{\text{pick-up freq}}{\text{7 days}} * \text{ press ratio } * \text{ assumed share } * \text{ container volume}}{\text{waste volume per day } * \text{ resident per household}} \tag{4.2}$$

The capacity of the Roboat container becomes therefore:

$$\mathrm{C}_{\text{Roboat}} = \frac{\frac{3}{\text{7 days}} * 3 * 60\% * 5}{0{,}0078 * 7{,}09} = 69,75 \quad \left[\frac{\text{buildings}}{\text{container}}\right] \tag{4.3}$$

The capacities are rounded to their lower integer since it is not possible to assign households only partly to a container. The same method is applied to calculate the container capacity for the other modalities. The results of these calculations are shown in table 4.7.

Capacity	Buildings	Households	Residents
Roboat	69	291	495
Truck	46	194	330
EVs	41	174	297

Table 4.7: Container capacity per modality

With these calculated capacities, it is possible to calculate the minimum required containers to serve every demand point. Therefore, all buildings within 150 meters of a possible Roboat container location are taken into account for the Roboat containers. The rest of the buildings are used for the calculation of the truck and EV container lower bound. There are 10.055 buildings located within the range of possible Roboat containers, which means that $\frac{10.055}{69} = 146$ is the minimum number of required containers if there is a perfect deviation. The rest of the 2195 buildings could be assigned to at least $\frac{2195}{46} = 48$ truck containers or $\frac{2195}{41} = 54$ EV containers. These values could be used as a starting point during the iterations discussed in chapter 5.

4.4 Software selection

The next important step during this research is to select the software to define the container locations. Therefore, the pros and cons of the different discussed solution methods have to be compared. The main advantage of a programming language is that the optimization will be developed from scratch. Therefore, it will be easier to make adjustments afterwards. Developing a model from scratch is also a disadvantage since that could take much time. Furthermore, it will be harder to apply the provided data from the municipality, since they are mostly shapefiles, WFS and WMS files. The advantage of GIS programs is that this software is developed for similar problems and therefore, less time consuming to work with. The build-in tools are already verified by other users which also saves time. The provided data is directly applicable, and it is easier to generate a network of streets. The generated visualizations as output are preferred to validate the calculation. The final advantage is that large data-sets are easily generated, for example, a matrix with the distances between all demand points and possible facility points. On the other hand, it is harder to make changes in a predefined software program. Nevertheless, since most GIS software programs are linked to a python command window, it is possible to do so.

After the pros and cons of a programming language and GIS software are weighted, it is decided to work with GIS software. QGIS is an open-source GIS software program which could be used for free. However, ArcGIS Pro is a more advanced program with professional network analysis tools (Flenniken, Stuglik, and Iannone, 2020).

After the software has been selected, the next step is to apply the data to the software and generate the required points, lines and polygons. This will be discussed in the following paragraphs.

4.5 Demand points

The demand points in this research represent all residents of the Centrum area. However, to increase the calculation speed, the first calculations are done with buildings containing at least one household. Therefore, these 12.250 buildings are generated into demand points and will be discussed in section 4.5.1. The final calculations of this research discussed in chapter 5, use all 51.132 households as input data. The household input data will be discussed in section 4.5.2.

4.5.1 Buildings

Since there was no accurate data available on the exact location of all 86.862 residents (Gemeente Amsterdam, 2019b), it was not possible to generate a demand point for each resident. Using the buildings containing at least one household is an estimation of the exact location and it limits the calculation time compared to using all households. There is a possibility to solve the problem for smaller areas within the Centrum area, but this is not preferred due to the negative effect of splitting areas. Therefore, this research starts with generating buildings in the whole centrum area containing at least one household. As shown in table 4.1, that means that there are 7,09 residents per building, on average. This is an inaccurate assumption since the number varies over the buildings. For example, one apartment block is seen as one building, containing over 100 residents.

4.5.2 Households

To increase the accuracy of the calculations it is preferred to use all 51.132 households as input data for the demand points. However, the calculation time will significantly increase. Therefore, it is suggested to start the initial calculations with the buildings and improve the accuracy by using the households after the preferred approach is determined. Figure 4.2 shows the density of the households per building. The darker the building, the more households they contain. By using the household data, the problem with a varying household density over the buildings is removed. From this point, there are on average 1,70 residents per household, which is much more accurate than using buildings.

Figure 4.2: The density of the number of household per building

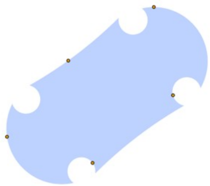
4.6 Facility points

The facility points in this research are the container locations. Since this research came to life due to the Roboat project, the main focus is on the Roboat container location. However, to give the municipality of Amsterdam insights in possible new waste collection systems, two other modalities and container types are also taken into account. The following section describes the generation of possible container locations.

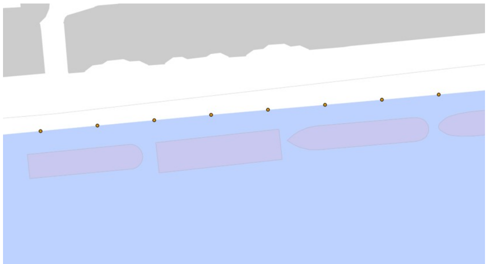
4.6.1 Roboat containers

The first step in the Roboat container generation in ArcGIS Pro is defining the waterways of Amsterdam Centrum. This consists of all open waters, so also small ponds in a park are taken into account. The next step is to generate a possible container point every ten meters along the edge of water and land. In most cases, this is a point along a canal or river. From this point, there is a set of possible Roboat container locations, and the final selected locations will be within this set. However, as earlier mentioned, there are several restrictions for locating a container along the border of water and land. To define potential facility points in the Centrum area, it is important to define the characteristics of an unsuitable location. So, a container can not be located if:

1. That point is not connected to the open water network. (Figure 4.3a)
2. A houseboat or vessel with a permit is located within 10 meters of that point. (Figure 4.3b)
3. It is under, or within a radius of 10 meters from a bridge. (Figure 4.4a)
4. A building is located on that point. (Figure 4.4b)
5. It is a backyard or where buildings are enclosing the area (courtyard). (Figure 4.5)

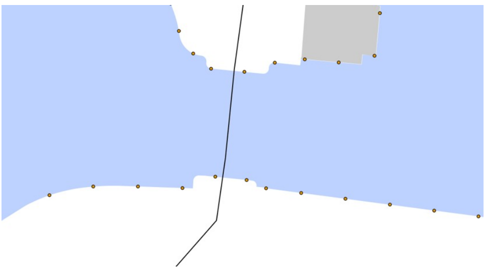


(a) Unsuitable rule 1

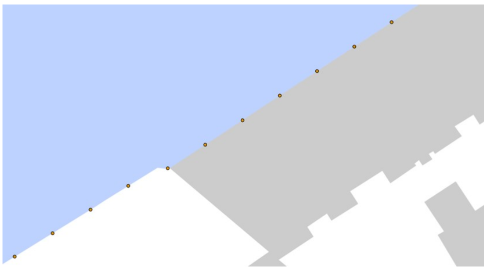


(b) Unsuitable rule 2

Figure 4.3: Examples of unsuitable container locations rule 1 and 2



(a) Unsuitable rule 3



(b) Unsuitable rule 4

Figure 4.4: Examples of unsuitable container locations rule 3 and 4

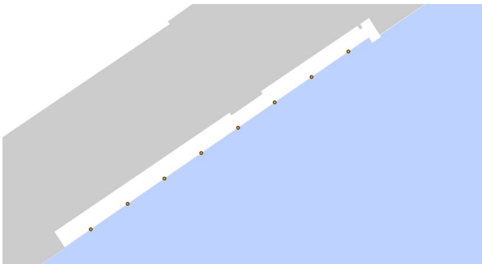


Figure 4.5: Example of unsuitable container locations rule 5

The next step is to remove the points which appear to be unsuitable based on the described restrictions. From that point, there are still enough possible locations to build Roboat containers and contribute to a potential new waste collection system. The result of the point generation is shown in figure 4.6. These points are randomly validated with google maps around questionable points.

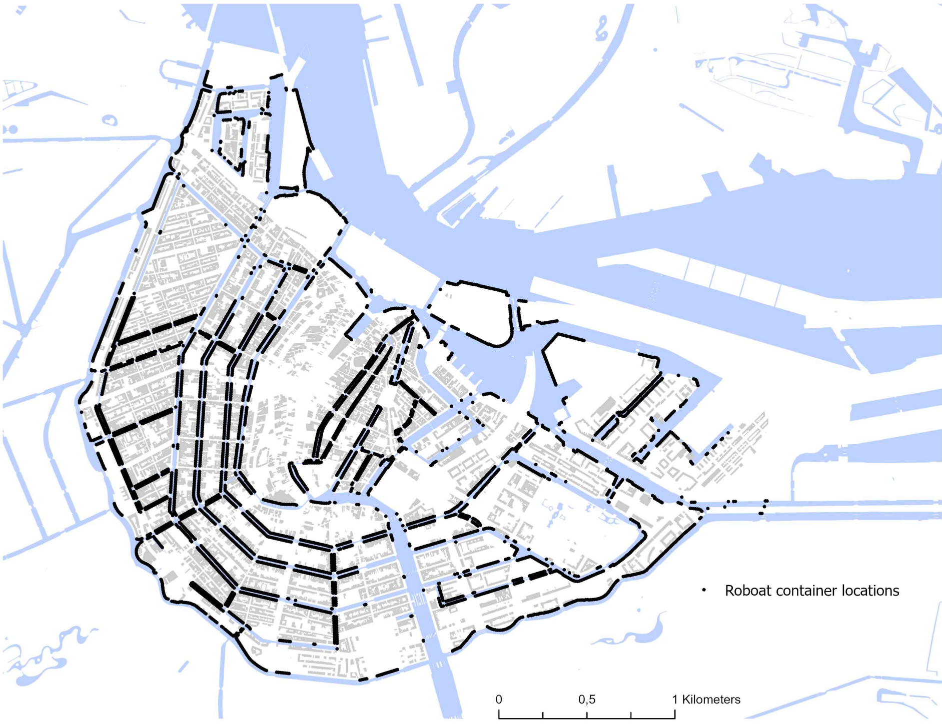


Figure 4.6: The generated possible Roboat container locations

4.6.2 Truck containers

It will not be possible in the future to collect waste using the current system due to the new and proposed rules about emission reduction, weight reduction on the quays and trying to remove the vehicles from the Centrum area. However, hybrid or electric trucks could be accepted on the main roads since they are strong enough to hold the heavy loads. This idea comes from the municipality itself (P. de Boer, 2020). The provided map[5] including these main roads is shown in figure 4.7.

[5]https://www.amsterdam.nl/parkeren-verkeer/bereikbaarheid/publicaties/hoofdroutes/

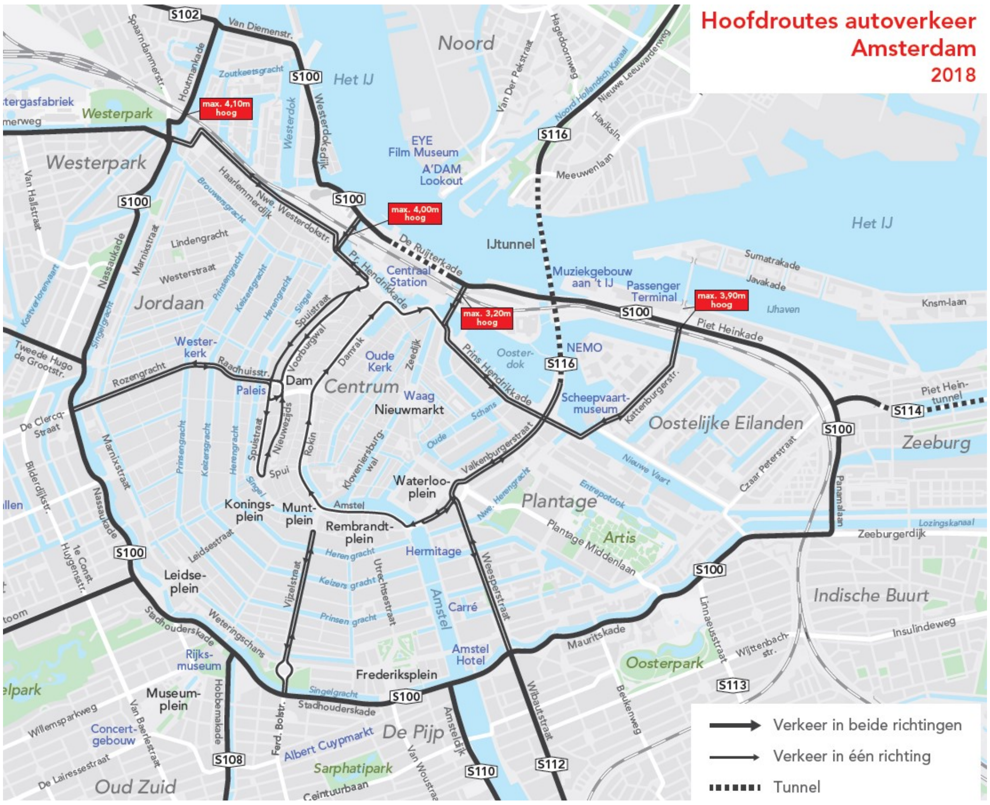


Figure 4.7: 'Hoofdroutes', the roads strong enough to carry heavy loads.

There are fewer restrictions taken into account for locating a truck container during this research than probably necessary. There is assumed that it is possible to locate a container along the main roads except for bridges. Also, parts of different roads are excluded, for example, the IJ-tunnel. Next, the possible container locations further than 150 meter from the nearest household is deleted to increase the calculation speed. The generated points in ArcGIS along these roads are shown in figure 4.8.

Figure 4.8: The generated possible truck container locations

4.6.3 EV containers

This research assumes that EcoCassettes (or containers with the same size and press ratio) are the used containers for the EVs, based on a current pilot in the Centrum area. The most significant advantage of these EcoCassettes is that they are relatively easy to pick up and locate somewhere else, which make them more adaptable to future changes. There is a possibility that commercial waste and household waste will be combined in the future and will all be collected with the same system. In that case, it is easy to add more EcoCassettes. These containers can be located on a single parking spot, on the sidewalk or in a park. Therefore, this research assumes that their will always be a place to locate these containers near selected container points, but validation is required. The possible container points are generated every twenty meters along with the road network instead of every ten meters to improve the calculation speed. Again, the points that are further than 150 meters away from the nearest household or within 10 meters of a bridge are also deleted. There is still a large data-set remaining shown in figure 4.9.

Figure 4.9: The generated possible EV container locations

Chapter 5

Calculation methodology

During this research, the container locations are defined with ArcGIS Pro 2.5. This geographical information software could be controlled with python commands or could directly be controlled with integrated features. During this calculation process, it became clear that both control methods have its pros and cons, and therefore both methods are applied. This chapter provides the calculation methodology based on the data and generated points described in Chapter 4. The chapter starts with the model setup and settings. Next, the so-called serial method is discussed with its corresponding calculation orders. Then, the parallel method will be explained. Finally, this chapter provides an overview of the applied calculation methods.

5.1 Model setup

As mentioned before, the calculations are done with ArcGIS pro 2.5, an advanced geographical information software. The road network of the city centre is used to calculate the travel distance from a certain facility (a container) towards the surrounded demand points (the buildings). The road network is shown in figure 5.2. The maximum walking distance was decided to be 150 meters by the municipality itself (Numan, 2020). The average of the maximum walking distances in the other districts in Amsterdam from a household to a container point is 97,6 meters, varying from 53 meters in the Nieuw-West area to 132 meters in the Noord area (Zhang et al., 2018). With a maximum walking distance of 150 meters, it is roughly estimated that the average walking distance of the calculations will be between 75 and 100 meters. Important to mention is the travelled distance along the network is the only distance that is taken into account. The distance from the network to the container point, and the distance from the network to the household itself, are both not taken into account. In general, that is a realistic assumption, since the front door of most of the buildings is next to the sidewalk as well as the container. Furthermore, the walking distance cost function is set as linear, since the 'costs' of the walking distance are linear to the network impedance. This is the best option for situations where the goal is to minimize the total average walking distance. Other options would be 'Power' where the cost is equal to the network impedance raised to a power, which is not the case within this method. Or, the final option is 'Exponential' where the cost has an exponential relationship to the network impedance. Another option within the setup pane in ArcGIS Pro 2.5 is selecting the arrive or depart time, which is possible when the cost units are time-based. However, during this research, the walking distance is set as a KPI instead of the walking time. The next option is to select the output of the walking distance, where it is possible to select straight lines or no lines. The best way to check which building is assigned to which container is to select the straight-line function. With this option, it is possible to validate if buildings are assigned to a container and to check if the selected containers are in a logical position. The final option within the program is essential and time-consuming; the number of facilities to be located. While using the maximize capacitated coverage method, the number of facilities is found by iterations and will be further explained in section 5.2. The more containers are located, the less efficient they are and the more buildings are served. The rest of the set parameters are calculated in section 4.3. The setup pane is shown in figure 5.1, in this case, for the Roboat containers in Method 1.

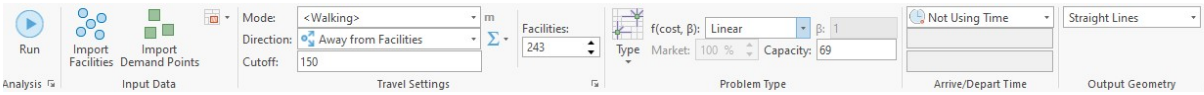


Figure 5.1: The setup pane in ArcGIS Pro 2.5

Figure 5.2: The used road network, consisting all roads of Amsterdam Centrum

5.2 Serial

The first applied method in ArcGIS Pro is based on the maximize capacitated coverage solver, which is a build-in solving method in the software. With this approach, the focus is on locating only efficient containers based on the number of assigned buildings to one specific container. The municipality is looking for multiple solutions to compare with each other. So, they are interested in using the containers in the quay walls and a second, or even third, type of waste collection system to serve all resident in the Centrum area. Some of the people working for the municipality prefer using the trucks since they are the cheapest way to collect waste according to them, others prefer a city centre without any heavy trucks soon. Therefore, this problem is solved for both situations.

Efficient containers

Method 1, 2 and 3 will assign buildings to a container until the containers are not 'efficient' anymore. If a large number of containers is located, a certain number of located containers will have a minimum number of buildings assigned to them. Since the containers must be emptied at least once per week, it would be very inefficient to locate containers which are only full for 20% or even less, for example. The costs of locating a container in the renovated quay walls are still unknown. However, they are estimated to be much higher than locating portable EV containers. Therefore, a definition of efficient containers has to be made.
If there are six pick-up moments over the week, theoretically this means every 28 hours, it means that every container with a pick-up frequency of three times per week will be emptied during a collection moment if it is filled between 66,67% and 100%. The other containers can wait until the next pick-up moment. If a container is filled for 66,67%, it cannot wait 28 more hours to be collected because it will exceed the maximum capacity of that container. Therefore, a 66,67% full container is set as the minimum tolerated percentage. The maximum capacity of a Roboat container was calculated to be 69 buildings. This means that if a container would only be emptied once per week, which will have a given capacity of 23 buildings, the lower bound of 66,67% will be a given capacity of 15 buildings since it is not possible to assign 15,33 buildings to one container.
This lower bound is also set for truck containers using the same method, which results in 10 buildings per container. The EV containers will not have a lower bound since they have to solve the final part of this facility location problem. This means that there is a chance that inefficient EV containers will be located, but are necessary to serve every resident in the Centrum area. To create a integer programming model with these values an efficiency vector $f_m = (f1, f2, f3)$ is defined, and with the described calculations this results in $f_m = (15, 10, 0)$.

Parameters for method 1, 2 and 3

There are three different implementations of the serial method divided into methods 1, 2 and 3. The difference between these methods is the order of the calculation. Method 1 starts with assigning Roboat container to buildings, then truck containers and finally the EV containers. The second switches the order of the Roboat containers and the trucks containers. Finally, the third method excludes the use of truck containers, still with the Roboat containers first and the EV containers at last. To explain the different calculations in the following paragraphs, the advanced model from chapter 3 will be used. The calculation order can be explained with the varying weighting factor, which is described as $w_m = (w_1, w_2, w_3)$ and their values are binary. The first calculation for only Roboat containers will be $w_m = (1, 0, 0)$ and a calculation for Roboat and EV containers together would be $w_m = (1, 0, 1)$.

5.2.1 Method 1: Roboat - Truck - EVs

The first method, called Method 1 in this research, starts with assigning buildings to the Roboat containers using the maximize capacitated coverage method. When it is not possible anymore to assign buildings to an efficient container, it will start assigning buildings to truck containers with the same method. Finally, when all efficient truck containers are located, the EV containers will solve the rest of the problem. The rest of the buildings are assigned with the 'Maximize coverage, minimize facilities' solver, so all the residents will have a container to deposit their waste. In figure 5.4 the calculation order and its corresponding capacities are visualized.
After applying the calculated capacities to the model, the optimal number of located containers is found by iterations. This means that the maximization of objective function 5.1 must be found for a set of containers, each serving a number of buildings that is between the maximum capacity and efficiency lower bound. First for the Roboat containers and next for the Truck containers. The iterations for the Roboat container are shown in figure 5.3. The final results of these iterations are shown in Chapter 6.

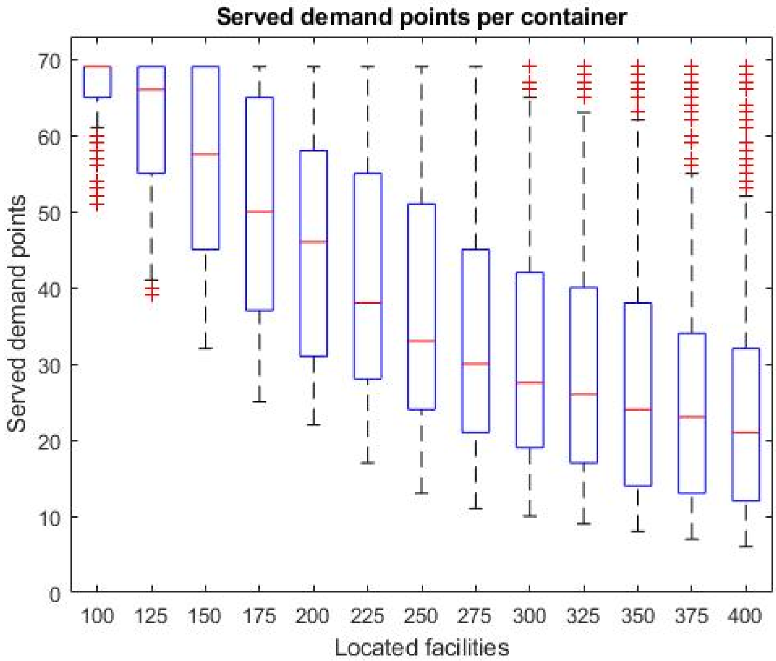


Figure 5.3: A boxplot of the served demand points per located Roboat container

Based on the defined advanced model in Chapter 3, the calculations executed by the ArcGIS Pro software could be described as follows:

$$\max \sum_{i \in I} (w_1 r_{i,j} + w_2 s_{i,k} + w_3 t_{i,l}) - \sum_{j \in J} \sum_{k \in K} \sum_{l \in L} y_{j,k,l} \tag{5.1}$$

$$\begin{aligned} &\text{calculation 1:} && w_m = (1,0,0) \\ &\text{calculation 2:} && w_m = (0,1,0) \\ &\text{calculation 3:} && w_m = (0,0,1) \end{aligned} \tag{5.2}$$

Subject to:

$$\sum_{j \in J} r_{i,j}, \sum_{k \in K} s_{i,k}, \sum_{l \in L} t_{i,l} \leq 1, \forall i \in I \tag{5.3}$$

$$\sum_{j \in J} y_j \leq p_j, \sum_{k \in K} y_k \leq p_k, \sum_{l \in L} y_l \leq p_l \tag{5.4}$$

$$\sum_{i \in I} r_{i,j} \leq C_j y_j, \sum_{i \in I} s_{i,k} \leq C_k y_k, \sum_{i \in I} t_{i,l} \leq C_l y_l, \forall j \in J, k \in K, l \in L \tag{5.5}$$

$$\sum_{i \in I} r_{i,j} \geq f_1 y_j, \sum_{i \in I} s_{i,k} \geq f_2 y_k, \sum_{i \in I} t_{i,l} \geq f_3 y_l, \forall j \in J, k \in K, l \in L \tag{5.6}$$

$$y_{j,k,l} d_{i,j,k,l} \leq d_{max}, \forall j \in J, k \in K, l \in L \tag{5.7}$$

$$y_{j,k,l}d_{i,j,k,l} \leq d_{i+1,j,k,l}, \forall j \in J, k \in K, l \in L \tag{5.8}$$

$$r_{i,j}, s_{i,k}, t_{i,l} \in \{0,1\}, \forall i \in I, j \in J, k \in K, l \in L \tag{5.9}$$

$$y_j \in \{0,1\}, \forall j \in J \tag{5.10}$$

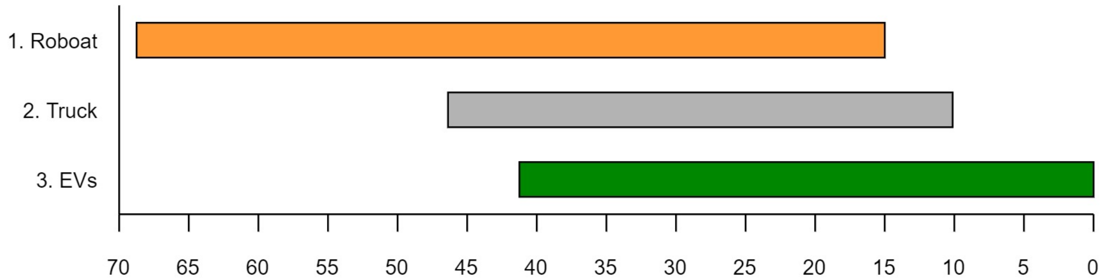


Figure 5.4: The order of calculation method 1 with its corresponding capacities

5.2.2 Method 2: Truck - Roboat - EVs

The second method, Method 2, applies the same strategy as Method 1, the only difference is the calculation order. Method 2 starts with assigning truck containers followed by the Roboat containers and finally the EV containers. The calculation order with its corresponding capacity and lower bound is shown in figure 5.5.

The calculations done by ArcGIS Pro for method 2 could be described by the following MIP model:

$$\max \sum_{i \in I}(w_1 r_{i,j} + w_2 s_{i,k} + w_3 t_{i,l}) - \sum_{j \in J} y_{j,k,l} \tag{5.11}$$

$$\begin{aligned} &\text{calculation 1:} && w_m = (0,1,0) \\ &\text{calculation 2:} && w_m = (1,0,0) \\ &\text{calculation 3:} && w_m = (0,0,1) \end{aligned} \tag{5.12}$$

Subject to:

$$\sum_{j \in J} r_{i,j}, \sum_{k \in K} s_{i,k}, \sum_{l \in L} t_{i,l} \leq 1, \forall i \in I \tag{5.13}$$

$$\sum_{j \in J} y_j \leq p_j, \sum_{k \in K} y_k \leq p_k, \sum_{l \in L} y_l \leq p_l \tag{5.14}$$

$$\sum_{i \in I} r_{i,j} \leq C_j y_j, \sum_{i \in I} s_{i,k} \leq C_k y_k, \sum_{i \in I} t_{i,l} \leq C_l y_l, \forall j \in J, k \in K, l \in L \tag{5.15}$$

$$\sum_{i \in I} r_{i,j} \geq f_1 y_j, \sum_{i \in I} s_{i,k} \geq f_2 y_k, \sum_{i \in I} t_{i,l} \geq f_3 y_l, \forall j \in J, k \in K, l \in L \tag{5.16}$$

$$y_{j,k,l} d_{i,j,k,l} \leq d_{max}, \forall j \in J, k \in K, l \in L \tag{5.17}$$

$$y_{j,k,l} d_{i,j,k,l} \leq d_{i+1,j,k,l}, \forall j \in J, k \in K, l \in L \tag{5.18}$$

$$r_{i,j}, s_{i,k}, t_{i,l} \in \{0, 1\}, \forall i \in I, j \in J, k \in K, l \in L \tag{5.19}$$

$$y_j \in \{0, 1\}, \forall j \in J \tag{5.20}$$

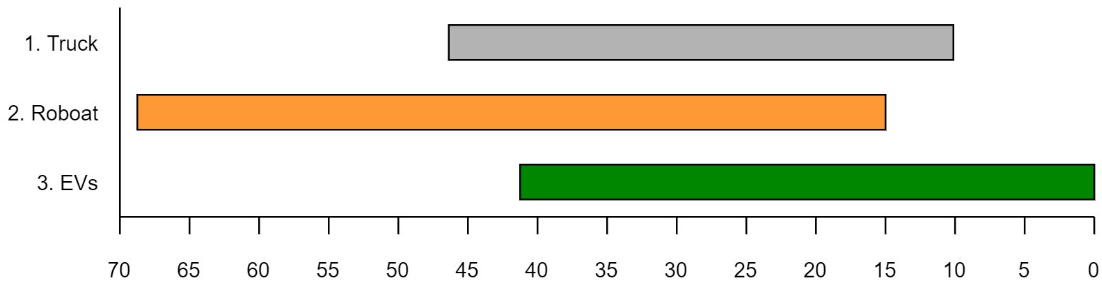


Figure 5.5: The order of calculation method 2 with its corresponding capacities

5.2.3 Method 3: Roboat - EVs

The final and third method of the serial approach focuses only on the use of Roboats and EVs. Again, this method starts with assigning buildings to Roboat containers. To complete the calculation, EV containers are assigned to the unserved buildings by using the 'Maximize coverage, minimize facilities' solver. There are no trucks taken into account during these calculations. Therefore, the weighting factor of the trucks $w_2 = 0$. The calculation order with its corresponding capacity and lower bound is shown in figure 5.6.

$$\max \sum_{i \in I} (w_1 r_{i,j} + w_2 s_{i,k} + w_3 t_{i,l}) - \sum_{j \in J} y_{j,k,l} \tag{5.21}$$

$$\begin{aligned} &\text{calculation 1:} && w_m = (1, 0, 0) \\ &\text{calculation 2:} && w_m = (0, 0, 1) \end{aligned} \tag{5.22}$$

Subject to:

$$\sum_{j \in J} r_{i,j}, \sum_{l \in L} t_{i,l} \leq 1, \forall i \in I \tag{5.23}$$

$$\sum_{j\in J} y_j \leq p_j, \sum_{l\in L} y_l \leq p_l \tag{5.24}$$

$$\sum_{i\in I} r_{i,j} \leq C_j y_j, \sum_{i\in I} t_{i,l} \leq C_l y_l, \forall j \in J, l \in L \tag{5.25}$$

$$\sum_{i\in I} r_{i,j} \geq f_1 y_j, \sum_{i\in I} t_{i,l} \geq f_3 y_l, \forall j \in J, l \in L \tag{5.26}$$

$$y_{j,l} d_{i,j,l} \leq d_{max}, \forall j \in J, l \in L \tag{5.27}$$

$$y_{j,l} d_{i,j,l} \leq d_{i+1,j,l}, \forall j \in J, l \in L \tag{5.28}$$

$$r_{i,j}, t_{i,l} \in \{0,1\}, \forall i \in I, j \in J, l \in L \tag{5.29}$$

$$y_j \in \{0,1\}, \forall j \in J \tag{5.30}$$

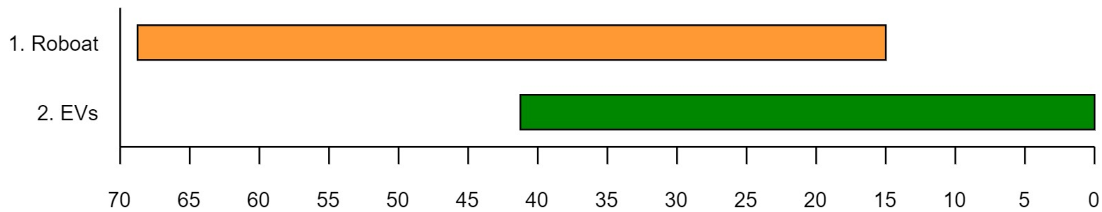


Figure 5.6: The order of calculation method 3 with its corresponding capacities

5.3 Parallel

The parallel method does not focus on the point where a container from a specific modality is not efficient anymore but tries to allocate as many efficient containers overall. This means that there is no preference between the modalities as long as the container assigns the most demand points. Therefore, it is possible that less Roboat containers will be assigned and more truck or EV containers will be. Another disadvantage could be that Roboat or truck containers will be located which serve a small number of buildings. This would be expensive and inefficient. However, in the end, it should result in less located containers overall. Methods 4 and 5 are solving this problem for all 12.250 buildings containing a household.

5.3.1 Method 4: Roboat - Truck - EVs

As mentioned earlier, the parallel approach focuses on assigning the overall most efficient facility points instead of finding the most efficient facility point for one specific modality. It is expected that this approach will use fewer facilities to serve the total demand than the serial approach. However, it might be possible that more expensive Roboat containers will be located for a small group of residents. The different facility types will all be assigned next to each other for methods 4 and 5. However, since the objective is to maximize the capacitated coverage and minimize the number of facilities, the first selected facilities will be Roboat containers due to their higher capacity. In the end, the smallest set of facilities is defined to serve the total demand of Amsterdam Centrum. This calculation could be explained with the following MIP model. Since the facilities are calculated together, the earlier described weighting factor $w_m = (w_1, w_2, w_3)$ will become $w_m = (1, 1, 1)$ for method 4.

$$\max \sum_{i \in I} (w_1 r_{i,j} + w_2 s_{i,k} + w_3 t_{i,l}) - \sum_{j \in J} y_{j,k,l} \tag{5.31}$$

$$\text{Calculation 1:} \qquad w_m = (1, 1, 1) \tag{5.32}$$

Subject to:

$$\sum_{j \in J} r_{i,j}, \sum_{k \in K} s_{i,k}, \sum_{l \in L} t_{i,l} \leq 1, \forall i \in I \tag{5.33}$$

$$\sum_{j \in J} y_j \leq p_j, \sum_{k \in K} y_k \leq p_k, \sum_{l \in L} y_l \leq p_l \tag{5.34}$$

$$\sum_{i \in I} r_{i,j} \leq C_j y_j, \sum_{i \in I} s_{i,k} \leq C_k y_k, \sum_{i \in I} t_{i,l} \leq C_l y_l, \forall j \in J, k \in K, l \in L \tag{5.35}$$

$$y_{j,k,l} d_{i,j,k,l} \leq d_{max}, \forall j \in J, k \in K, l \in L \tag{5.36}$$

$$y_{j,k,l} d_{i,j,k,l} \leq d_{i+1,j,k,l}, \forall j \in J, k \in K, l \in L \tag{5.37}$$

$$r_{i,j}, s_{i,k}, t_{i,l} \in \{0, 1\}, \forall i \in I, j \in J, k \in K, l \in L \tag{5.38}$$

$$y_j \in \{0, 1\}, \forall j \in J \tag{5.39}$$

An visualization of the capacity range is shown in figure 5.7.

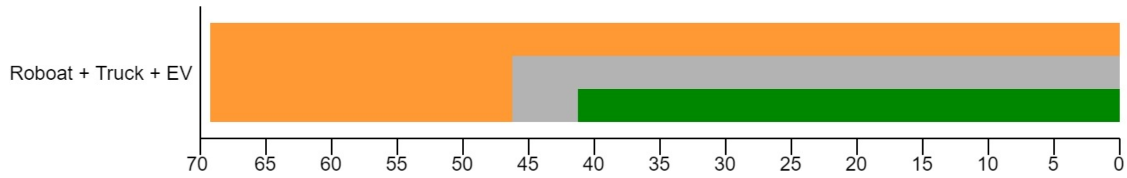


Figure 5.7: The capacity range for method 4

5.3.2 Method 5: Roboat - EVs

Method 5 applies the same strategy as method 4, only leaving the trucks out of the calculation. The weighting factor is therefore given by $w_m = (1, 0, 1)$. The calculation could be explained with the following MIP model:

$$\max \sum_{i \in I} (w_1 r_{i,j} + w_2 s_{i,k} + w_3 t_{i,l}) - \sum_{j \in J} y_{j,k,l} \tag{5.40}$$

$$\text{Calculation 1:} \qquad w_m = (1, 0, 1) \tag{5.41}$$

Subject to:

$$\sum_{j \in J} r_{i,j}, \sum_{l \in L} t_{i,l} \leq 1, \forall i \in I \tag{5.42}$$

$$\sum_{j \in J} y_j \leq p_j, \sum_{l \in L} y_l \leq p_l \tag{5.43}$$

$$\sum_{i \in I} r_{i,j} \leq C_j y_j, \sum_{i \in I} t_{i,l} \leq C_l y_l, \forall j \in J, l \in L \tag{5.44}$$

$$y_{j,k,l} d_{i,j,k,l} \leq d_{max}, \forall j \in J, k \in K, l \in L \tag{5.45}$$

$$y_{j,l} d_{i,j,l} \leq d_{i+1,j,l}, \forall j \in J, l \in L \tag{5.46}$$

$$r_{i,j}, t_{i,l} \in \{0, 1\}, \forall i \in I, j \in J, l \in L \tag{5.47}$$

$$y_j \in \{0, 1\}, \forall j \in J \tag{5.48}$$

An visualization of the capacity range is shown in figure 5.8.

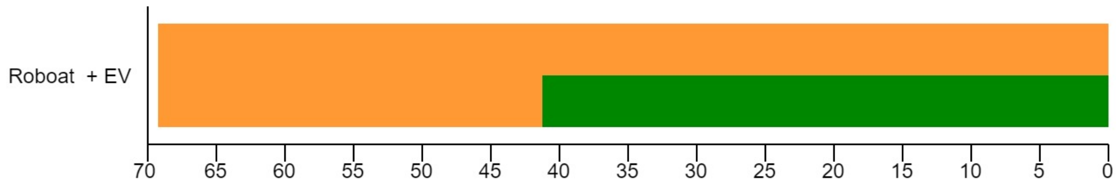


Figure 5.8: The capacity range for method 5

5.4 Method overview

This section provides a short overview of the discussed methods. The methods could be divided into two groups: the serial approach and the parallel approach. These five methods all use 12.250 buildings containing a household as input for the demand points. This is done to increase the calculation speed. After these two different approaches are compared to each other, the most efficient approach will be recalculated with all households as input for the demand points. This update will be discussed in section 6.7. The order of the calculation is as follows:

Serial	**Parallel**	**Update**
Method 1: Roboat ⇒ Truck ⇒ EVs	Method 4: Roboat + Truck + EVs	Method 6: ...
Method 2: Truck ⇒ Roboat ⇒ EVs	Method 5: Roboat + EVs	Method 7: ...
Method 3: Roboat ⇒ EVs		

Chapter 6

Evaluation

This chapter will provide an evaluation of the calculations. First, the different methods will be evaluated one by one. Next, the different methods will be compared with each other to find the preferred approach. The selected approach will be updated with new input for the demand points, which is the set of all households. The last section will compare the different results with each other and conclude which method is preferred.
The first calculations of this research were executed to get an overview of the possibilities of Roboat containers in the Centrum Area. Therefore, various numbers of containers were located to get insight in the number of households that will be served. The curve of the served percentage of households is shown in figure 6.1 within a range of 100 and 400 Roboat containers. Remarkable is the relatively steep increase at the beginning of the curve and the flat end of the curve. It is interpreted that it is worthwhile to locate more container than 100. However, due to the flat end of the curve locating 400 containers will probably not be cost-efficient. Hence, a definition of efficient containers was developed in chapter 5. The outcome of efficient Roboat containers would be somewhere in the middle of the curve.

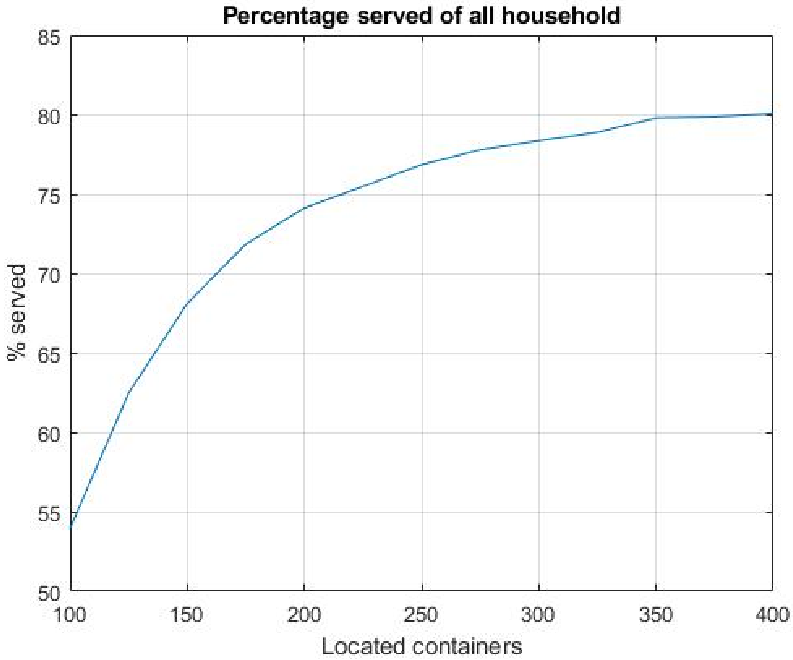


Figure 6.1: Percentage served buildings in Centrum vs. located containers

The second conclusion that is drawn from this graph is that multiple modalities are needed to assign every household to a container, or increase the maximum walking distance. Therefore, trucks and small EVs are taken into account during the calculations. Figure 6.2 shows the area that could be covered by the Roboat containers, following the road network up to 150 meters from all possible container points. This area is called the in-scope area for Roboat containers. In figure 6.3, the buildings which contain a household within the in-scope area are shown in orange. Roboat containers could cover around 81,76% of all households, the other 18,24%, the unserved households, are mostly located in the areas Jordaan and Burgwallen-Nieuwe Zijde. There are more clearly visible spots outside the service area such as Central Station, Frederiksplein, Marineterrein and Artis (Zoo). However, there are no households in that area.

Figure 6.2: The possible service area for Roboat containers

Figure 6.3: The buildings within the possible Roboat service area

Again, a curve is plotted of the percentage served households, but this time by only taking the in-scope households into account. This plot is shown in figure 6.4. Near 400 located containers, the curve approaches a flat line, which means that around 98% of the in-scope household could be served. The other two per cent of the in-scope households are not able to be served due to the assigned capacity to the containers. Especially in the area Jordaan there is limited space available due to houseboats and vessels. Therefore, only one or two containers could be located on a specific location, although there are more required.

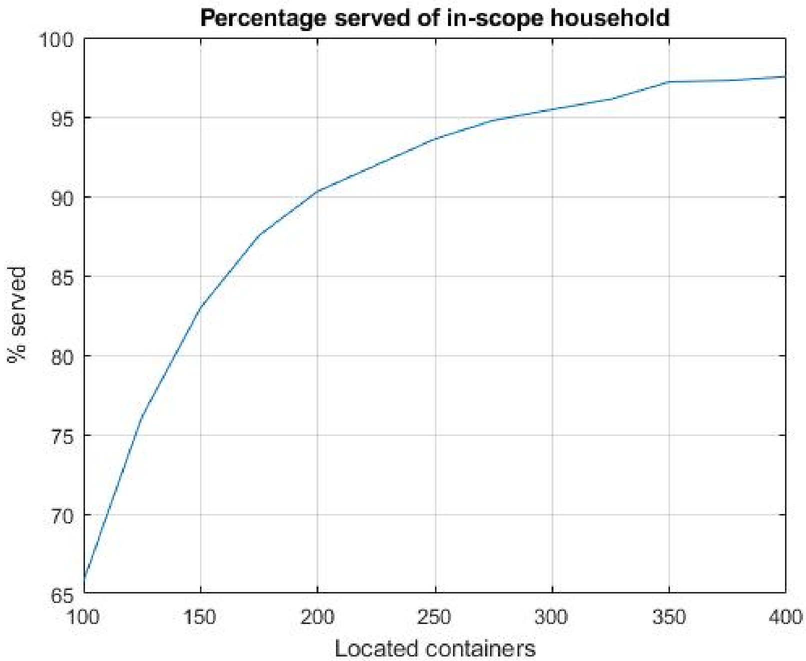


Figure 6.4: Percentage served buildings within service area vs. located containers

One of the options for a new municipal waste system could be applying self-driving drones. The households which are not assigned to a specific Roboat container could be served by these drones, described in section 2.3.4. The other options, trucks and EVs, both require the same method as applied to the Roboat container location-allocation. The results of these methods will be discussed in the following sections.

6.1 Method 1

The first method, as described in section 5.2.1, starts with the allocation of Roboat containers, next the truck containers and finally the EV containers. This calculation method uses the 12.250 buildings containing one or more households. The results of the calculation are shown in figure 6.1. The first column shows the number of located containers, with a total of 423. The percentage of all served residents and the number of all served residents, shown in column two and three respectively, are estimated by multiplying the number of assigned buildings by the average number of residents per building, which is 7,09. The average walking distance per modality is displayed in column four, followed by the average number of assigned buildings per container in column five. These values are calculated with a post-processing algorithm within Matlab after the optimization method in ArcGIS Pro.

Method 1	**Containers**	**% served**	**People served**	**Avg walking distance**	**Avg buildings per container**
Roboat	243	76,74	66.660	74,55	38,69
Truck	42	8,34	7.247	83,53	24,33
EV	138	14,91	12.955	48,03	13,24
Total	423	100,00	86.862	71,35	25,42

Table 6.1: The results of method 1 in numbers

The location-allocation solver from ArcGIS Pro calculated the minimum required number for serving all households in the Centrum area for this strategy. These calculations result in the following locations shown in figure 6.5. The orange dots are symbolic for the 243 Roboat containers, the grey dots represent the 42 truck containers and the green dots represent the 138 EV container locations. The earlier mentioned problem about the lack of space for a Roboat container in the Jordaan and Burgwallen-Nieuwe Zijde is clearly visible in this figure as well. Since there are no main roads (Hoofdroutes) within the Jordaan, there are only EV containers located to serve the complete demand. However, in the Burgwallen-Nieuwe Zijde there are also truck containers located to solve the problem. With 76,74% of all households assigned to a Roboat containers, which is 93,86% of the in-scope households, method 1 has the largest share of Roboat containers compared to the other methods. However, method 1 also locates the most containers overall.

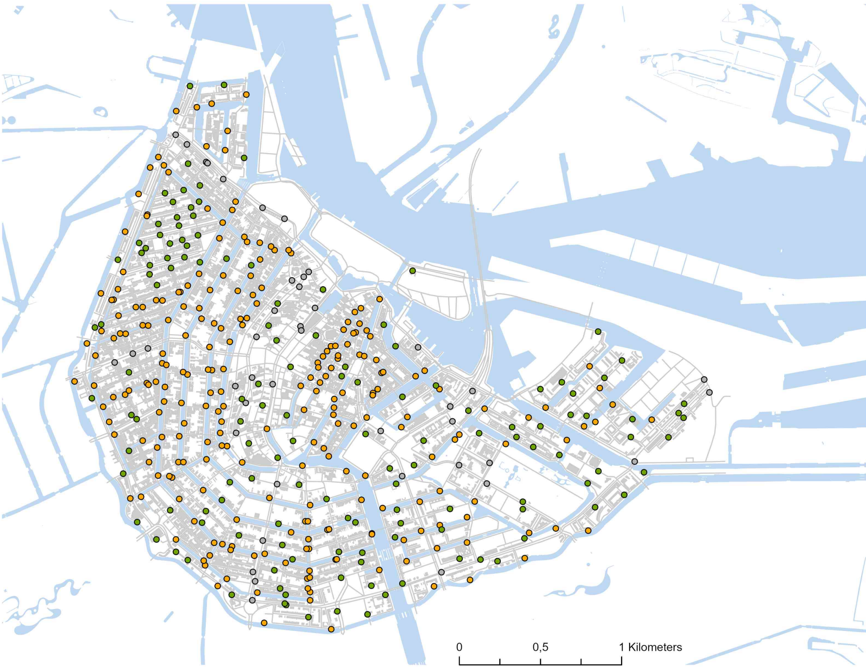
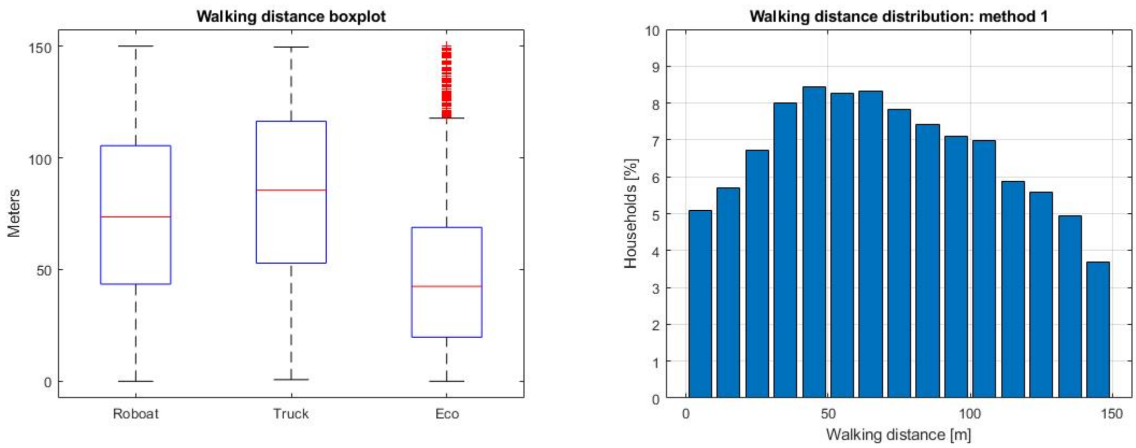


Figure 6.5: Method 1 allocation

The fourth column provides the results of the average walking distance. The overall average walking distance equals 71,35 meters and satisfies the demand of the municipality. However, the average walking distance does not display all preferred information. Therefore, a boxplot of the walking distance per modality is shown in figure 6.6a and a histogram of the modalities combined is shown in figure 6.6b.



(a) Boxplot of walking distance **(b)** Walking distance histogram

Figure 6.6: Walking distance plots for all modalities of method 1

The last column of table 6.1 shows the average number of buildings assigned to one container.

This number could be used to identify an efficiency score of each container based on the filling rate and could be calculated by dividing the average number of buildings per container by the capacity. This means that the Roboat containers have an average efficiency of $38,69/69 = 56.07\%$. With the same calculation method, the efficiency of the trucks and EVs is calculated, $30,56/46 = 52,89\%$ and $13,24/41 = 32,29\%$, respectively. The higher efficiency rate of the first two modalities could be explained by the fact that they stop assigning households to containers after they are defined as inefficient, described in section 5.2.

6.2 Method 2

The calculation of method 2 is executed in the same way as method 1, only the order of the modalities has changed. Method 2 starts with locating truck containers along the main roads, next the Roboat containers are allocated along the canals and finally the EV containers. Section 5.2.2 describes this method further in detail. The results of the calculations are displayed in table 6.2. There are 176 Roboat containers located, which is 67 containers less than method 1. However, there are 109 truck containers (67 more than method 1) located and 137 EV containers (1 less than method 1). In total, it comes down to 422 allocated containers throughout the Centrum area, which is one container less than the first method. It is remarkable that by locating more containers with a smaller capacity than the Roboat containers, there are in total fewer containers required to serve the whole demand. This should be visible in the efficiency score based on the average number of buildings located per container, given in the fifth column. The Roboat container has an efficiency score of $40,47/69 = 58,65\%$, which is $2,58\%$ higher than the efficiency score for Roboat containers in method 1. The truck containers have a score of $30,56/46 = 66,43\%$, which is $13,54\%$ higher, and the EV containers have a score of $13,11/41 = 31,98\%$, $0,31\%$ lower. This means that the Roboats and trucks allocated more efficient containers with method 2 than with method 1, and the EV container score stays almost equal.

Method 2	**Containers**	**% served**	**People served**	**Avg walking distance**	**Avg buildings per container**
Roboat	176	58,15	50.508	74,59	40,47
Truck	109	27,19	23.619	83,65	30,56
EV	137	14,66	12.735	50,58	13,11
Total	422	100,00	86.862	73,53	28,05

Table 6.2: The results of method 2 in numbers

The location of the allocated containers is shown in figure 6.7. The orange dots represent the Roboat containers, the grey dots the truck containers and the green dots the EV containers. The Roboat containers serve around 58,15% of the total demand, which is equal to 50.508 residents.

The truck containers take care of 27,19% of the total produced amount of municipal waste, which represents 23.619 residents. Finally, the rest of the 12.735 residents (14,66%) are assigned to the EV containers.

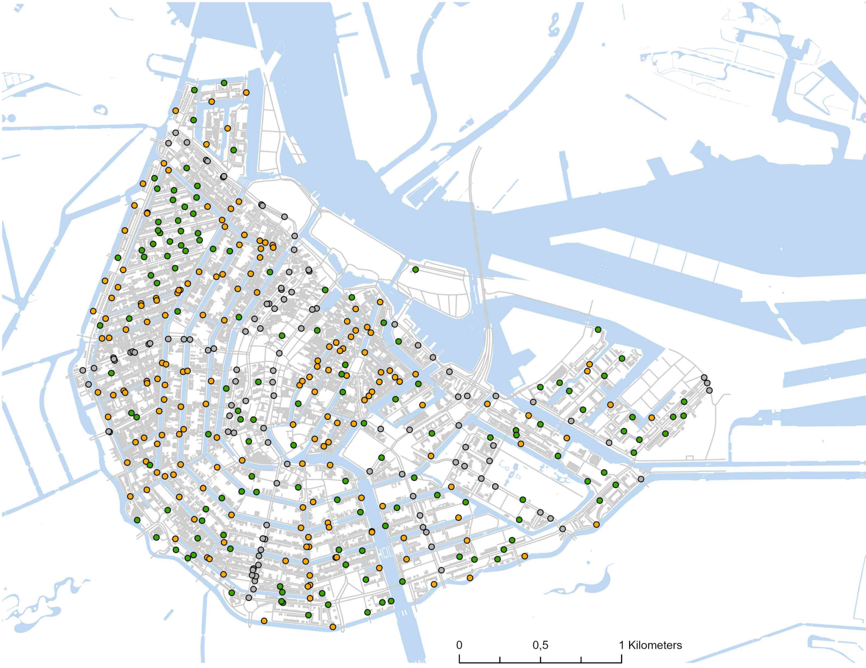
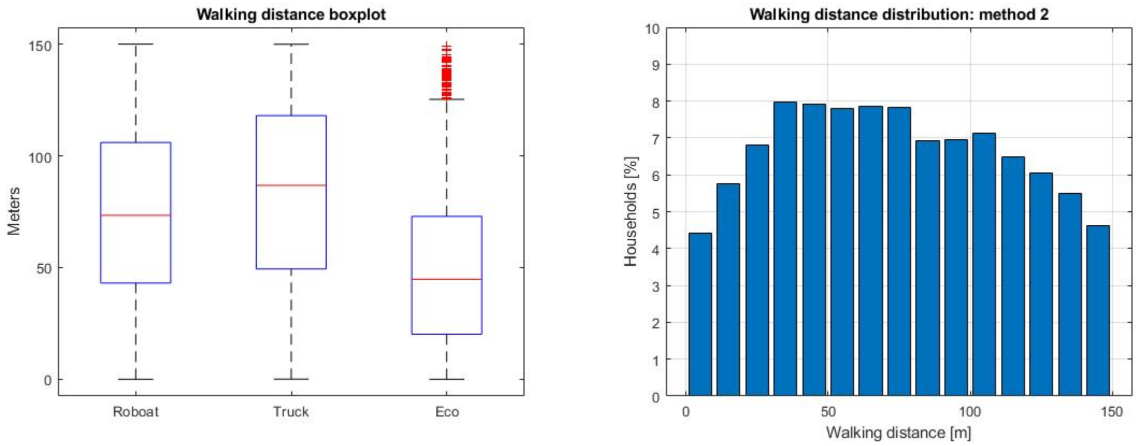


Figure 6.7: Method 2 container allocation

The fourth column provides the results of the average walking distance per modality. The total average walking distance is 2,18 meters more than method 1, but the maximum walking distance stays under the restricted 150 meters. The deviation of the walking distance per modality is shown in figure 6.8a and a histogram of the walking distance of all modalities combined is displayed in figure 6.8b.



(a) Boxplot of walking distance **(b)** Walking distance histogram

Figure 6.8: Walking distance plots for all modalities of method 2

6.3 Method 3

The third method distinguishes from the first two methods because it is only using two modalities instead of three. The truck containers are left out since the municipality sees a future without waste collection trucks as a serious possibility and is maybe even necessary to achieve the climate goals and to prevent the quay walls from collapsing. The first calculation for method 3 is allocating Roboat containers along the canals of Amsterdam Centrum. This results in 243 Roboat containers, which is exactly the same as in method 1. This actually make sense since the same calculation, with the same parameters, is repeated. Therefore, also 76,74% of all demand is served by a Roboat containers, which represents 66.660 residents. The rest of the demand is as singed to 170 EV containers. The rest of the results from the calculations are shown in table 6.3, which were calculated with a post processing algorithm.

Method 3	Containers	% served	People served	Avg walking distance	Avg buildings per container
Roboat	243	76,74	66.660	74,55	38,69
EV	170	23,26	20.202	38,69	16,76
Total	413	100,00	86.862	66,21	27,72

Table 6.3: The results of method 3 in numbers

The locations of the total 413 located containers are shown in figure 6.9, where the orange dots represent the Roboat containers and the green dots display the EV container locations. The EV containers cover 23,36% of the total demand, which is equal to 20.202 residents. With this deviation, the EV containers have a higher efficiency score than they have in methods 1 and 2, based on the average number of buildings assigned to a container. That is, $16,76/41 = 40,88\%$, which is 10,77% higher than method 2 and 9,59% higher than method 1. The efficiency score for the Roboat containers is with $38,69/69 = 56.07\%$, logically, equal to method 1 and 2,58% lower than method 2. Overall, method 3 locates ten and nine containers less than methods 1 and 2, respectively. Based on the number of located containers, the conclusion could be drawn that method 3 is the most efficient so far.

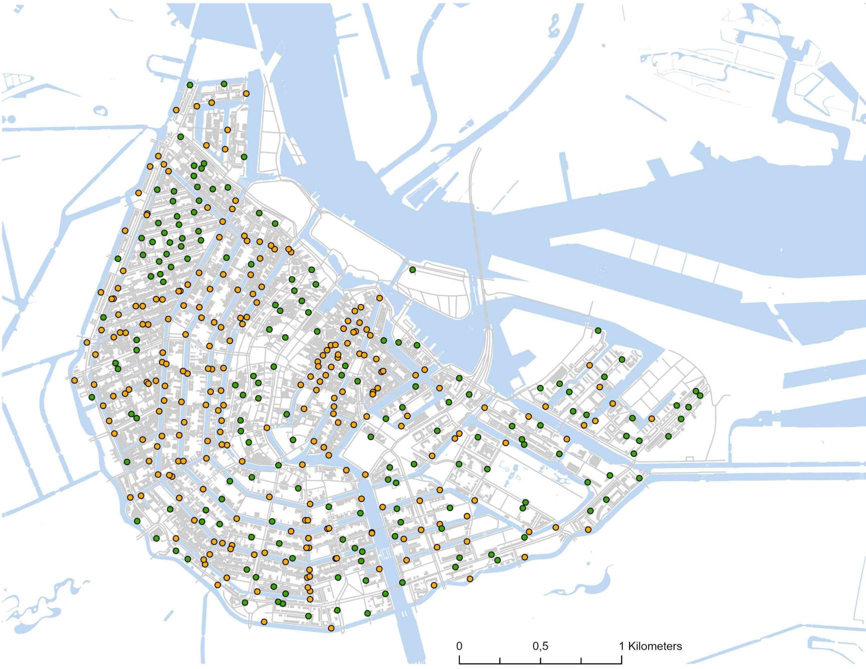
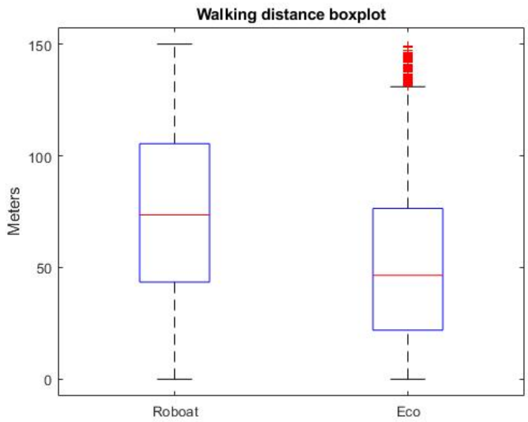


Figure 6.9: Method 3 allocation

The fourth column displays the average walking distance per modality. The total average walking distance is lower than the previous methods as well, which could be explained by the increased number of EV containers with a smaller capacity than the other types of containers. The boxplots of the walking distance for both the Roboat and EV containers is shown in figure 6.10a. Figure 6.10b shows a histogram of the modalities combined.



(a) Boxplot of walking distance

(b) Walking distance histogram

Figure 6.10: Walking distance plots for all modalities of method 3

6.4 Method 4

The fourth method of this research uses the parallel approach described in section 5.3. In short, the container locations for the three different modalities are determined together until all demand is served. The result of this calculation is summarized in table 6.4. ArcGIS Pro allocated 158 Roboat containers, 39 truck containers and 170 EV containers. In total, that is 367 containers, which is 46 containers less than the least amount of located containers by the previous methods. The Roboat containers take care of 55.471 residents their household waste, which is 63,86% of all residents from the Centrum area. The truck containers only serve 9,46% of the residents, which is equal to 8218 people. Finally, the 170 EV containers serve the demand of 23.173 inhabitants, which equals 26,68%.

Method 4	Containers	% served	People served	Avg walking distance	Avg buildings per container
Roboat	158	63,86	55.471	80,75	49,51
Truck	39	9,46	8.218	85,80	29,72
EV	170	26,68	23.173	57,33	19,22
Total	367	100,00	86.862	74,98	32,82

Table 6.4: The results of method 4 in numbers

The selected container locations of the total 367 containers is shown in figure 6.11. Again, the orange dots symbolize the Roboat container locations, the grey dots represent the truck container locations and finally, the green dots symbolize the EV containers. The average number of buildings per located Roboat container is 49,51 and could be transformed into an efficiency score by dividing this number by its capacity. This results in an efficiency score of $49,51/69 = 71,75\%$, which is directly the highest score of the previous methods. The 39 truck containers have a score of $29,72/46 = 64,61\%$, which is slightly lower than the score of method 2. Finally, the 170 EV containers have an average of 32,82 buildings assigned to a container, equal to an efficiency score of $19,22/41 = 46,88\%$, which is significantly higher than methods 2 and 3. However, method 4 locates overall the least amount of containers in the Centrum area, without exceeding the maximum walking distance of 150 meters.

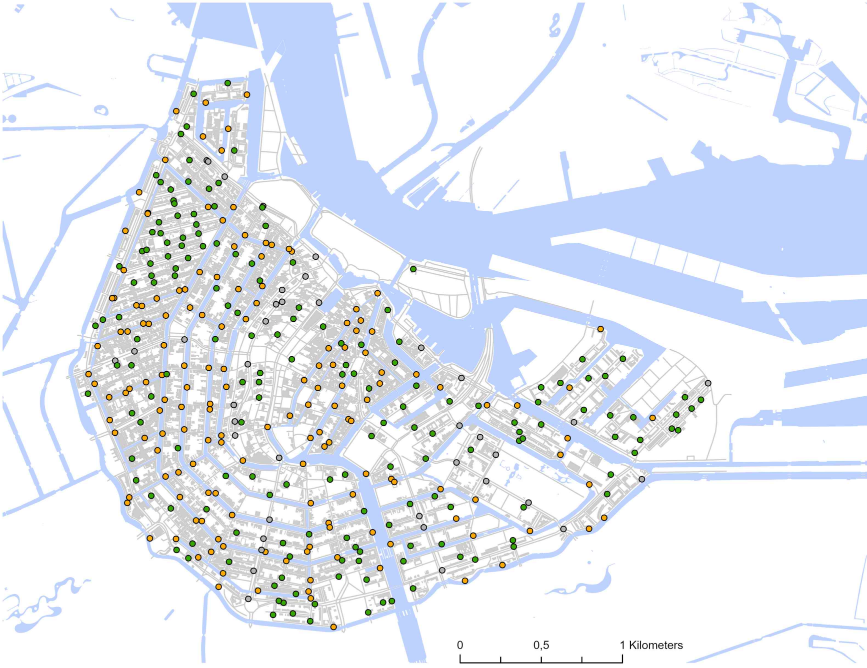
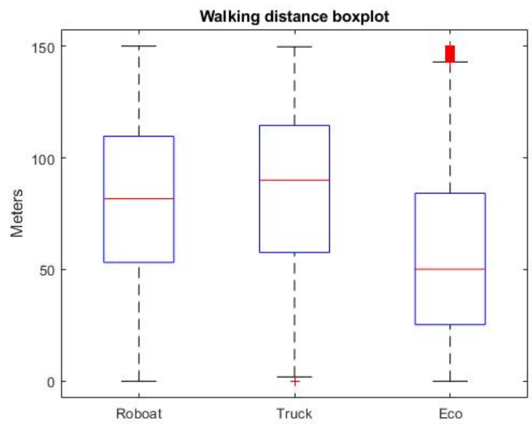


Figure 6.11: Method 4 allocation

Since method 4 locates 47 containers less then the least amount of containers of the previous methods, it is likely that the average walking distance will increase. The boxplots of the walking distance per modality are shown in figure 6.12a. Figure 6.12b displays the histogram of all walking distances combined. The total average walking distance increases by 1,45 meters compared to the longest average walking distance of the previous methods and 8,77 meters compared to the shortest average.



(a) Boxplot of walking distance

(b) Walking distance histogram

Figure 6.12: Walking distance plots for all modalities of method 4

6.5 Method 5

Method 5 uses the parallel approach as well, but this time the truck containers are not taken into account. The results of the calculations are shown in table 6.13. The location-allocation solver selected 146 Roboat containers and 218 EV containers, what comes down to a total of 364 containers. That is three containers less than method 4. Noticeable is that the number of Roboat containers has decreased compared to method 4 although there is one modality less to solve the problem. This means that there is a shift towards the EV containers. The second noticeable fact is that more EV containers are used, which have a smaller capacity than Roboat and truck containers, but this method assigns the least containers of all previous methods. That means that the located containers will have a higher efficiency score. The allocated Roboat containers serve on average 53,51 demand points, that is equal to an efficiency score of $53,51/69 = 77,55\%$, which is 5,8% higher than method 4. The selected EV container points serve on average 20,36 buildings, that is equal to an efficiency score of $20,36/41 = 49,66\%$. Also the efficiency score of the EV containers is higher than the score of method 4, namely 2,78%.

Method 5	Containers	% served	People served	Avg walking distance	Avg buildings per container
Roboat	146	63,77	55.393	80,36	53,51
EV	218	36,23	31.469	56,69	20,36
Total	364	100,00	86.862	71,78	36,93

Table 6.5: The results of method 5 in numbers

The total 364 located containers are spread out over the Centrum area and the location of each container is shown in figure 6.13. The 146 Roboat containers, orange dots, serve 63,77%

of the total 86.862 residents in the city centre, which equals 55.393 people. The EV containers, green dots, are assigned to the rest of the 36,23%, which are 31.469 residents.

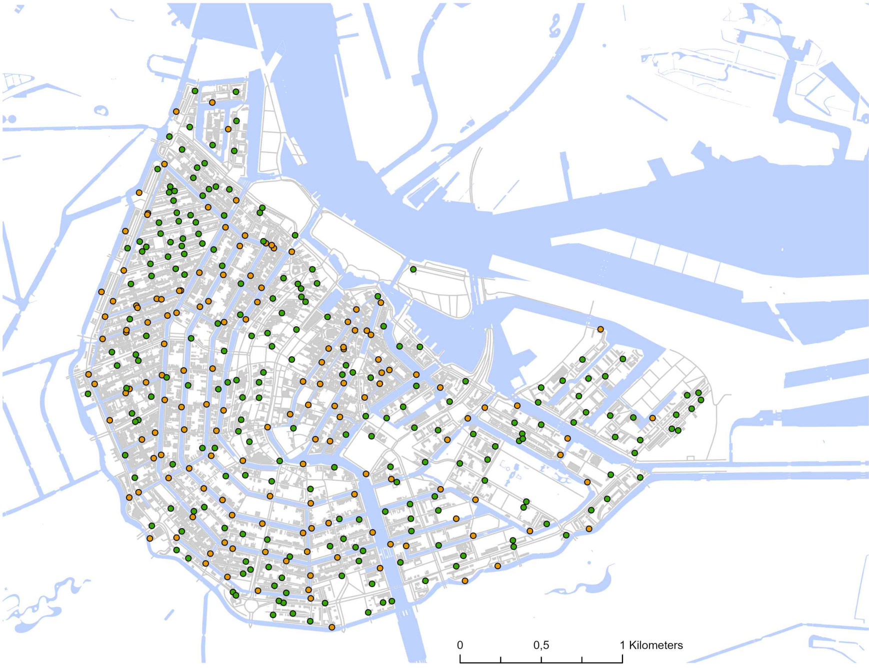
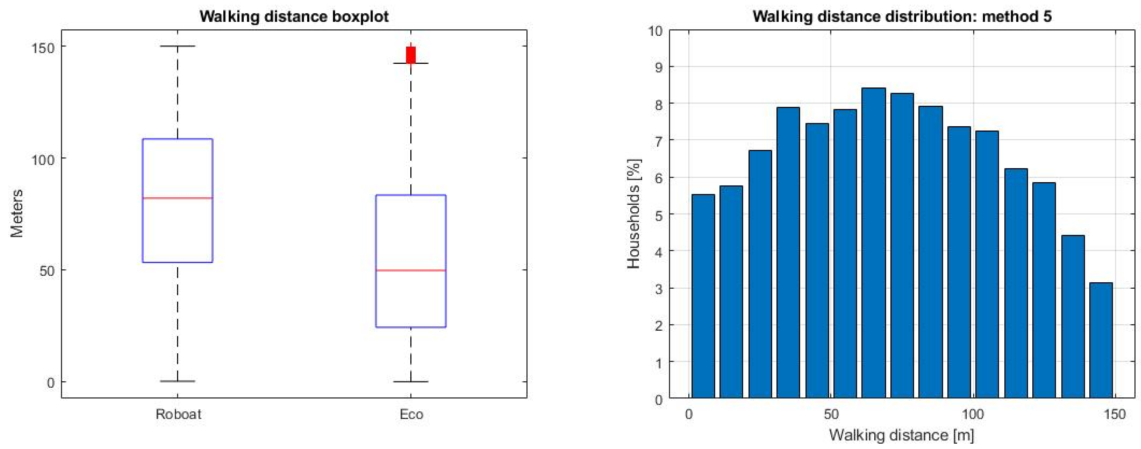


Figure 6.13: Method 5 allocation

So far, method 5 seems to be an improvement compared to method 4 since the number of located containers reduces and the efficiency score increases. Furthermore, the average walking distance decreases as well. For method 4, it is calculated to be 74,98 meters, for method 5, it is 71,78 meters. The walking distance for both modalities is visualized with a boxplot in figure 6.14a. All walking distances combined are displayed in a histogram in figure 6.14b. After all, it can be concluded that the parallel approach has a more preferred outcome than the serial approach. In general, the located containers have higher efficiency, and therefore fewer containers are required to serve all the demand. The increased average walking distance is not preferred, but the maximum distance is still within the restricted 150 meters. Therefore, this approach is still acceptable.



(a) Boxplot of walking distance **(b)** Walking distance histogram

Figure 6.14: Walking distance plots for all modalities of method 5

6.6 Method comparison

From this point, it is possible to compare the results of the five different methods. Where the serial approach avoids locating inefficient Roboat and truck containers, the parallel approach is focused on locating the least containers overall. The objective of this research is to maximize the total capacitated coverage with the least facilities. Roboats were not able to assign the total demand by itself, and therefore, two different modalities were added. With this approach, all methods assigned the total 100% of the demand to a specific container within the maximum walking distance. This means that the coverage is completely maximized. The results of the first part of the objective are shown in figure 6.15.

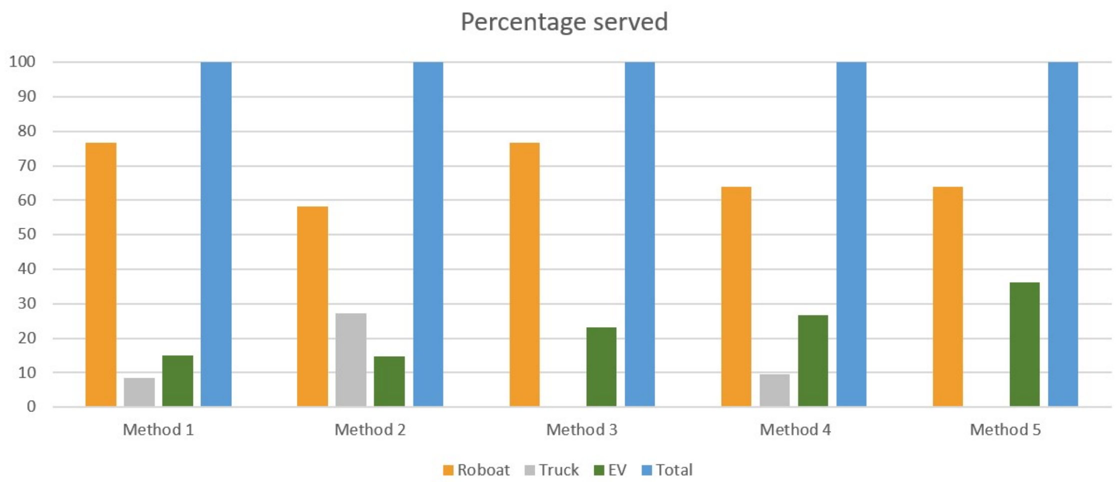


Figure 6.15: Percentage of served demand for the different methods

The blue bars represent the total served demand and are all 100%, but the percentage per modality varies over the different methods. However, to select the preferred approach, it is interesting to take the second part of the objective into account; locating the least amount of containers to achieve the goal. The number of located containers are shown in figure 6.16. The parallel approach, methods 4 and 5, require fewer containers to serve the total demand of the Centrum area. An impressive result is that the parallel approach assigns fewer Roboat containers to the demand points as well. However, the focus of the serial approach was only to locate efficient Roboat containers. Therefore, the parallel approach is selected to further develop towards a realistic applicable model.

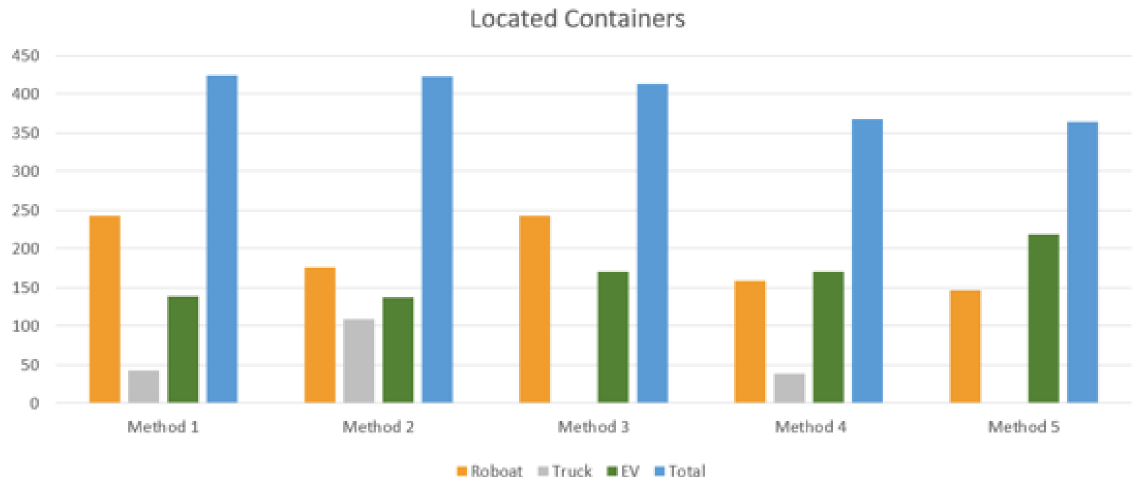


Figure 6.16: Number of located containers for the different methods

6.7 Improving accuracy

This research could only be translated into reality if the taken assumptions are realistic. Therefore, it is essential to increase the resolution of the calculations. Since the previous calculations used 12.250 buildings containing at least one household as input for the demand points, it means that an average of $\frac{86.862}{12.250} = 7,09$ residents per demand point was assumed. That is a rough and inaccurate assumption since 62,87% of all buildings contain three or fewer households and there are ten buildings with over a hundred households. The buildings were used to improve the calculation speed to get an approximated result of the different methods. From this point, the 51.132 households will be used since that is the most accurate available data. This means that an average of $\frac{86.862}{51.132} = 1,70$ residents per demand point are taken into account, which is a significant improvement in the accuracy.

Methods 6 and 7

Two new methods are developed to define the ideal container locations. Methods 6 and 7 will use all households as input data for the demand points. The same strategy is applied to method 6 as method 4, with the same weighting factor $w_m = (1, 1, 1)$. Method 7 is the update of method 5, applying weighting factor $w_m = (1, 0, 1)$. The difference between the parallel approach and this update is the demand point input. This results in a different capacity as well, calculated in paragraph 4.3: $C_{Roboat} = 291$, $C_{Truck} = 194$ and $C_{EV} = 174$ households per container. The objective and corresponding constraints for methods 6 and 7 are equal to the described model of methods 4 and 5, respectively.
The visualization of the capacity range for method 6 is given in figure 6.17, and for method 7 in figure 6.18. The new capacities are taken into account as well.

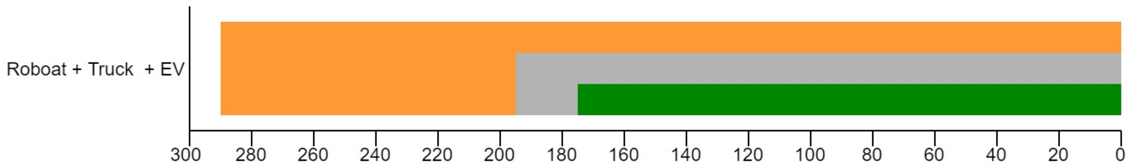


Figure 6.17: The capacity range for method 6

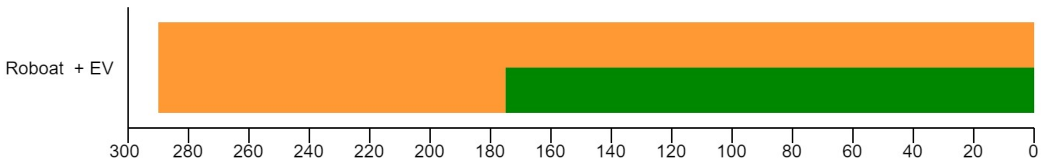


Figure 6.18: The capacity range for method 7

6.8 Method 6

After concluding the parallel approach is preferred over the serial approach, it is interesting to take a closer look at this approach and try to improve the resolution. The updated calculation defined a total of 359 container locations for the three different modalities, which is eight containers less than method 4. The calculated results are shown in table 6.6.

Method 6	Containers	% served	People served	Avg walking distance	Avg buildings per container
Roboat	156	63,78	55.404	86,37	50,09
Truck	36	9,40	8.166	87,14	31,99
EV	167	26,81	23.292	58,82	19,67
Total	359	100,00	86.862	79,06	33,92

Table 6.6: The results of method 6 in numbers

The 156 located Roboat containers take care of 63,78% of all residents of the Centrum area, equal to 55.404 people. There are 36 truck containers allocated along the main roads, which serve 9,40% of the households, equal to 8.166 residents. Finally, the EV containers serve the rest of the 23.292 residents, which is around 26,81% of all households in the city centre. The exact locations of the total 359 located containers are shown in figure 6.19, where the orange dots represent the Roboat containers, the grey dots symbolize the trucks and the green dots represent the EV containers. The efficiency scores of the Roboat, truck and EV containers are $50,09/69 = 72,59\%$, $31,99/46 = 69,54\%$ and $19,67/41 = 47,98\%$, respectively. These efficiency scores are all higher than the scores from method 4 while the resolution of the calculations also improved.

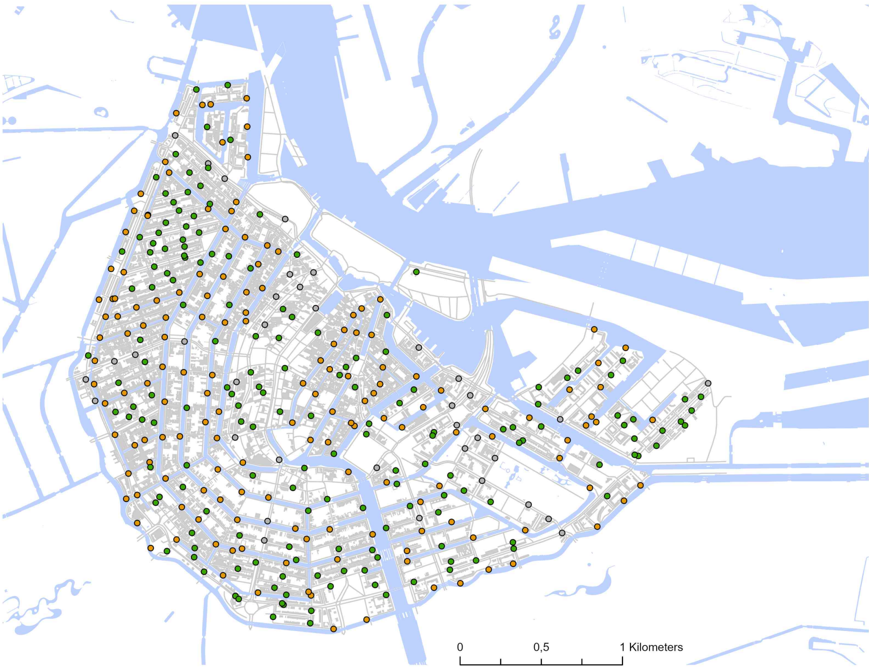
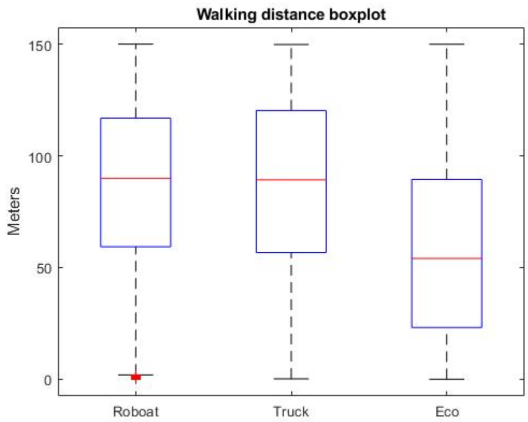
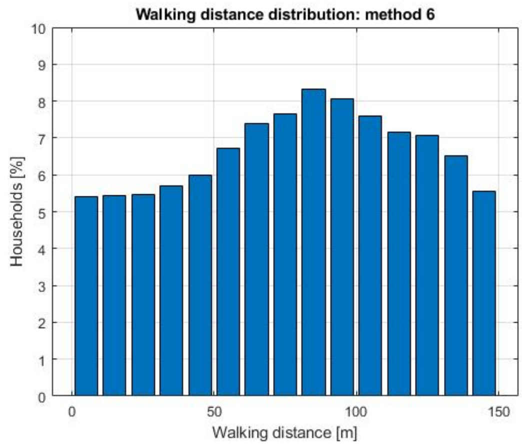


Figure 6.19: Method 6 allocation

Due to the decreased number of located containers, it is expected that the overall average walking distance has increased. The fourth column shows that this is true compared to method 4. The average walking distances for the Roboat (86,37 meters) and truck containers (87,14 meters) are significantly higher than the walking distance for the EV containers (58,82 meters). The deviation of the walking distance per modality is shown in figure 6.20a. Figure 6.20b shows a histogram of all walking distances combined. The histogram also shows that the limit of 150 meters is not exceeded.



(a) Boxplot of walking distance



(b) Walking distance histogram

Figure 6.20: Walking distance plots for all modalities of method 6

6.9 Method 7

The final calculation uses the same strategy of method 5, which assigns Roboat containers next to the EV containers. However, the demand points and their corresponding capacities are updated. Since the capacity of the Roboat containers is larger than the capacity of the EV containers, the calculation prefers assigning Roboat containers over the EV containers as long as it can assign more households. However, EV containers can serve households almost everywhere in the city centre. These calculations result in 171 Roboat containers and 199 EV containers. Together that is 370 containers, six more than method 5 that uses the same strategy as method 7. The results of method 7 are shown in table 6.7.

Method 7	**Containers**	**% served**	**People served**	**Avg walking distance**	**Avg buildings per container**
Roboat	171	66,72	57.956	86,51	47,80
EV	199	33,28	28.906	59,69	20,49
Total	370	100,00	86.862	77,59	34,14

Table 6.7: The results of method 7 in numbers

The 171 Roboat containers serve around 66,72% of all households in the Centrum area, that is similar to 57.956 residents. The EV containers serve the rest of the 28.906 residents with 199 containers. The efficiency score of the Roboat containers is 8,27% lower than the score from method 5, $47,80/69 = 69,28\%$ compared to 77,55%. The efficiency scores for the EV containers are with 0,32% difference almost equal to each other, $20,49/41 = 49,98\%$ compared to 49,66% for method 5. The calculated optimal deviation of the container points is shown in figure 6.21, where the orange dots are the Roboat containers, and the green dots represent the EV containers.

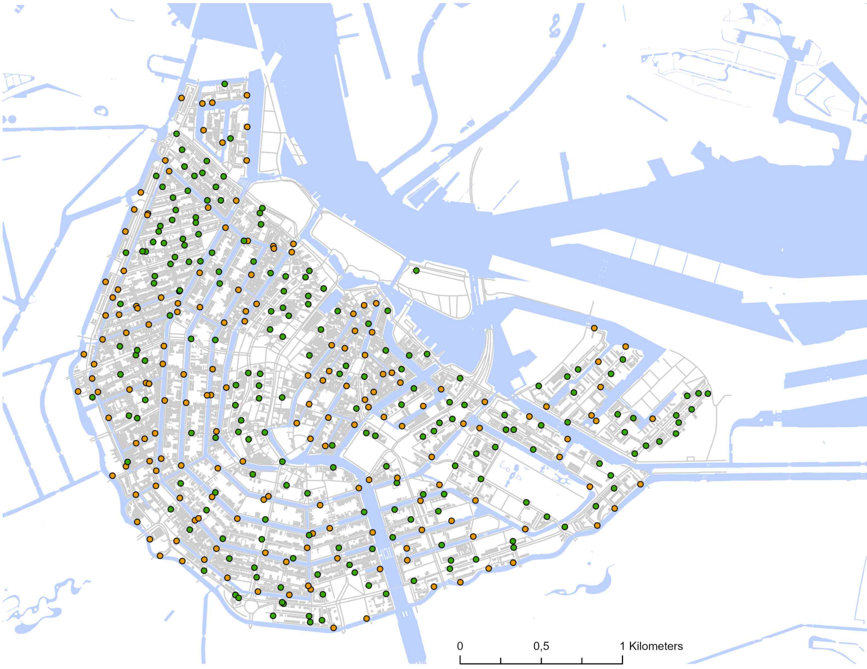
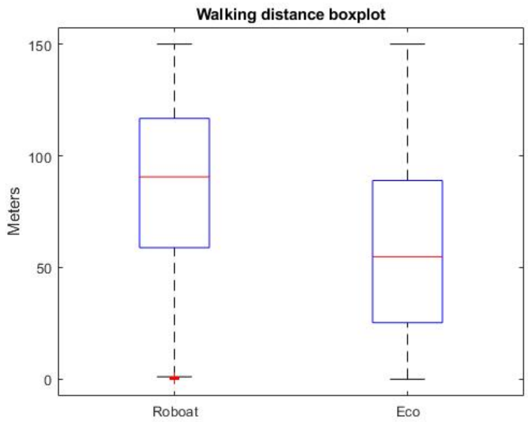
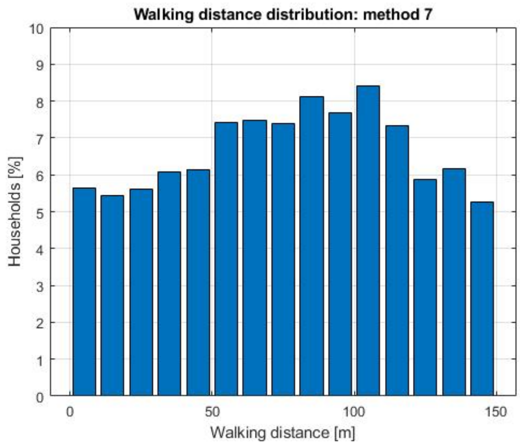


Figure 6.21: Method 7 allocation

The average walking distance of both modalities combined is 77,59 meters, which is 5,81 meters more than the total average walking distance of method 5. The deviation of the walking distances for both modalities is shown in figure 6.22a. The histogram of all walking distances from a household to their assigned container is shown in figure 6.22b. Again, the maximum walking distance of 150 meters is not exceeded.



(a) Boxplot of walking distance



(b) Walking distance histogram

Figure 6.22: Walking distance plots for all modalities of method 7

6.10 Results overview

This section gives an overview of the results of the calculations. Most of the results were already shown in previous sections. However, this section displays the results per method next to each other. Some results are new, for example, the pick-up frequency, discussed in section 6.10.5. In the following graphs, the orange bars represent the Roboat containers, the grey bars symbolize the trucks and the green bars symbolize the EV containers. The blue bars represent the total sum or average, depending on the diagrams.

6.10.1 Number of served residents

The first two diagrams show the number of residents that are served, expressed in numbers and percentage in figure 6.23 and 6.24, respectively. Methods 1 and 3 assign more households to Roboat containers than the other methods. Method 2 assigns the least households to Roboat containers. Method 5 and 7 assign the most households to EV containers compared to the other methods, which is expected since they do not assign households to truck containers. The goal of this research is to optimize the container locations for a new municipal waste management system in the Centrum area using Roboats. This optimization is defined as maximizing the coverage of the containers while minimizing the number of located container. Therefore, it is interesting to realize that all residents in the Centrum area are assigned to a specific container.

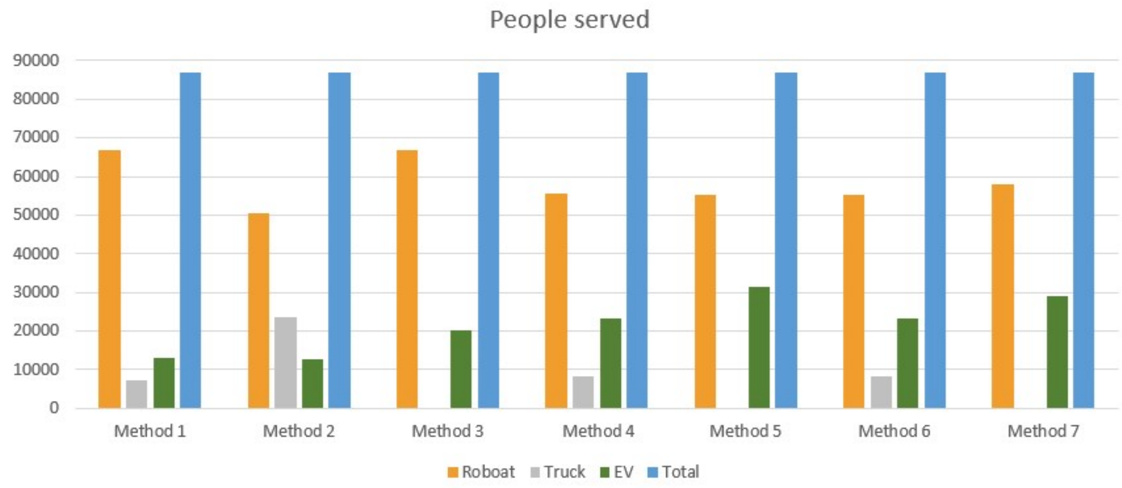


Figure 6.23: Final number of served buildings per method

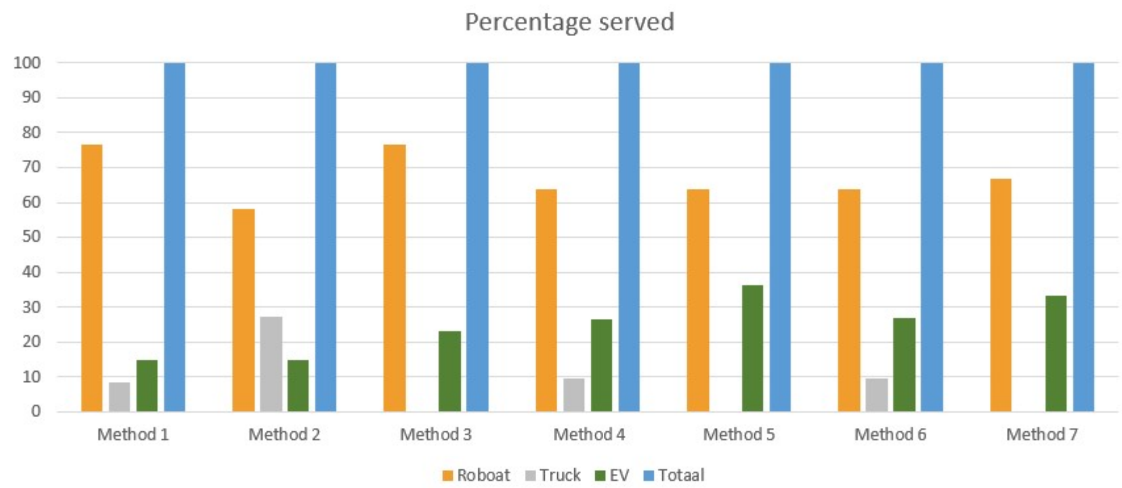


Figure 6.24: Final percentage of served residents

6.10.2 Located containers

The second defined objective is to use the least amount of containers for the served demand points. The diagram shown in figure 6.25, shows the number of located containers per method. In this overview, it is clear that the serial approach, methods 1,2 and 3, need considerably more containers to satisfy the demand of all residents. The parallel approach uses between 359 and 370 containers, which is a relatively small gap. Also remarkable is the shift in container types from methods 5 to 7, where method 7 uses relatively more Roboat containers and fewer EV containers.

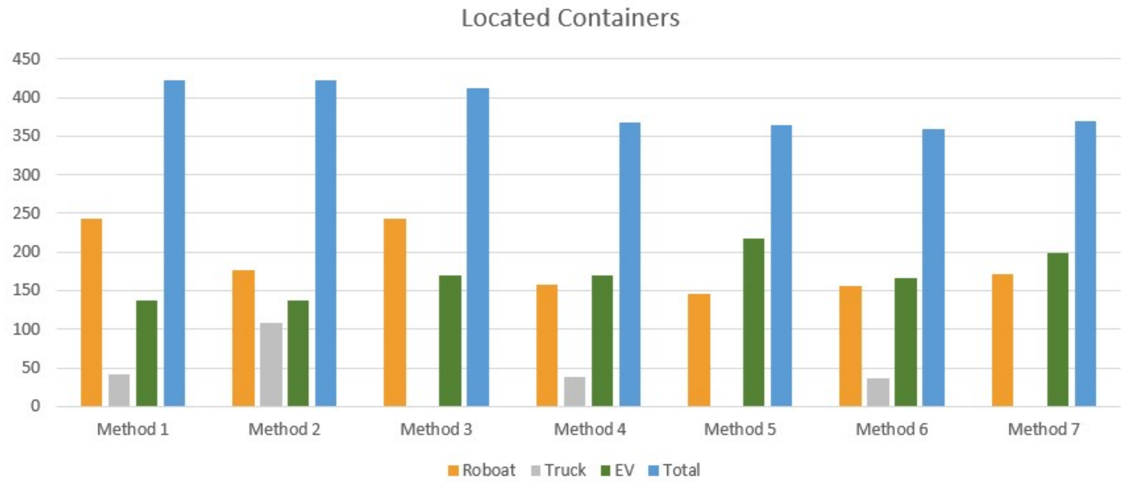


Figure 6.25: Final number of located containers per method

6.10.3 Average walking distance

One of the requirements by the municipality is that the walking distance between the household and container may not exceed 150 meters, and this requirement has been met. An as short as possible walking distance is preferred since this reduces the chance that people will throw their waste on the streets. Therefore, it is interesting took take a closer look at the average walking distances for each method. Although the average walking distance does not contain all the preferred information about the walking distance, it is still informative during the comparison of all methods. The average walking distances per modality and method are shown in figure 6.26. Method 3 has the overall lowest average with 66,21 meters. For the methods that use the parallel approach, method 5 has the lowest average walking distance with 71,78 meters. Method 6 has the overall highest average with 79,06 meters.

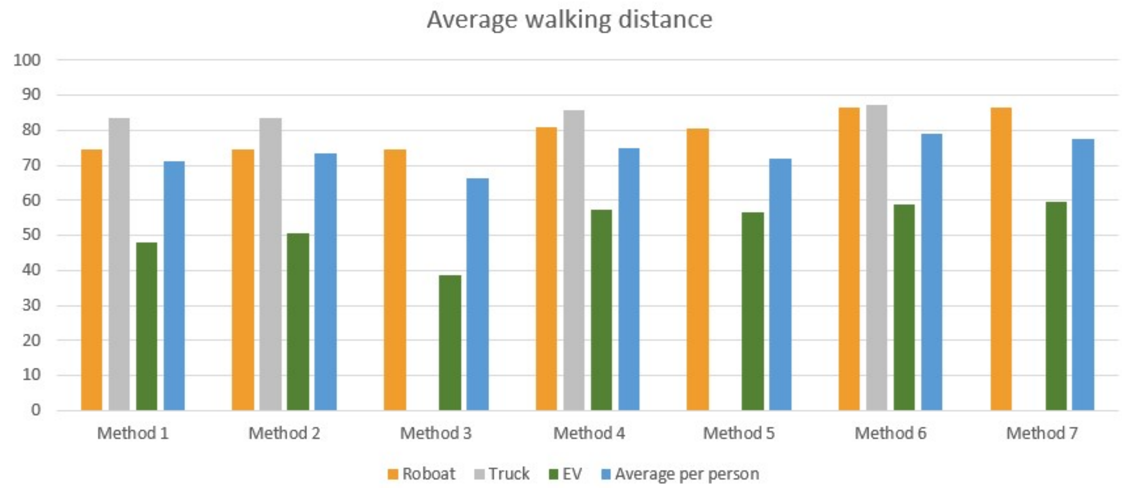


Figure 6.26: Final average walking distance per method

6.10.4 Container efficiency

An efficiency score is defined during the evaluation of the different methods. The efficiency score gives insight in the coverage rate per modality. This is defined by the average number of buildings assigned to a container per container type, divided by the capacity of that container type. Figure 6.27 shows this efficiency score for each modality per method. Also, the average efficiency score per method is shown. Method 2 has the highest score of the methods that use the serial approach with 51,72%. The overall highest score is method 5, with 60,85%, followed by method 6, with 60,84%. Method 7 has the lowest score of the methods with the parallel approach with 58,90%, which is still better than all serial methods.

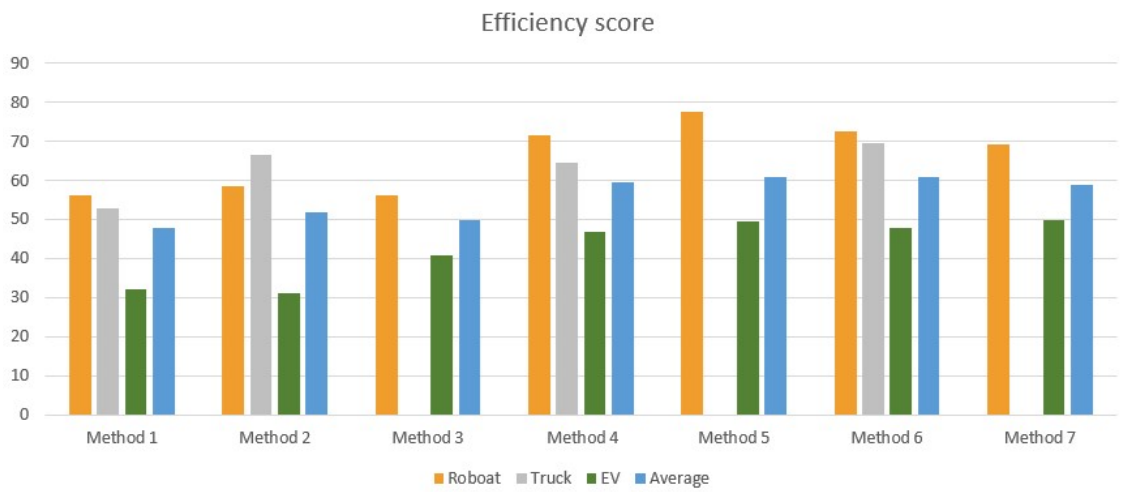


Figure 6.27: Indication of efficient containers

6.10.5 Pick-up frequency

This paragraph describes the required pick-up frequency per modality for each method. Although the containers will be smart-containers that could send a signal if they are (almost) full, an estimation is made on the pick-up frequency. The maximum capacity of the Roboat and EV containers is based on a maximum pick-up frequency of three times per week, while the maximum pick-up frequency of the truck containers is only twice per week. The pick-up frequency per modality for each method is shown in figure 6.28 and assumes that waste production is the same every week. The red bar in the diagram represents containers which have to be emptied more than twice a week up to a maximum of three times per week. It could be that a container needs to be emptied twice in week one and two, but has to be emptied three times in week three. In that case, it is still counted as three times per week. The same applies to the yellow bars, which represent a maximum pick-up of two times per week and more than once over the weeks. The blue bars symbolize the containers that will be emptied once. As discussed earlier in this research, all containers need to be emptied at least once a week to prevent them for a bad smell.

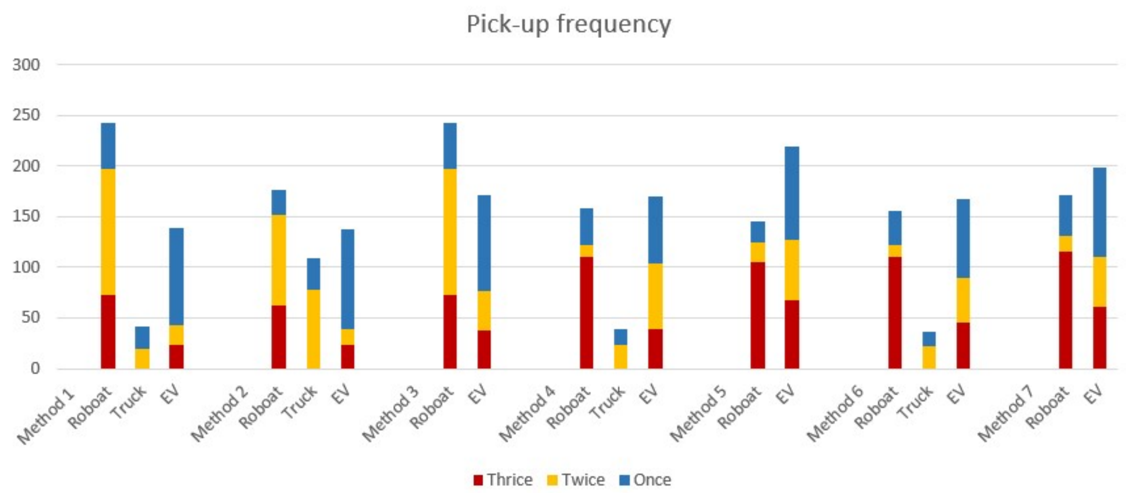


Figure 6.28: Final pick-up frequency per method

6.11 Conclusion

The overall conclusion that can be drawn is that the parallel approach is preferred over the serial approach based on the number of located containers and the efficiency score. However, the serial approach is invented to locate Roboat and truck containers with a lower bound, such that no inefficient containers will be located. This is based on the fact that the underground containers are probably more expensive in locating them as well as maintenance. In the end, the highest number of located Roboat and truck containers are both within the serial approach.

Therefore, the parallel approach is overall the preferred method. Methods 4 and 5 apply the same strategy as methods 6 and 7, except for the demand points input and its corresponding capacities. Although the results of method 5 are preferred over the results of method 7 based on the number of located containers and their efficiency score, the resolution of method 5 is worse than the resolution of method 7. Therefore, method 5 is less realistic and will not be recommended to apply. Based on the much more accurate approach of methods 6 and 7, they will always be more preferred over methods 4 and 5. Methods 4 and 5 are still useful to compare the serial and parallel approach with each other since they both use the same demand points as input.

Method 7 uses 171 Roboat containers, which are assigned to 57.956 residents. This means that by using Roboats for the new municipal waste management system, around 44.761 kilograms of waste will not be transported via the roads anymore, daily. This is equal to a reduction of 16.338 metric ton every year. The rest of the waste will be transported via the roads but only with small EVs, which have a lower weight than the regular trucks.

Parallel with buildings vs households

By taking a closer look at the density of households per building in the Centrum area, it becomes clear that there are some areas where methods 4 and 5 would cause a problem based on the high density. Especially in the neighbourhoods Marken and Kadijken, which are next to each other. Figure 6.29 has a black square around this area with a relatively high density of household per buildings.

Figure 6.29: One of the areas with a relatively high density of households per building

After zooming in on this area, figure 6.30a shows the location of the containers for method 5 and figure 6.30b shows the container locations of method 7. The three building blocks on the Rapenburgerstraat (left side of both images) have only one EV container with method 5, which would cause a problem if that method was integrated in the city. Method 7 assigns multiple EV containers for these apartment blocks to satisfy the full demand of that area. The same principle happens on the right side of the images on the Plantage Doklaan and Entrepotdok.

(a) The located containers for method 5

(b) The located containers for method 7

Figure 6.30: The located containers with the household density

Chapter 7

Conclusion and Future Research

This chapter contains the conclusions and recommendations for further research. Section 7.1 briefly answers the sub research questions, followed by an answer to the main research question. Section 7.2 describes the contribution of the research. Next, section 7.3 provides the discussion on this research. Finally, this research ends with recommendations for future research.

7.1 Conclusion

Throughout this thesis the research question with its corresponding sub questions were answered. This section provides a retrospect of these questions and answers them. Finally, the answers on the sub questions provide the answer to main research question:
How to optimize the container type selection and location for a new household waste collection system in Amsterdam Centrum using autonomous vessels (Roboats)?

What are the municipality's requirements and preferences for the new waste collection system, and how are these implemented in the model?

First of all, the municipality want a new household waste collection system that works better than the current system and it should be affordable. This means that the least amount of containers should be located and that each container serves as many demand as possible. It is important that the new household waste collection system does not harm the quay walls anymore. This means that the heavy trucks have to be replaced by other modalities. The new modalities are not allowed to use a combustion engine and the system should be in line with UNESCO-world heritage. Furthermore, if the municipality will change its current waste collection system, they want to be sure that it will work for the upcoming decades. Section 4.1.2 discusses the population growth until 2050 and the change in waste production. The conclusion is that less waste will be produced in the future. Therefore, the new waste management system does not have to be resilient for growth in waste production. Another requirement from the municipality is that no more waste will end up on the streets after a new system is implemented. To prevent people from throwing waste on the street, an acceptable maximum walking distance of 150 meters is set by the municipality combined with a realistic capacity for each container. Next, the total waste production of one household belongs all to one container and the number of located containers may not exceed a certain number. Preferably, the municipality uses a progressive system that shows Amsterdam is still one of the most innovative cities in the world. If the Roboats are used for the new waste collection system in Amsterdam, it will be the worlds first city to use autonomous vessels to collect household waste.

What are the possible waste collection concepts for water or land application, and which combination is the most efficient?

As discussed in chapter 2, there are many solution possibilities to collect all MSW. Since this research is in collaboration with AMS Institute and MIT, the Roboat will be included as one of the modalities. The municipality of Amsterdam will start a pilot in 2021 for waste collection in the Centrum area, and there is a plausible chance that Roboat will participate since the municipality is enthusiastic about this solution as well. Another possible modality on land are the currently used trucks but only applied on the main roads due to the weak quay walls. The trucks will collect waste from underground containers. Next, small EVs could be applied, collecting on-ground portable containers. Also, self-driving drones could visit each household once there is waste to collect. This could be an option in the future. However, many transport moves will be made to collect all waste, and the narrow sidewalks in Amsterdam are not ideal for these drones. The final waste collection system that is taken into account is a vacuum pipe system. Since this would replace the Roboat containers, it is not used for further calculations. However, the designed framework in ArcGIS will be useful to define the locations for the pipe inlets. Therefore, a combination of Roboat, trucks and EVs is assumed during this research. According to section 6.10.4, the Roboat containers are the most efficient. However, this could be explained by the simulation order. Method 2 locates truck containers before the Roboat containers and has directly a higher efficiency score. Plausible is that EV containers would be the most efficient containers if they would be located first since the possible EV locations are not limited to any restriction, and they have to smallest capacity.
The proposed methods are all an improvement compared to the current situation when it comes to quay wall protection, waste reduction on the streets, mice, rats and seagulls, and on the long term financially.

Which methods could be used for solving the facility location problem, and how does this method contribute to the current research field?

Before the solution method could be defined, it is important to describe the requirements for the new system and to translate them into a mathematical model, which is described in chapter

3. Once this is done, the available data has to be investigated. As described in chapter 2, there are several possible solution methods for MIP models, such as a programming language or GIS software. However, most of the data was provided in WFS, WMS and Shapefiles. These document types are directly connectable to GIS software, even with an web link. GIS software is also an advanced tool for creating, managing and analyzing spatial data, which is useful for the waste collection problem. The network analyst tools calculate the travelling distance between all demand points and possible facility points following a given network of roads. Therefore, ArcGIS Pro was selected as software to solve this problem, described in chapter 4. Previous research is done for locating facilities throughout a city. However, none of these researches applies the same strategy as this research proposed, which is the use of multi-facility types, assigning all demand to different facilities, using a network for the travelling distance and use different solving approaches to compare the strategies. Most of the previous researches use the Euclidean distance between the facilities and demand points.

Which different strategies could be applied to the solution method and which obtains a more favourable result on the objective?

During this research seven different solving methods were developed, based on two different approaches, explained in chapter 5. The first approach was to solve the location-allocation one-by-one. A set of one specific container type was found for only efficient containers. Containers were defined as efficient based on their filling rate. The second approach was to calculate a set of the different container types together, where the focus was to locate the least amount of containers. This could result in expensive and inefficient containers. However, as discussed in chapter 6, the parallel approach obtained a better result based on the number of located containers. All methods served every demand point in the Centrum area. Afterwards, the parallel approach was updated to improve the accuracy of the calculation by using 51.132 households as demand point input, instead of the 12.250 buildings.

Which method would be recommended for Amsterdam Centrum based on the approach and results?

First of all, the parallel approach proved to be more efficient than the serial approach. This means that methods 4 until 7 are better than method 1, 2 and 3. Between the four parallel methods, method 6 and 7 would always be preferred over method 4 and 5 since they use the same strategy, only the accuracy is higher for method 6 and 7. The model could also be applied for a system were Roboats will be used in combination with drones, or a situation where a vacuum pipe system would be installed along the canals. The parameters of the framework should be recalculated within the Matlab file which could be implemented in ArcGIS. The new results would be calculated within a couple of hours.

Main research question

Using the sub research questions, the main question 'How to optimize the container type selection and location for a new household waste collection system in Amsterdam Centrum using autonomous vessels (Roboats)?' has been answered and it will be explained in this paragraph. The first step in answering this research question is to identify the current problem and develop a deeper understanding of the situation and possible collection methods. Next, identify the requirement for the new system and translate this into a mathematical model. With the given requirements, the container types and collection modalities could be selected. After gaining useful data, the solution method could be defined, also based on the mathematical model. From this point the calculation methods could be developed and tested. Finally, the calculations could be executed and compared to each other. At the end, there is a developed framework that could be applied to new scenarios as well as the defined problem. If the municipality prefers a waste management system with other modalities, a vacuum system or to integrate DifTar, new container locations are defined within a day.

7.2 Contribution of this research

This research contributes to the current research field by developing a framework to assign all demand points to selected containers, using a network for the calculated impedance, applying multiple facility types, develop different strategies for the solving methods and solve the explicit location-allocation with different solvers. This combination is not executed before in literature. There are multi-facility solutions using GIS described in the literature. However, these researches use the euclidean distance between the facilities and demand points or not assigning the total demand (Rathore, Sarmah, and Singh, 2019), (Park and Sohn, 2017).
Furthermore, this research provides an in-depth overview of the current waste collection system in Amsterdam Centrum. Information is obtained by personal communication which is not provided on the internet yet as well as by literature research. For example, the fact that companies use 40% of household containers. Without this knowledge, the applied parameters would not make sense. Also, the different possible modalities are investigated as well as the solution methods.
Finally, the result of this research is an adaptable framework in ArcGIS Pro, combined with a calculation model in Matlab that could be applied to different waste collection solutions. For example, if a Roboat container of 3 m^3 will be used instead of 5 m^3, this parameters could easily be changed in Matlab, and the rest of the parameters will be given. Also, the output of ArcGIS is loaded into Matlab for the post-process calculations.

7.3 Discussion

Possible container locations are based on data from the municipality and validated by Google Maps and cycling through the area. However, since the validation is done by random sampling, it could be possible that some points are causing a conflict. There are some vessels located in the Amsterdam canals which are not shown in the data from the municipality, in that case, it is unclear if the vessels do not have a permit, or that the data is outdated. Also, 40% of the volume of a container is currently used by commercial waste, but this will probably vary over the areas. This percentage could be reduced by stricter rules or better monitoring.

7.4 Recommendations for further research

It would be recommended to develop more strategies for the calculation methods based on the costs of the implementation of the containers. Therefore, a financial overview of the costs must be developed, and the financial acceptance of the municipality have to be investigated. With that information, the parameters can be chosen to achieve the objective for the container locations and the financial objective. This could also lead to a new multi-objective facility location problem where the costs are taken into account.
Secondly, the vessel design needs further research. The suggestion of this research is to apply large engine-less barges which will be tugged by Roboat tugboats. In this case, a minimum number of Roboats is required, which could save costs. Next, the container design should be taken into account. Currently, AMS Institute is researching the possibilities of these build-in containers and the possible emptying systems. If these containers are developed, the noise should be measured during the emptying process to check if the operations could be executed in the night. This will define the number of required vessels.
Another essential factor is the quay wall height. The height of the quay walls vary through the city and affect the possible container size. Currently, there is no accurate data on the quay wall height. Currently, tests are performed with Roboats to scan the surroundings with LiDAR. This data could be useful for container location determination. Also, the restoring locations of the quay walls should be taken into account. If a quay wall will not be restored, it is essential to check if it is possible to build a container on that location.
The second recommendation is to take a closer look at small areas just outside the service area of 150 meters. By assigning a few households to a specific container with a slightly larger walking distance than 150 meters, it could save some extra located containers. Figure 7.1 shows the areas outside the service area. Several small areas are discovered, and there is no law anymore for a maximum walking distance. However, it is not preferred that residents will start throwing waste on the streets again due to the long walking distance.

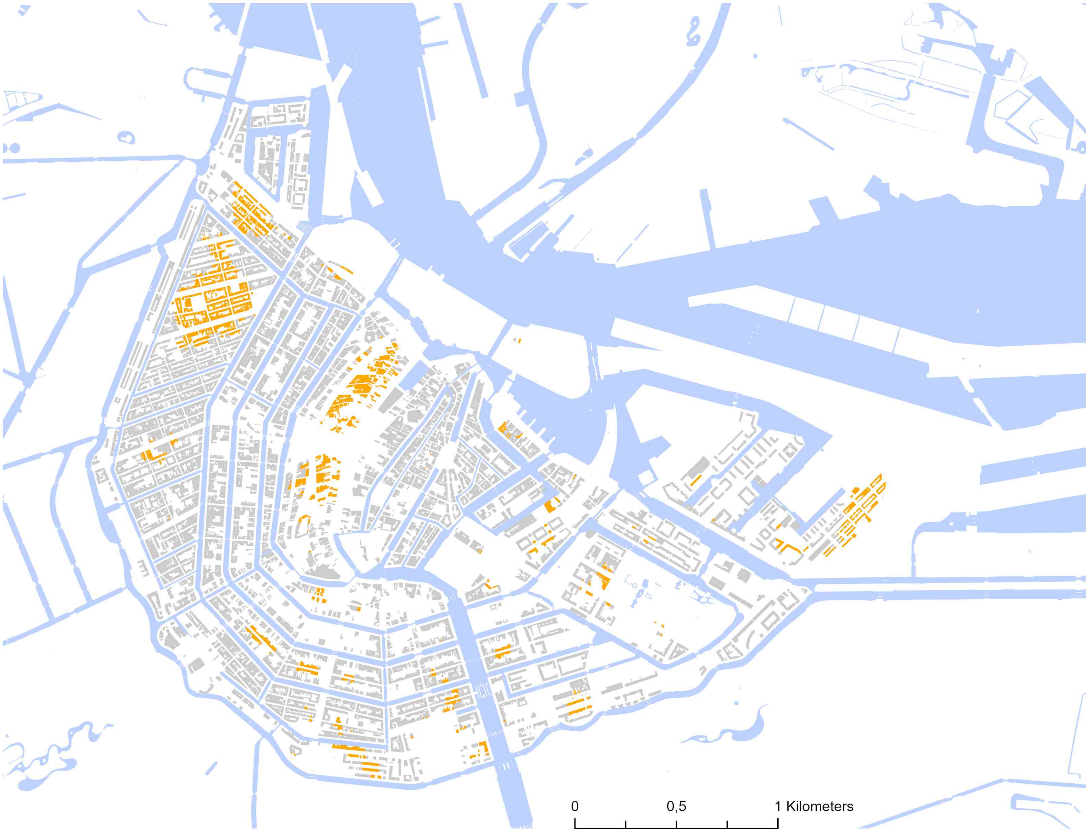


Figure 7.1: The buildings outside the possible Roboat service area

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Appendix A

Scientific research paper

Optimization of Container Type Selection and Location for Household Waste Collection in Amsterdam Centrum with Autonomous Vessels

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This research strives to contribute to the solution of the Amsterdam waste problem by improving the location determination of the various container types within the Centrum area. One of the modalities is an autonomous surface vehicle (ASV), and in this case, a Roboat. Since it is not possible to assign all demand to one modality, also trucks and small electric vehicles are taken into account. This waste collection problem is represented through a facility location problem with different facility types in order to maximize the coverage with a minimum number of containers. Case studies are designed in Amsterdam Centrum, and different calculation strategies are executed to compare different methods.

Autonomous surface vehicles | GIS | facility location | multi-facility | location-allocation | waste management

1. Introduction

The last decade has been a revolution for digitization, which affects various industries. In many sectors people are replaced by machines, robots or computers, which results in a world where a machine picks your order, stocks are traded by algorithms, and even coffee is brought to customers by a robot to keep distance between human beings. The reason why companies are switching towards a more autonomous world is clear; autonomy could provide costs savings, is not dependent on time, it reduces the number of errors and most of all it should be an improvement in safety. One of the industries where autonomy starts to grow is the maritime industry. An era of intelligent vessels has begun where shipowners, captains and control posts will be able to use the new technologies and their developments to manage assets, optimize decisions, and deploy remote and autonomous operations. Most applications of autonomous vessels are related to seaworthy container vessels, but smaller vessels could contribute to the solution of waste collection along the canals in Amsterdam Centrum. Therefore, MIT and AMS Institute started the Roboat project, developing a four by two-meter autonomous vessels with different purposes in Amsterdam Centrum. One of them is collecting household waste.

In the current situation, the household waste of almost all 86.862 residents (1) in the Centrum area is located on the sidewalk within specific time-slots twice a week. Garbage collectors collect the 67 MT of bags by hand and throw them into the heavy trucks, daily (2). The garbage bags attract unpleasant animals such as mice, rats and seagulls, next to the smell they produce. However, the heavy trucks do even more harm to the city; they destroy the fragile and poorly maintained quay walls. The restoring costs of these quay walls are estimated to be several billion euros. During this restoring process, there is a possibility to implement containers in the quay walls, which was not possible before due to tree roots, cables or pipes. The collected household waste within these build-in containers could be collected by Roboats, small autonomous vessels developed for the canals of Amsterdam. This will reduce the stress on the quay walls and follows the restrictions of the city centre to be combustion engine free in 2025 (3)(4)(5).

The objective of this research is to optimize the container type selection and location for a new household waste collection system in Amsterdam Centrum, which uses autonomous vessels and is applicable in the upcoming years. In other words, the suitable waste collection types have to be investigated, next the container locations for the chosen modalities have to be defined. This research will not investigate the details of the used container for waste collection with autonomous vessels.

The requirements given by the municipality are essential for the proposed system. First of all, the municipality is looking for a new household waste collection system that works is an improvement of the current situation and should be affordable. This means that the least amount of containers should be located and that each container serves as many demand points as possible. It is important that the new household waste collection system does not harm the quay walls anymore. This means that the heavy trucks have to be replaced by other modalities. The new modalities are not allowed to use a combustion engine, and the system should be in line with UNESCO-world heritage. Furthermore, if the municipality will change its current waste collection system, they want to be sure that it will work for the upcoming decades. Another requirement from the municipality is that no more waste will end up on the streets after a new system is implemented. To prevent people from throwing waste on the street, an acceptable maximum walking distance of 150 meters is set by the municipality combined

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with a realistic capacity for each container. Next, the total waste production of one household belongs all to one container, and the number of located containers may not exceed a specific number.

This research focuses on a household waste collection system in the Centrum area with Roboats in combination with trucks and EVs. The municipality does not want to focus yet on one specific system before all possibilities, costs and effects are elaborated. Therefore, both a system with and without trucks will be taken into account. Although it is still unknown if the EVs will be the future of waste collection, it is the solution which is the closest to reality and proven system compared to the drones. However, if the municipality of Amsterdam decides to collect waste with Roboats and drones, this research is still applicable. The drones could serve the households which are not assigned to a Roboat container. No specific locations have to be defined for the container location since drones are a dynamic solution. Only the number of applied drones should be calculated based on their capacity and operation speed. Furthermore, the model could be used for floating dumpsters (6) as well as build-in containers, only the capacity should be adjusted. This is also true for a vacuum waste system; only an uncapacitated solver would be used since the capacity of that system is infinite.

So, there are two proposed systems which will be compared with each other; Collecting waste in the centre of Amsterdam with Roboats, trucks and EVs, and the second waste collection system only consists of Roboats and EVs.

This paper has the following outline. First of all, a literature review is provided on facility location problems and its solution methods. Secondly, a model is developed based on the given requirements by the municipality. Next, the data about waste collection and Amsterdam Centrum will be provided in combination with the experimental setup. Also, the software selection is discussed in this chapter. Then, the calculation methodology is discussed combined with the applied strategies for the solution method. Next, the results of the calculations will be evaluated. The paper is finalized with a conclusion and recommendations for future research.

2. Literature review

There are multiple modalities applicable to collect all household waste in Amsterdam Centrum. The first possible solution is the application of autonomous Roboats, which will collect and transport the waste via the canals (7). This could either be done as a tugboat or as a waste vessel itself. The heavy trucks will not be allowed to drive over the quays anymore in the near future. However, the main roads through the city centre are strong enough to carry these heavy loads. A possibility is to collect waste from the households near these main roads by installing underground containers. This will probably be the cheapest method in the short term (8). The third possible modality is a small electric vehicle (EV) that could collect portable containers. These containers will be smaller than the underground containers and will be located on parking lots, for example (9). The last modality taken into account is the self-driving drone, which is currently tested with package delivery in the United States. These drones could also work the other way around; collecting bags on appointment. The final possibility is the application of an underground vacuum network. The pipes could be located in the canals to save costs. This system is already applied in different neighbourhoods in Europe (10), one of them is the Sluisbuurt in Amsterdam (11).

A common problem with great practical importance is to choose the location of facilities, such as fire departments or warehouses, in order to minimize or maximize a specific objective while satisfying the demand for some commodity (12). Depending on the specific problem to be tackled, costs, travel distance or market share could be one of the objectives. These problems are called facility location problems (FLPs). If each demand area can be covered by two or more facilities that each covers a percentage of demand, it is called an implicit approach (13). Other variations of the FLP could be assigning a capacity (CFLP) (14)(15), multi-objectives (MOFLP) (16), multi-level (MLFLP) (17), multi-echelon (MEFLP) (18)(19)(20), multi-facility (MFLP) (21), or hierarchical (HFLP) (22)(23)(24)(25)(26).

These problems could be solved in several ways. The most common method is to use mixed integer programming (MIP) or linear programming (LP). These MIP or LP packages could be added to programming software such as Python. The advantage of using these programs is that the algorithm is built from scratch and relatively easy to make adjustments within the code. At the same time, that is a disadvantage: it is relatively time-consuming to build the whole algorithm, and it is harder to validate the model.

A different and relatively new method is solving these kinds of problems with Geographical Information Systems (GIS). One of the reasons for the success of GIS is their capacity to generate visualizations of data, which greatly assist in such a complex decision-making process as a retail site or container location (27)(28). An advantage of using GIS is that the software itself easily generates large data sets. For example, the origin-destination cost matrix, which calculates all walking distances between the possible facility and demand points using the road network. Using GIS software makes it easy to check if the output makes sense due to the visualizations. Also, the interface is user friendly, and it is possible to give demands to the system with integrated tools as well as with Python commands.

The GIS software is a proven success for accurate outcomes within municipal solid waste management systems (29)(30)(31). The visual output creates a direct confirmation of the quality and reliability of the calculation. Finally, once all required shapefiles are uploaded, and the calculation settings are set, it is easy to compare calculations by adjusting the parameters.

ArcGIS Pro consists of several predefined location-allocation solving methods. The most relevant solving approaches for this research are the 'minimize weighted impedance', 'maximize coverage', 'maximize capacitated coverage' and the 'maximize coverage, minimize facilities'.

The minimize weighted impedance method is commonly used for the warehouse problem; it minimizes the weighted impedance between facilities and demand points (32)(33). This method is also known as the P-Median method. Facilities are located such that the sum of all weighted costs between demand points and solution facilities is minimized for the given number of located facilities, which will be the walking distance in this research. This optimization method does not take any cut-off distance into account, neither capacity for each facility point.

The maximize coverage method is used for the uncapacitated facility location problem, which aims to find a set of facilities that serve the maximum possible number of demand points within the impedance cut-off. The number of located facilities has to be predetermined, or could be obtained by iterations.

The maximize capacitated coverage method has the same objectives as the maximize coverage method, only this time a capacity is assigned to the facilities. Therefore, this solution method is applied to capacitated FLPs. Again, facilities are located such that as many demand points as possible are allocated to solution facilities within the impedance cut-off. The number of located facilities is defined in advance (34).

The maximize coverage and minimize facilities approach is a variation on the maximize coverage method (35). Both methods are usually applied to uncapacitated FLPs, possibly restricted to a certain impedance cut-off. The difference between the two approaches is that the maximize coverage and minimize facilities method calculates the minimum required number of facilities to serve the total possible demand, where the maximize coverage method calculates the maximum number of demand points that could be assigned to the given number of facilities.

This research contributes to the current research field by developing a framework to assign all demand points to selected containers, using a network for the calculated impedance, applying multiple facility types, develop different strategies for the solving methods and solve the location-allocation with different solvers. This combination is not executed before in literature. There are multi-facility solutions using GIS described in the literature. However, these researches use the euclidean distance between the facilities and demand points or not assigning the total demand (36)(37).

3. Modelling

This section describes the MIP models corresponding to the location-allocation problem. The models are described by the following sets, indices, parameters and decision variables. Consider a set of demand points $i \in I$ and a set of possible facility locations $j \in J$, with a distance $d_{i,j} \geq 0$ between demand point $i \in I$ and facility $j \in J$. The first objective $x_{i,j}$ describes if demand node $i \in I$ is assigned to a specific facility $j \in J$. The following decision variable is y_j, which describes if a facility is located at $j \in J$.

Sets

I	Set of all demand points [Households]
J	Set of all possible facility points [Containers]

Indices

$i \in I$	Demand point in the set of demand points
$j \in J$	Facility point in the set of facility points

Parameters

$d_{i,j}$	Travel distance [m] between demand point $i \in I$ to facility $j \in J$
d_{max}	Maximum walking distance [m]
p	Maximum number of located facilities
C	Capacity of each located facility

Decision variables

$x_{i,j} =$	1,	if demand node $i \in I$ is assigned to facility located at $j \in J$
	0,	otherwise
$y_j =$	1,	if facility is located at $j \in J$
	0,	otherwise

Minimize weighted impedance This P-median problem (PMP) chooses facilities such that the sum of the walking distances between the demand points and facilities is minimized for a given amount of facilities. With the described sets, indices, parameters and decision variables, the formulation of the PMP method is as follows (32)(33):

$$\min \sum_{j \in J} \sum_{i \in I} d_{i,j} x_{i,j} \quad [1]$$

Subject to:

$$\sum_{j \in J} x_{i,j} = 1, \forall i \in I \quad [2]$$

$$x_{i,j} - y_j \leq 0, \forall i \in I, j \in J \quad [3]$$

$$\sum_{j \in J} y_j \leq p \quad [4]$$

$$x_{i,j} d_{i,j} \leq x_{i,j} d_{max}, \forall i \in I, j \in J \quad [5]$$

$$x_{i,j} \in \{0,1\}, \forall i \in I, j \in J \quad [6]$$

$$y_j \in \{0,1\}, \forall j \in J \quad [7]$$

The objective function in [1] describes the minimization of distance $d_{i,j}$ summed over all facilities and demand nodes. The first constraint in [2] states that a demand point i can only be assigned to one facility j. The next constraint, described in [3], states that demand node i can be serviced by a facility at j only if there is a facility at j, because if $y_j = 0$ then we must have that $x_{i,j} = 0$. The constraint [4] means that exactly p facilities must be located. Constraint [5] states that every assigned demand point is limited by a certain maximum walking distance. Lastly, the constraints [6] and [7] force the decision variables to be binary.

Maximize Coverage The maximize coverage method does not take the walking distance into account within the objective function. The maximize coverage model aims to cover as many demand as possible with a given number of facilities. The number of facilities is defined in advance. Therefore, this model could be used as an iteration tool. The objective is described in equation [8].

$$\max \sum_{i \in I} x_{i,j} \quad [8]$$

Subject to:

$$\sum_{j \in J} x_{i,j} \leq 1, \forall i \in I \quad [9]$$

$$\sum_{j \in J} y_j \leq p \quad [10]$$

$$x_{i,j} - y_j \leq 0, \forall i \in I, j \in J \quad [11]$$

$$x_{i,j} d_{i,j} \leq x_{i,j} d_{max}, \forall i \in I, j \in J \quad [12]$$

$$X_{i,j} \in \{0,1\}, \forall i \in I, j \in J \quad [13]$$

$$Y_j \in \{0,1\}, \forall j \in J \quad [14]$$

Maximize Capacitated Coverage The maximize capacitated coverage has the same objective as the maximize coverage model. However, this model is limited by a given capacity. Consider a set of demand points $i \in I$ and a set of possible facility locations $j \in J$, with a distance $d_{i,j} \geq 0$ between demand point $i \in I$ and facility $j \in J$. Other parameters are p for the maximum number of facilities and C for the capacity of each located facility. The formulation of the maximized capacitated coverage problem is as follows (34):

$$\max \sum_{i \in I} x_{i,j} \qquad [15]$$

Subject to:

$$\sum_{j \in J} x_{i,j} \leq 1, \forall i \in I \qquad [16]$$

$$\sum_{j \in J} y_j \leq p \qquad [17]$$

$$\sum_{i \in I} x_{i,j} \leq C y_j, \forall j \in J \qquad [18]$$

$$x_{i,j} - y_j \leq 0, \forall i \in I, j \in J \qquad [19]$$

$$x_{i,j} d_{i,j} \leq x_{i,j} d_{max}, \forall i \in I, j \in J \qquad [20]$$

$$X_{i,j} \in \{0,1\}, \forall i \in I, j \in J \qquad [21]$$

$$Y_j \in \{0,1\}, \forall j \in J \qquad [22]$$

Unlike the maximize coverage method, the maximize capacitated coverage model does not require an impedance cut-off. However, when an impedance cut-off is specified, any demand point outside all the facilities' impedance cut-off is not allocated. If the total demand within the impedance cut-off of a facility is greater than the capacity of the facility, only the demand points that maximize total captured demand and minimize total weighted impedance are allocated. An allocated demand point has all or none of its demand weight assigned to a facility; that is, demand is not apportioned with this problem type.

Maximize coverage and minimize facilities For the maximize coverage and minimize facilities method, it is not possible to set a specified number of containers. Therefore, this model can not be used as an iteration tool. This method is commonly used for uncapacitated FLPs. The objective of the model is to assign as much demand points to the least possible facility points. The objective is described in equation [23] (35).

$$\max \sum_{i \in I} x_{i,j} - \sum_{j \in J} y_j \qquad [23]$$

Subject to:

$$\sum_{j \in J} x_{i,j} \leq 1, \forall i \in I \qquad [24]$$

$$\sum_{i \in I} x_{i,j} \leq C y_j, \forall j \in J \qquad [25]$$

$$x_{i,j} - y_j \leq 0, \forall i \in I, j \in J \qquad [26]$$

$$x_{i,j} d_{i,j} \leq x_{i,j} d_{max}, \forall i \in I, j \in J \qquad [27]$$

$$X_{i,j} \in \{0,1\}, \forall i \in I, j \in J \qquad [28]$$

$$Y_j \in \{0,1\}, \forall j \in J \qquad [29]$$

Advanced model The following advanced model is developed to describe the applied strategy and translates the system requirements into a mathematical model. It contains the three containers types, collected by the different modalities. This model could be described as an explicit capacitated multi-facility location problem with assigned priorities. The model is described as follows:

Sets

I	Set of all demand points [Households]
J	Set of all possible Roboat container points
K	Set of all possible truck container points
L	Set of all possible EV containers points

Indices

$i \in I$	Demand point in the set of demand points
$j \in J$	Roboat container point in the set of Roboat container points
$k \in K$	Truck container point in the set of truck container points
$l \in L$	EV container point in the set of EV container points

Parameters

$d_{i,j,k,l}$	Travel distance [m] from demand point $i \in I$ to facility $j \in J, k \in K$ or $l \in L$
d_{max}	Maximum walking distance [m]
$p_{j,k,l}$	Maximum number of facilities j, k or l
$C_{j,k,l}$	Capacity of facility j, k or l
$w_m =$	Weighting factors (w_1, w_2, w_3) $\quad w_m \in \{0,1\}$

Decision variables

$r_{i,j} =$	1,	if demand node $i \in I$ is assigned to a Roboat container located at $j \in J$
	0,	otherwise
$s_{i,k} =$	1,	if demand node $i \in I$ is assigned to a truck container located at $k \in K$
	0,	otherwise
$t_{i,l} =$	1,	if demand node $i \in I$ is assigned to an EV container located at $l \in L$
	0,	otherwise
$y_{j,k,l} =$	1,	if facility is located at $j \in J, k \in K$ or $l \in L$
	0,	otherwise

$$\max \sum_{i \in I} (w_1 r_{i,j} + w_2 s_{i,k} + w_3 t_{i,l}) - \sum_{j \in J} y_{j,k,l} \qquad [30]$$

Subject to:

$$\sum_{j \in J} r_{i,j}, \sum_{k \in K} s_{i,k}, \sum_{l \in L} t_{i,l} \leq 1, \forall i \in I \qquad [31]$$

$$\sum_{j \in J} y_j \leq p_j, \sum_{k \in K} y_k \leq p_k, \sum_{l \in L} y_l \leq p_l \qquad [32]$$

$$\sum_{i \in I} r_{i,j} \leq C_j y_j, \sum_{i \in I} s_{i,k} \leq C_k y_k, \sum_{i \in I} t_{i,l} \leq C_l y_l, \quad \forall j \in J \forall k \in K \forall l \in L \qquad [33]$$

$$y_{j,k,l} d_{i,j,k,l} \leq d_{max}, \forall j \in J, k \in K, l \in L \qquad [34]$$

$$y_{j,k,l} d_{i,j,k,l} \leq d_{i+1,j,k,l}, \forall j \in J, k \in K, l \in L \qquad [35]$$

$$r_{i,j}, s_{i,k}, t_{i,l} \in \{0,1\}, \forall i \in I, j \in J, k \in K, l \in L \qquad [36]$$

$$y_j \in \{0,1\}, \forall j \in J \qquad [37]$$

The objective in [30] maximizes the number of assigned demand points for the three different container types and minimizes the number of required containers to do so. The first constraint, equation [31], states that at most one facility point is assigned to the demand of a certain demand point, either a Roboat, truck or EV container. The following constraint in [32] states the number of located containers may not exceed a given maximum number of containers, which creates to possibility to limit the costs if there will be a price difference between the containers. The capacity requirement is translated into equation [33], which limits the assigned facility point by its capacity. Next, constraint [34] makes sure that facility points could only be assigned to demand points within the maximum walking distance, which is 150 meters in this particular case. The final requirement prefers a short walking distance, but is submissive to the objective. Constraint [35] is added to meet this requirement, which states that the shortest walking distance will be assigned before a demand point that is further away. Finally, the last constraints makes sure that the decision variables are binary. Now, the system requirements are translated to a mathematical model. This means that from this point the solution method could be defined, based on this model and the provided data. This will be explained in the following chapter.

4. Data and Experimental setup

The data on the buildings and households contain information about their geographical position, address, building date, if it is bought or rented, number of households per building, and others. This file consists of 12.250 buildings containing at least one of the 51.132 households in the Centrum Area (38). The number of residents in 2019 is measured to be 86.862 (1).

The waste data are based on the total waste production of Amsterdam, which results in the table 1.

Fraction	Density [kg/m3]	Produced [kg]	Volume [m3]
Rest	100	219	2,19
Paper	50	19	0,38
Glass	300	18,3	0,061
Textile	25	3,5	0,14
Plastic	150	4,2	0,028
Organic	400	17,9	0,045
Annually	99.13 (Average)	281,9	2,8438
Daily	99.13 (Average)	0,7723	0,0078

Table 1. Waste density and production per resident of Amsterdam (2)

This comes down to a daily production of more than 67 MT in the Centrum area. However, the waste production is shrinking every year for at least the past four years, around 10 kg on average per capita per year. An important note is that two different researches have proven that 40% of the container volume is used by companies, who mostly do not have the licence to use that container. Since the municipality prefers to rely on this open waste system, it is assumed that this 40% will be used by companies in the future as well.

For the calculations, several assumptions have to be made. First of all, this research assumes that walking distance does not vary over time. Secondly, it is assumed that waste production is constant over time. There is only data available on the waste collection over the week, but this does not give insight into the production of waste. Next, the specifications of the underground containers for the trucks are used for the specifications of the build-in containers in the quay walls. However, these containers are not developed yet. The specifications of the EV containers are based on the EcoCassettes, currently used in a pilot in Amsterdam (39). The final assumption is that the Roboat and EV containers will be collected a maximum of three times per week. Currently, every time waste is dropped at the AEB (9), costs are taken into account. Therefore, it is preferred to visit as least as possible with as many as possible waste. Since the trucks are estimated to have the largest capacity of the three modalities, it is accepted to collect the waste twice per week. The results of the container specifications are shown in table 2.

Modality	Volume [m^3]	Press ratio	Max. pick-up [$week^{-1}$]
Roboat	5	3	3
Truck	5	3	2
EVs	3	3	3

Table 2. Applied container details

With the specifications defined, it is possible to calculated the capacity of each applied container. This is done with the following equation for the buildings:

$$C_{\text{Modality}} = \frac{\frac{\text{pick-up freq}}{\text{7 days}} * \text{ press ratio } * 60\% * \text{ cont. vol.}}{\text{waste volume per day } * \text{ resident per building}} \quad [38]$$

This results in the following capacities per modality:

Capacity	Buildings	Households	Residents
Roboat	69	291	495
Truck	46	194	330
EVs	41	174	297

Table 3. Container capacity per modality

The next important step during this research is to select the software to define the container locations. Therefore, the pros and cons of the different discussed solution methods have to be compared. The main advantage of using programming language is that the optimization will be developed from scratch. Therefore, it will be easier to make adjustments afterwards. Developing a model from scratch is also a disadvantage since that could take much time. Furthermore, it will be harder to apply the provided data from the municipality, since they are mostly shapefiles, WFS and WMS files. The advantage of GIS programs is that this software is developed for similar problems and therefore, less time consuming to work with. The generated visualizations as output are preferred to validate the calculation. The final advantage is that large datasets are easily generated, for example, a matrix with the distances between all demand points and possible facility points. On the other hand, it is harder to make changes in a predefined software program. Nevertheless, since most GIS software programs are linked to a python command window, it is possible to do so.
After the pros and cons of using programming language and GIS software are weighted, it is decided to work with GIS software. QGIS is an open-source GIS software program which could be used for free. However, ArcGIS Pro is a more advanced program with professional network analysis tools (40).
After the software has been selected, the next step is to apply the data to the software and generate the required points, lines and polygons. This will be discussed in the following paragraphs.

The demand points in this research represent all residents of the Centrum area. However, it is not possible to use all residents as input data. Therefore, the buildings containing at least one household are generated into demand points. The facility points represent possible container locations. The Roboat containers are generated every 10 meters on the border of water and land, which is mostly along the canals. The points within a range of 10 meters within a bridge, vessel or houseboat are deleted. Also, the points not connected to the open water network are deleted as well as if the points are located on a building or in a backyard. This results in the following possible locations:

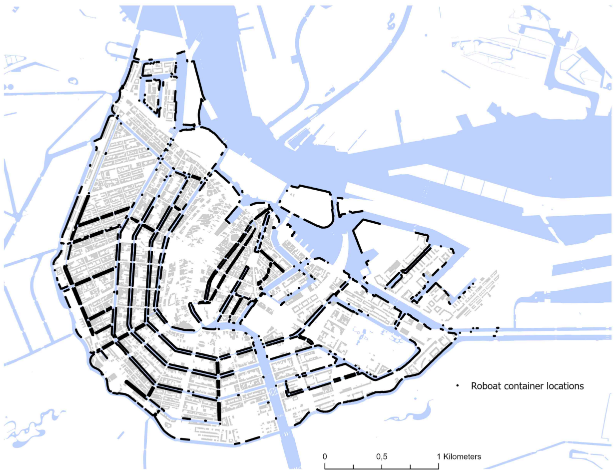

Fig. 1. The generated possible Roboat container locations

As discussed earlier, the truck containers can only be located on the main roads, the so-called 'Hoofdroutes'. The WFS from the municipality was uploaded to ArcGIS and points were generate along these roads every 10 meter, shown in figure 2.

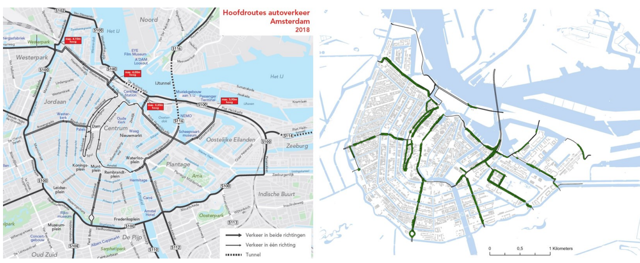

Fig. 2. The main roads and generated truck containers

Finally, possible EV container locations have to be defined. These containers can be located on a single parking spot, on the sidewalk or in a park. Therefore, this research assumes that their will always be a place to locate such a container around the selected container points, but validation is required. The possible container points are generated every twenty meters along with the road network.

5. Calculation methodology

The calculations during this research were executed by ArcGIS Pro. The parameters discussed in chapter 4 were used for the setup of the calculation. One of the constraints given by the municipality is that the maximum walking distance between a container and household is 150 meters. This distance is calculated along with the road network, so it is not the Euclidean distance. The costs of the walking distance are set on linear.

During this research two different approaches were executed to compare the calculation methods. The first method is called the Serial approach and the second method is the Parallel approach. The first calculations were done using the 12.250 buildings as input data. Finally, the most efficient approach will be updated to improve the accuracy.

A Serial The first applied method is a combination of the maximize capacitated coverage and the maximize coverage, minimize facilities method. The different container types are located one by one, until the containers are not efficient anymore. The efficiency of a container is calculated based on the pick-up frequency and the filling rate. The Roboat containers have an acceptable capacity as long as it assigns 15 buildings. The lower bound of the truck containers is calculated to be 10 buildings per container. The EV containers will assign the rest of the buildings. This results in an efficient lower bound vector $f_m = (15, 10, 0)$. Method 1, 2 and 3 use this serial approach. Method 1 starts with assigning Roboat containers, next the truck containers and finally the EV containers. The second method switches the order of the Roboat and truck containers. The third method assigns only Roboat and EV containers, since the municipality is not sure if trucks will be used in the future. The applied MIP model by ArcGIS Pro software could be defined as follows:

$$\max \sum_{i\in I}(w_1 r_{i,j} + w_2 s_{i,k} + w_3 t_{i,l}) - \sum_{j\in J} y_{j,k,l} \quad [39]$$

Subject to:

$$\sum_{j\in J} r_{i,j}, \sum_{k\in K} s_{i,k}, \sum_{l\in L} t_{i,l} \leq 1, \forall i \in I \quad [40]$$

$$\sum_{j\in J} y_j \leq p_j, \sum_{k\in K} y_k \leq p_k, \sum_{l\in L} y_l \leq p_l \quad [41]$$

$$\sum_{i\in I} r_{i,j} \leq C_j y_j, \sum_{i\in I} s_{i,k} \leq C_k y_k, \sum_{i\in I} t_{i,l} \leq C_l y_l, \quad \forall j \in J, k \in K, l \in L \quad [42]$$

$$\sum_{i\in I} r_{i,j} \geq f_1 y_j, \sum_{i\in I} s_{i,k} \geq f_2 y_k, \sum_{i\in I} t_{i,l} \geq f_3 y_l, \quad \forall j \in J, k \in K, l \in L \quad [43]$$

$$y_{j,k,l} d_{i,j,k,l} \leq d_{max}, \forall j \in J, k \in K, l \in L \quad [44]$$

$$y_{j,k,l} d_{i,j,k,l} \leq d_{i+1,j,k,l}, \forall j \in J, k \in K, l \in L \quad [45]$$

$$r_{i,j}, s_{i,k}, t_{i,l} \in \{0,1\}, \forall i \in I, j \in J, k \in K, l \in L \quad [46]$$

$$y_j \in \{0,1\}, \forall j \in J \quad [47]$$

The different calculations per method are defined by the order and weighting factor. The calculations for method 1 are expressed as follows:

calculation 1: $w_m = (1, 0, 0)$

calculation 2: $w_m = (0, 1, 0)$

calculation 3: $w_m = (0, 0, 1)$

The order and weighting factors for method 2 are expressed with: 1. $w_m = (0, 1, 0)$, 2. $w_m = (1, 0, 0)$, 3. $w_m = (0, 0, 1)$. For method 3 the order and weighting factor are given by: 1. $w_m = (1, 0, 0)$, 2. $w_m = (0, 0, 1)$.

B Parallel The parallel method does not focus on the point where a container is not efficient anymore but tries to allocate as many efficient containers overall. This means that there is no preference anymore between the modalities as long as the container assigns the most demand points. Therefore, constraint 43 is removed for the parallel approach. The locations of the different container types will be defined at the same time. However, since the Roboat containers have a larger capacity than the other types, these will be prefered since they can assign more demand points to one facility point. Methods 4 and 5 also use 12.250 buildings as demand points. The same MIP model for the serial approach is taken into account, only the efficiency lower bound is removed. Furthermore, the weighting factors vary compared to the serial approach. This results in the following weighting factors for methods 4 and 5.

Method 4: $$w_m = (1, 1, 1)$$
Method 5: $$w_m = (1, 0, 1)$$

6. Results and Evaluation

The first calculations of this research were focused on the possibilities of the application of Roboat containers in the Centrum Area. Therefore, various numbers of containers were located to get insight in the number of households that will be served. The curve of the served percentage of households is shown in figure 3 within a range of 100 and 400 containers. Remarkable is the relatively steep increase at the beginning of the curve and the flat end of the curve.

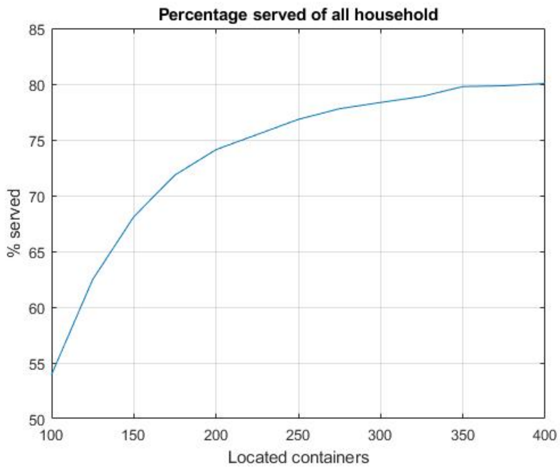

Fig. 3. Percentage served buildings in Centrum vs located containers

By taking a closer look at all buildings within a range of 150-meter walking distance from all possible Roboat container locations, the orange buildings in figure 4 are in-scope. Figure 5 is the result of trying to assign as many demand points as possible to the in-scope buildings. With the given capacity, around 98% of all in-scope buildings could be assigned with 400 containers.

Fig. 4. The buildings within 150 meter from a possible Roboat container

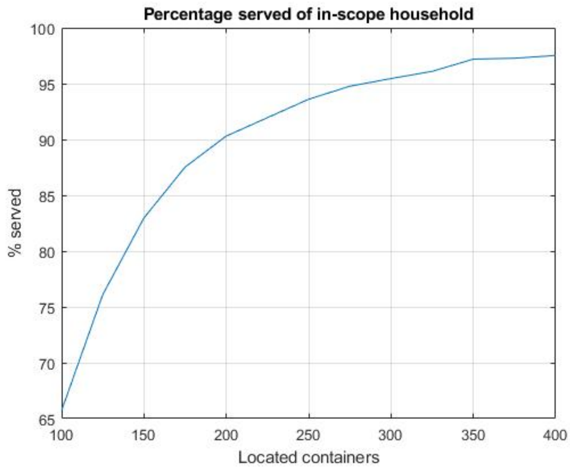

Fig. 5. Percentage served buildings in Centrum vs located containers

The conclusion can be drawn that multiple modalities are required to serve the total demand, or the walking distance should be increased. The objective of the municipality was to locate the least amount of containers while serving the maximum demand. Every household is assigned to a specific container, shown in figure 6. The number of located containers is shown in figure 7.

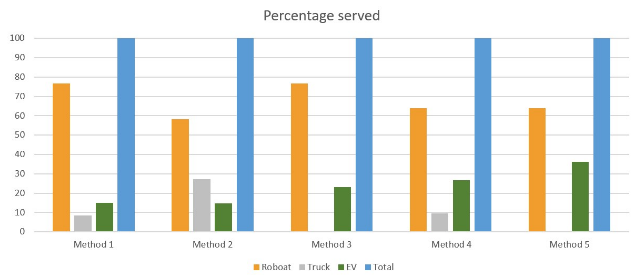

Fig. 6. Percentage of served buildings for the five methods

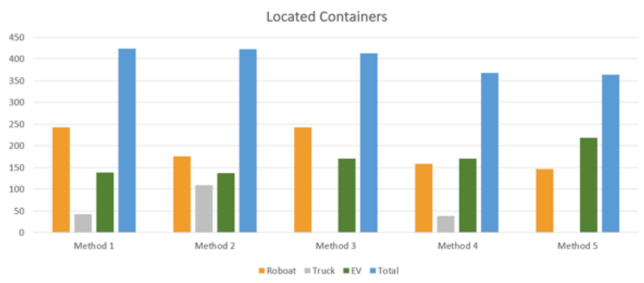

Fig. 7. Number of located containers for the five methods

Method 1, 2 and 3 require more containers to assign the total demand. Every calculation has assigned 100% of the total demand to a specific container with a given geographical location. The Roboat containers have the largest share in serving residents. According to the objective of the calculations, the parallel approach is more efficient. Therefore, the parallel approach will be updated to improve the accuracy. This is done by using the 51.132 household points as input data instead of the 12.250 buildings containing a household, resulting in methods 6 and 7. Where method 6 is the update of method 4 using weighting factor $w_m = (1, 1, 1)$, and method 7 is the update of method 5, applying the weighting factor $w_m = (1, 0, 1)$. The capacity changes according to table 3. Methods 6 and 7 serve the total demand as well. The number of located containers for all methods is provided in figure 8.

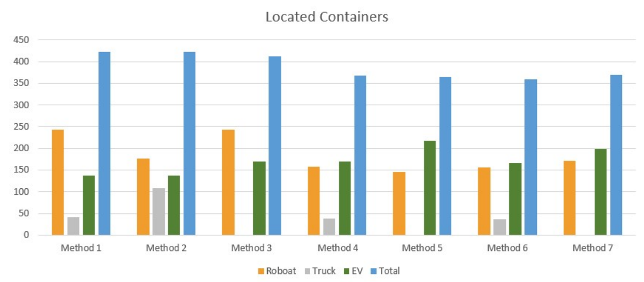

Fig. 8. Number of located containers for all methods

The parallel approach uses between 359 and 370 containers, which is a relatively small gap. Also remarkable is the shift in container types from method 5 to 7, where method 7 uses relatively more Roboat containers and fewer EV containers.

Logically, the average walking distance is increasing if fewer containers are located. However, the maximum walking distance does not exceed the restricted 150 meters. The average walking distances per modality are shown in figure 9.

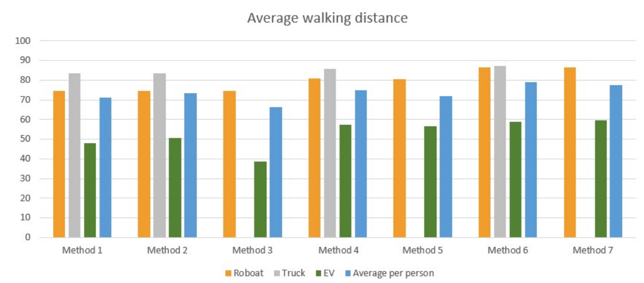

Fig. 9. Average walking distance per modality

Finally, an efficiency score is calculated by the average number of buildings assigned to a container per container type, divided by the capacity of that container type. These efficiency scores are shown in figure 10. Again, it is clear that the parallel approach is more efficient that the serial approach.

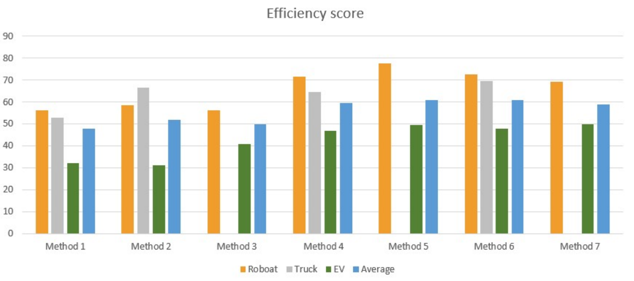

Fig. 10. Efficiency score per modality

The defined locations for all containers through Amsterdam Centrum are shown in appendix A, combined with their corresponding walking distances.

7. Conclusion and Future Research

First of all, it can be concluded that the parallel approach is more efficient than the serial approach based on the number of located containers and the calculated efficiency score. Secondly, method 6 and 7 have higher accuracy than method 4 and 5. However, method 4 and 5 are useful to compare the serial approach with the parallel approach. Method 4 and 5 assume that the households are equally distributed over the buildings, which mean that on average, 7.09 residents live in one building. However, this is not true since some buildings are apartment blocks and some buildings are small houses. Figure 11 shows the difference in container location based on the household density per building. The darker building blocks have a higher density. On the right image, it is clear that more containers are required around these blocks.

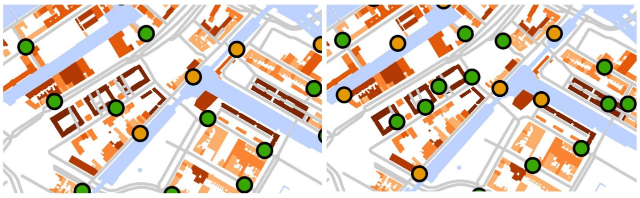

Fig. 11. Left: method 5, right: method 7

Depending on the preferences of the municipality, a decision can be made to transform method 6 or 7 into reality. If the municipality decides to use different modalities, a vacuum system or drones, this framework is still beneficial for the container location definition. With the Matlab file, the parameters are easily recalculated, which could afterwards be implemented in ArcGIS Pro.

Recommendations It would be recommended to develop more strategies for the calculation methods based on the costs of the implementation of the containers. Therefore, a financial overview of the costs must be developed, and the financial acceptance of the municipality have to be investigated. With that information, the parameters can be chosen to achieve the objective for the container locations and the financial objective. This could also lead to a new multi-objective facility location problem where the costs are taken into account.

Secondly, the vessel design needs further research. The suggestion of this research is to apply large engine-less barges which will be tugged by Roboat tugboats. In this case, a minimum number of Roboats is required, which could save costs. Next, the container design should be taken into account. Currently, AMS Institute is researching the possibilities of these build-in containers and the possible emptying systems. If these containers are developed, the noise should be measured during the emptying process to check if the operations could be executed in the night. This will define the number of required vessels.

Another essential factor is the quay wall height. The height of the quay walls vary through the city and affect the possible container size. Currently, there is no accurate data on the quay wall height. Soon tests will be performed with Roboats to scan the surroundings with LiDAR. This data could be useful for container location decisions. Also, the restoring locations of the quay walls should be taken into account. If a quay wall will not be restored, it is essential to check if it is possible to build a container on that location.

The final recommendation is to take a closer look at small areas just outside the service area of 150 meters. By assigning a few households to a specific container with a slightly larger walking distance than 150 meters, it could save some extra located containers.

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Appendix A

The exact container locations are shown in the following figures for all seven methods. The orange dots represent the Roboat container locations, the grey dots represent the truck containers, and the green dots represent the EV containers. The locations are followed by the walking distances per method.

Method 1

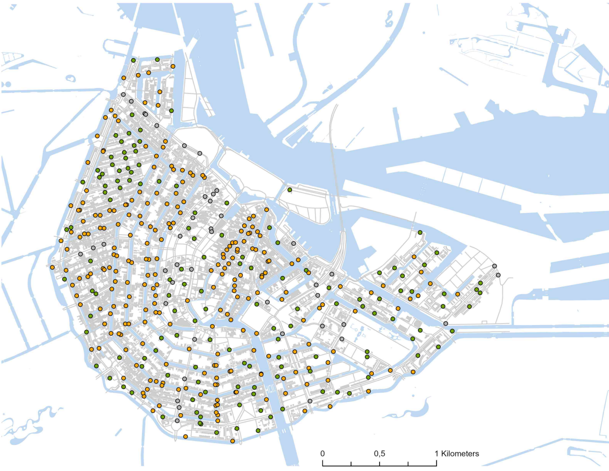

Fig. 12. The located containers for method 1

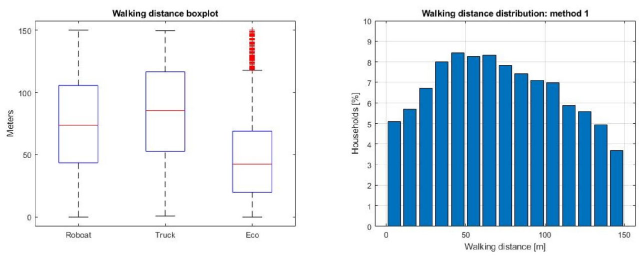

Fig. 13. The walking distances for method 1

Method 2

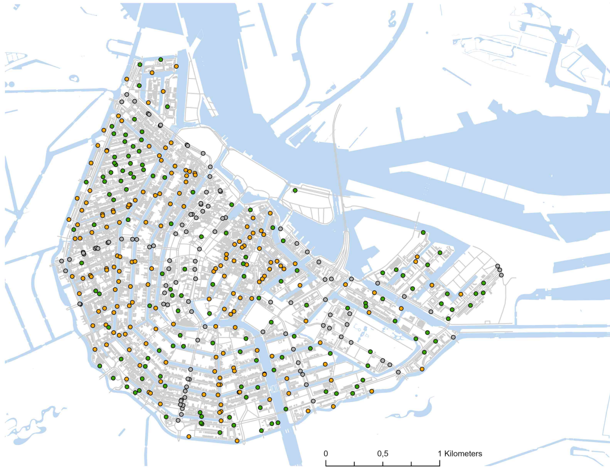

Fig. 14. The located containers for method 2

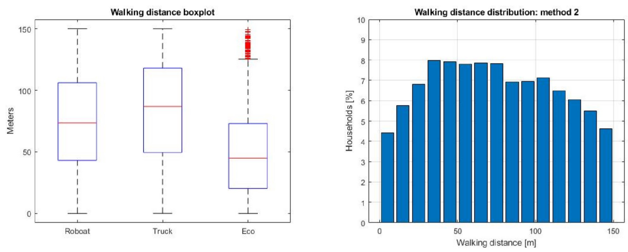

Fig. 15. The walking distances for method 2

Method 3

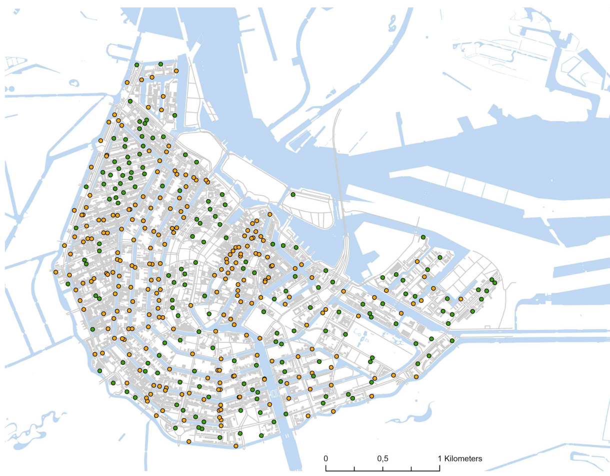

Fig. 16. The located containers for method 3

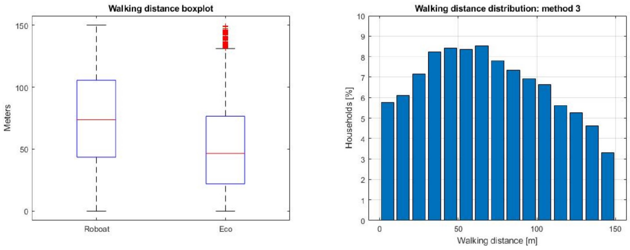

Fig. 17. The walking distances for method 3

Method 4

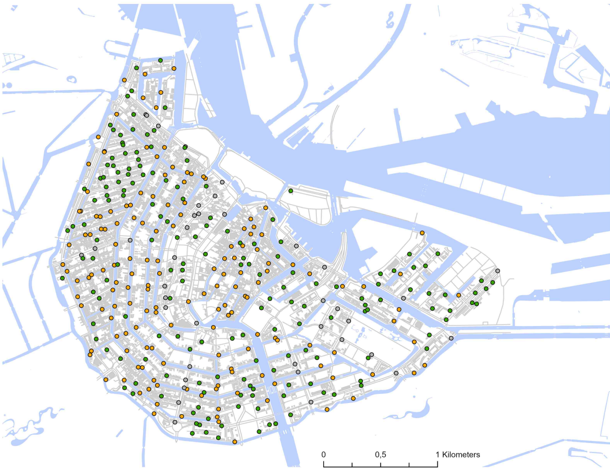

Fig. 18. The located containers for method 4

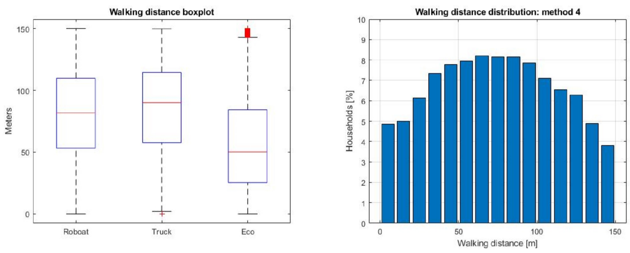

Fig. 19. The walking distances for method 4

Method 5

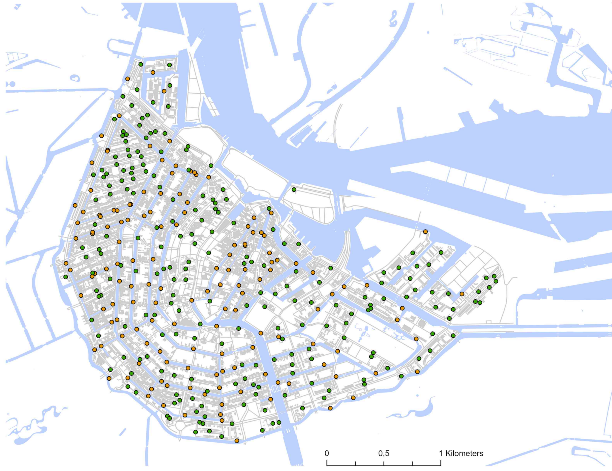

Fig. 20. The located containers for method 5

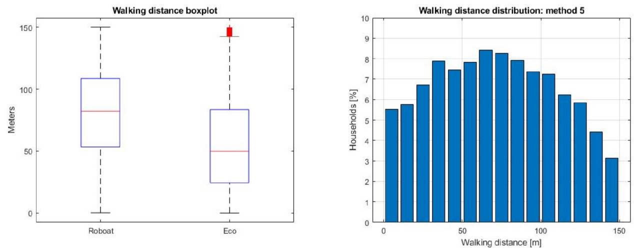

Fig. 21. The walking distances for method 5

Method 6

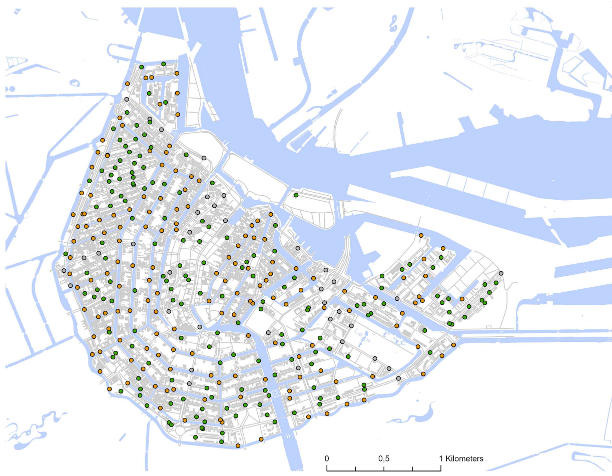

Fig. 22. The located containers for method 6

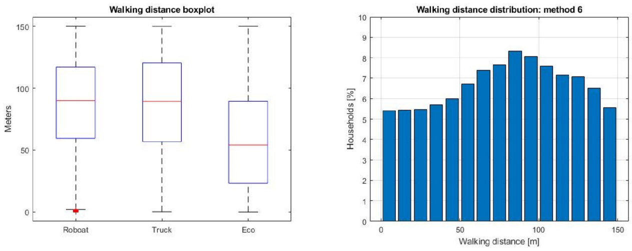

Fig. 23. The walking distances for method 6

Method 7

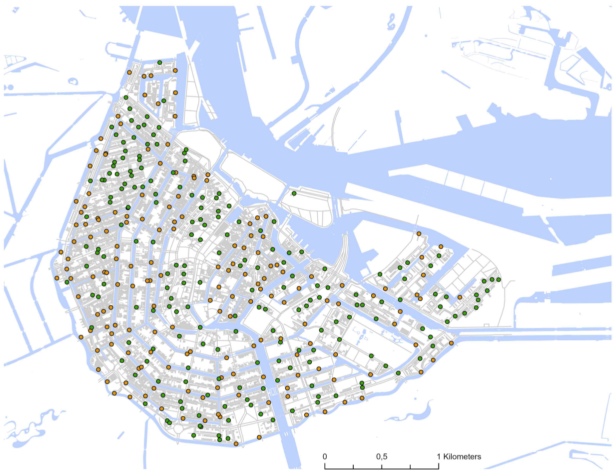

Fig. 24. The located containers for method 7

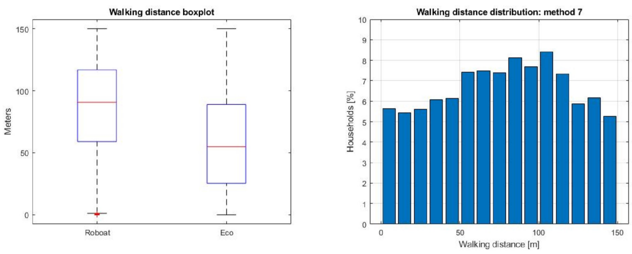

Fig. 25. The walking distances for method 7

Appendix B

Results

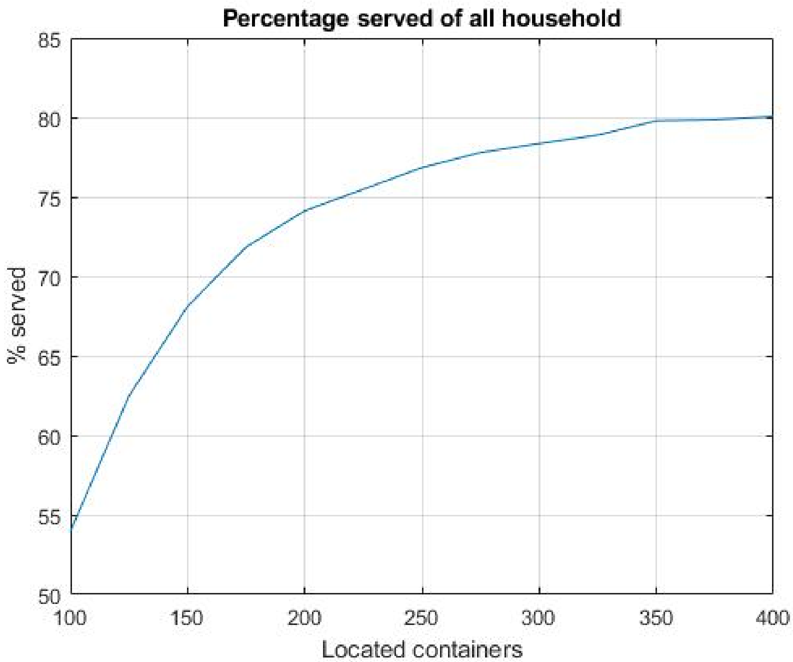

Figure B.1: Percentage allocated containers all household

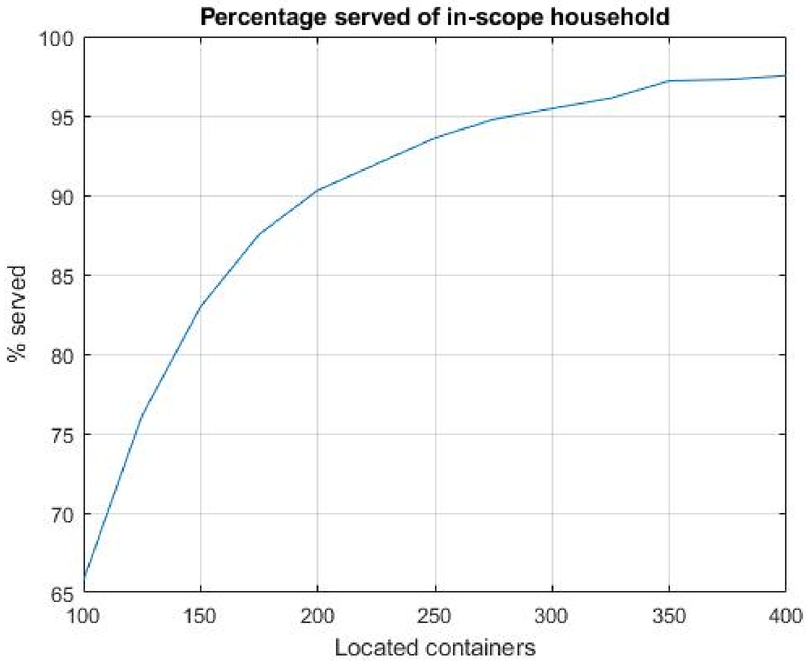

Figure B.2: Percentage allocated containers in-scope household

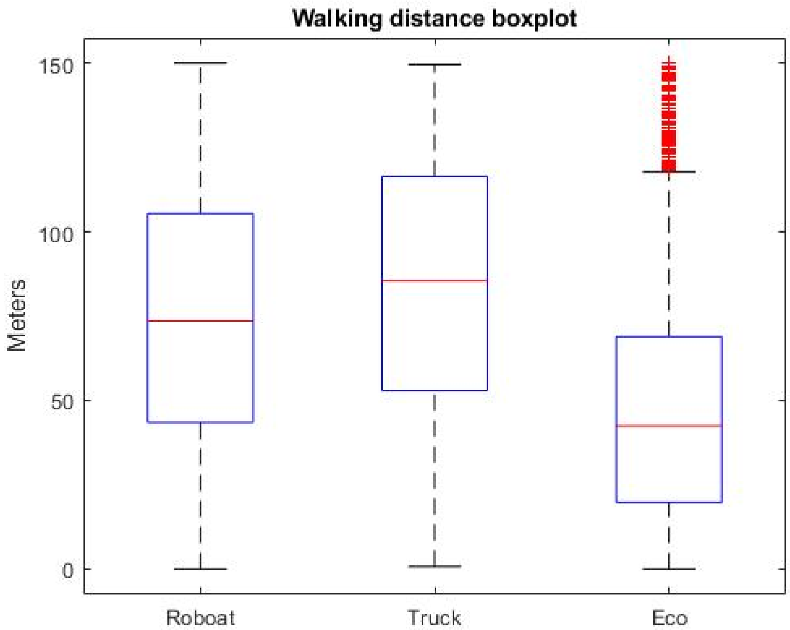

Figure B.3: Boxplot of walking distance: method 1

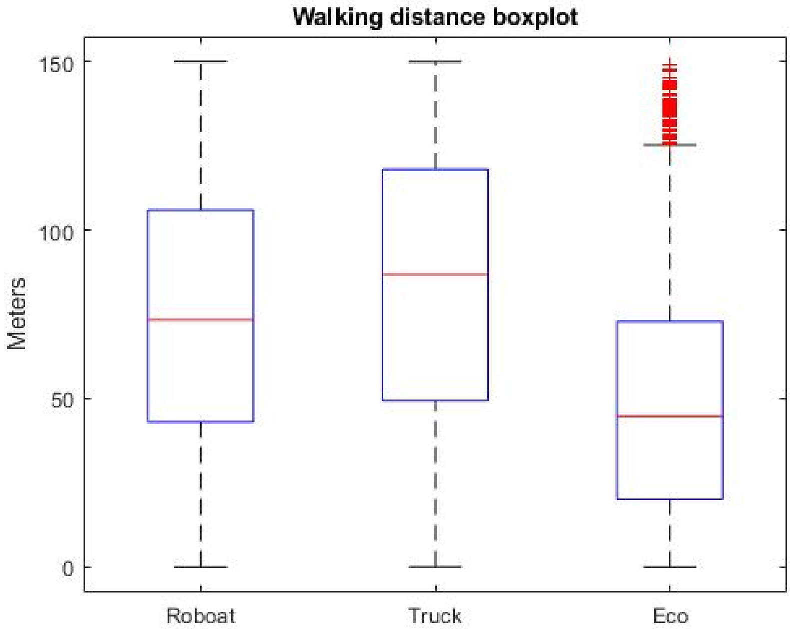

Figure B.4: Boxplot of walking distance: method 2

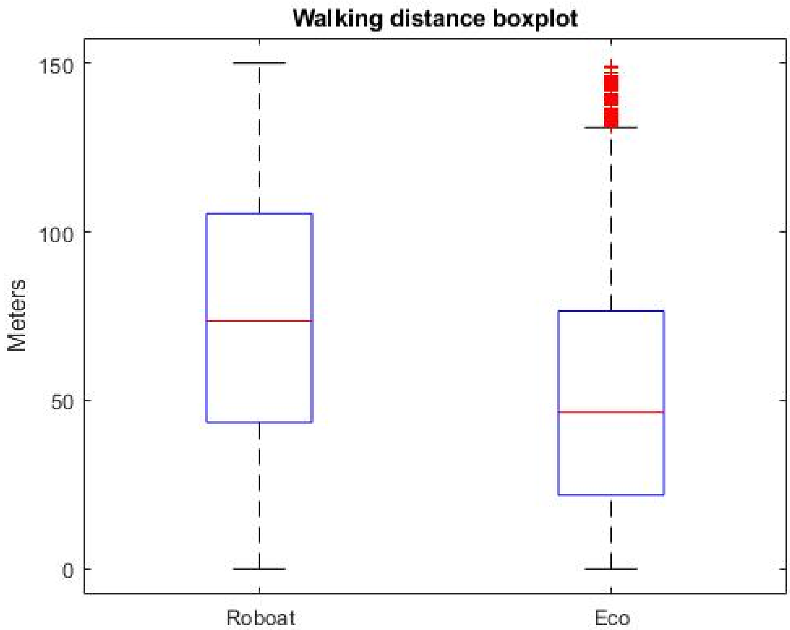

Figure B.5: Boxplot of walking distance: method 3

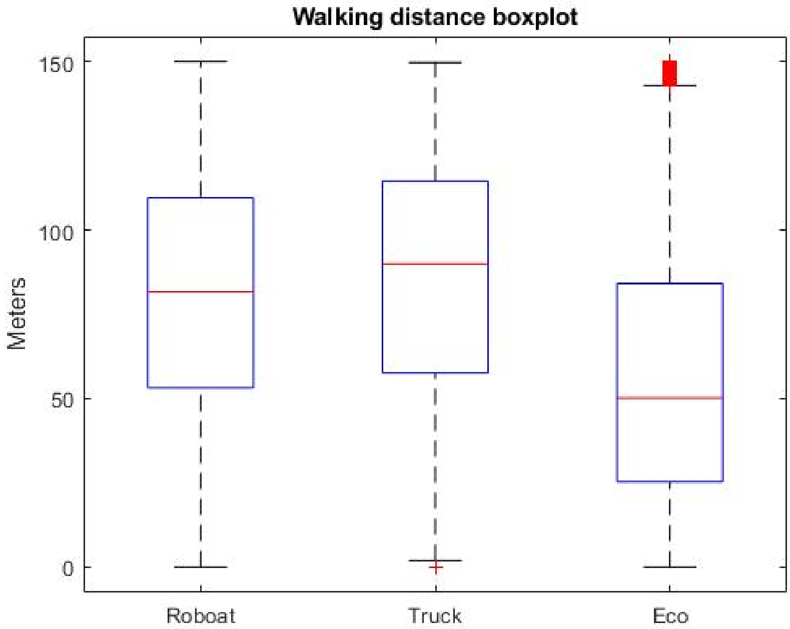

Figure B.6: Boxplot of walking distance: method 4

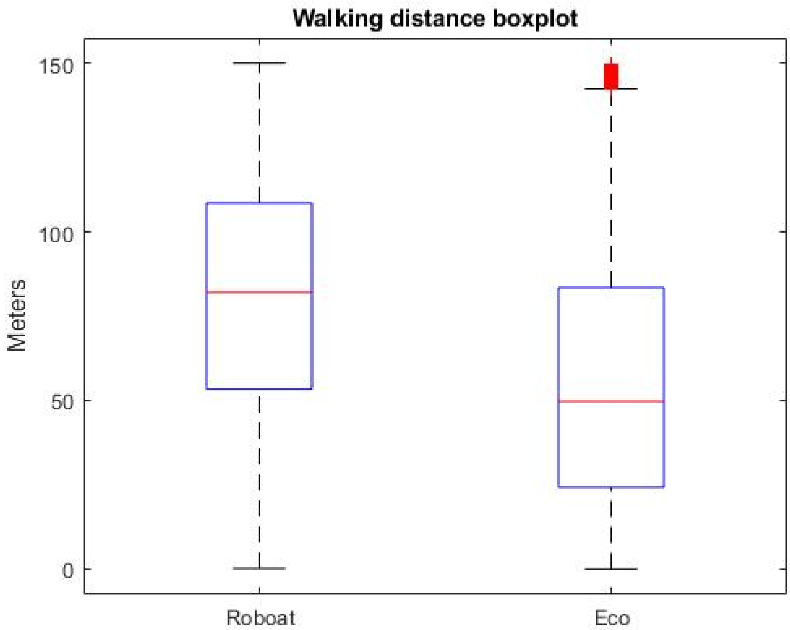

Figure B.7: Boxplot of walking distance: method 5

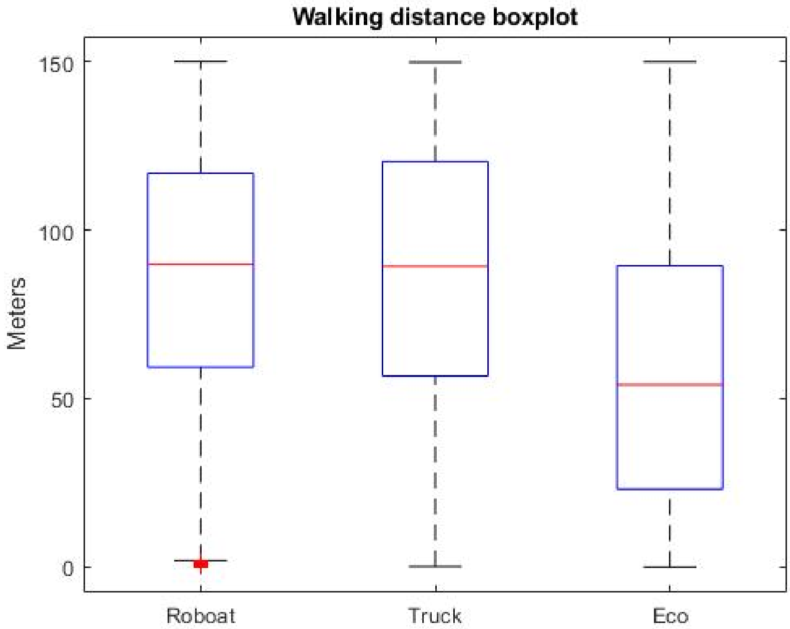

Figure B.8: Boxplot of walking distance: method 6

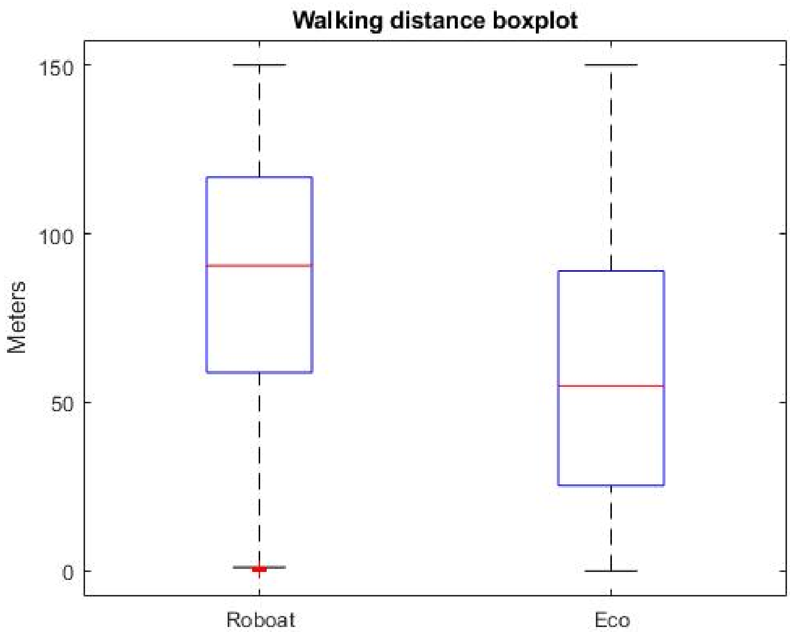

Figure B.9: Boxplot of walking distance: method 7

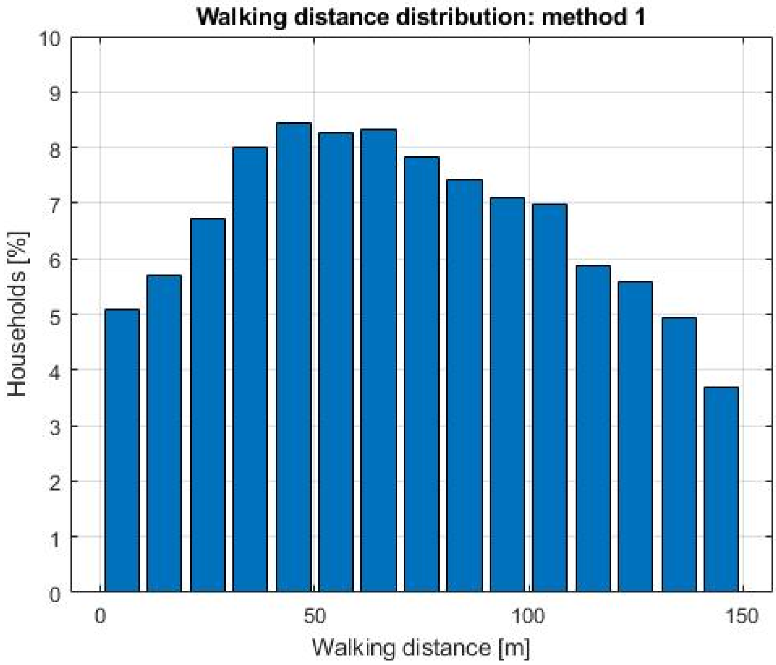

Figure B.10: Histogram of walking distance: method 1

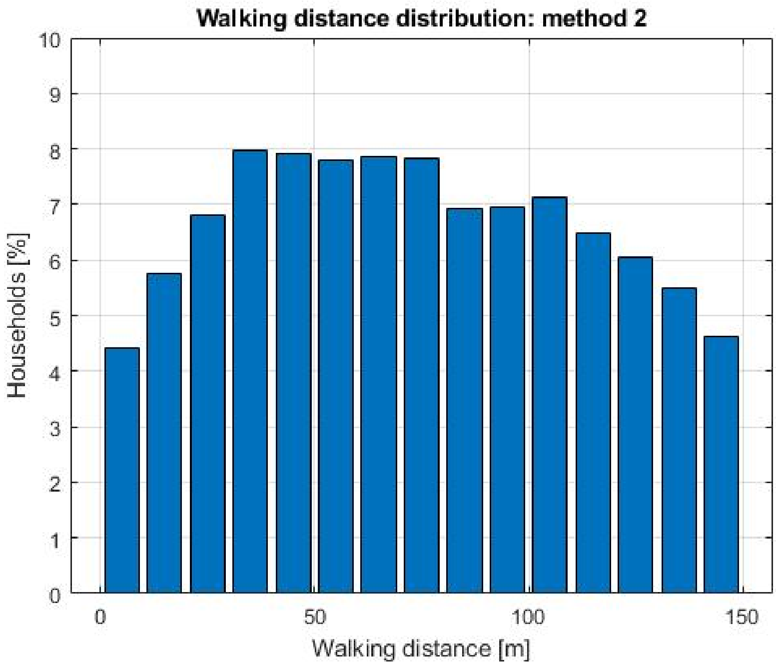

Figure B.11: Histogram of walking distance: method 2

Figure B.12: Histogram of walking distance: method 3

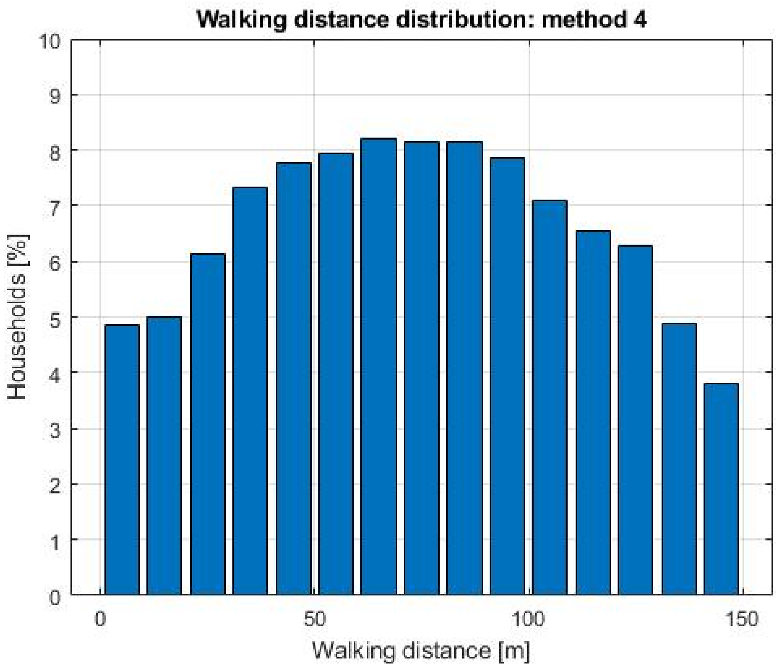

Figure B.13: Histogram of walking distance: method 4

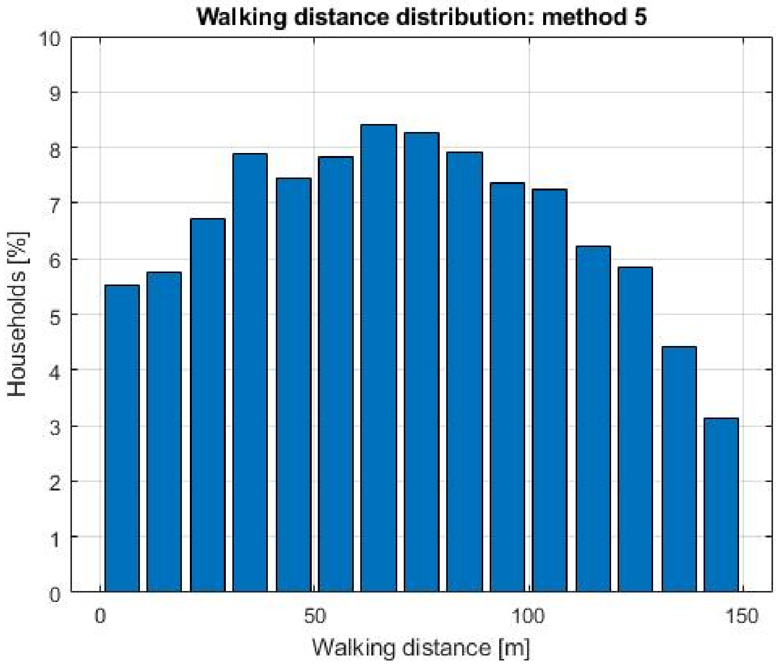

Figure B.14: Histogram of walking distance: method 5

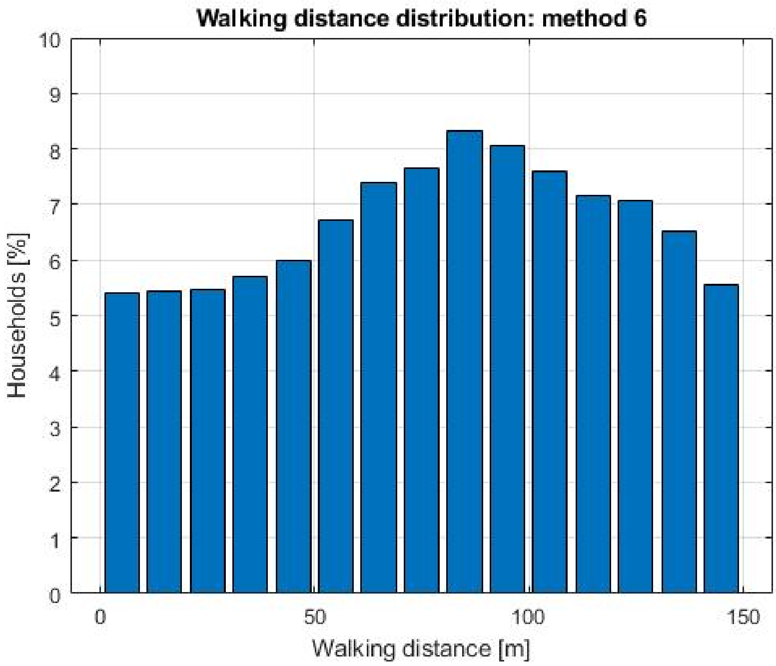

Figure B.15: Histogram of walking distance: method 6

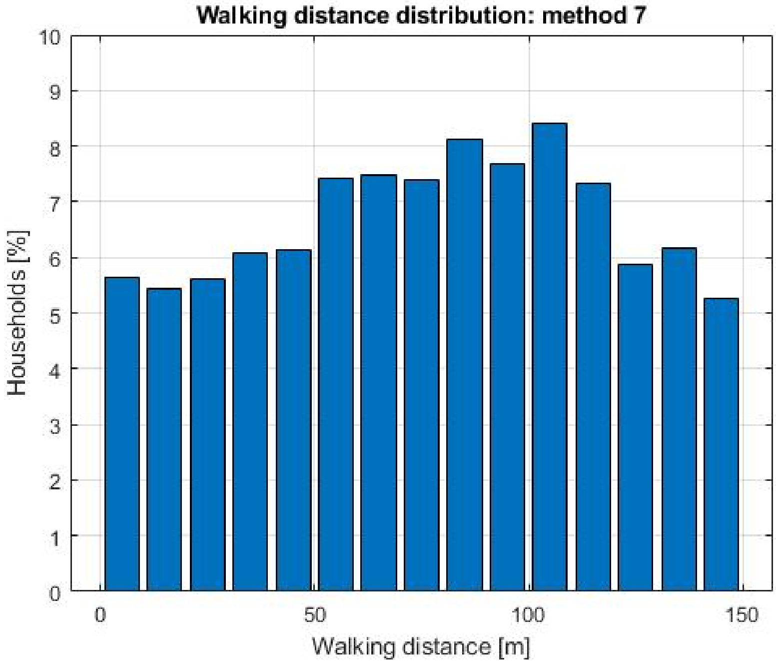

Figure B.16: Histogram of walking distance: method 7