POLITECNICO DI TORINO

Master Degree Course in Engineering
and Management

Master's Degree Thesis

Designing Optimization Models for IoT-Based Waste Management

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"To women of my country,

may you always live a life full of beauty, grace, and freedom. May your voices be heard, and your rights be respected. You are strong, resilient, and capable of achieving anything you set your mind to. Keep shining your light and inspiring those around you. You are the embodiment of womanhood, and you deserve nothing but the best in life."

"Woman, Life, Freedom"

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Abstract

Waste management is a great concern in many countries due to the increasing growth of human societies and the expansion of cities. A waste management system can include waste collection, separation, transfer, disposal, and recycling, as a strategic issue. One of the possible solutions is designing a more efficient route for garbage trucks. Historically, waste management systems have scheduled garbage collection emptying regardless of whether they were full or not using a pre-defined path based on past patterns but nowadays, IoT devices flip this model on its head by using smart trash bins to detect location, temperature, and fill level in real time. This information is then utilized to determine the best collection routes, resulting in a pickup procedure that is effective and saves both time and fuel. This assumption is considered into account in this research work.
As a result, designing an effective waste management system in order to greatly reduce environmental, social and economic impacts is necessary. Therefore, in this research work, two models are suggested to optimize the routes for waste collection: firstly, single-stage waste collection system using multi-compartment vehicle routing (MCVRP) and secondly, two-stage waste collection system using the Location-routing problem (LRP) and Location- allocation (LA).
The first model includes waste bins and separation centers, and the second suggested model includes city waste collection, separation centers, processing centers and landfills. The second sub-model takes into account waste separation and transferring to the different centers including recycling, incineration and composting. In this thesis, a numerical simulation is implemented by using the GAMS solver. GAMS offers useful features needed to develop, test, deploy, and maintain optimization models. It also enables the formulation of a broad range of mathematical model types, including linear, mixed-integer, nonlinear, mixed-integer nonlinear, mixed complementary, etc. The models are tested by 3 level samples consisting of: small, medium and large. In the end, this study employs sensitivity analyses to test how a change in the objective function variables affects the objective function itself, and multiple scenario evaluations to gauge

the effectiveness of the proposed problem, taking into account different levels of tightness. The optimization results determine the optimal number of vehicles needed, along with their corresponding distance and cost, providing a valuable tool for managers and decision-makers facing similar constraints.

Chapter 1
Introduction

1.1 Overview

In the modern world, waste management is becoming an increasingly critical topic. When we talk about waste management, we include the entire management system from planning to disposal; therefore, an efficient waste management can be a success factor not only for municipalities but also for the environment and society.
Of the 2.01 billion tonnes of municipal solid waste generated annually worldwide, 33 percent is thought to not be handled in a way that is environmentally safe. The average daily waste produced per person worldwide is 0.74 kilograms, but there is a large variation, ranging from 0.11 to 4.54 kilograms. Despite only making up 16% of the global population, high-income countries produce about 34%, or 683 million tonnes_per year, of the waste generated worldwide (The world bank, 2016). Solid waste poses a number of health and safety risks to the environment and the general public when improperly managed. This work will focus on improving proposing such a system with the help of smart context.

In this study, we consider a waste management system (WMS) that addresses the following strategic and tactical decisions:

- In the first suggested WMS one-stage model, the goal is to consider multi-compartment vehicles with flexible compartment sizes for collecting different types of waste.

- In second suggested two-stage model, for the first sub-model the aim is to determine the number of solid waste separation facilities (SF) that transfer bulk waste to the specific processing centers and landfill; and
- designing the routes of collection vehicles that depart from SFs, collect waste from bins, and return to SFs.
- In the second sub-model, the aim is to determine the location of processing centers (composting, incineration and recycling) with the required capacity size and allocating the relevant wastes from SFs to processing centers.
- In this suggested two-stage model, the output of the first stage will be calculated and used as input for the next stage.

We created this WMS as a location-routing problem (LRP) and location-routing (LA) for a two-layer reverse logistics system. Then we create a Mixed Integer Programming (MIP) formulation that is as follows:

First model with MCVRP:
- vehicle capacity reserved for different types of waste, routing of MCVs.
- The objective is to minimize the sum of fixed cost of dispatching vehicles and penalty per CO2 consumption.

Second model:
First sub-model (LRP):
- Number of required vehicles and SFs, fleet and SFs capacities.
- The objective is to minimize the sum of fixed cost of opening processing centers, fixed cost of dispatching the collection vehicles and variable operating cost.

Second sub-model (LA):
- The location of the processing centers and their capacity level, fleet size, transportation and landfill capacity, portion of different types of waste which requires relevant processing method and portion of resultant waste from processing.

- The objective is to minimize the sum of daily fixed cost of opening processing centers, cost of transportation to landfill and processing centers.

1.2 Thesis Structure

The next sections are organized as follows.

- Chapter 2 is a literature review. It introduces the theorical definition of waste management and vehicle routing problems explaining its main variants developed during the last decades. In particular more emphasis is given to MCVRP, LRP and LA as well as to some publications that have most influenced the present work.
- Chapter 3 includes the statement of the problem. The problem is contextualized according to literature lexicon, then the problem structure is formalized using a mathematical modelling. After introducing the main assumptions needed to develop the problem, a solver is used to simulate the problem numerically.
- Chapter 4 includes results and sensitivity analysis for both suggested models.
- Chapter 5 includes conclusions of this research work alongside suggestions for future research.

Chapter 2
Literature Review

2.1. What is waste?

Waste has always been created by human activity. When the human population was relatively small, this was not a significant concern, but with urbanization and the expansion of massive conurbations, it became a significant issue. Ineffective waste management had a significant negative influence on human health by contaminating the water, soil, and atmosphere. Epidemics brought on by water tainted with germs destroyed the population of Europe in the 19th century, and cholera was a frequent occurrence as recently as the 19th century (Giusti, 2009). Mismanagement of waste has certain health effects, particularly in developing countries. The management of an ever-growing volume of waste has become a highly complex activity. With changes in lifestyle, waste material characteristics changed as well, and the amount of new chemicals found in the various waste streams dramatically increased. It is more challenging to quantify the long- term health impacts of exposure to compounds produced at waste disposal facilities or in waste, especially when their concentrations are very low and there are other exposure pathways (e.g., food, soil). Lack of evidence can concern the public. Strong opposition to the construction of landfills, incinerators, or other waste disposal facilities is brought on by widely reported industrial accidents that are frequently unrelated to waste management activities. The public is putting more and more pressure on government and health authorities to present epidemiological proof of any potential negative health effects brought on by these activities. The effects of emissions near waste disposal facilities have been the subject of thousands of published manuscripts. Many writers have produced reviews as well as reviews of reviews (Giusti,2009).

2.2. The importance of waste management

- Urbanization

As of 2010, 52 percent of the world's population resided in urban areas, and that percentage is expected to rise linearly until 2050, when the average urban proportion is projected to reach 60 percent by 2030 and 66.5 percent by 2050, according to the UN World Urbanization Prospects. According to UN 2010 values, the European Union has a more urbanized structure than the rest of the world, with a 74 percent urban proportion. As a result, the rate of urbanization is lower than that of the rest of the world, where the urban proportion in the EU-28 is anticipated to reach 78% by 2030 and 83% by 2050 as indicated in figure 1. In order to measure the proportion of urban areas in Europe, LUISA proposes a novel methodology based on the new degree of urbanization classification based on population grids. The results of this new methodology show that as of 2010, the urban proportion (the percentage of the population living in cities, towns, and suburbs) within the EU is close to 80%. Due to a faster growth rate during the first 20 years and a slower growth rate during the second, this percentage differs significantly from UN estimates, reaching 87 percent in 2030 and 88 percent in 2050 (figure 1) (Kompil et la., 2015).

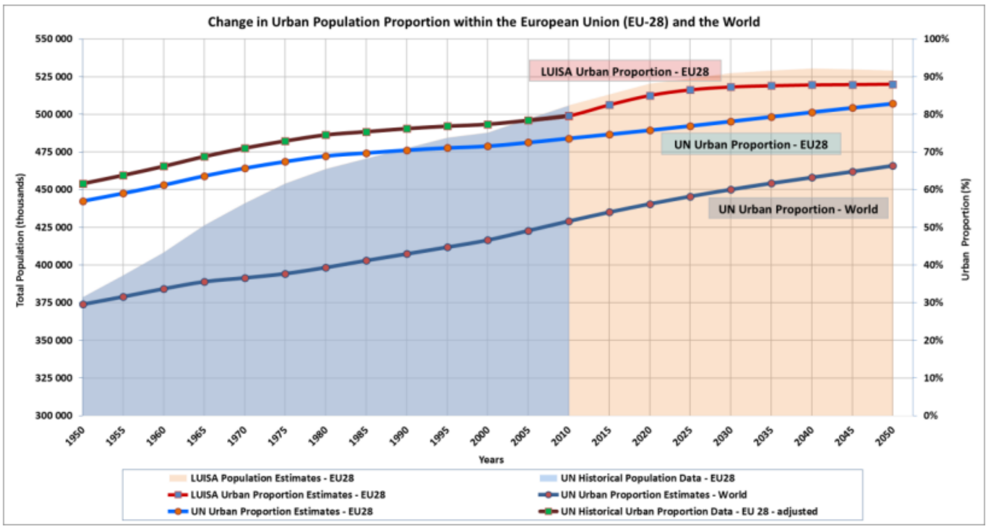


Figure 2. 1: Change in urban proportion within the European Union and the World (Kompil et la.,2015).

As indicated in figure 2, Up until 2050, less urbanized nations will largely close the gap between them and more urbanized nations. Ireland, Luxembourg, Romania, Lithuania, Estonia, and Poland show the most striking changes in urban proportion between 2010 and 2050 (Kompil et la., 2015).

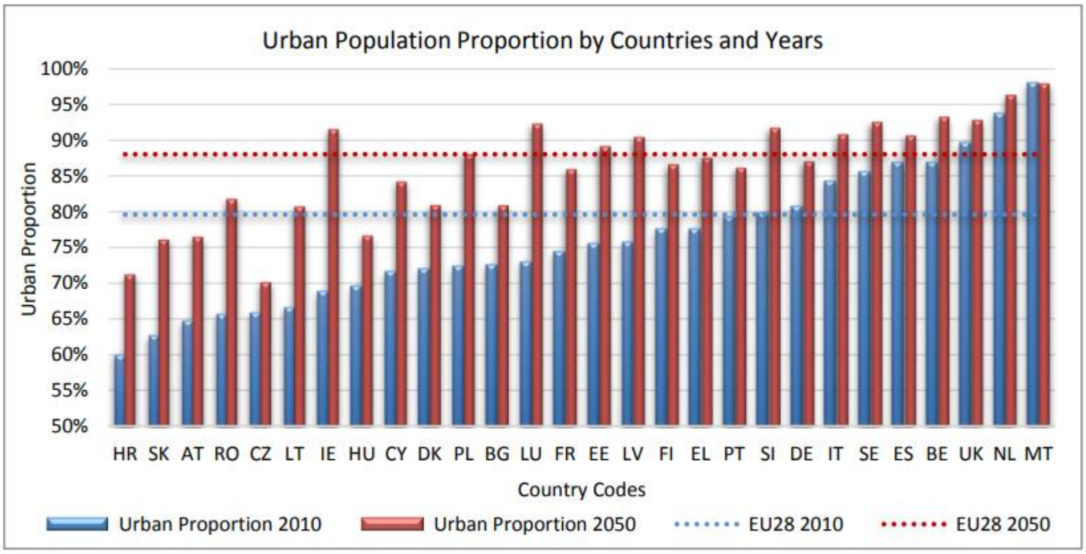


Figure 2. 2: Urban proportion by countries and years (Kompil et la., 2015).

2.3. Environmental Impacts

- Contamination

Poor waste management directly impacts many ecosystems and species as well as air pollution and climate change. Landfills release methane, a potent greenhouse gas linked to climate change and the waste hierarchy's last resort. Microorganisms in landfills convert biodegradable waste, including food, paper, and yard waste, into methane. Landfills may contaminate soil and water depending on how they are constructed. Waste is collected, transported, and treated after being gathered. Air pollutants, such as particulate matter, and carbon dioxide, the most common greenhouse gas, are released into the atmosphere during transportation (EEA Europa, 2014).

- Greenhouse gas emissions of poor waste management

The GHG report program (GHGRP) states that the waste sector generates GHG from a number of sources, including municipal solid waste landfills, industrial waste landfills, wastewater treatment systems, and incinerators for non-hazardous solid waste. The trash industry is primarily responsible for 5% of global GHG emissions. The two most significant GHGs produced by the management of urban waste are carbon dioxide (CO2) and methane (CH4) (Kristanto et la., 2020).

2.4. Social Impact

Waste has a variety of negative effects on our health and wellbeing, whether they are direct or indirect. For example, methane gases contribute to climate change, air pollutants are released into the atmosphere, freshwater sources are contaminated, crops are grown in contaminated soil, and fish ingest toxic chemicals, which then end up on our dinner plates. Illegal activities like illegal dumping, burning, or exports also contribute, but it is challenging to gauge their full scope or the effects of such activities (the worldBank, 2016).

2.5. Economic Impact

Waste costs our society money and burdens it. When the "leftovers" are thrown away, labor and other resources (such as land, energy, etc.) used in its extraction, production, dissemination, and consumption phases are also wasted. Additionally, waste management is expensive. Recycling can generate income and create jobs once the infrastructure for collecting, sorting, and recycling is in place. Operating costs for integrated waste management, which include collection, transport, treatment, and disposal, typically exceed $100 per tonne in high-income countries. With costs of about $35 per tonne and occasionally higher, lower-income countries spend less on waste operations in absolute terms, but they have much more trouble recovering costs. Waste management requires a lot of labor, and the cost of transportation alone is $20 to $50 per tonne. Across income levels, cost recovery for waste services varies greatly. With full or nearly full cost recovery being largely restricted to high-income countries, user fees range from an average of $35 per year in low-income countries to $170 per year in high-income countries. Depending on the kind of user being charged, user fee models can be either fixed or variable. Typically, local governments pay for about half of the costs associated with investing in waste management systems; the remaining costs are primarily covered by national government subsidies and the private sector (the worldBank, 2016).

2.6. Generation and Composition of Solid Waste Management

An estimated 33 percent of the 2.01 billion tonnes of municipal solid waste produced annually around the world is not handled in an environmentally safe manner. The average amount of waste produced per person per day around the world is 0.74 kilograms, but the range is wide, from 0.11 to 4.54 kilograms. High-income nations produce about 34%, or 683 million tonnes, of the world's waste, despite having only 16% of the world's population (the worldBank, 2016). It is anticipated that global waste will increase to 3.40 billion tonnes by 2050, more than double the population growth during that time. The generation of waste and income level are generally positively correlated. In contrast to low- and middle-income countries, where it is anticipated to rise by roughly 40% or more, daily per capita waste generation in high-income countries is projected to rise by 19% by 2050. When income levels change incrementally, waste generation initially declines at the lowest income levels and then rises more quickly there than at higher income levels. By 2050, it's anticipated that the total amount of waste produced in low-income countries will have increased by more than three times. The Middle East and North Africa region produces the least amount of waste globally, at 6%, while East Asia and the Pacific account for 23% of global waste production. The fastest growing regions, however, are Sub-Saharan Africa, South Asia, and the Middle East and North Africa, where by 2050 it is anticipated that the total amount of waste generated will more than triple, double, and double, respectively. More than half of the waste in these areas is currently disposed of openly, and the trajectory of waste growth will have significant negative effects on the environment, human health, and economic growth, necessitating immediate action (the worldBank, 2016).

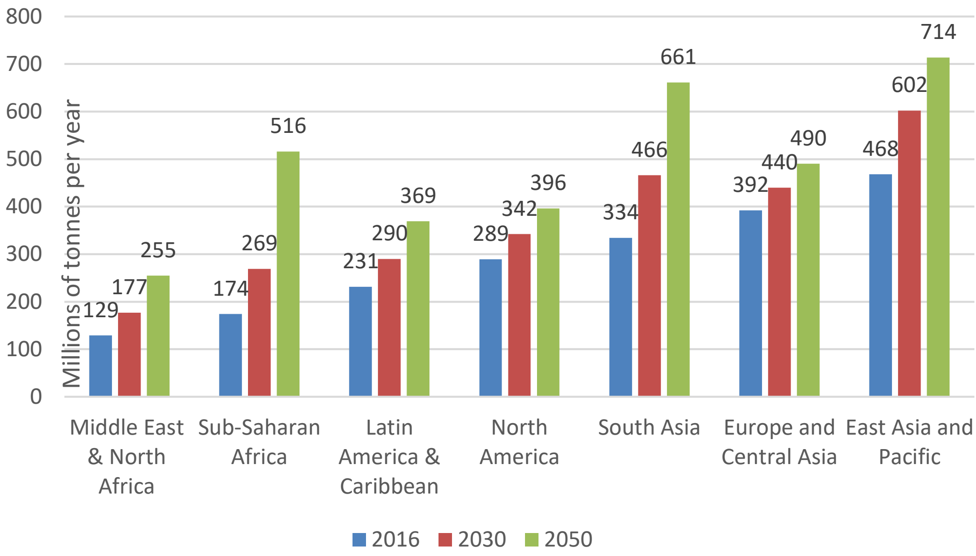


Figure 2. 3: Projected waste generation, by region (millions of tonnes/year) (the worldBank, 2016).

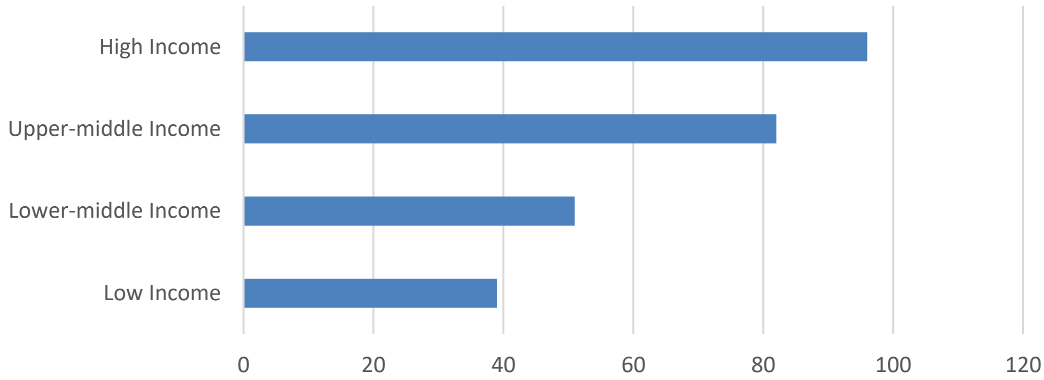


Figure 2. 4: Waste collection rates, by income level (percent) (the worldBank, 2016).

Depending on income level, waste composition varies, reflecting various consumption patterns. High-income nations produce relatively less food and green waste (which makes up 32 percent of total waste) and more dry waste that can be recycled (which makes up 51 percent of waste), including plastic, paper, cardboard, metal, and glass. 53 percent and 57 percent of food and green waste are produced in middle- and low-income countries, respectively, with the proportion of organic waste rising as economic development levels fall. Only 20% of the waste stream in low-income countries consists of recyclable materials. The only waste streams that differ across regions are those that correspond to income. Every region produces an average of 50% or more organic waste, with the exception of Europe, Central Asia, and North America, which produce a higher percentage of dry waste (the worldBank, 2016).

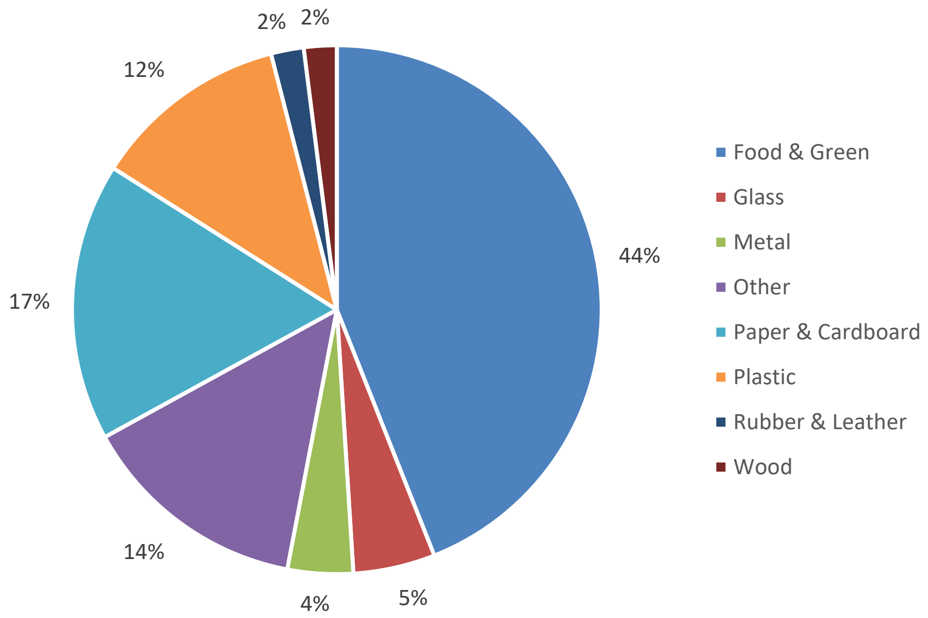


Figure 2. 5: Global waste composition (the worldBank, 2016).

2.7. Methods of Solid Waste Disposal

Due to globalization and industrial development, solid waste disposal has seen many changing technologies, but the effectiveness of these methods is dependent on a variety of environmental, social, and economic factors (Marimuthu et la., 2021). There are more methods but in this research work only those ones that are already considered in the network are explained.

- Landfill

Some low-lying areas, such as dried-up water bodies and marshlands, can be found throughout the city, mostly on the outskirts. The required area will be determined by the amount of waste generated, the city's population, and the availability of other landfill areas. The waste that cannot be recycled or processed should ideally be divided into different types and distributed over the chosen area in a series of thin layers, each one separated by a layer of soil. The area is declared to be only useful as a playground or park after being allowed to deteriorate for at least 20 years, preventing construction and other heavy-duty use of the space (Marimuthu et la., 2021).

- Incineration

The second most common and hygienic method is incineration, which involves burning waste in a controlled environment to create waste gas, ash, and heat as byproducts. The ash and heat can be used for other industrial processes like building and power generation, while the waste gas will be treated and released into the environment (Marimuthu et la., 2021).

- Composting

This is one of the most common methods for disposing of food waste. Not only does this effectively dispose of food waste, but it also enriches the soil by reloading nutrients back into the soil, increasing its water retention capacity. This works on the principle of breaking down organic materials with microorganisms such as bacteria and fungi to decay and produce manure for the soil. Typically, food waste is dumped into specially constructed pits and left to decay. This is one of the simplest ways to dispose of organic waste. This also helps organic agriculture, which produces chemical-free food (Marimuthu et la., 2021).

- Recycling

Complex recycling systems are unlikely to be appropriate, but some waste items may be recyclable on occasion. Plastic bags, containers, tins, and glass are frequently recycled automatically because they are likely to be scarce commodities in many situations. Most developing countries have a strong recycling tradition, resulting in lower waste volumes than many more developed societies (EC Europa chapter 7, 2018). Figure 6 depicts the global scenario of waste disposal and treatment. Based on their economic and environmental status, the following countries have the most preferred waste disposal and treatment options: East Asia and Pacific countries (46%) prefer landfill (unspecified), Europe and Central Asia (25.6%), Middle East & North Africa (52.7%), South Asia (75%), Sub-Saharan Africa (69%) prefer open dump, Latin America & Caribbean (52%), and North America (52%) (Jebaranjitham et la., 2022).

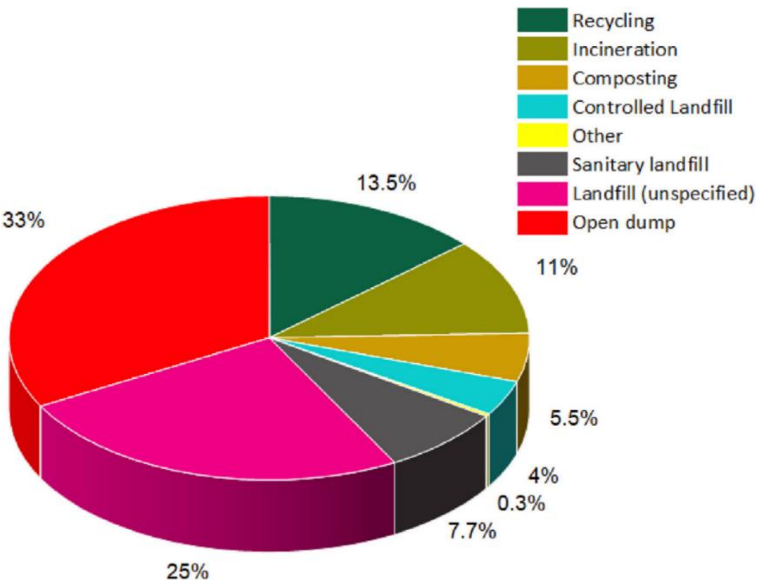


Figure 2. 6: Global trend in waste treatment and disposal followed as reported on year 2018 (Jebaranjitham et la., 2022).

It is estimated that 1.6 billion tonnes of carbon dioxide (CO2) equivalent greenhouse gas emissions, or 5% of global emissions, were produced from the treatment and disposal of solid waste in 2016. This figure is based on the volume of waste produced, its composition, and how it is managed. Waste disposal in open dumps and landfills without landfill gas collection systems is the main cause of this. Nearly 50% of emissions come from food waste. If no changes are made in the industry, solid waste-related emissions are predicted to rise to 2.38 billion tonnes of CO2-equivalent annually by 2050 (the worldBank, 2016).

2.8. Digitalization in waste management

The widespread adoption of digitalization technologies is largely due to ongoing advances in miniaturization, increased processing power, and falling costs. Waste management is no exception, and it is benefiting from advances in digital technologies as well. Specific digital technologies that are currently being used and are expected to have a significant impact on waste industry efficiency in the future include robotics, the internet of things, cloud computing, artificial intelligence, and data analytics (figure 2.7) (EEA europe, 2021).

	Robotics	Artificial intelligence and neural networks	Internet of things	Cloud computing	Data analytics
PROCESS	Advancements in the pneumatic sorting process as a result of automation technology allow producing defined waste streams of high purity (over 90 %).	Machine learning — using neural networks based on the use of data or examples to solve problems without explicit programming — is used for classification and pattern recognition in the waste management context, improving the efficiency of sorting.	As more and more devices are connected to the internet or other networks, sensor-supported containers can collect data and transfer it to central units.	Storing and processing of sensor data and cloud based software solutions make it easy to optimise workflows and document failure to collect, failure in sorting or detect waste bins that are not paid for.	Processing and analysing data plays an important role in the recycling industry in order to identify patterns, extract information, discover trends or calibrate models. This knowledge is important in order to evaluate different options for the transition to a recycling economy.
EXAMPLES	- Robots that are able to identify and sort recyclables and critical materials through image recognition/IR scanning/ AI vision systems when dismantling used phones/electronics	- Autonomous, self-driving street sweepers, refuse trucks	- Smart waste bins with identification systems, weighing systems, level sensors, temperature sensors, sofware for optimising logistics	Cloud based software for: - Connection, standardising and optimising internal procedures - Real-time order management, route planning and optimisation, customer self-service, order-tracking and evaluation	- Electronically supported diposition of waste collection vehicles - Evaluation of sensor data for automated sorting plants - Control of waste incineration plants - Drone based data collection on landfills

Figure 2. 7: role of digitalization in waste management (EEA Europe, 2021).

Waste management operations are a complex logistical challenge that requires significant manual handling and, as a result, labor costs. Digitalization provides opportunities to reduce these costs while also creating more job opportunities in higher-value parts of the business chain. The sorting process, which is required for high-level recycling, is one important field of application. AI image processing techniques supported by robotic sorters are rapidly evolving and are already used by several global commodity manufacturers such as electronics. Other approaches include product labeling with watermarks, quick-response (QR) codes, or other types of digitally readable markers. These can assist automated sorters by feeding them information on material composition and product configuration, allowing for the recovery of high-value materials. Robotic sorters can also produce data about the materials they have sorted, helping to improve AI or further optimize subsequent steps. As an illustration, these data streams can be used to forecast patterns in incoming waste loads and learn about the effectiveness of waste sorting to forecast the layout of sorting lines. Processes can also be modified if these data are connected to other pertinent data, such as prices in secondary raw material

markets (EEA Europe, 2021).
Different facets of IoT technology for waste management solutions are covered in a number of published papers. For instance, (Catania & Ventura, 2014) present a solution that enables the planning of garbage collection through intelligent monitoring. Interoperable applications from various information and communication domains can be implemented with great ease using the Smart-M3 platform (extension of cross-domain search for triple-based information). The solution is created in two stages: the monitoring phase, during which the waste levels inside the compartments are continuously measured, transmitted, and stored; and the implementation phase. The second phase involves applying the computation of the gathered data to improve the waste collection routes. A solution known as cloud-based smart waste management (Cloud SWAM) is offered by (Aazam et la., 2016). Each type of waste (organic, plastic, bottles, and metal) is addressed with a unique container that is fitted with sensors that continuously monitor and update its status to the cloud, where stakeholders are connected to receive information pertinent to their interests. The system plays a role in both waste management and choosing the best collection route, choosing one that is more cost-effective for the metropole as a whole (Pardini et la., 2019).

2.9. Implementing WMS within the smart city with IoT concept

The traditional method of waste collection and transportation is filling up all the waste bins and driving trucks along predetermined routes to the disposal facility to dispose of the waste. The cost of this procedure is extremely high and the majority of waste management system spending accounts for labor expenses, fuel costs, maintenance costs, etc. (Wu et la., 2020). Waste separation and recycling are two crucial elements that play a key role in how to handle waste when implementing an effective waste management system in a smart city. In various research, the benefits of waste separation and recycling were highlighted. In addition, a smart city's waste collection system needs a detective system to determine when a bin is full or empty. The Internet of Things (IoT) application and its features are quite beneficial in this regard (Salehi-Amiri et la., 2022).

2.10. An Introduction to VRP

The first section introduces the main ideas of the Vehicle-Routing Problem (VRP), a complex problem that serves as a basic component of mentioned variants. The definition, uses, and categorizations of MCVRP, LRP and LA are covered in the second section.

One of the fundamental components of logistics systems is physical distribution which depicts the movement of commodities from manufacturing facilities or distribution hubs through transportation networks to the customer. Customers are served by several cars in the vehicle routing problem (VRP), which is a class of combinatorial optimization problems. The goal is to reduce the costs associated with the vehicle route. Each truck generally departs from the depot, serves customers, and then, after finishing its route, returns to the depot. Each client is only served once (Režnar et la., 2017).

The earliest entry in the VRP literature was done by the study by Dantzig, Fulkerson, and Johnson (1954) which examined a large-scale TSP and suggested a method as solution. A great volume of other TSP articles was published after this study. It is safe to say that TSP is a specific version of VRP. Golden, Magnanti, and Nguyan (1972) were the first authors that used the "Vehicle Routing" in the title as" Implementing vehicle routing algorithms". Other versions of VRP emerged in the early 1970s, e.g. fleet routing (Levin, 1971), dial-a-bus systems (Wilson & Sussman, 1971), transportation network design (O'Connor & De Wald, 1970), routing of public service vehicles (Marks & Stricker, 1970), distribution management (Eilon, Watson-Gandy, & Christofides, 1971), and solid waste collection (Liebman, 1970). Golden and Stewart introduced probabilistic content to the VRP (1978). Solomon (1983) improved the traditional VRP to time-window constraints and created a group of well-known benchmark problems as "Solomon Instances" (Eksioglu et la., 2009).

Jafari-Eskandari et la. (2010) depicted a classification of different kinds of VRP in the following figure 2.8:

1. capacitated vehicle routing problem (CVRP)
2. vehicle routing problem with time window (VRPTW)
3. vehicle routing problem with backhauls (VRPB)
4. vehicle routing problem with pick-up and deliveries (VRPPD)
5. multiple depots vehicle routing problem (MDVRP)
6. periodic vehicle routing problem (deliveries in some days) (PVRP)

7. split delivery vehicle routing problem (SDVRP).

This type of modeling has different types of objectives that need to be minimized, including inventory and transportation expenses.

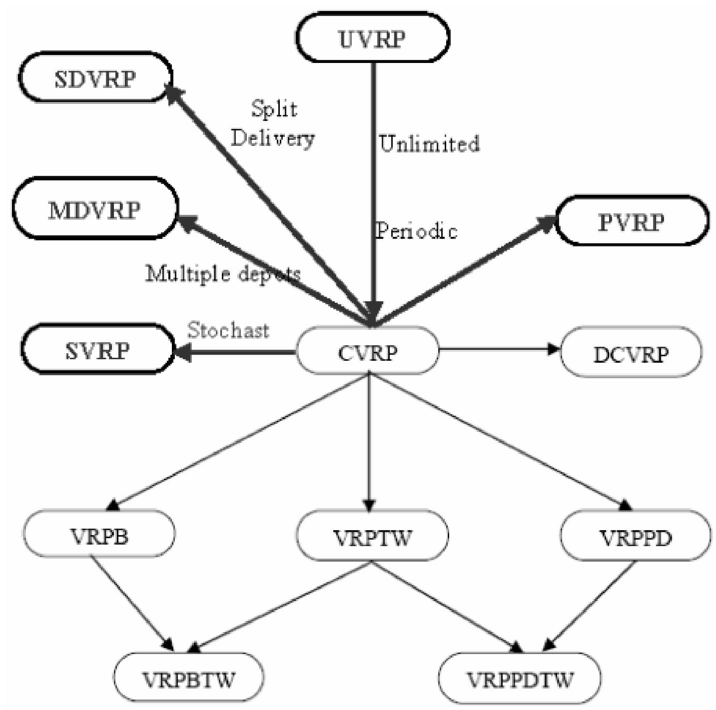


Figure 2. 8: Classification of VRP (Jafari-Eskandari et la., 2010)

Let $G = (V, A)$ be a complete graph where $V = \{0, 1, \ldots, n\}$ is the vertex set and A is the arc set. Vertices $j = 1, \ldots, n$ correspond to the customers, each with a known non-negative demand, d_j, whereas vertex 0 corresponds to the depot. A non-negative cost, c_{ij}, is associated with each arc $(i, j) \in A$ and represents the cost of traveling from vertex i to vertex j. If the cost values satisfy $c_{ij} = c_{ji}$ for all $i, j \in V$, then the problem is said to be a symmetric VRP; otherwise, it is called an asymmetric VRP. In several practical cases the cost matrix satisfies the triangle inequality, such that $c_{ik} + c_{kj} \geq c_{ij}$ for any $i, j, k \in V$. The VRP consists of finding a collection of k simple circuits, each corresponding to a vehicle route with minimum cost, defined as the sum of the costs of the circuits' arcs such that:

i. each circuit visits vertex 0, i.e., the depot.

ii. each vertex $j \in V \setminus \{0\}$ is visited by exactly one circuit; and

iii. the sum of the vertices' demand visited by a circuit does not exceed the vehicle capacity, C (Eksioglu et la., 2009).

Let $G = (V, A)$ be a complete graph, with $V = \{0,1,2, \ldots, n\}$ representing the set of vertices $(0\text{:}\, depot, 1 \ldots n\ representing\ customer\ sites)$ and $A = \{(i,j)|i,j \in V, i \neq j\}$ representing the arc set. The non-negative cost c_{ij} associated with arc (i,j) A denotes the cost of travel from i to j. Assume K identical vehicles with capacity C exist. Let $S \subseteq V\{0\}$ represent the customer set and $r(S)$ represent the minimum number of vehicles needed to service all customers in S. If arc (i,j) belongs to the optimal route, the decision variable x_{ij} is 1, otherwise it is 0. The basic VRP model described in is (kim et la., 2015).

$$
\begin{aligned}
\text{(VRP)} \quad Min \sum_{i \in V} \sum_{j \in V} c_{ij} x_{ij} \quad & (1) \\
\text{s.t.} \sum_{i \in V} x_{ij} = 1, \forall j \in V \setminus \{0\} \quad & (2) \\
\sum_{j \in V} x_{ij} = 1, \forall i \in V \setminus \{0\} \quad & (3) \\
\sum_{i \in V} x_{i0} = K \quad & (4) \\
\sum_{j \in V} x_{0j} = K \quad & (5) \\
\sum_{i \notin S} \sum_{j \in S} x_{ij} \geq r(S), \forall S \subseteq V \setminus \{0\}, S \neq \emptyset \quad & (6) \\
x_{ij} \in \{0,1\}, \forall I, j \in V. \quad & (7)
\end{aligned}
$$

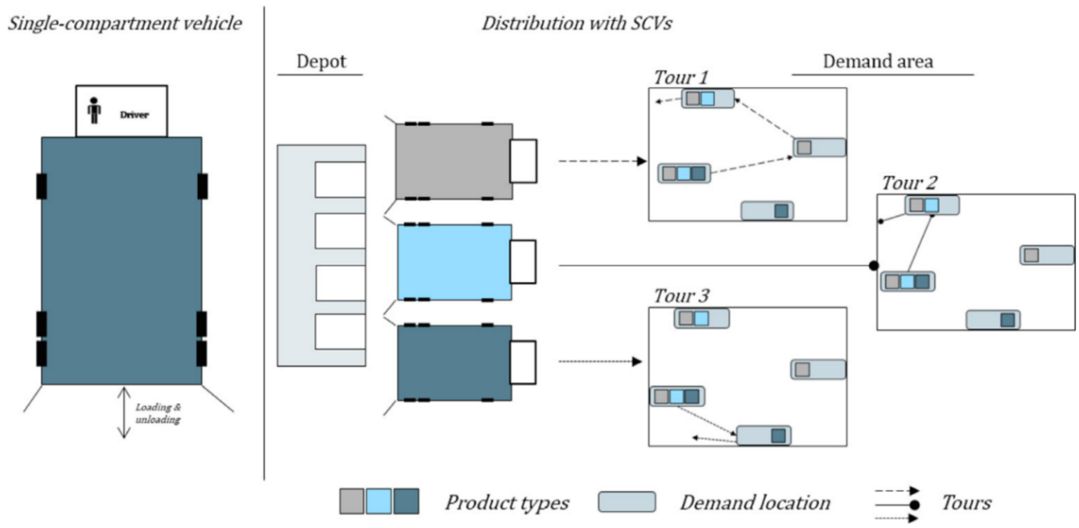
Figure 2. 9: CVRP formulation (Kim et la., 2015).

The objective function (1) seeks to reduce the total travel cost. Constraint (2) is the indegree, which states that each node has exactly one arc leave it. Similarly, (3) denotes the outdegree, which states that each node is served by exactly one arc. The requirements for the depot node are imposed by constraints (4) and (5). The capacity cut constraint (6) ensures that the vehicle capacity requirements and solution connectivity are met (Kim et la., 2015)

2.10.1 Multi-Compartment Vehicle Routing Problem (MCVRP)

In waste collection, it is frequently necessary to consider multiple waste types, so vehicles with multiple compartments are a very efficient option (Hong et la., 2022). MCVs are used to consolidate product flows in situations where different product types must be kept separate during transportation. Typical applications include delivering various petroleum products (e.g., diesel and super fuel) to gas stations, delivering various temperature-sensitive groceries (e.g., frozen, fresh, and ambient products) to supermarkets, and collecting various waste types (e.g., different-colored glass waste) from containers at waste collection points. The use of MCVs enables the joint transportation of various product types on one vehicle from a depot to customers (such as gas stations and supermarkets) or from customers (such as waste collection points) to a depot, and offers many benefits, particularly when different product types have been ordered by the same customer or must be collected at the same collection point. An MCV can significantly reduce the number of stops at customer locations or collection points, the number of necessary vehicles, and the length of all tours, in contrast to situations where only single-compartment vehicles (SCVs) are available and each product type must be transported on a separate SCV (see figure 10). Ostermeier et la. (2021) in figures 10 demonstrate that three dedicated SCV tours with a total of seven stops are necessary, whereas an MCV may only require a single tour with four stops (assuming sufficient MCV capacity) (Ostermeier et la., 2021).

In the following, Ostermeier et la. (2021) only refers to the distribution of products to customer locations for the sake of clarity. However, unless otherwise specified, the presentation also applies to the collection of goods from collection points (Ostermeier et la., 2021).



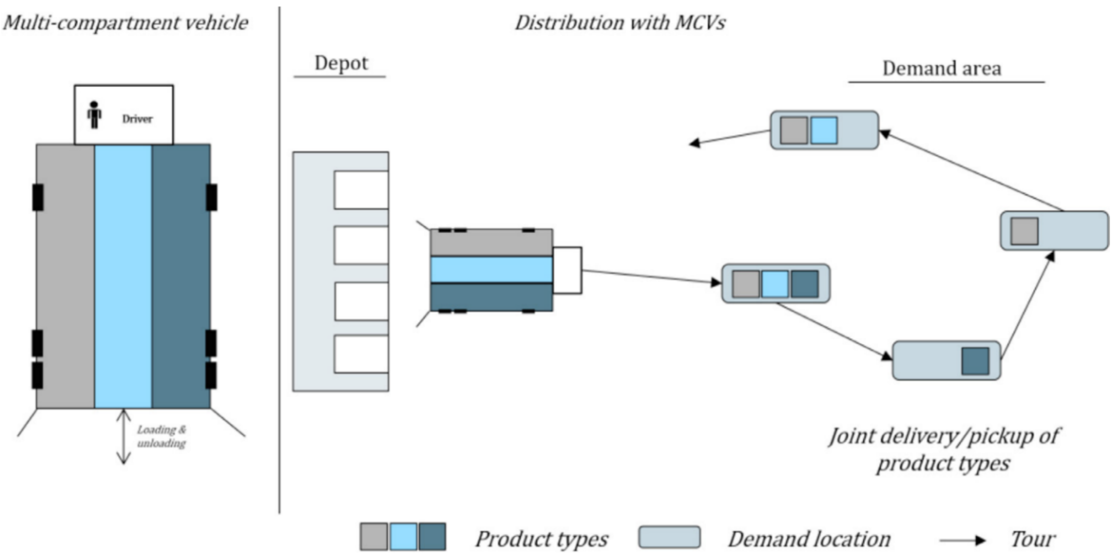


Figure 2. 10: Distribution process with SCVs (above) and MCVs (below) (Ostermeier et la., 2021).

2.10.2 Location-Routing Problem (LRP):

In the real world, decisions about where to locate depots and how to distribute goods from these depots are difficult aspects of the supply chain. This is due to the fact that there are several situations that necessitate the optimal location of several depots from which delivery routes originate, each serving a specific set of customers. This is referred to as the Location Routing Problem (LRP). To mention an important issue is that since there are not thorough literature reviews in waste management by using LRP method, we assume that bins are customer demands.

The LRP entails simultaneously locating depots, assigning customers to depots, and determining their associated routes based on a set of costs, distances, and capacity criteria. If depot location and vehicle routing decisions are made independently, they may result in highly suboptimal planning outcomes (Salhi and Rand, 1989).

The basic concepts of LRPs were introduced by Boventer (1961), Maranzana (1965), Webb (1968), Lawrence and Pengilly (1969), Higgins (1972) and Christofides and Eilon (1969). The complexity of LRP was not taken into account in these initial studies. LRP was first introduced and expanded as a combined problem in the late 1970s and early 1980s. The articles that were published between 1972 and 1996 indicate the following as potential future research areas:

- Stochastic LRPs

- Time windows LRPs
- Dynamic LRPs
- LRPs with multiple objectives

It seems necessary to define LRP's position within location problems in order to comprehend how it relates to the traditional location problems. As a result, we first focus on the kinds of journeys where the primary distinction between the LRP and the traditional location-allocation problem exists. It is typically assumed that customers or users have direct access to facilities. These trips are referred to as out-and-back, direct, or return trips between customers and facilities (Hassanzadeh et la., 2009).

However, there are numerous instances where the journey starts at a facility and involves numerous clients. The following must be determined in addition to the quantity and location of the facilities:

- The allocation of customers to the facilities
- The allocation of customers to the routes
- The order of visiting the customers in a route

These two kinds of trips are presented in figure 13.

Location issues can be divided into two categories from the perspective of customer service:

- The customers are being serviced in their own locations.
- The customers take trips to facilities to get serviced.

The common examples of the second category are schools and hospitals. Usually, there are two cases in the first category. In the case of fire engines (direct trips), the server must return to the facility after serving the customer. In the case of repairmen and postmen, however, the server can visit multiple customers at once (tour trips). This division is shown in figure 17. As a result, if direct trips are available, the issue is a location-allocation problem, and if tour trips are available, the issue is an LRP. Consequently, an LRP includes both locations and tours (Hassanzadeh et la., 2009).

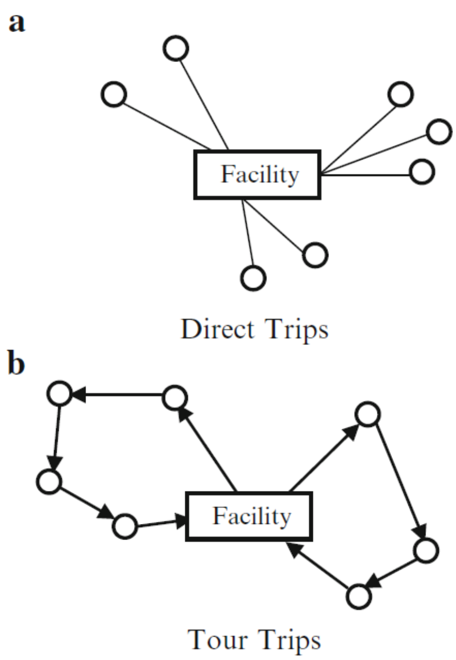


Figure 2. 11: Two types of trips between customers and facilities (a) direct trips (b) tour trips (Hassanzadeh et la., 2009).

The LRP turns into a standard location problem if we mandate that every customer be directly linked to a depot. However, if the depot locations are fixed, the LRP becomes a VRP (Hassanzadeh et la., 2009).

- Applications of LRP

Although distribution of consumer goods or packages is the main focus of most location-routing applications, there are also some in the fields of communications, military, and health. These applications include some in (Hassanzadeh et la., 2009):

- Food and drink distribution
- Waste collection
- Blood bank location
- Newspaper distribution

2.10.3 Location-Allocation Problem

The location-allocation (LA) problem involves choosing the best number of facilities to locate in a desired area in order to meet customer demand while minimizing the cost of transportation between facilities and customers. This issue arises in a variety of real-world situations where facilities offer uniform services, such as when deciding where to locate production facilities, distribution centers, and warehouses. Cooper (1963) first proposed the LA problem and Hakimi (1964) extended it to a weighted network. (Azarmand et la., 2009).

- Classification of Location-Allocation Problem

Facilities, locations, and customers can be considered to be the fundamental elements of location-allocation problems. In this section, various location-allocation models will be covered along with the definitions and properties of these fundamental elements. The paper by Scaparra and Scutell'a (2001), which proposes a unified framework for characterizing the various aspects of location problems, has had an impact on the presentation provided in this section (Azarmand et la., 2009).

- Classifications of Facilities

The quantity, variety, and price of the facilities are typically used to describe them. Profit, capacity, the attraction range (the area from which customers are drawn to the facility), and the kind of service offered are some other properties related to the facility. The number of new facilities is one of the characteristics, and the single-facility problem, in which only one new facility is to be established, is the simplest case. The multi-facility problem is a more general case where the goal is to simultaneously locate multiple facilities (Azarmand et la., 2009). Another crucial characteristic is the type of facility. In the simplest scenario, all facilities should be identical in terms of their size and the services they provide. Locating facilities that are distinct from one another, such as hospitals and smaller health care facilities, is frequently necessary. Based on whether the facilities can offer a single service or a variety of services, location-allocation models can also be divided into single-service and multi-service categories. The facilities' ability to meet finite or infinite demand, or whether their production and supply capacity is constrained, can also be taken into account. In this regard, the issues are frequently divided into incapacitated and capacitated categories (Azarmand et la., 2009).

- Classified on the Physical Space or Locations

There are three different ways to represent the set of locations that are eligible: discrete, continuous, and network. Since the generation of suitable sites is left up to the model in question, continuous space models are occasionally referred to as site-generation models. Since we are aware of the site candidates beforehand, discrete space models are also known as site-selection models. The third category of location models that can be distinguished in terms of the locations is the network-based model. Depending on whether the links of the network are regarded as a continuous set of candidate locations or whether only the nodes are eligible for the placement of new facilities, problems defined on networks can either be continuous or discrete (Azarmand et la., 2009).

- Classifications of the Demand

The demands of customers are deterministic or probabilistic (Azarmand et la., 2009).

2.11. Main references

- MCVRP in the Waste Management Literature

- Koch et la. (2016) developed an MCVRP-FCS (The multi-compartment vehicle routing problem with flexible compartment sizes in the context of glass waste collection) that takes into account the possibility that the number of product types and the maximum number of compartments that can be used in a single vehicle may be equal or different. To resolve the model, a genetic algorithm was proposed.
- Oliveira et al. (2015) use a heuristic approach to investigate the impact of using vehicles with multiple compartments in a recyclable waste collection system.
- Gajpal et la. (2017) consider the garbage collection problem in which multiple compartment vehicles are used to collect garbage. The vehicles are classified as Alternative Fuel Vehicles (AFVs). They provided a mathematical formulation and two approaches to solving the problem. The first approach is based on the saving algorithm, while the second is based on the metaheuristic of the ant colony system (ACS). To assess the performance of the proposed algorithms, new problem instances have been generated.

Basic differences of our study from the previous Waste Management related. MCVRP studies can be listed as follows:

- Most of the previous studies include only one type of waste.

- LRP in the Waste Management Literature

Several models have attempted to find the best waste flow in MSWM networks. These networks typically consist of a facility for waste treatment using a particular technology, a transfer station, and a separation facility.

- Alumur and Kara (2007) created a mathematical model for a hazardous waste LRP to reduce the overall costs of facilities establishment and transportation, as well as to reduce the transportation risks, which are gauged by the number of people exposed to the designated routes. While recycling centers were not taken into account in their addressed problem, they studied the site selection of disposal and treatment centers as well as the routing problem of various types of hazardous waste from generation nodes to compatible treatment centers and from treatment centers to disposal facilities.
- To choose the locations of treatment and disposal facilities and to route multiple hazardous wastes, Zhao and Zhao (2010) proposed a goal-programming optimization approach to a hazardous waste management system. They also looked at the issue of how to route hazardous waste from generation nodes to treatment centers that can handle them and from treatment centers to disposal facilities.
- By adding some additional real-world considerations, such as site selection for recycling centers and mapping out waste routes to and from recycling centers, Samanlioglu (2013) created a more comprehensive model that built on the models introduced by Alumur and Kara (2007) and Zhao and Zhao (2010).
- Asefi et la. (2015) formulates a new location-routing problem for an integrated MSWM system considering both hazardous and non-hazardous wastes. The proposed model's primary goal is to locate the waste management system's facilities, such as transfer stations, treatment centers, recycling centers, and disposal centers, as well as to determine the best routes to and from those locations. The mathematical model, which takes into account real-world factors, is presented to reduce the system's overall cost, which includes transportation costs and facility opening costs. Real data collected across Australia's New South Wales is also used to test the formulation.

- LA in the Waste Management Literature

- Using geological, topographical, and land use criteria, Yesilnacar and Cetin (2005) conducted a study on the location of suitable sites for the disposal of hazardous waste. This essay describes a procedure for choosing suitable sites for hazardous waste disposal areas using a site screening study.
- Erkut et al. (2008) developed a multi-criteria MILP model to solve the location-allocation problem of solid waste management in North Greece.
- An effective integer programming model was created by S. Ghiani et al. (2012) for the placement of collection centers with a limited capacity in a waste collection management system. Ghiani et al. (2014) investigated the effectiveness of locating collection centers by zoning the service areas in another study. When allocating large waste bins to collection centers, they took into account the compatibility of various types of large waste bins.
- Rathore and Sarmah (2019) proposed a MILP model to solve the problem of waste transfer station location in terms of waste source separation. They were able to validate their model by using a real-world case study problem implemented by CPLEX solver and ArcGIS. The developed model is unique in that it includes strategic allocation of transfer stations for three scenarios: (i) solid waste collected without segregation from sources (Scenario (I)); (ii) waste collected with source separation and transfer stations accepting only one type of waste (Scenario (II)); (iii) waste collected with source separation and transfer stations accepting multiple types of waste (Scenario (III)).

Basic differences of our study from the previous Waste Management related. LRP and LA studies can be listed as follows:

- Only hazardous wastes have been studied as an application of LRP in waste management in nearly all the current studies. Our research, on the other hand, is concerned with the location-routing of non-hazardous municipal solid waste.
- Most of the previous studies include multi-objective decisions such as minimizing cost, minimizing transportation and routing risks. However, our study deals with a single objective of minimizing overall costs.
- In recent years, these two methods have not been taken into account for a two-stage waste management problem together.

Chapter 3
Problem Definition

3.1 Problem Assumption

In this thesis, the problem assumption is the same as Salehi-amiri et la. (2022). We assumed that the waste collection problem is applied in a smart city in which smart bins are used. Bins are intelligent, so whenever their volumes need to be refilled, a connection is established to the operations center. Likewise, each time a bin is emptied, the operation center receives its identification number. As a result, this center is aware of the location of the vehicle at all times, and the operations center is equipped with information about the weight of the loaded waste, bin identification, and the vehicle remaining weight capacity. The vehicle then receives the necessary information from the operations center to pursue the following bins in accordance with the advised routing model (Salehi-amiri et la., 2022).

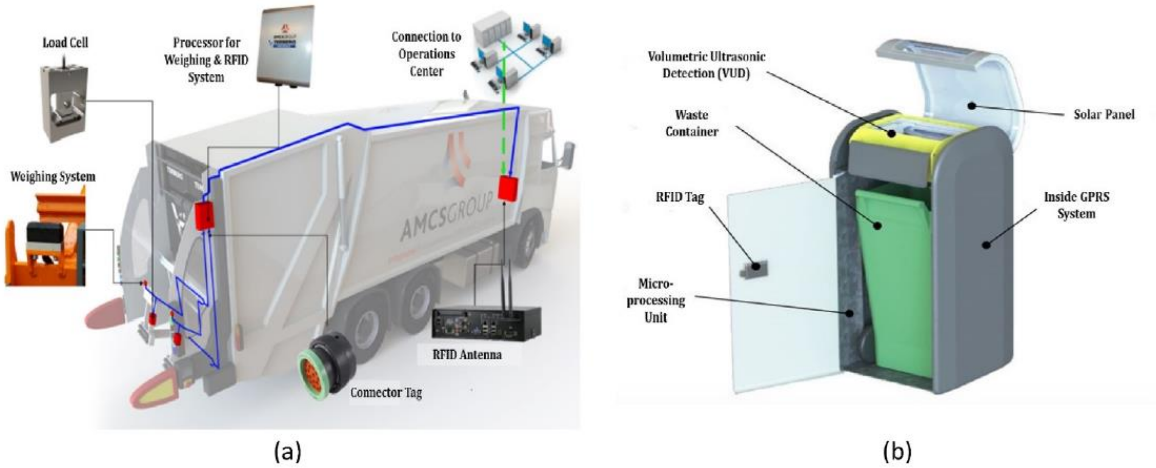


Figure 3. 1: Proposed WMS accommodations based on Salehi-amiri et la. (2022)

A sensor is created to determine the condition inside each bin in order to define the weight and level of refill in each bin. Additionally, planning to obtain an optimized model aids the WMS as a whole. There are numerous research studies that are included in the literature review that discuss the general IoT enabled with WMS construct. The design includes RFID-tagged bins for identification, waste volume sensors, actuators to lock bins when they are full, and wireless antennas to transfer data to the network. This study categorized ICTs for waste management into four categories: spatial technologies (such as GIS and GPS), identification technologies (such as RFID and barcodes), data acquisition technologies (such as sensors and imaging), and data communication technologies (e.g., GSM, Wi-Fi, Bluetooth). The fact that this bin is not necessarily small must be noted. To inform the Internet of Things system about the current state of the waste inside it, a large bin could be used for an entire neighborhood. Such a clever IoT system can be utilized in other industries, such as home healthcare, allowing for the verification of patients' conditions in real-time using small devices connected to them (Salehi-amiri et la., 2022).

3.2 Problem Statement

3.2.1 Single-stage MCVRP

This model takes multi-compartment vehicles (MCVRP) into account so that every vehicle can find the best route. The collected waste must then be moved into separation centers. This paper assumes the same scenario for smart cities as described in (Shah et al. 2018). The smart city is divided into a number of distinct areas, and vehicles are taken into account to help manage the operation of waste collection. In this model, a central separation center is considered for each area.

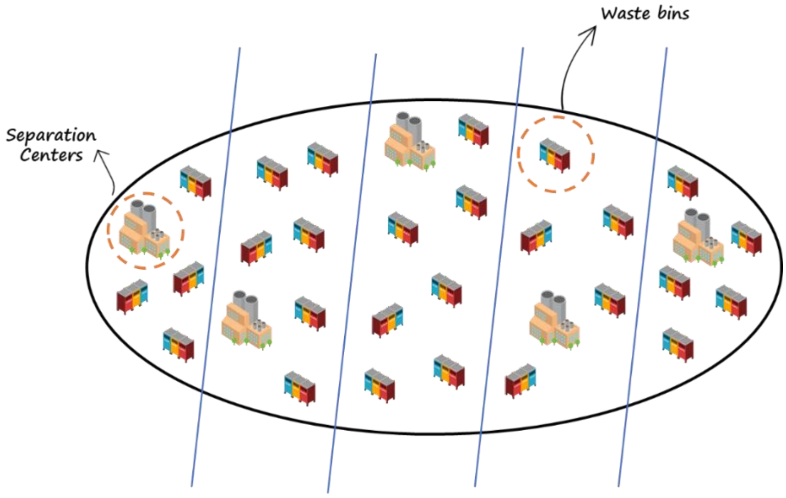


Figure 3. 2: MCVRP model schema.

In the current thesis, the MCVRP model for optimization is developed. This model tries to minimize CO2 emission by considering penalty cost and fixed cost of dispatching the MCVs.

- Assumptions:

1. Sub-areas are divided into various, identically sized groups.
2. Location of bins is known.
3. Municipalities set the upper limits for producing CO2 emissions.
4. A diverse fleet departs from and arrives at the same separation point.
5. Only one MCV visits a bin.
6. The total capacity of the MCV for collection exceeds the total capacity of the bins.

- Notations

Let $G = (V, A)$ be a complete graph where $V = \{i | i = 0, \ldots, n\}$ is the node set and V_0 is the separation facility. $A = \{(i,j) : i, j \in V\}$ is the arc set, where each arc (i, j) is associated with a non-negative distance, d_{ij}.

- Index

$i, j \in \text{V}$	Set of all nodes (bins and separation centers)
$k \in K = \{1, 2, \dots, \lvert K \rvert\}$	Set of MCVs
$p \in P = \{1,2, \dots, \lvert P \rvert\}$	Set of compartments

- Parameters

FC_k	Fixed cost of using MCV k
GA_k	Penalty of Co_2 consumption per MCV k per unit distance
q_{ip}	The amount of waste type p in jth bin
Cap_{kp}	vehicle capacity reserved for waste type p
Cap_k	The capacity of MCV k
d_{ij}	Distance between node i, j

- Integer Variables

q_{ijk}	The amount of shipped waste from node j to node i by MCV k
X_{ijk}	1 if MCV k moves from node i to node j in; Otherwise, 0.
Y_{ipk}	1 if waste of type p at bin i belongs to the route of MCV k; Otherwise, 0.
A_k	1 if MCV k is used; Otherwise, 0.

- Model

$Min\ (Z_1) = \sum_{k \in K} FC_k \cdot A_k + \sum_{i \in V} \sum_{j \in V} \sum_{k \in K} GA_k \cdot d_{ij} \cdot X_{ijk}$ Subject to:		(1)
$\sum_{j \in V} X_{0jk} = A_k$	$\forall k \in K$	(2)

$\sum_{\substack{i\in V \\ i\neq j}} \sum_{k\in K} X_{ijk} \geq 1$	$\forall j \in V\backslash\{0\}$	(3)
$\sum_{\substack{i\in V \\ i\neq j}} \sum_{k\in K} X_{ijk} \leq \lvert k\rvert$	$\forall j \in V\backslash\{0\}$	(4)
$\sum_{k\in K} Y_{ipk} = 1$	$\forall i \in V\backslash\{0\}\ , p \in P$	(5)
$\sum_{\substack{i\in V \\ i\neq j}} X_{ijk} = Y_{jpk}$	$\forall j \in V\backslash\{0\}\ , p \in P, k \in K$	(6)
$\sum_{\substack{i\in V \\ i\neq j}} X_{jik} = Y_{jpk}$	$\forall j \in V\backslash\{0\}\ , p \in P, k \in K$	(7)
$\sum_{i\in V} q_{ip} \cdot Y_{ipk} \leq cap_{kp} A_k$	$\forall k \in K, p \in K$	(8)
$\sum_{i\in V} \sum_{p\in P} q_{ip} \cdot Y_{ipk} \leq cap_k \cdot A_k$	$\forall k \in K$	(9)

The objective functions (1) of the proposed first sub-model are:

- Minimizing the costs of transportation.
- Minimizing the costs of air pollution.

Constraints:

Eq. 2 MCV k will start its trips from the separation center.

Eq. 3 And Eq.4 All bins may not be visited by all vehicles.

Eq. 5 consider the assignment of products to vehicles and compartments. It ensures that only a single product type can be assigned to each compartment of a vehicle.

Eq. 6 and Eq. 7 Ensures the condition of uninterruptedness That is, if MCV k enters a vertex, it should exit the node as well.

Eq. 8 Corresponds to the capacity reserved for waste type p in MCV k

Eq. 9 Corresponds to the total capacity of MCV k

3.2.2 Two-stage LRP+LAP

In this study, a two-stage model is developed. The first sub-model introduces Location-Routing problem (LRP) and the second one uses Location-Allocation problem (LAP). Each sub-model is explained in detail in further sections. An overall schema has been depicted as follows (figure 15).

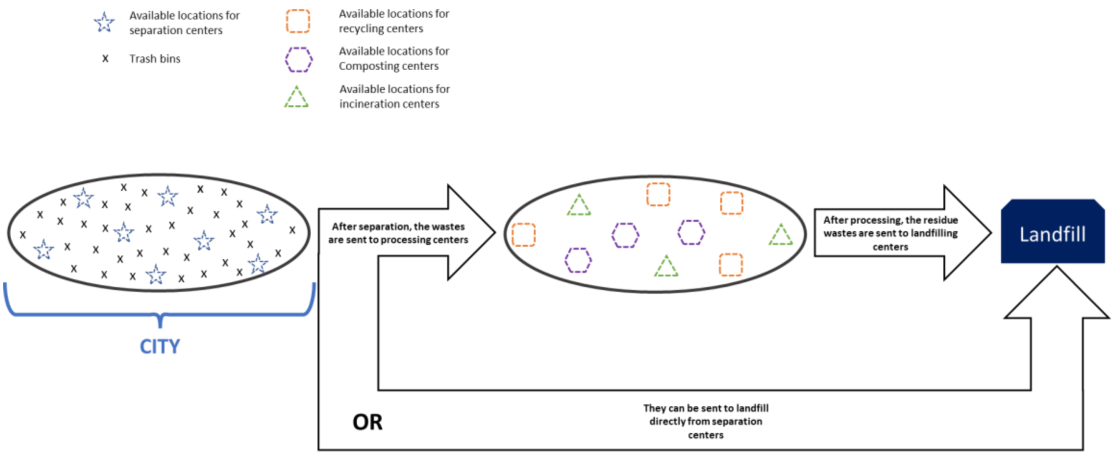


Figure 3. 3: Schema of proposed two stage WMS model.

- First sub-model (LRP)

In this section, the goal is to collect waste from waste generation nodes. Therefore, a single-objective mixed-integer linear multi-product for the waste management network is proposed. The considered network consists of waste generation nodes and separation centers. Separation centers are also depots for vehicles.
This section develops the LRP optimization model to determine the number of required separation centers and the best route for taking into account. As a result, the best fleet of vehicles is used to boost productivity. In other words, different routes between nodes i and j are taken into account, and it is also assumed that the cost of routing at each distance is diverse. Both the type of vehicle and the distance affect this price.

- Assumptions

1. Each waste node is served by exactly one vehicle,
2. The total volume of waste on each route is less than or equal to the capacity of the vehicle assigned to that route,
3. The first sub-waste model is separated into wet and dry clusters,
4. A diverse fleet departs from and arrives at the same separation point,

Let $G = (M, A)$ be a complete graph where $M = \{i | i = 0, \ldots, n\}$ is the node set. $A = \{(i, j) : i, j \in M\}$ is the arc set, where each arc (i, j) is associated with a non-negative distance, d_{ij}.

- Index

$i, j \in$ M	Set of waste generating nodes
$w \in W = \{1,2, \dots, \lvert W \rvert\}$	Set of waste types
$v \in V = \{1,2, \dots, \lvert V \rvert\}$	Set of Light commercial vehicles (LCVs)
$d \in D = \{1,2, \dots, \lvert D \rvert\}$	Set of Separation centers

- Parameters

g_{wi}	Amount of waste w generated at node i
FCV_v	Fixed cost of using LCV v
VCV_v	variable cost of LCV v
FCD_d	Fixed cost of establishing separation center d
cap_v	Capacity of LCV v
cap_{dw}	Capacity of separation center d for waste type w

- Integer Variables (location-Routing variables)

X_{vij}	1 if LCV v traverses arc (i,j); otherwise,0
YD_d	1 if separation center d is established; otherwise, 0
YV_v	1 If LCV v is used; otherwise, 0
S_{id}	1 if waste at node i shipped to separation center d; otherwise, 0

- Model

$$Min\ Z_1 = \sum_{v \in V} FCV_v \cdot YV_v + \sum_{v \in V} \sum_{i \in M} \sum_{j \in M} VCV_v \cdot d_{ij} \cdot X_{vij} + \sum_{d \in D} FCD_d \cdot YD_d \quad (1)$$

Subject to:

$\sum_{d \in D} S_{id} = 1$	$\forall i \in M \backslash \{0\}$	(2)
$\sum_{\substack{j \in M \\ i \neq j}} X_{vij} = 1$	$\forall i \in M \backslash \{0\}, v \in V$	(3)
$\sum_{\substack{j \in M \\ i \neq j}} X_{vji} = 1$	$\forall i \in M \backslash \{0\}, v \in V$	(4)
$\sum_{j \in M} X_{vij} = \sum_{j \in M} X_{vji}$	$\forall i \in M, v \in V$	(5)
$X_{vij} \leq YV_v$	$\forall i, j \in M, v \in V$	(6)
$X_{vid} \leq YD_d$	$\forall i \in M, d \in D, v \in V$	(7)
$\sum_{\substack{j \in M \\ i \neq j}} X_{vij} + \sum_{\substack{j \in M \\ i \neq j}} X_{vjd} \leq 1 + S_{id}$	$\forall i \in M, d \in D, v \in V$	(8)
$u_{iv} - u_{jv} + \lvert M \rvert X_{vij} \leq \lvert M \rvert - 1$	$\forall i, j \in M, v \in V$	(9)
$\sum_{i,j \in M} \sum_{w \in W} g_{wi} \cdot S_{id} \leq cap_v \cdot YV_v$	$\forall v \in V$	(10)
$\sum_{i \in M} g_{wi} \cdot S_{id} \leq cap_{dw} \cdot YD_d$	$\forall d \in D, w \in W$	(11)

The objective functions (1) of the proposed first sub-model are:

- Minimizing the fixed costs of dispatching LCVs.
- Minimizing the variable costs of transportation.
- Minimizing the fixed costs of establishing separation center d.

Constraints:

Eq. 2 Considers the assignment of each waste node to separation center for visiting.

Eq. 3 And Eq.4 Each waste node is served by exactly one vehicle.

Eq. 5 Represents the vehicle flow constraints. That is, if LCV v

enters a vertex, it should exit the node as well.

Eq. 6

Eq. 7 Ensures that the needed separation center is established.

Eq. 8 Represents the vehicle flow constraints. That is, LCV v will return to separation center in the end.

Eq. 9 Subtour elimination constraint.

Eq. 10 Corresponds to the total capacity of LCV.

Eq. 11 Corresponds to the total capacity of separation center.

- Second sub-model (LA)

In this section, a single-objective mixed-integer linear multi-product for the sustainable waste management network is proposed. The considered network consists of three echelons, including separation, recycling, composting, incineration and landfill centers. The assumed network has forward flow. In this proposed network, waste in separation stations is separated and being sent to recycling, incineration, composting facilities and landfills. After the separation processing in separation centers, the relevant wastes are transported to established processing centers through forward flow. The residues of the process are usually sent to the landfill. There are wastes that cannot produce energy, or they are hazardous must be landfilled, this transportation can happen either directly from separation centers or from processing centers after processing.

- Assumptions

1. The number of established processing facilities is unknown. These facilities should be built at the start of the planning horizon,
2. Each processing/disposal facility has unique operational, establishment, and transportation costs,
3. Each region will have a limited number of permanent facilities. Furthermore, each facility type has its own capacity constraint.

- Index

$w \in W = \{1,2,\ldots,\|W\|\}$	Set of waste types
$d \in D = \{1,2,\ldots,\|D\|\}$	Set of separation centers
$k \in K = \{1,2,\ldots,\|K\|\}$	Set of potential sites for centers

$p \in P = \{1,2, \dots, \lvert P \rvert\}$	Set of processing methods on waste (for example, in $\lvert P \rvert = 3$, we have recycling, composting and incineration processes)
$s \in S = \{1,2, \dots, \lvert S \rvert\}$	set of capacity levels (for example in $\lvert S \rvert = 3$, we have small, medium and large capacity levels)
$l \in L = \{1,2, \dots, \lvert L \rvert\}$	Set of available landfilling locations

- Parameters

FC_{kps}	Fixed cost of establishing center k of type p with capacity level s
PC_{wkp}	Processing cost of waste type w under processing method type p at center k
TC_{dk}	Per unit transportation cost from separation center d to center k
TC_{kl}	Per unit transportation cost from center k to landfilling l
CL_{wdl}	Per unit transportation cost of waste type w from separation center d to landfilling l
V_{dw}	Amount of waste type w in separation center d
cap_{kps}	Capacity of center k of type p with capacity level s
cap_l	Capacity of landfill l
$captr_{dk}$	Maximum transportation capacity from separation center d to center k
α_{wp}	The portion of waste type w which requires processing method p $(\sum_{p}^{\lvert p \rvert} \alpha_{wp} = 1, w \in W)$
β_{wp}	The portion of resultant waste from processing method p

- Integer Variables (location-allocation variables)

QL_{wdl}	Amount of waste type w shipped from separation center d to landfilling l
QP_{wdk}	Amount of waste type w shipped from separation center d to center k
Q_{wkp}	Amount of waste type w under processing method p in center k
U_{kl}	Amount of waste type w shipped from center k to landfilling l
X_{kps}	$\begin{cases} 1 \text{ if center } k \text{ of type } p \text{ with capacity level } s \text{ is established} \\ 0 \text{ otherwise.} \end{cases}$

- Model

$Min(Z_1) = \sum_{k\in K}\sum_{p\in P}\sum_{s\in S} FC_{kps}\cdot X_{kps} + \sum_{w\in W}\sum_{k\in K}\sum_{p\in P} PC_{wkp}\cdot Q_{wkp}$ $+ \sum_{w\in W}\sum_{d\in D}\sum_{k\in K} TC_{dk}\cdot QP_{wdk} + \sum_{k\in K}\sum_{l\in L} TC_{kl}\cdot U_{kl} + \sum_{w\in W}\sum_{d\in D}\sum_{l\in L} Cl_{wdl}\cdot QL_{wdl}$ Subject to:		(1)
$V_{dw} = \sum_{k\in K} Q_{wdk} + \sum_{l\in L} QL_{dwl}$	$\forall d \in D, w \in W$	(2)
$QP_{wdk} \leq \left(\sum_{p\in P}\sum_{s\in S} X_{kps}\right) M$	$\forall\, w \in W, d \in D, k \in K$	(3)
$Q_{wkp} \leq \left(\sum_{s\in S} X_{kps}\right) M$	$\forall\, w \in W, k \in K, p \in P$	(4)
$Q_{wkp} = \sum_{d\in D} \alpha_{wp}\cdot QP_{wdk}$	$\forall\, w \in W, k \in K, p \in P$	(5)
$\sum_{w\in W} Q_{wkp} \leq \sum_{s\in S} cap_{kps}\cdot X_{kps}$	$\forall k \in K, p \in P$	(6)
$\sum_{w\in W} QP_{wdk} \leq captr_{dk}$	$\forall d \in D, k \in K$	(7)
$\sum_{k\in K} U_{kl} \leq cap_l$	$\forall l \in L$	(8)
$\sum_{l\in L} U_{kl} = \sum_{w\in W}\sum_{p\in P} \beta_{wp}\cdot Q_{wpk}$	$\forall k \in K$	(9)
$\sum_{s\in S} X_{kps} \leq 1$	$\forall k \in K, p \in P$	(10)
$\sum_{l\in L} QL_{wdl} \leq 0.2V_{dw}$	$\forall d \in D, w \in W$	(11)

The objective functions (1) of the proposed first sub-model are:

- Minimizing the fixed cost of establishing waste processing centers
- Minimizing the cost of processing wastes under different available methods

- Minimizing the cost of transportation from separation centers to processing centers and from processing centers to landfill
- Minimizing the cost of transportation from separation centers to landfill

Constraints:

Eq. 2 Demonstrates the volume of waste at separation centers.

Eq. 3 Ensures that waste at each separation center should be assigned to its corresponding processing centers with a certain capacity level.

Eq. 4 Ensures that waste at each processing center should be processed to its corresponding method.

Eq. 5 Ensures that waste at each processing center should be processed to its corresponding method.

Eq. 6 Corresponds to the capacity constraint of each center.

Eq. 7 Corresponds to the capacity constraint of transportation.

Eq. 8 Indicates the capacity of landfilling.

Eq. 9 Determines the amount of resultant wastes at each processing center.

Eq. 10 Examines the possibility of establishing waste processing centers of certain processing methods at the candidate sites which ensures that each candidate location for establishing a processing center can be equipped by at most one processing method of a certain capacity level.

Eq. 11 Examines the waste shipped directly to landfill from separation centers should be utmost 0.2 of total wastes volume at each center.

Chapter 4
Implementation and Results

4.1 Data Generation

There is insufficient literature to test the developed WMS because the proposed model is quite novel. As a result, a solution to the problem is required. Six instances involving three categories, i.e., small-sized: SP1 to SP2, medium-sized: MP3 to MP4, and large-sized: LP5 to LP6 are introduced. Tables show the size of the problem instances, which are divided into three categories as previously mentioned.

4.1.1 Single-stage MCVRP Model

Category	**Samples**	**Sizes $(\boldsymbol{I}, \boldsymbol{K}, \boldsymbol{P})$**
Small	SP1	(23,3,2)
Medium	MP2	(60,6,2)
Large	LP3	(200,14,3)

Table 4. 1: The classification of single-stage MCVRP model

Parameters	**Value**	**Units**
g_{ip}	$Uniform \sim [1,20]$	Cubic meter (m^3)
FC_k	$2 * Cap_k$	Dollar ($)
GA_k	$Uniform \sim [10,20]$	Dollar ($)
Cap_{kp}	$\frac{1}{\lvert p \rvert} * Cap_k$	Kilogram (Kg)

Cap_k	$\frac{1}{\lvert k \rvert} * uniform \sim [2,4] * \sum_{i \in M} \sum_{p \in P} q_{ip}$	Kilogram (Kg)
d_{ij}	$Uniform \sim [1,20]$	Kilometer (Km)

Table 4. 2: Coordinates of single-stage MCVRP model.

4.1.2 Two-stage LRP+LAP

- First sub-model (LRP)

Category	**Samples**	**Sizes $(\boldsymbol{I}, \boldsymbol{W}, \boldsymbol{V}, \boldsymbol{D})$**
Small	SP1	(30,3,10,20)
Medium	MP2	(100, 2, 8, 20)
Large	LP3	(320, 2, 20, 40)

Table 4. 3: The classification of first sub-model (LRP)

Parameters	**Value**	**Units**
g_{wi}	$Uniform \sim [20, 50]$	Cubic meter (m^3)
FCV_v	$Uniform \sim [5, 10] * cap_v$	Dollar ($)
VCV_v	$Uniform \sim [0.2, 0.5] * cap_v$	Dollar ($)
FCD_d	$Uniform \sim [5, 10] * \sum_{w \in W} Cap_{dw}$	Dollar ($)
cap_v	$\frac{1}{\lvert V \rvert} * uniform \sim [3, 6] * \sum_{w \in W} \sum_{i \in M} g_{wi}$	Kilogram (Kg)
cap_{dw}	$\frac{1}{\lvert W \rvert} * uniform \sim [2, 5] * \sum_{i \in M} g_{wi}$	Kilogram (Kg)
d_{ij}	$Uniform \sim [10, 100]$	Kilometer (Km)

Table 4. 4: Coordinates of first sub-model (LRP)

- Second sub-model (LA)

Category	**Samples**	**Sizes $(\boldsymbol{W}, \boldsymbol{D}, \boldsymbol{K}, \boldsymbol{P}, \boldsymbol{S}, \boldsymbol{L})$**
Small	SP1	(3, 5, 5, (re,co,in), (S,M,L), 2)
Medium	MP2	(3, 20, 20, (re,co,in), (S,M,L), 3)
Large	LP3	(3, 40, 60, (re,co,in),(S,M,L), 4)

Table 4. 5: The classification of second sub-model (LA)

Parameters	Value	Units
FC_{kps} $for\ small\ size$	$Uniform \sim [20, 25]$	Dollar ($)
FC_{kps} $for\ medium\ size$	$2 * FC_{kps}$ $for\ small\ size$	Dollar ($)
FC_{kps} $for\ large\ size$	$2.5 * FC_{kps}$ $for\ medium\ size$	Dollar ($)
PC_{wkp}	$Uniform \sim [2,90]$	Dollar ($) per Kg
TC_{dk}	$Uniform \sim [0.5, 1]$	Dollar ($)
TC_{kl}	$Uniform \sim [1, 2]$	Dollar ($)
CL_{wdl}	$uniform{\sim}[2, 10]$	Dollar ($)
V_{dw}	$uniform{\sim}[200, 1000]$	Kilogram (Kg)
cap_{kps} $for\ small\ size$	$uniform{\sim}[2000,3000]$	Kilogram (Kg)
cap_{kps} $for\ medium\ size$	$1.5 * cap_{kps}$ $for\ small\ size$	Kilogram (Kg)
cap_{kps} $for\ large\ size$	$2.5 * cap_{kps}$ $for\ medium\ size$	Kilogram (Kg)
cap_l	$0.5 * \sum_{d \in D} \sum_{w \in W} V_{dw}$	Kilogram (Kg)
$captr_{dk}$	$Uniform \sim [1000, 2000]$	Kilogram (Kg)

Table 4. 6: Coordinates of second sub-model (LA)

4.2 Numerical Results

4.2.1 Single-stage MCVRP Model

Category	Samples	Sizes $(\boldsymbol{I}, \boldsymbol{K}, \boldsymbol{P})$	Z	Solver Run time (seconds)
Small	SP1	(10,2,2)	729.382	0.687
Medium	MP2	(23,4,2)	1706.346	21.219
Large	LP3	(60,5,3)	6151.408	118.282

Table 4. 7: Output of MCVRP model for different sample sizes

As shown in figure 4.3, the single-stage MCVRP model involves MCVs that visit waste bins to pick up the waste and carry collected waste to the separation center. The path of each fleet is shown with a distinguishable colorful line. The output is the result of the medium size sample.

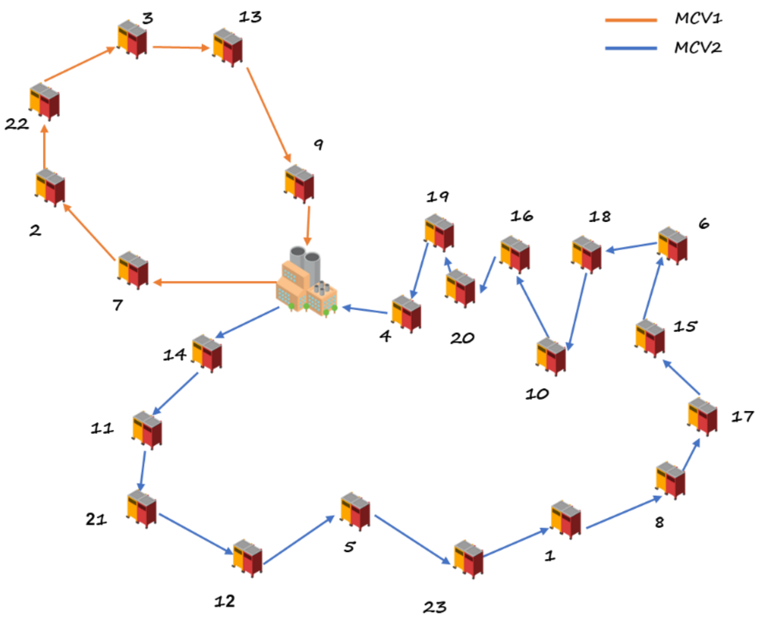


Figure 4. 1: Schematic of the single-stage MCVRP output.

4.2.2 Two-stage LRP+LAP

- First sub-model (LRP)

Category	Samples	Sizes $(\boldsymbol{I}, \boldsymbol{W}, \boldsymbol{V}, \boldsymbol{D})$	Z	Solver Run time (seconds)
Small	SP1	(20,3,10,15)	157361.667	113.297
Medium	MP2	(60, 4, 15, 25)	534120.113	301.265
Large	LP3	(90, 4, 15, 40)	1061702.025	306.063

Table 4. 8: Output of LRP model for different sample sizes

As shown in figure 4.4, the LRP model involves LCVs that visit waste bins to pick up the waste and carry collected waste to the separation center. The path of each fleet is shown with a distinguishable colorful line. The output is the result of the small size sample.

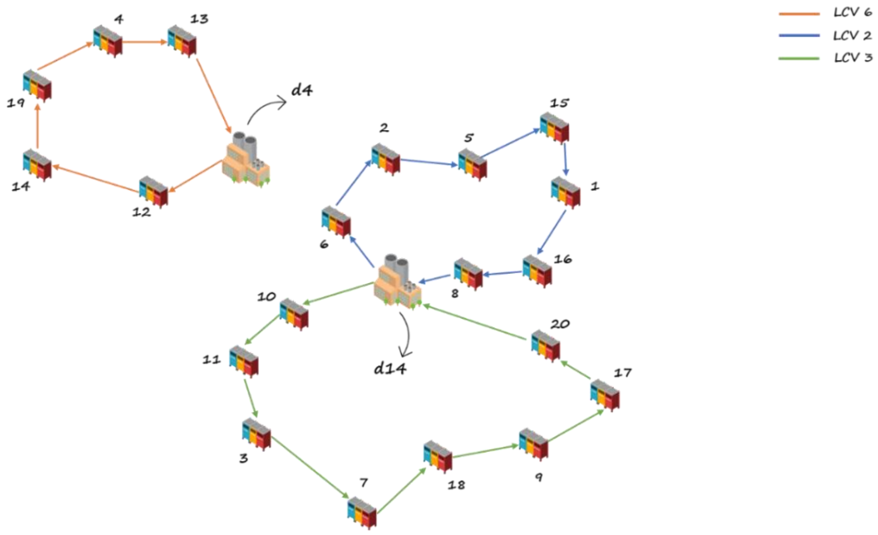


Figure 4. 2: Schematic of the first sub-model (LRP) output

- Second sub-model (LA)

Category	**Samples**	**Sizes (W, D, K, P, S, L)**	**Z**	**Solver Run time (seconds)**
Small	SP1	(3, 10, 15, (re,co,in), (S,M,L), 2)	203937.11	0.094
Medium	MP2	(4, 40, 60, (re,co,in), (S,M,L), 3)	774896.41	1.015
Large	LP3	(4, 80, 120, (re,co,in), (S,M,L), 3)	1390380.56	4.921

Table 4. 9: Output of LA model for different sample sizes

These results are calculated without considering the output of the first stage as an input for second stage. In the following the mentioned solution is considered. The output of first stage is the amount of each type of waste in the separation centers for further operations, therefore; $V(d, w)$ is calculated in the first stage and insert as the second stage input.

Category	Samples	Sizes of LA-second stage $(\boldsymbol{W}, \boldsymbol{K}, \boldsymbol{P}, \boldsymbol{S}, \boldsymbol{L})$	Sizes of LRP-first stage $(\boldsymbol{I}, \boldsymbol{W}, \boldsymbol{V}, \boldsymbol{D})$	Z (LA without the input of first stage)	Z (LA with the input of first stage)
Small	SP1	(3, 15, (re,co,in), (S,M,L), 2)	(20,3,10,15)	203937.117	67177.061
Medium	MP2	(4, 60, (re,co,in), (S,M,L), 3)	(60, 4, 15, 25)	774896.419	429488.923
Large	LP3	(4, 120, (re,co,in), (S,M,L), 3)	(90, 4, 15, 40)	1390380.569	611464.592

Table 4. 10: Output of LA model with and without the input of fist stage

4.3 Sensitivity and Data Analysis

- Single-stage MCVRP Model

Figure 4.3 depicts the waste-to-capacity tightness as tightness1 and the waste-to-distance tightness as tightness2, respectively. The former measures the effectiveness of the proposed plan by the amount of waste collected in a given capacity.

$$\text{Tightness1 (waste/capacity)}= \frac{Total\ collected\ waste}{Total\ capacity\ of\ n\ vehicles}$$

The latter defines the effectiveness of the proposed plan by the amount of waste collected in a given distance.

$$\text{Tightness2 (waste/distance)}= \frac{Total\ collected\ waste}{Total\ distance\ of\ n\ vehicles}$$

Larger values of the tightness measure are indicative of greater performance, and there is a positive association between the tightness measure's size and the degree of success in obtaining the targeted objective.

A variety of vehicles are used to test the best and most optimized scheme. Based on the results, the first scenario suggests the best plan. The best plan suggests that by using 2 vehicles, more waste can be transported while less capacity remains empty. According to figure 4.3, the first scenario with 2 vehicles is the best strategy. It is worth noting that more waste is collected in this scenario over a given distance, demonstrating its effectiveness.

Vehicle capacity	Distance	Collected Waste
k_1(2000)	124	800
k_2(2000)	287	1600
Total collected waste	2400	
Total distance	411	
Total capacity of 2 vehicles	4000	
Tightness1 (waste/capacity)	$\frac{2400}{4000} = 0.6$	
Tightness2(waste/distance)	$\frac{2400}{411} = 5.84$	

Table 4. 11: The behavior of the model using two vehicles in its collection route.

Vehicle capacity	Distance	Collected Waste
k_2(2000)	153	800
k_3(2000)	170	800
k_5(2000)	157	400
k_6(2000)	141	400
Total collected waste	2400	
Total distance	621	

Total capacity of 4 vehicles	8000
Tightness1 (waste/capacity)	$\frac{2400}{8000} = 0.3$
Tightness2(waste/distance)	$\frac{2400}{621} = 3.86$

Table 4. 12: The behavior of the model using four vehicles in its collection route.

Vehicle capacity	**Distance**	**Collected Waste**
$\boldsymbol{k_1}$(2000)	102	342.8
$\boldsymbol{k_2}$(2000)	149	685
$\boldsymbol{k_3}$(2000)	177	343
$\boldsymbol{k_4}$(2000)	118	687
$\boldsymbol{k_5}$(2000)	135	343
$\boldsymbol{k_6}$(2000)	106	342
Total collected waste	2400	
Total distance	787	
Total capacity of 4 vehicles	12000	
Tightness1 (waste/capacity)	$\frac{2400}{12000} = 0.2$	
Tightness2(waste/distance)	$\frac{2400}{787} = 3.05$	

Table 4. 13: The behavior of the model using six vehicles in its collection route.

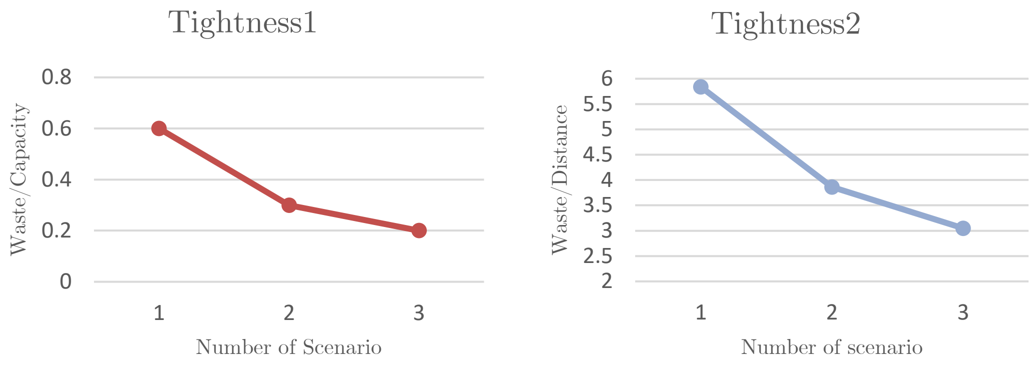


Figure 4. 3: Comparison of tightness between scenarios

- Two-stage WMS (LRP+LAP)
- First sub-model LRP

In Figure 4.4, results show that the first scenario with 2 vehicles is the optimal plan for both tightness1 and tightness2.

Vehicle capacity	**Distance**	**Collected Waste**
V_1(2000)	305	2300
V_2(2000)	41	800
Total collected waste	3100	
Total distance	346	
Total capacity of 2 vehicles	4000	
Tightness1 (waste/capacity)	$\frac{3100}{4000} = 0.77$	
Tightness2(waste/distance)	$\frac{3100}{346} = 8.9$	

Table 4. 14: The behavior of the model using two vehicles in its collection route.

Vehicle capacity	Distance	Collected Waste
$V_1(2000)$	96	987
$V_2(2000)$	243	1080
$V_3(2000)$	188	1033
Total collected waste	3100	
Total distance	527	
Total capacity of 3 vehicles	6000	
Tightness1 (waste/capacity)	$\frac{3100}{6000} = 0.51$	
Tightness2(waste/distance)	$\frac{3100}{527} = 5.8$	

Table 4. 15: The behavior of the model using three vehicles in its collection route.

Vehicle capacity	Distance	Collected Waste
$V_1(2000)$	130	1075
$V_2(2000)$	219	1121
$V_3(2000)$	164	904
$V_4(2000)$	141	667
Total collected waste	3100	
Total distance	621	

Total capacity of 4 vehicles	8000
Tightness1 (waste/capacity)	$\frac{3100}{8000} = 0.3$
Tightness2(waste/distance)	$\frac{3100}{621} = 4.9$

Table 4. 16: The behavior of the model using four vehicles in its collection route.

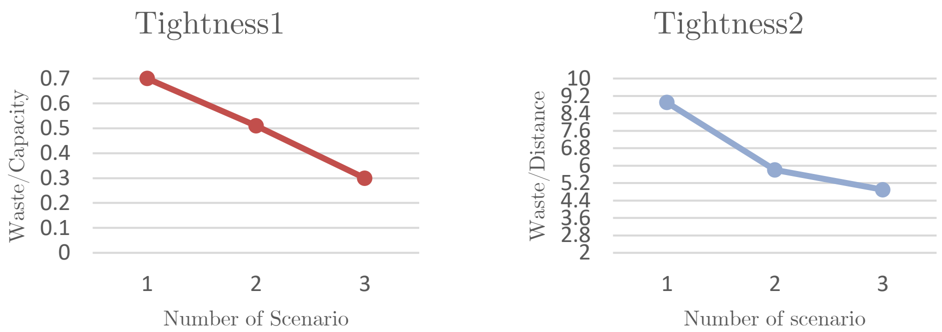


Figure 4. 4: Comparison of tightness between scenarios

Here, a modification is applied in some parameters to observe their modes in various conditions. A medium-sized problem, e.g., MP2 considering four types of waste, 60 site locations, and 3 landfills is selected. In the following, the QL_{wdl}, QP_{wdk}, Q_{wkp} and U_{kl} parameters are changed in the second model. Due to figure 19, in the first step, the value of QL_{wdl} , QP_{wdk}, Q_{wkp} and U_{kl} is increased from 0 to 50% and then reduced from 0 to 50% to extend the variability and sensitivity of the proposed model and also objective functions.

As it is shown, the overall cost would increase as the amount of waste shipped directly to landfill decreases. The main reason is that by decreasing this amount the municipality should invest more on establishing or using other disposal facilities (e.g., recycling). If the municipality plans to transfer a considerable portion of the wastes directly to landfill, the consequence will be more costly in terms of environmental impacts specifically.

	Cost ↑	QL(w,d,l) ↓	Delta
1	257640.385	15161.030	-50.000
2	262569.333	13421.941	-40.000
3	267006.469	12250.424	-30.000
4	270335.101	9557.458	-20.000
5	272884.234	8248.502	-10.000
6	274856.180	5974.314	
7	276221.409	4816.829	10.000
8	277176.617	3509.520	20.000
9	277897.222	2730.781	30.000
10	278405.570	1998.602	40.000
11	278761.624	1209.897	50.000

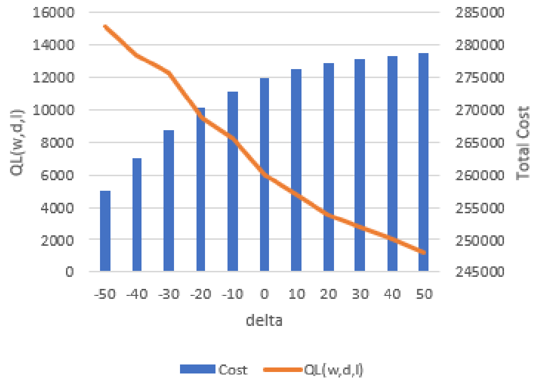


Figure 4. 5: The relationship between overall cost and amount of waste shipped from separation center d to landfilling l

In the contrary of above statement, the overall cost would increase if the municipality used different methods of disposal. In this case, the cost and amount of shipped waste to landfill will decrease while other costs such as establishing and using different forms of waste management centers will increase. The numerical results are shown in figure 4.4 respectively. Figure 4.5 confirms that the less disposal centers used for sustainability of waste, the more overall cost will soar. The more updated technology, the less labor cost. Digitalization provides opportunities to reduce these costs while also creating more job opportunities in higher-value parts of the business chain (EEA Europe, 2021).

	Cost ↑	QP(w,d,k) ↓	Delta
1	249310.311	81869.273	-50.000
2	254465.759	81660.566	-40.000
3	259594.858	81339.215	-30.000
4	264698.746	81090.575	-20.000
5	269787.051	81003.821	-10.000
6	274856.180	80861.466	
7	279880.064	80213.642	10.000
8	284890.028	80038.381	20.000
9	289871.105	79475.856	30.000
10	294745.516	79465.729	40.000
11	299574.941	78923.647	50.000

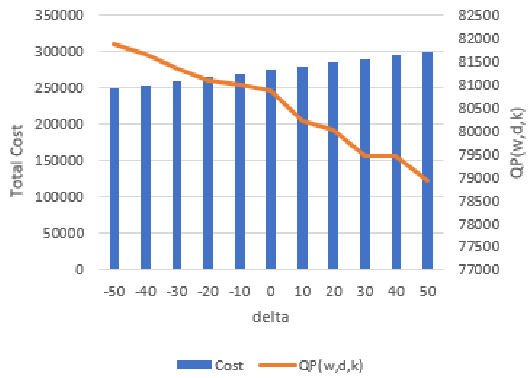


Figure 4. 6: The relationship between overall cost and amount of wastes shipped from separation center d to center k

	Cost	Q(w,k,p)	Delta
1	178747.914	86144.788	-50.000
2	198655.788	84932.694	-40.000
3	218212.521	83915.647	-30.000
4	237394.865	83044.856	-20.000
5	256288.010	81896.989	-10.000
6	274856.180	80861.466	
7	293061.240	79314.711	10.000
8	310948.794	78029.956	20.000
9	328670.723	77796.798	30.000
10	346230.942	76683.854	40.000
11	363531.486	75236.195	50.000

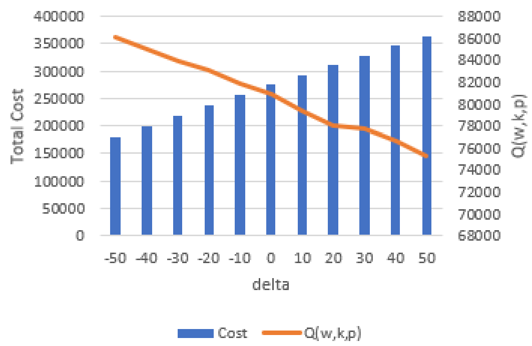


Figure 4. 7: The relationship between overall cost and amount of wastes under processing method p in center k

Figure 4.7 demonstrates that as the amount of wastes shipped to landfills from disposal centers decreases the overall cost will increase, which is due to the using of different operations and technologies on wastes, therefore; the result waste would be less in amount.

	Cost	U(k,l)	Delta
1	263281.086	20318.602	-50.000
2	265614.952	20271.470	-40.000
3	267942.840	20245.444	-30.000
4	270257.640	20196.761	-20.000
5	272567.011	20196.761	-10.000
6	274856.180	20154.055	
7	277117.022	20018.964	10.000
8	279352.277	19967.388	20.000
9	281582.540	19967.321	30.000
10	283803.281	19933.877	40.000
11	286014.214	19918.554	50.000

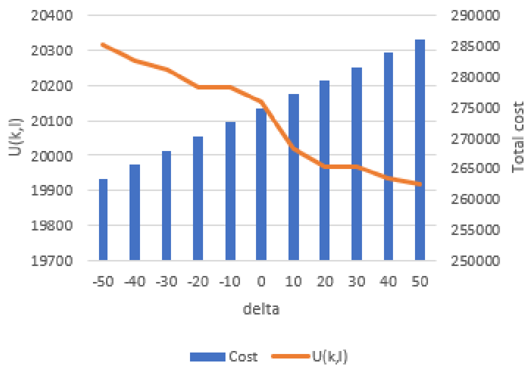


Figure 4. 8: The relationship between overall cost and amount of wastes shipped from center k to landfilling l

Chapter 5
Conclusion

In this chapter, in addition to stating the summary of the research, we provide practical suggestions for future research as well.

- Research review

The increased production of waste has been viewed as a major problem for major urban centers around the world and as a crucial issue for nations with accelerated urban population growth. Cyberphysical systems made possible by the Internet of Things (IoT) and cloud computing have the potential to automate solid waste management (Perdini et la, 2019).

This thesis tries to propose models in the field of waste management by considering smart city context as the main assumption. For this reason, three topics related to the optimization of waste management including: MCVRP, LRP and LA are discussed. MCVRP, LRP and LA for effective waste management are reviewed with the focus on both theoretical and experimental contributions to related works in the research community. The main contributions of this thesis include proposing two optimization models MCVRP and LRP+LA that take into account separation and processing centers alongside economic impacts. These models were inspired by literature.

This thesis consists of 5 chapters. Firstly, Chapter 1 offers an introduction to show the full picture of the issues, their significance, and real-world applications. The key theoretical ideas, the evolution of the major contributions from earlier studies, and various approaches to solving problems have all been reviewed in Chapter 2. This effort is made in order to be aware of previous research in the field, to spot a gap in the literature, and to present a unique contribution.

Next in chapter 3, the problem assumptions are explained. The MCVRP problem has been analyzed when a waste management system with only a single depot (separation center) is used. In the second problem, a two-stage network is designed including LRP by considering multi separation centers as the first stage following LA consisting various processing centers as the second stage.

Then in chapter 4, numerical results and analysis are taken into account. Since smart city concept is still at the assumption level, there are no real-world case studies to examine; therefore, data generation is considered to test the models. Data is generated based on 3 sample sizes (small, medium and large) for each model. In the end, a sensitivity analysis is done to show the impact of objective function variables on total cost. To evaluate the effectiveness of the proposed solution under various degrees of tightness, multiple scenarios are assessed. Based on the findings, it may be concluded that fewer vehicles are capable of transporting a greater volume of waste over a shorter distance.

- Future work

In future studies, there is plenty of room to extend the problems and implement different algorithms to solve them. The following are some potential future extensions to the work:

1- Future research could include testing different models, including stochastic models, and considering different additional objectives such as social objectives with regard to customers and drivers such as customer satisfaction, noise pollution, or quality of service in terms of service time and cost.

2- Another suggestion would be the use of electric vehicles in place of the traditional trucks. When designing an Electric Vehicle Routing Problem (EVRP) mathematical model, some important vehicle parameters to consider are battery capacity, charging time, and maximum driving range and for Charging station parameters like capacity, location, and charging rate should be taken into consideration.

3- A potential future work could consist of applying heuristic and/or metaheuristic algorithms to improve the quality of the proposed methods in the current thesis. VRP is classified as an NP-hard problem; therefore, the size of problems that can be solved optimally using mathematical programming may be constrained and time-consuming, specifically for large sample size. Heuristic and meta-heuristic approaches are useful when the problem is too complex to be solved optimally in a reasonable amount of time using traditional optimization methods.

4- Another promising future research suggestion is to solve the models with stochastic techniques such as robust optimization. In this current thesis, for instance, β_{wp} which is the portion of resultant waste from processing method p in second stage of suggested two-stage model, was considered certain. While the generated amount can be calculated as an uncertain parameter decided by uncertainty optimization methods.

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