UNIVERSITI TEKNOLOGI MARA

A FACILITY LOCATION MODEL WITH FIXED CAPACITIES FOR RECYCLING FACILITIES' LOCATIONS - A CASE STUDY IN SEREMBAN, MALAYSIA

MUHAMMAD ZULHAZWAN BIN ROSNI

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CONFIRMATION BY PANEL OF EXAMINERS

I certify that a Panel of Examiners has met on 21 October 2025 to conduct the final examination of Muhammad Zulhazwan Bin Rosni on his Masters of Science thesis entitled "A Facility Location Model with Fixed Capacities for Recycling Facilities' Locations – A Case Study in Seremban, Malaysia" in accordance with Universiti Teknologi MARA Act 1976 (Akta 173). The Panel of Examiners recommends that the student be awarded the relevant degree. The Panel of Examiners was as follows:

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ABSTRACT

Malaysia encounters considerable challenges in waste management and recycling, driven by population growth, urbanization, and evolving lifestyles. Despite the government's goal of a 40% recycling rate by 2025, over 80% of recyclable waste continues to be disposed of in landfills. This is largely due to low public participation in source separation activities, especially among households, which is a critical step in promoting recycling practices. A key obstacle to enhance recycling rates is the insufficient accessibility and availability of recycling infrastructure, including collection points and appropriately sized containers. To address this, optimal location of recycling facilities is critical to encourage public participation and efficiently managing recyclable waste. Hence, this research focuses on a variant of the Facility Location Problem (FLP) model, utilizing the set covering problem to guarantee that areas generating recyclable waste have access to at least one operational facility within an acceptable travel time. Moreover, the uncapacitated model of Maximal Expected Coverage Location Problem is unrealistic for real-world applications, as it fails to account for varying container sizes and demand constraints. Therefore, the proposed model of Maximal Covering Location Problem incorporates capacity considerations to ensure more practical and effective coverage in real-life scenarios. The proposed methodology was validated using both randomly generated datasets and small-scale real-world data to demonstrate its applicability and practical relevance. The model was then applied to Seremban, which comprises approximately 315 household areas with a population of 422,710 in 2024. These figures indicate a growing volume of recyclable waste, highlighting the need for a strategic approach to locating recycling facilities with optimal capacity level to support a better waste management system of the city. Using the proposed methodology, nine recycling facility locations were identified to serve selected areas in Seremban. Of these, six are the existing facility locations, while the remaining three are newly proposed locations. Scenario testing was also carried out by imposing limitations on the authorities' capacity to serve users. The analysis indicates that operating a single facility, which serves only 10% of total demand, results in significantly lower coverage efficiency compared to operating eight facilities, which serve 90% of demand. The findings emphasize that the commitment of both users and authorities plays a vital role in the success of recycling efforts. This reflects the strength of proposed methodology in accounting for stakeholder perspectives and operational capacities in the process of identifying optimal locations for recycling facilities. To conclude, the proposed mathematical model for the FLP shows significant potential to improve the current Malaysia's recycling system. By optimizing facility locations, it enhances service coverage, reduces infrastructure costs, and supports user engagement while accounting for authority constraints. For future research, it is recommended to apply the proposed model to other urban settings across Malaysia to assess its scalability and adaptability. Further research could also explore dynamic demand patterns, integration with smart waste technologies, and multi-objective optimization to enhance decision-making in sustainable waste management.

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Lastly, I dedicate this thesis to the cherished memory of my loving grandparents, my beloved father and mother, who instilled in me the importance of education and perseverance. Their unswerving vision and determination have been a beacon of inspiration throughout this pursuit. I offer this achievement as a tribute to their love, sacrifices, and enduring legacy. Alhamdulillah, all praises to Allah.

In conclusion, I am keenly aware that this academic milestone would not have been attainable without the permission and benevolence of Allah SWT, the Almighty, and the continuous support of my supervisors, family and colleagues. I am profoundly thankful for these blessings and resolve to utilize the knowledge and skills acquired to serve the society diligently.

With utmost gratitude and humility,

Muhammad Zulhazwan bin Rosni

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF SYMBOLS

Symbols	
I	Set of demand locations $\{1, 2, 3, \dots, n\}$
J	Set of potential recycling bin's locations $\{1, 2, 3, \dots, m\}$
D	Maximum travel distance between demand i and recycling bin location j
W	Maximum recycling bin's locations in the selected area of study
d_i	Number of demands at location i
k	Number of recycling bin's locations located at each location j which is at most K
$dist_{ij}$	Distance between demand i and recycling bin's location j
a_{ij}	If the travel distance is less than or equal to D units, the binary variable a_{ij} indicates it as 1, else as 0.
q_{ik}	Busyness level of having k bins at each recycling bin's location j
x_j	If a recycling bin is at j, the binary variable x_j is equal to 1, else it is 0.
y_{ik}	The binary variable y_{ik} is 1 if k bins cover the demand at location i, and 0 otherwise.
σ	The maximum number of activated recycling facilities limited to σ locations
q_j	Capacity at facility recycling location located at each location j
T	The upper limit for travel times between demand i and recycling facility location j
$trav_{ij}$	The travel times between demand i and recycling facility location j
s_{ij}	The binary variable s_{ij} equals to 1 indicates that the travel distance (in minutes) is less than or equal to T, and 0, otherwise

y_t	The binary variable y_t equals to 1 if the demand at location i is served by j facilities,and 0, otherwise.
$\sum$	Signifies summation and serves as a concise representation of the sum of terms that adhere to a particular pattern.

LIST OF ABBREVIATIONS

Abbreviations	
FLP	Facility Location Problem
CP	Covering Problem
LSCM	Location Set Covering Model
MCLP	Maximum Coverage Location Problem
MEXCLP	Maximum Expected Coverage Location Problem
MILP	Mixed Integer Linear Programming
ILP	Integer Linear Programming
RTFLP	Ring Tree Facility Location Problem
LP	Linear Programming
FRLM	Flow Refuelling Location Model
ALNS	Adaptive Large Neighbourhood Search Algorithm
GP	Goal Programming
BLP	Binary Programming
TAZ_OPT	Time-based Ambulance Zoning Optimization
EMS	Emergency Medical Service
MCDM	Multi-Criteria Decision-Making
GIS	Geographic Information System
SC	Set Covering
MC	Maximal Covering

RALMTD	Rest-Area Location Model for Time-Driven Demands
CB-VRPPA	Collaborative Bidirectional Multi-Period Vehicle Routing Difficulties Under Profit-Sharing Agreements
BT	Bulk Transportation
LoRP	Location-or-Routing Problem
MO	Multi-objective Optimization
MSW	Municipal Solid Waste
MSWM	Municipal Solid Waste Management
HWM	Hazardous Waste Management
ISWM	Integrated Solid Waste Management
PV	Photovoltaic
MINLP	Mixed Integer Non-Linear Programming
SWM	Solid Waste Management
CPLEX	Complex Linear Programming Expert
MBS	Majlis Bandaraya Seremban
MOFLP	Multi-Objective Facility Location Problem
JPSPN	National Solid Waste Management Department

CHAPTER 1
INTRODUCTION

1.1 Research Background

The world is increasingly facing challenges in health, social, economic, and environmental areas (Marchesini, 2025), which have a direct impact on the performance of waste management and recycling systems. These issues are apparent in many countries, including Malaysia. Malaysia encounters numerous obstacles in the fields of waste management and recycling. For example, household waste (65%), commercial and institutional refuse (28%), and industrial waste (7%) are all components of municipal solid waste (MSW) (Shakil et al., 2023). In 2021, the per capita generation rate was 1.17 kilograms/capita/day, and an estimated 14 million tonnes of MSW were produced (Ng et al., 2023). The increase in solid waste in Malaysia is attributed to population growth, lifestyle changes, and the rapid urbanization and development process (International Trade Administration, 2024). Nevertheless, excessive landfilling, inadequate infrastructure, and methane emissions continue to pose environmental hazards. The government's objective is to ensure that waste management enhancements align with climate action objectives, which include achieving a 40% recycling rate by 2025 (New Straits Times, 2022). In order to resolve existing obstacles, strategic enhancements such as optimizing the locations of recycling facilities can be implemented.

Facility location studies are not a new concept. They have been conducted in both the public and private sectors for decades. The facility location problem (FLP) is a well-known optimization problem that involves determining the optimal sites for facilities to meet the demand of identified locations, at the minimum possible cost (Markarian et al., 2022). In other words, it concerns the optimal placement of facilities, achieved by minimizing the associated costs and/or maximizing the desirability gained through the selected locations. In general, facility location challenges involve placing facilities on a network to meet a set of demands while adhering to specific constraints to ensure the facilities' availability and accessibility (Marín et al., 2010; Štádlerová et al., 2024). Notably, choosing the most suitable location for a facility can enhance service quality and reduce risk. However, making these decisions is not a simple task, especially considering their long-term and strategic implications, as well as the difficulty of changing them after implementation (Kidd et al., 2024). Overall, before deciding on the location, it is crucial to consider some related issues. In both the public and private sectors, facility location is a critical decision-making issue. In the public sector, this involves determining suitable locations for services such as fire stations, ambulances, and other emergency facilities. In the private sector, it includes selecting sites for retail stores, distribution centres, warehouses, and other operational facilities. The FLP can be addressed through various methodologies, one of which involves formulating a mathematical model to determine the optimal placement of facilities based on specific objectives and constraints.

The set covering problem is one of the most well-established formulations of the FLP. One of its notable variations is the maximal covering model. This model aims to determine a set of facility locations that can cover the maximum number of demand points within a specified travel distance or time, typically measured in physical units (e.g., kilometres or miles) or temporal units (e.g., minutes or seconds). The formulation can be tailored using various constraints and parameters to suit the specific requirements of the case study being addressed. In terms of sustainable waste management, the FLP model with consideration of coverage would guarantee that the maximum amount of waste generation areas are served within a predetermined distance of recycling facilities, thereby optimizing efficiency and coverage (Tirkolaee et al., 2020). Through the set covering problem approach, recycling facilities are strategically located to ensure they are within a specified distance from all waste generation areas. By strategically positioning recycling facilities, especially within public accessibility, recycling objectives can be achieved, promote environmental sustainability, and improve public health and safety (Adeleke & Olukanni, 2020).

Overall, there is room for improvement in the current recycling system, particularly in Malaysia, by adopting scientific approaches. Therefore, this research proposes a mathematical formulation based on the set covering problem of the FLP to determine the optimal locations for recycling facilities, along with suitable capacity levels for each location. The main contributions of this research lie in the development of a mathematical formulation for determining recycling facility locations and its application to a real-world case study. The proposed method also considers the roles of key stakeholders in the recycling system, namely, users and authorities. It provides a clearer understanding of the impact of authority decisions, while variations in recycling coverage percentages help reflect the level of user participation in recycling activities.

1.2 Motivation for This Research

Malaysia's recycling rate has demonstrated a steady upward trend over recent years, increasing from 28.1% in 2019 (Anon, 2020) to 31.52% in 2021, 33.17% in 2022, 35.38% in 2023 (Zainal, 2023), and 37.9% in 2024 (SWCorp, 2024). By 2025, recycling rates are anticipated to reach 40% (Bernama, 2020). The country continues to face challenges in achieving its national recycling targets, despite various efforts by the authorities to improve waste management infrastructure and campaigns such as the Drive Thru Recycling Centre (DRTC) and "Recycling to Cash." While these initiatives show promise, a lack of comprehensive programs remains, which effectively attracts and sustains active public participation in recycling efforts. Additionally, factors such as population density, types of waste generated, and limited accessibility to recycling facilities pose significant barriers to public participation in recycling activities. In line with the Comprehensive Action Plan for Solid Waste Management in Malaysia (2015-2020), additional recycling facilities in public locations are necessary to promote separation-at-source activity (Moh and Abd Manaf, 2017). A more efficient and effective approach is needed to support national sustainability efforts and to align with global frameworks such as the Sustainable Development Goals (SDGs). Specifically, this research supports Goal 11 (Sustainable Cities and Communities) and Goal 12 (Responsible Consumption and Production) (Ram et al., 2025). This research is motivated by the need to strengthen such initiatives through improved facility planning. Specifically, it addresses gaps in existing approaches to locate recycling infrastructure by proposing a modified set covering model of FLP that identifies optimal facility locations while accounting for user accessibility and capacity constraints.

In Seremban, for example, interest in recycling has shown positive growth with the launch of the second KITARecycle drive-through facility. This initiative, a collaboration between SWM Environment and OSK Property Holdings, aims to educate residents about the benefits of recycling and the significance of protecting the environment (The Star, 2024). It encourages public participation by providing dedicated collection cages where recyclable materials can be deposited. Seremban is increasingly regarded as a growing urban centre that complements Kuala Lumpur and Putrajaya, attracting new residents and businesses due to its strategic location and ongoing urban development (Ismail, 2017). As the city continues to expand, the demand for a more effective and sustainable waste management system becomes increasingly important. However, studies specifically focusing on Seremban's recycling infrastructure and planning strategies remain limited. Thus, to address this gap, the research is motivated by the need to develop and implement a modified facility location model in the context of Seremban. The implementation of this model in Seremban serves both as a practical application and to validate and verify its effectiveness in a real-world setting.

1.3 Problem Statement

Despite continuous national efforts to promote recycling, more than 80% of recyclable waste in Malaysia is still disposed of in landfills due to low public participation, particularly among households (Khamaruddin et al., 2019; Michel Devadoss et al., 2021; Moh & Abd Manaf, 2014). In 2018 alone, recyclable waste valued at approximately RM476 million was discarded in landfills (Tarmiji, 2020), highlighting inefficiencies in the country's waste management system. The current challenge lies in determining the optimal locations for recycling facilities that can accommodate the expected volume of recyclable waste while also encouraging active public participation. Optimal locations of recycling facilities, with adequate capacity to oversee the expected waste volume, can significantly enhance recycling engagement among communities (Teo, 2016).

However, existing capacity-constrained covering models, although successful in other domains, have seen limited application in the recycling context. Since recycling relies heavily on voluntary participation, poorly located facilities may discourage public engagement in waste separation practices. Seremban, a rapidly urbanizing city with nearly one million residents and 241,843 households across 628 residential areas (Majlis Bandaraya Seremban, 2025), is facing an increase in recyclable waste generation as urban development accelerates. Yet, there remains no comprehensive, model-based approach to determine optimal facility locations that considers demand proximity, accessibility, space availability, and capacity constraints. Therefore, this study addresses the lack of a systematic and data-driven framework to guide the strategic placement and allocation of recycling facilities for a more efficient, sustainable, and participatory recycling system.

The keys to sustainable MSWM are based on the local authority and users' perspectives, especially for the success of recycling activities. The local authority provides facilities for users to deposit recyclable waste, and generally, they focus on minimizing the operational cost for the system. Some of the provided facilities may be restricted to the public due to cheaper rental space or a larger area. In contrast, users want the recycling facility to be located within the household areas or within an acceptable travel time (Choon, Tan, and Chong, 2017). The conflicting perspectives and needs of both stakeholders are often overlooked in decision-making, particularly when determining the location of recycling facilities and distributing optimal bins to accommodate the expected volume of recyclable waste. For example, local authorities may prioritize cost and logistics, while community members emphasize accessibility and ease of use.

1.4 Research Question

The questions of this research are:

a) What are the problem factors of the recycling facility locations based on the existing model objective function, constraints, parameters, and decision variables?
b) How can a mathematical model be adapted to find the optimal locations for recycling facilities using the FLP approach?
c) How can a modified mathematical model be used to determine the optimal amount of recyclable waste collected?
d) What are the optimal strategies for locating and allocating recycling facilities that could benefit users and local authorities?

1.5 Research Objectives

The objectives of this research are:

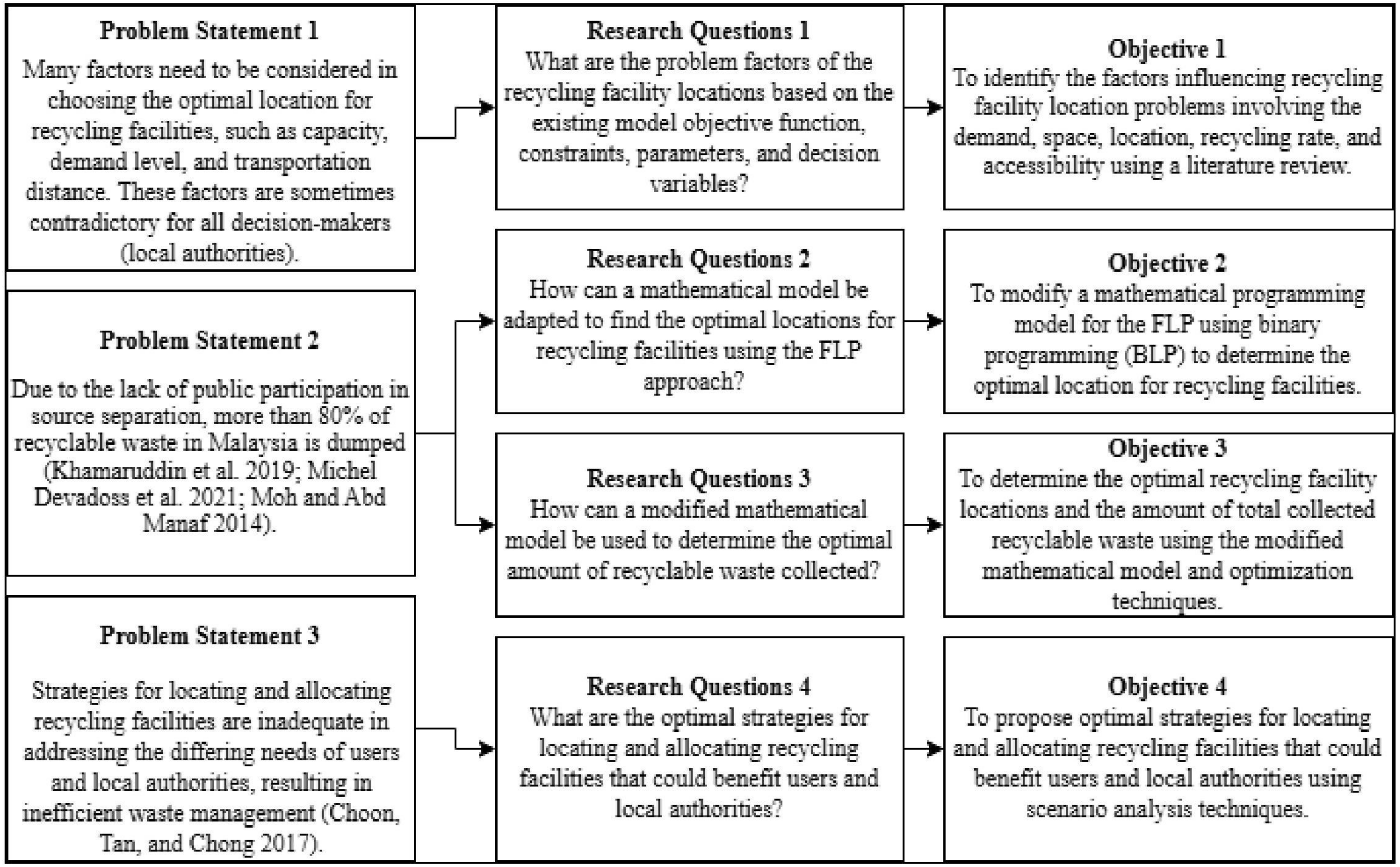
a) To identify the factors influencing recycling facility location problems involving the demand, space, location, recycling rate, and accessibility using a literature review.
b) To modify a mathematical programming model for the FLP using binary programming (BLP) to determine the optimal location for recycling facilities.
c) To determine the optimal recycling facility locations and the amount of total

collected recyclable waste using the modified mathematical model and optimization techniques.

d) To propose optimal strategies for locating and allocating recycling facilities that could benefit users and local authorities using scenario analysis techniques.

1.6 Summary of Research Work

The following figure maps the entire research work.



Problem Statement 1

Many factors need to be considered in choosing the optimal location for recycling facilities, such as capacity, demand level, and transportation distance. These factors are sometimes contradictory for all decision-makers (local authorities).

Problem Statement 2

Due to the lack of public participation in source separation, more than 80% of recyclable waste in Malaysia is dumped (Khamaruddin et al. 2019; Michel Devadoss et al. 2021; Moh and Abd Manaf 2014).

Problem Statement 3

Strategies for locating and allocating recycling facilities are inadequate in addressing the differing needs of users and local authorities, resulting in inefficient waste management (Choon, Tan, and Chong 2017).

Research Questions 1

What are the problem factors of the recycling facility locations based on the existing model objective function, constraints, parameters, and decision variables?

Research Questions 2

How can a mathematical model be adapted to find the optimal locations for recycling facilities using the FLP approach?

Research Questions 3

How can a modified mathematical model be used to determine the optimal amount of recyclable waste collected?

Research Questions 4

What are the optimal strategies for locating and allocating recycling facilities that could benefit users and local authorities?

Objective 1

To identify the factors influencing recycling facility location problems involving the demand, space, location, recycling rate, and accessibility using a literature review.

Objective 2

To modify a mathematical programming model for the FLP using binary programming (BLP) to determine the optimal location for recycling facilities.

Objective 3

To determine the optimal recycling facility locations and the amount of total collected recyclable waste using the modified mathematical model and optimization techniques.

Objective 4

To propose optimal strategies for locating and allocating recycling facilities that could benefit users and local authorities using scenario analysis techniques.

Figure 1.1 Summary of the Research Work

1.7 Significant of the Research

This research proposes a modified model for the FLP, considering demand, space, location, recycling rate, and accessibility. The maximal covering model for the FLP is used as the main reference, where several modifications, including capacity level, were integrated into the proposed model. This would enrich the variant of the existing mathematical model for solving the recycling facility location problem.

The modified model to identify optimal recycling facility locations and their performance has been verified through a validation experiment. The contributions of this research include modifying the maximal covering location model to enhance the allocation of recycling facilities. This model enables the placement of multiple facilities in strategic locations, ensuring adequate service capacity and a high volume of recyclables. The real-world constraints, such as demand levels and spatial limitations, are expected to improve service coverage and efficiency in waste management through the proposed model. These findings represent a significant advancement in solving facility location problems using fixed capacity constraints.

The modified model adopted in this research identifies optimal locations for recycling facilities and is validated through experimental testing in the selected study area, which is Seremban. Notably, the implementation would demonstrate that the proposed model can be applied in any area of study, particularly in urban network settings.

This approach contributes in three key ways. First, it enables users to identify improved locations for recycling facilities, enhancing accessibility and efficiency in waste services. Second, it allows authorities to focus on better urban planning and more effective resource allocation. Third, it provides researchers with valuable insights into optimizing locations for sustainable waste management.

1.8 Scope and Limitation

This study focuses on optimizing the location and allocation of recycling facilities within an urban context, specifically targeting selected residential zones in Seremban, Negeri Sembilan. The research applies the FLP framework using a BLP approach to determine the most suitable facility sites, considering capacity, distance, and accessibility constraints. The model builds upon the set covering variant proposed by Rosni et al. (2022) and extends it by incorporating additional factors such as population density, spatial availability, and estimated recycling rates. This, in turn, provides a more realistic representation of urban recycling conditions. However, the study is geographically limited to Seremban, which may constrain the generalizability of the findings to other cities with differing demographic, infrastructural, or policy characteristics.

The research is further limited to residential areas, excluding commercial and industrial sectors that also contribute significantly to the generation of recyclable waste. The estimation of recycling demand relies primarily on population-based assumptions, which may not fully account for behavioral or socioeconomic differences in recycling practices among residents. Additionally, the model assumes fixed service capacities for recycling facilities, which may not reflect operational flexibility in real-world applications. Data for model development and validation are derived from secondary sources, including demographic records, recycling statistics, and spatial data provided by the MBS and relevant agencies. Meanwhile, the distance data are gathered using Google Maps with specific setting controls to ensure consistency and accuracy. The study also employs a single optimization model and solver (CPLEX), thereby limiting its comparative evaluation against other modeling approaches or solution techniques.

1.9 Definition of Terms

The following terms and their definitions are used to expand on the subject matter of this research:

Table 1.1
Definition of Terms

No	Terms	Definition
1	Recycling	The transformation of waste into usable material.
2	Household Waste	Waste generated in the residential environment consists of household daily disposal of any material, and is also known as domestic waste.
3	Municipal Solid Waste (MSW)	Waste is generated by urban areas, including residential, commercial, and institutional sources.
4	Facility Location Problem (FLPs)	A problem that identifies the optimal location based on geography, facility costs, and transit distances identifies the optimal location for manufacturing or a warehouse.
5	Covering Problem (CP)	A problem that involves minimisation and linear programming, packing problems are covering problems.
6	Binary Linear Programming (BLP)	To assess the feasibility of offering optional courses across various time slots. The model is then solved using a genetic algorithm, resulting in a feasible allocation of optional courses for each time slot.
7	Recycling Facility Location Model	The use of mathematical programming models to address the challenge of where to locate recycling facilities.

1.10 Organisation of Research

This research is organized into five main chapters: Introduction, Literature Review, Research Methodology, Results and Discussion, and Conclusions and Recommendations.

Chapter 1 introduces the research by outlining its background, problem statement, research questions, objectives, significance of the research, scope, limitations, and the overall structure of the thesis.

Chapter 2 presents a review of the existing literature, focusing on previous work related to the FLP. It includes a discussion on the application of covering models in similar contexts and assesses whether parameter estimation has been used in models for locating recycling facilities. The chapter concludes by examining a selected mathematical model relevant to the research.

Chapter 3 details the research methodology, including the development and analysis of the proposed model. It discusses the modifications applied to the model, the experimental procedures, and how the model is implemented in a real-world case study. Data collection methods and scenario testing are also addressed.

Chapter 4 presents the results of model validation and its real-world application. It explores whether the model performs and discusses the potential for converting between different types of FLP to address practical challenges. The findings are interpreted in line with the research objectives.

Chapter 5 concludes the research by summarizing the objective and contributions. It also offers recommendations for future research, based on the outcomes and limitations identified throughout the study.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

This chapter presents an overview of existing facility location problem (FLP) models. The structure of the literature review is illustrated in Figure 2.1, which uses three colours: orange, yellow, and blue. The orange section refers to general studies on the FLP, focusing on covering-based mathematical models, as discussed in Section 2.2. The yellow section represents studies that apply covering models to the second scope of this research, explained in Section 2.3. The blue section focuses on past research related to recycling facility location problems, which is covered in Section 2.4. Section 2.5 then highlights several recycling facility location models, with emphasis on their objective functions, decision variables, and parameters. Finally, the chapter identifies research gaps between this study and previous work, also discussed in Section 2.5.

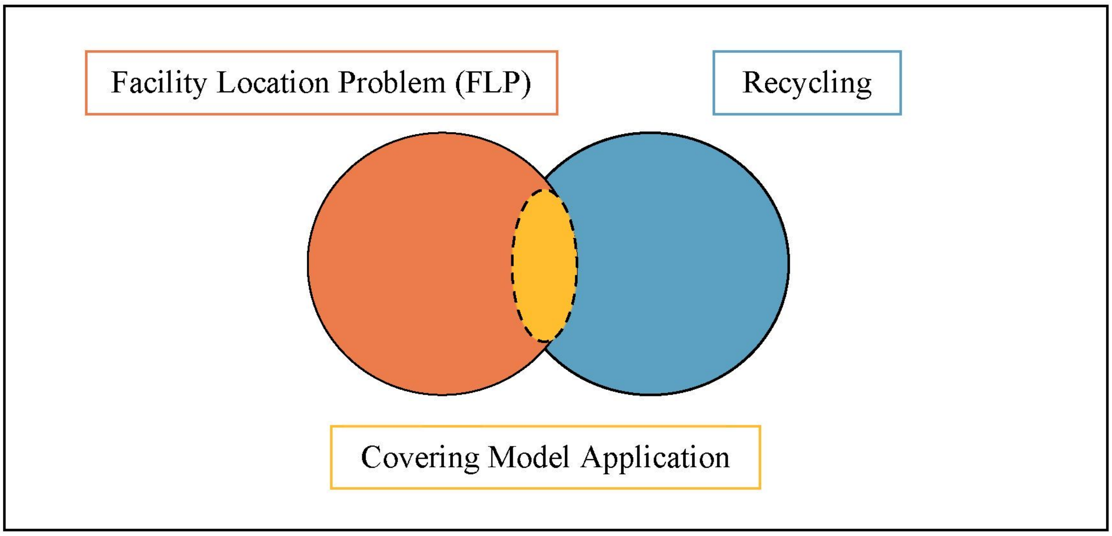


Figure 2.1 The Scope of Literature Review

2.2 Previous Facility Location Problem (FLPs)

The FLP theoretical model can be categorized into three classic location models: the p-median problem, the covering problem, and the p-centre problem. The p-median problem focuses on determining the optimal locations for a fixed number of facilities to serve a set of demand points, aiming to minimise the total distance or cost of service. This model is widely applied in logistics, transportation, and public service planning. The p-centre problem, on the other hand, seeks to locate p facilities such that each demand point is served by its nearest facility, to minimize the maximum distance any demand point must travel (Dantrakul et al., 2014). Lastly, the covering problem is commonly used in site selection and network location scenarios, particularly for emergency services such as firefighting units, police stations, hospitals, and disaster response centres. It ensures that all demand points are within a specified coverage radius of at least one facility, prioritizing accessibility and rapid response (Ma et al., 2019).

Among the earliest studies on facility location were those conducted by Kuehn and Hamburger (1976). Their heuristic method is designed for a wider variety of geographical issues. Greedy and exchange heuristics form the foundation of many approximation techniques for solving mathematical programming models, specifically for the FLP. Next, when using a heuristic to determine a final answer, it is essential to establish an upper bound so that the user can be certain that the heuristic solution value is not too far from the ideal weight. These limitations for greedy and exchange heuristics were established by Cornuejols et al. (1984).

Hu et al. (2013) proposed a budget-constrained integer nonlinear programming approach to optimize the location of service facilities, aiming to reduce response times during traffic congestion. The authors explained that the goal is to maximise the demand met within the period specified by the service provider and present an approach that combines greedy and genetic algorithms to address this problem. Their analysis revealed that the system waiting time distribution function was concave with the number of servers. The finding is supported by Mirzapour et al. (2013), who used a similar approach that considers the probabilistic distribution of demand locations and a fixed line barrier in an area. Furthermore, their research aimed to determine the optimum location for two relief rooms and the corresponding allocation, minimising the maximum estimated weighted distance between them and all demand zones. Together, these studies indicate that the mixed-integer nonlinear programming model was adequate for the various problems from previous studies.

Abe et al. (2015) proposed two integer programming models to solve the RTFLP, which focuses on designing layered networks that connect two types of customers to a central depot. The models aim to minimize total costs, including facility location costs and layer-dependent edge costs. Their approach extended concepts from vehicle routing and Steiner tree problems. Results indicated that the non-compact formulation produced tighter dual bounds, making it suitable for telecommunication and transportation network planning. Meanwhile, the research by Xiao et al. (2016) aimed to locate departments with distinct zones inside a given building to reduce total material handling costs. A linear programming (LP) model is created to determine the locations and dimensions of departments with specified sizes within the facility while meeting their maximum aspect ratio requirement and shape constraints.

Lee and Han (2017) focused on planning recharging infrastructure for electric vehicles. The objective is to maximize the amount of traffic that can travel between origin and destination pairs by recharging at built-in facilities. Their models include a Benders-and-Price algorithm, which combines Bender's decomposition and column generation to solve the proposed formulation, as well as a Flow Refueling Location Model (FRLM) adapted to a mixed-integer nonlinear programming framework. Furthermore, Shunjing et al. (2018) presented park-and-ride as a primary traffic demand management strategy that can effectively alleviate urban traffic congestion and parking issues. A commuter corridor system incorporating park-and-ride facilities introduces challenges in determining optimal facility locations and parking fees. To address these challenges, the authors developed bi-level programming models and solved them using a branch-and-bound algorithm based on sensitivity analysis.

The facility location problem is a suitable model for numerous practical applications across diverse domains. Congestion-causing facilities, such as shopping malls and stadiums, can be identified as contributing to this problem. Therefore, Zabudsky and Lisina (2018) proposed a mathematical model using nonlinear programming to address the problem. The results of computational experiments investigating the maximin problem of placing a single facility on a flat network with a transport cost constraint are presented. Moreover, Suzuki et al. (2020) applied the cutting plane approach to a facility location problem to demonstrate its efficiency. Their model incorporated probabilistic constraints that must be satisfied at a specified level of probability and account for uncertainty in the parameters involved. Subsequently, the authors reformulated the problem as a 0-1 mixed-integer programming model under specific conditions. The cutting plane method is then applied, utilizing valid inequalities to define the feasible region.

Lin and Tian (2021) examined exact solution techniques for a generalized competitive facility location problem, focusing on businesses with sufficient resources to launch products to the public. The objective of their research is to maximize profit while accounting for both revenue and fixed costs. Based on Luce's choice axiom, when customers are presented with a set of open facilities, they distribute their purchasing power among those facilities and an outside option. Therefore, the authors proposed a branch-and-cut method based on an extended Benders decomposition scheme as their key contribution (B&C-Benders). Bayraktar et al. (2022) developed a multi-period location problem involving movable facilities and demand distributed across a network. The core challenge is determining facility locations in each period to minimize overall setup and travel costs while meeting service demand. Their research proposed a mixed-integer linear programming (MILP) formulation and introduced an adaptive large neighbourhood search (ALNS) algorithm to address large-scale instances.

Zhang et al. (2023) focused on hazardous waste recycling infrastructure in China, developing a bi-level programming model to minimize total transportation and operational costs under government regulation. This study incorporated capacity integration to reflect realistic operational limits. Singh et al. (2024) examined municipal recycling center locations in India, using a GIS-integrated FLP model to minimize collection costs and improve spatial accessibility. Their model accounted for facility capacity and urban population density. Alharbi (2025) reviewed the use of MOEAs in waste management, focusing on facility location and allocation. The research aimed to minimize environmental impact, boost energy recovery, and improve operational efficiency, with applications in routing, WTE systems, and facility siting across cities like Braga, Lisbon, Uppsala, and Cyprus.

The summary of the section can be observed in Table 2.1. In this research, the concept of covering problems is adapted to address the recycling facility location problem. As a well-established approach, the covering problem has been widely used in various mathematical models. Due to its broad applicability across different fields, this concept has gained significant attention. Therefore, the following section presents a review of previous studies related to facility location problems based on covering models.

Table 2.1
Summary of Previous Facility Location Problem (FLPs)

Authors (Year)	Case study area	Objective function	Capacity integrates	Methodology	Application field
Abe et al. (2015)	Facility location variant	To minimize overall costs, which include layer-dependent edge costs and facility location costs.	/	Ring Tree Facility Location Problem (RTFLP)	Telecommunication and transportation networks.
Xiao et al. (2016)	Covering location model	To minimize the total cost or maximum cost associated with locating facilities.	/	Mixed Integer Linear Programming (MILP) model	Real-world scenarios, such as locating schools, hospitals, warehouses, libraries, and other facilities.
Lee and Han (2017)	Real-life Texas highway network	To maximize the flow of EVs traveling between origin and destination pairs.	/	Flow refueling location model (FRLM)	Refueling stations for electric vehicles (EVs)
Shunjing et al. (2018)	Park and ride facilities	To optimize the location and parking fees for park-and-ride facilities.	-	Bi-level programming models Branch and bound algorithm	Traffic Demand Management (TDM)
Zabudsky and Lisina (2018)	Undesirable facility	To maximize the weighted distance to all nodes in the network.	-	Nonlinear programming model	Various fields, including logistics, urban planning, and supply chain management.
Suzuki et al. (2020)	MSW management, Malaysia.	To minimize GHG emissions associated with MSW management.	/	Solid-Waste-Management Greenhouse-Gas (SWM-GHG)	Environmental policy and waste management
Lin and Tian (2021)	Company's plan of introducing a service	To maximize profit while considering both revenue and fixed	-	Branch-and-cut algorithm	Competitive facility location problems

Authors (Year)	Case study area	Objective function	Capacity integrates	Methodology	Application field
		costs			
Bayraktar et al. (2022)	Humanitarian organizations aiding refugee groups en route	To minimize the total setup and travel costs of mobile facilities	-	Mixed Integer Linear Programming (MILP) model	Locating mobile facilities
Zhang et al. (2023)	Hazardous waste recycling infrastructure	To minimize total transportation and operational costs under regulatory constraints	/	Bi-level programming	Hazardous waste recycling facility planning
Singh et al. (2024)	Locations of municipal recycling centers	To minimize collection costs and improve spatial accessibility for urban populations	/	GIS-integrated FLP	Municipal solid waste recycling
Alharbi (2025)	Facility location and allocation	To minimize environmental impact, boost energy recovery, and enhance operational efficiency	-	Multi-Objective Evolutionary Algorithms (MOEAs)	Waste collection routing, waste-to-energy systems, facility location, and allocation

2.3 Covering Models Applications

The traditional covering approach is widely used in facility location models to assess user accessibility to potential facility sites. Considerable attention has been given to the concept of coverage, which is commonly represented by a coverage gap or a defined service radius. One of the earliest and most well-known models is the Location Set Covering Model (LSCM). This model aims to determine the optimal facility locations that can meet all demand points within a specified time or distance, while minimising the number of facilities required (Jia et al., 2007). Later studies examined the effectiveness of the Maximal Covering Location Problem (MCLP) in determining facility locations by maximising demand for a fixed number of facilities (Youshanlo & Sahraeian, 2015). Daskin (1983) introduced the Maximum Expected Covering Location Problem (MEXCLP), an extension to MCLP that considers the probability of a server (facility) being busy when maximising demand covered, with the likelihood determined using a heuristic procedure.

Research on ambulance location with a covering problem was conducted by Shuib and Zaharudin (2011) determined the satellite locations and allocations of ambulances. This research uses the LR-MEXCLP model and the goal programming (GP) model as references. The model, after modification from the reference model, is called TAZ_OPT. The objective function is to identify strategic satellite locations for emergency medical service (EMS) ambulances and determine the optimal number of ambulances for each location. A similar approach was proposed by Zaharudin et al. (2012), who modified the MEXCLP model to locate an appropriate place for ambulances, particularly for identifying a suitable location for mobile ambulances in Shah Alam, Selangor, Malaysia. The objective function of the model is to maximise the sum of demand and coverage reliability. Jagtenberg et al. (2015) also utilised MEXCLP to solve scalable real-time algorithms for dynamic ambulance redeployment, aiming to reduce predicted late arrivals. Meanwhile, Nilsang et al. (2018) focused on a social media analysis-based coverage model for an ambulance reallocation system using the MEXCLP model.

Deng et al. (2021), Zhao and Ke (2019), and Sitepu et al. (2019) focused their research on EMS problems. Deng et al. (2021) employed a GIS to determine the shortest distance between demand and EMS facilities. The authors analysed the performance of the current EMS facilities provided by the local government in Chengdu, China, using the suggested covering model. The bi-level programming model was established by Zhao and Ke (2019), where the regulator in the upper level minimises the total risk to decide on the locations and maintenance capacities of emergency facilities in City Daojiao, China. Sitepu et al. (2019) analysed the current location of the emergency unit of a health facility using LSCM. They then proposed new units with patient assignments using MCLP to determine the optimal method for relocating post offices in Palembang, Indonesia. Similarly, the covering problem approach is also applied to disaster and emergency management to locate emergency management facilities optimally in the pre-event phase. Doungpan et al. (2018) proposed a maximal covering, p-median, and p-centre model to identify the most effective model in a real-world scenario in Chiang Rai, Thailand, where the models' objective functions aim to maximise demand point coverage under distance constraints.

Grot et al. (2022) proposed a covering model designed to allocate limited resources within emergency medical service (EMS) networks. Their mathematical approach involves selecting facility sites based on capacity constraints, with models specifically developed for this purpose. The research focuses on maximizing the expected number of emergency calls reached within a predefined time threshold in Germany. In particular, the MEXCLP model seeks to maximize the fraction of demand covered within a specified distance, while accounting for average server unavailability. Meanwhile, Van den Berg and Aardal (2015) proposed a time-dependent probabilistic location model for EMS vehicles. The author considered time-dependent travel times, demand, and ambulance availability. The MEXCLP model for expected coverage throughout the day aims to simultaneously minimize the number of opened facilities and the frequency of ambulance repositioning within Amsterdam, the Netherlands.

The application of the covering model in resolving healthcare location is well-known. Khodaparasti et al. (2018) proposed a multi-period probabilistic location-allocation model for evaluating the criteria and sub-criteria established by three experts working on the analysis. It offered management insights into the current status of nursing care facilities and the possibilities for enhancing recent performance. Set covering was utilised in Bangkok, Thailand. Hassan et al. (2021) introduced a hybrid modelling approach that combines the maximal covering and p-median models to optimize emergency medical service (EMS) facility placement in Upper Egypt. The p-median component aims to minimize the demand-weighted total (or mean) travel distance. At the same time, the maximal covering aspect seeks to maximize the number of patients served within a predefined distance threshold using established field hospitals.

Kakimoto and Shimakawa (2022) proposed a set covering problem for non-emergency scenarios. The proposed model is the rest-area location model for time-driven demands (RALMTD), which determines the location of facilities, vehicle crowding at the facilities, and time-dependent locations of vehicles. The authors aimed to increase the operational performance of a road network in Tokyo, Japan. Furthermore, Maneengam and Udomsakdigool (2020) addressed covering problems in collaborative bidirectional multi-period vehicle routing under profit-sharing agreements (CB-VRPPA) within bulk transportation (BT) networks involving multiple shippers, carriers, and a centralized control tower. They utilized a set covering model to screen routing techniques, eliminate unattractive path options in the initial stage, and reduce the overall problem size in the context of Thailand.

Some past research offered a covering model for other types of facilities. Kheybari et al. (2020) proposed a linear set covering model by applying information from a multi-criteria decision-making (MCDM) model to select suitable sites for a number of data centres. The objective function is to maximise the normalised performance function, which assigns an appropriate performance score. This indicates how much a province deserves to be a centre without considering the utility or distance of other regions. Using a set covering model to measure the utility of prospective sites and the MCDM model as a tool for selecting suitable locations for a set of data centres, the model’s results highlight the optimal location of data centres.

Yu and Solvang (2018) offered two classical location models for relocating post offices in Narvik, Norway. These include the p-median problem and the maximal coverage problem approach. Arslan (2021) identified location optimisation applications for retail stores, supermarkets, shopping malls, schools, urban delivery centres, and medical testing centres. The author presented a set covering model with an exponential number of variables for solving a location-or-routing problem (LRP) in the transportation community, where facility location and vehicle routing are closely related. Hao and Zhang (2019) applied a set covering model to optimize the location and distribution of electric vehicle (EV) charging stations. They incorporated Korea’s power transmission and traffic distribution networks to refine the selection of potential charging sites. In addition, their research estimated the optimal number of emergency care physicians needed in the study area. This dual focus highlights the model’s flexibility in addressing both healthcare and transportation infrastructure, with the EV charging station component specifically benefiting from spatial optimization based on accessibility and network efficiency.

The location of recycling facilities was also determined using MEXCLP, proposed by Jamiron et al. (2021) and Rosni et al. (2022), which considers circular economy strategies when determining the location of recycling bins in Malaysia. Johor Bharu and Seremban were the focus of studies by Jamiron et al. (2021) and Rosni et al. (2022), respectively. The MEXCLP model's goals and objectives are similar to those of the earlier research and use a set covering model to address the location of recycling facilities. Zaharudin et al. (2021) and Ye et al. (2011) focused on the location application. Zaharudin et al. (2021) proposed a conceptual covering model to ensure maximum demand can be satisfied within predetermined distances or periods. In addition, Ye et al. (2011) proposed two models for their research: first, LSCP, and second, *p*-median. This model aims to reduce the number of recycling centres, and Taiwan was selected as a case study. In light of the recycling facility location problem, the search is restricted to other types of facility location models that address similar challenges.

Zaharudin et al. (2023) aimed to develop an MILP model to identify the most suitable locations for recycling facilities. The objective function is designed to minimize the distance that waste must travel to these facilities while simultaneously optimizing household coverage. The methodology is based on the MILP approach, a mathematical technique for solving resource allocation problems. The model ensures a proportional distribution of recyclables by considering various constraints, including facility capacity levels. The field of applicability is urban waste management, with a particular emphasis on the urban area of Nilai in Malaysia. The model's applicability is designed to increase recycling rates by improving public access to recycling facilities.

Villicaña et al. (2024) optimized mobile COVID-19 lab locations in Nuevo Leon, Mexico, to maximize accessibility using weighted coverage measures. They applied a MILP model to support facility location decisions in public health. Yu and Jiao (2025) conducted a study in Xinxiang, China, to minimize transport distance while maximizing coverage, considering capacity constraints using a genetic algorithm in healthcare waste management and facility location planning. Table 2.2 summarizes the existing coverage problems discussed in previous research.

Table 2.2

Summary of Covering Problems in Prior Research

Authors (Year)	**Case study area**	**Objective function**	**Capacity integrates**	**Methodology**	**Application field**
Zhao and Ke (2019)	City Daojiao, China	To minimise the total network risk To minimise the total network cost	/	BI-LEVEL	Emergency facilities
Kheybari et al. (2020)	Iran	To maximise the normalised performance function	/	MCDM	Data centres
Deng et al. (2021)	Chengdu, China	To minimise the number of new network hospitals needed to achieve the policy goal	/	LSCP	Emergency facilities
Hassan et al. (2021)	Upper Egypt	To maximise the number of patients covered by the established field hospitals	/	SC MC P-MEDIAN	Healthcare location model
Jamiron et al. (2021)	Johor Bahru, Malaysia	To maximise the amount of demand covered	/	MEXCLP	Recycle bin location model
Zaharudin et al. (2021)	-	To ensure that maximum demand can be met within predetermined distances or periods	/	MEXCLP	Recycling facilities location model
Rosni et al. (2022)	Seremban, Malaysia	To maximise the amount of demand featured	/	MEXCLP	Recycle bin location model
Grot et al. (2022)	Germany	To maximise demand covered within the defined distance, consider server unavailability	/	MEXCLP	Emergency medical services (EMS) networks
Kakimoto and Shimakawa (2022)	Tokyo, Japan	To minimise the number of facilities to be placed in a road network	/	LSCM	Restore the location model
Zaharudin et al. (2023)	Nilai, Malaysia	To minimize the distance the user must travel to these facilities	/	MCLP	Recycle bin location model
Villicaña et al. (2024)	Nuevo Leon,	To maximize accessibility using weighted coverage	/	MILP	COVID-19 testing, facility location

Authors (Year)	Case study area	Objective function	Capacity integrates	Methodology	Application field
	Mexico	measures			
Yu & Jiao (2025)	Xinxiang, China	To minimize transport distance while maximizing coverage and respecting capacity constraints	/	Genetic Algorithm	Healthcare logistics, waste management, and facility location

2.4 Recycling Facility Location Model

Sgalambro et al. (2025) developed a multi-objective facility location problem (MOFLP) to support the redesign of household waste recycling centres (HWRCs) in Sheffield, UK. Their model aims to minimize operating costs while maximizing user satisfaction, aligning with strategic planning goals and legislative requirements. In contrast, Zaharudin et al. (2024) proposed a set covering problem (SCP) that focuses on minimizing travel distance, maximizing service coverage, and ensuring facility capacity constraints are met. Their work contributed to broader public service planning and waste management applications.

Aghakhani et al. (2023) addressed the critical issue of pharmaceutical waste management by formulating a location-routing problem (LRP) aimed at optimizing the collection and disposal of expired and unused medications. Their model focuses on minimizing transportation costs, construction of collection centers, disposal expenses, and carbon dioxide emissions, thereby promoting both economic efficiency and environmental sustainability. This approach supports the healthcare sector in managing hazardous waste more effectively.

This section focuses on past studies on the recycling facility location problem. Yu and Tong (2021) suggested using a mixed-integer linear programming (MILP) model to find the most suitable photovoltaic (PV) recycling collection sites in the province of Zhejiang. This model is the most comprehensive classification of two scenarios: (i) municipal waste recycling facilities given by the government and (ii) recycling facilities provided by photovoltaic producers, and the model seeks to reduce the overall cost.

Hrabec et al. (2018) employed a multi-objective (MO) and MILP model to determine the most effective waste management strategy. Their approach allowed stakeholders to decide how much funding to allocate toward waste prevention and recycling advertising. Meanwhile, by reducing the overall number of bins at the lowest possible cost, Rathore et al. (2020) proposed an MILP and Geographic Information System (GIS) model. The model aims to determine the optimal number of waste collection bins and identify the most suitable locations for bin allocation in Bilaspur, India. To allocate refuse bins to different collection areas where waste is collected, Bautista and Pereira (2007) proposed a mathematical model and an algorithm to minimise the volume of recyclable goods and the amount of refuse outside bins.

In the Marmara region of Turkey, Utku and Erol (2020) also employed the MILP model to identify the most advantageous and cost-effective hazardous waste treatment, recycling, and disposal facilities near the designated candidate locations. A MILP was proposed by Tirkolaee et al. (2020) to locate municipal solid waste (MSW) in Isfahan, Iran, with a reduction in the total costs of collection, processing, and disposal facilities, as well as reasonable costs for facilities, transportation, and pollution-related costs.

Moreover, similar approaches were used by Asefi et al. (2019). They used a multi-period element to reduce the overall cost of the integrated solid waste management (ISWM) system, including transportation and facility establishment costs. Waste volumes and changes in polluter fees at incineration centres can have a significant impact on the hazardous waste management (HWM) system's overall profitability. Aydemir-Karadag (2018) took these factors into account to maximise the total annual profit of the entire HWM system. Rentizelas et al. (2018) employed an MILP model to evaluate the viability and economic performance of agricultural plastic waste supply networks, along with the potential environmental benefits for farms in Scotland. The model's objective functions aim to maximise the utilization of heat demand at selected locations, such as for district heating or industrial processes. Additionally, the model incorporates annual operating and investment costs, ensuring that the selected solution strikes a balance between environmental benefits and financial feasibility.

To minimize the total investment costs and shorten the typical distance between homes and containers, Tralhão et al. (2010) developed an MILP model, which included multiple objectives that could be solved. To lessen the environmental impact, Vahdani et al. (2012) developed a fuzzy mixed nonlinear model that considers both the imprecise nature of the data and its lack of availability or incompleteness to minimise the cost structure of the obsolete scrap steel recycling network.

To allocate refuse bins to different collection areas where waste is collected, Bautista and Pereira (2007) proposed a mathematical model and an ant algorithm to minimise the volume of recyclable goods and the amount of refuse outside bins. The mathematical model, the objective functions, and their application to real-world issues provide a summary of the literature discussed regarding the location of recycling facilities. Table 2.3 presents a summary of the highlighted mathematical models, including their objective functions, proposed mathematical models, areas of application, and case study areas.

Table 2.3

Summary of Recycling Facility Location Models

Authors (year)	**Objective functions**	**Mathematical model proposed**	**Capacity integrates**	**Application to real-life problem**	**Case study area**
Sgalambro et al. (2025)	To minimize operating costs To maximize user satisfaction	MOFLP	/	HWRC redesign, planning	Sheffield, UK
Zaharudin et al. (2024)	To minimize travel distance while maximizing coverage and satisfying facility capacity	SCP	/	Public service planning, waste management, and facility location	-
Aghakhani et al. (2023)	To minimize transport, construction, disposal costs, and CO_2 emissions	LRP	/	Pharmaceutical Waste Management	-
Yu and Tong (2021)	To minimise the overall cost	MILP	/	Recycling facilities location	Zhejiang, China
Medrano-Gómez et al (2020)	To maximise the number of end-of-life products collected	MILP	/	Network recycling facilities location	Brazil
Rathore et al. (2020)	To minimise the number of bins	MILP GIS	/	Allocation of bins	Bilaspur, India
Utku and Erol (2020)	To minimise the total cost To maximise the energy recovery	MILP	/	Hazardous waste facility location and routing models	Marmara Region, Turkey
Tirkolaee et al. (2020)	To minimise the total cost of the waste management network	MILP	/	Location – allocation - inventory problem (LAIP)	-
Asefi et al. (2019)	To minimise the total cost of transportation	MILP	/	Location - routing model for (ISWM)	Tehran, Iran

Authors (year)	**Objective functions**	**Mathematical model proposed**	**Capacity integrates**	**Application to real-life problem**	**Case study area**
Aydemir-Karadag (2018)	To maximise the total annual profit of the entire Hazardous waste management system	MILP	/	Location of recycling facilities	Turkey
Rentizelas et al. (2018)	To maximise heat utilization at the location	MILP	/	Potential for a recycling facility	Scotland

2.5 Gap Analysis on Selected Mathematical Models and Methods

The following section analyses four selected research studies. These research studies were selected based on their similarity to the present research area. The mathematical model proposed in each article is further examined, with a focus on its elements, to illustrate where our model differs. To support this analysis, the table below provides an overview of the selected articles, including the authors.

Table 2.4
Selected Research Works from the Literature

No	Author
[1]	Jamiron et al. (2021)
[2]	Yu and Tong (2021)
[3]	Rosni et al. (2022)
[4]	Zaharudin et al. (2023)

Table 2.4 presents four selected research works: Jamiron et al. (2021), Yu and Tong (2021), Rosni et al. (2022), and Zaharudin et al. (2023). These research works were selected due to their strong relevance to the objectives of this study, particularly in developing the recycling facility location model. For clarity and to aid the analysis process, each research work is assigned a numerical designation as follows: Jamiron et al. (2021), Yu and Tong (2021), Rosni et al. (2022), and Zaharudin et al. (2023). The discussion of these research works focuses on their objective functions, decision variables, constraints, and parameters. An objective function refers to a mathematical expression that defines the goal of a problem, subject to a set of constraints. Constraints define the system's limitations or requirements that must be satisfied to achieve the desired results. Meanwhile, a decision variable represents a choice within an optimization problem, determined by achieving the optimal value of the objective function while adhering to all constraints.

2.5.1 Objective Function

The objective function that each research aims to achieve through its optimization approach. Table 2.5 summarizes the objective functions used in selected research works.

Table 2.5
Summary of Objective Function in Selected Research

Research	**Maximises the amount of demand covered**	**Maximise the amount of generated waste collected**	**Minimise the overall cost**
[1]	/		
[2]	/		
[3]	/		/
[4]			/
Present Research		/	

Based on Table 2.5, [1] and [2] formulated their mathematical models to maximise the amount of demand covered. In contrast, research [3] pursued a dual objective: to both maximise demand coverage and minimise overall cost. Research [4], however, focused solely on minimising overall cost. Building on these approaches, the present research adopts a different objective, maximizing the amount of generated waste that is successfully collected.

2.5.2 Decision Variable

The selected research defines various decision variables based on their modeling objectives and operational contexts. These variables represent the core elements that guide the structure and outcomes of each proposed model, which presented in Table 2.6.

Table 2.6
Summary of Decision Variable in Selected Research

Research	**The number of recycling bins or containers**	**Recycling facility location**	**The location of demand that will be covered by the allocated bins**
[1]	/		/
[2]	/		/
[3]	/	/	/
[4]		/	/
Present Research	/	/	/

According to Table 2.6, [1], [2], [3], and [4] employ binary decision variables to represent the presence or absence of operational facilities. In addition, research [1] and [2] included two decision variables: (i) the number of recycling bins or containers, and (ii) the location of demand to be served by the allocated bins. Research [3] introduced three decision variables: (i) the number of recycling bins or containers, (ii) the location of recycling facilities, and (iii) the location of demand covered by the allocated bins. Research [4] considered two decision variables: the location of recycling facilities and the location of demand served. This research adopts a similar structure to research [3], incorporating all three decision variables.

2.5.3 Constraints

The selected research incorporates various constraints to reflect operational, spatial, and resource limitations within their models. Table 2.7 summarizes these constraints, highlighting the specific considerations addressed in each study.

Table 2.7
Summary of Constraints in Selected Research

Constraint	**Research**				**Present research**
	[1]	**[2]**	**[3]**	**[4]**	
Maximum number of operating facilities	/	/	/	/	/
Maximum number of containers/bins	/	/		/	
Maximum capacity of facility/container/bin	/	/		/	/
Minimum facility service rate				/	/

Table 2.7 presents the set of constraints applied in the selected key papers. All research imposes a limit on the number of operational recycling facilities. Research [1], [2], and [4] additionally specified constraints on the maximum number of recycling containers and their respective capacities. However, study [4] incorporated the service rate directly into its mathematical formulation. Research [1] and [3] considered the service rate, but only as a component of the parameter sets. In alignment with these approaches, the present research includes constraints on the maximum number of operating facilities, the maximum container capacity, and the minimum facility service rate.

2.5.4 Parameters

This section outlines the key parameters extracted from selected research, forming the basis for comparison and model development. These parameters are summarized in Table 2.8.

Table 2.8
Summary of Parameters in Selected Research

Definition	Research				Present research
	[1]	[2]	[3]	[4]	
Demand location/Population location	/	/	/	/	/
Recycling bin location/Potential Recycling Facility Location	/	/	/	/	/
Distance between the demand location and the recycling bin location	/	/	/	/	/
Number of recycling bin locations at each facility location	/		/	/	/
The busyness level of having bins at each recycling bin location	/		/		
Fixed cost of locating a facility at the node recycling facility location		/			
Capacity Level of Recycling Facilities		/		/	/
Overall Service Rate of the Operating Facilities				/	/

The parameter sets utilized in the selected research works are summarized in Table 2.8. Commonly considered parameters include the locations of demand or waste generation, potential facility sites, and the distances or proximities between demand points and facility locations. Research works [1] and [3] defined the level of facility utilization at each recycling bin location, measured by the number of recycling bins, an approach adapted from Shuib and Zaharudin (2011). Research [2] incorporated the fixed cost of establishing a facility at a designated node. Conversely, research works [2] and [4] explicitly included the capacity levels of recycling facilities within their parameter sets. Notably, among the selected research works, only [4] included service rates as part of its model inputs. The present research incorporates the parameter design from research [4] to fulfil its modelling objective.

A thorough analysis of the selected research works indicates that the capacity levels of recycling facilities are frequently represented through the number of allocated containers. To refine this approach, the present research addresses the limitation by incorporating fixed capacity levels for operational facilities, aligning with standardized container capacities as specified by manufacturers.

2.5.5 Identified Research Gap

The following gap analyses can be summarised as follows. Existing research using mathematical modelling, specifically the covering location model for solving recycling facility location-allocation problems, remains limited. Although the covering model was established nearly 60 years ago, there are few variants for determining the location of a recycling facility. According to our literature review, several articles were identified under specific subtitles, and this thesis selected four of them for gap analysis. Thus, the proposed model would represent a significant advance in knowledge and fill a gap in the existing mathematical model for determining recycling facility locations.

The objective function of the conventional covering model is to maximize demand location coverage. In contrast, Rosni et al. (2022) proposed a location-allocation model designed to optimize the volume of recyclables collected at designated sites, determining the number of bins based on their likelihood of usage. Extending this framework, the present research incorporates recyclable volume as a capacity constraint. It also introduces a model that simultaneously determines both the number of containers and the location of recycling facilities. This dual optimization enhances operational efficiency and supports more effective infrastructure configuration.

Recent research focusing on the enhancement of recycling facilities in Malaysia through mathematical modelling remains limited. Key contributions include Rosni et al. (2022), Jamiron et al. (2021), and Zaharudin et al. (2023), each of which presents methodological frameworks for facility planning in Seremban, Johor Bahru, and Nilai, respectively. Building upon these foundational works, the present research applies an advanced location-allocation model in Seremban, offering broader spatial coverage than Rosni et al. (2022) and integrating sustainability-oriented variables derived from Zaharudin et al. (2023). This integrated approach addresses the regional application gap in recycling infrastructure planning across Malaysia.

To illustrate the methodological distinctions and regional applications of these models, Table 2.9 presents a comparative overview of selected research. It includes the works of Rosni et al. (2022), Jamiron et al. (2021), and Zaharudin et al. (2023), as well as the present research conducted in Seremban.

Table 2.9
Comparative Analysis of Recycling Facility Models in Malaysia

Criteria	**Rosni et al. (2022)**	**Jamiron et al. (2021)**	**Zaharudin et al. (2023)**	**Present research**
Study Location	Seremban	Johor Bahru	Nilai	Seremban
Model Type	Location-allocation model using mathematical optimization	Location-allocation model tailored for urban municipalities	Covering model emphasizing sustainable city planning	Location-allocation model with integrated container and capacity optimization
Objective Function	Maximize the number of recyclables collected at designated facilities	Optimize bin placement to enhance sustainable waste collection	Promote waste separation and minimize landfill dependency	Maximize recyclables collected while simultaneously optimizing bin quantity and placement
Use of Recyclables Data	Incorporated to guide facility location based on collection efficiency	Focused primarily on bin location and urban coverage	Emphasizes source-level waste separation	Utilized as a capacity input to determine optimal bin allocation and facility planning
Area Coverage	Selected zones within Seremban	Urban sectors of Johor Bahru	City-wide coverage in Nilai with a sustainability emphasis	Expanded coverage in Seremban, incorporating variables from Zaharudin et al. (2023)
Contribution to Literature	Introduces a mathematical framework for recycling facility planning in Seremban	Highlights the need for structured urban recycling infrastructure	Aligns with sustainable development goals and promotes integrated waste management	Builds upon Rosni's model while integrating sustainability and operational efficiency considerations

2.6 Summary

An overview of the fundamental theory of FLP was presented. Then, research on various application facility location models covering problems was reviewed. Decision variables, parameters, objective functions, and constraints were examined based on models of prior research on recycling facility location. This chapter also highlighted research gaps. The next chapter highlights related works on adapting the facility location model to the covering problem. The data and methods of this research were also elaborated.

CHAPTER 3

RESEARCH METHODOLOGY

3.1 Introduction

This chapter begins with an elaboration of the research framework, which includes the implementation steps of the research activities. Then, the reference model to be adapted by the research is presented, in which suggestions for modification and improvements to the selected model are described. The expected outcomes of this research are also highlighted.

3.2 Research Framework

The proposed research framework is categorized into three phases, as illustrated in Figure 3.1. Phase one focuses on developing the proposed mathematical model. The process begins with an analysis of the existing covering model, including its objective functions, parameters, decision variables, and constraints. This is followed by the construction of a reference model to establish a baseline for comparison. Next, modifications are introduced to improve or adapt the model. Finally, the proposed model is tested to assess its performance. If the proposed model successfully validates the solution, the process proceeds to phase two. If not, the model must return to the reference stage for further refinement.

Phase two focuses on implementing the proposed model within a selected case study area. The first step involves selecting an appropriate case study. The second step is implementing the proposed model. This is followed by the validation and verification of the results obtained from the case study. If the results confirm the validity of the solution, the process continues to phase three. Otherwise, the model returns to the reference model for further refinement.

Phase three focuses on conducting scenario analysis. In this stage, a calibration technique is applied to identify suitable locations for the proposed recycling facilities. Accordingly, the framework is finalized at the end of this phase.

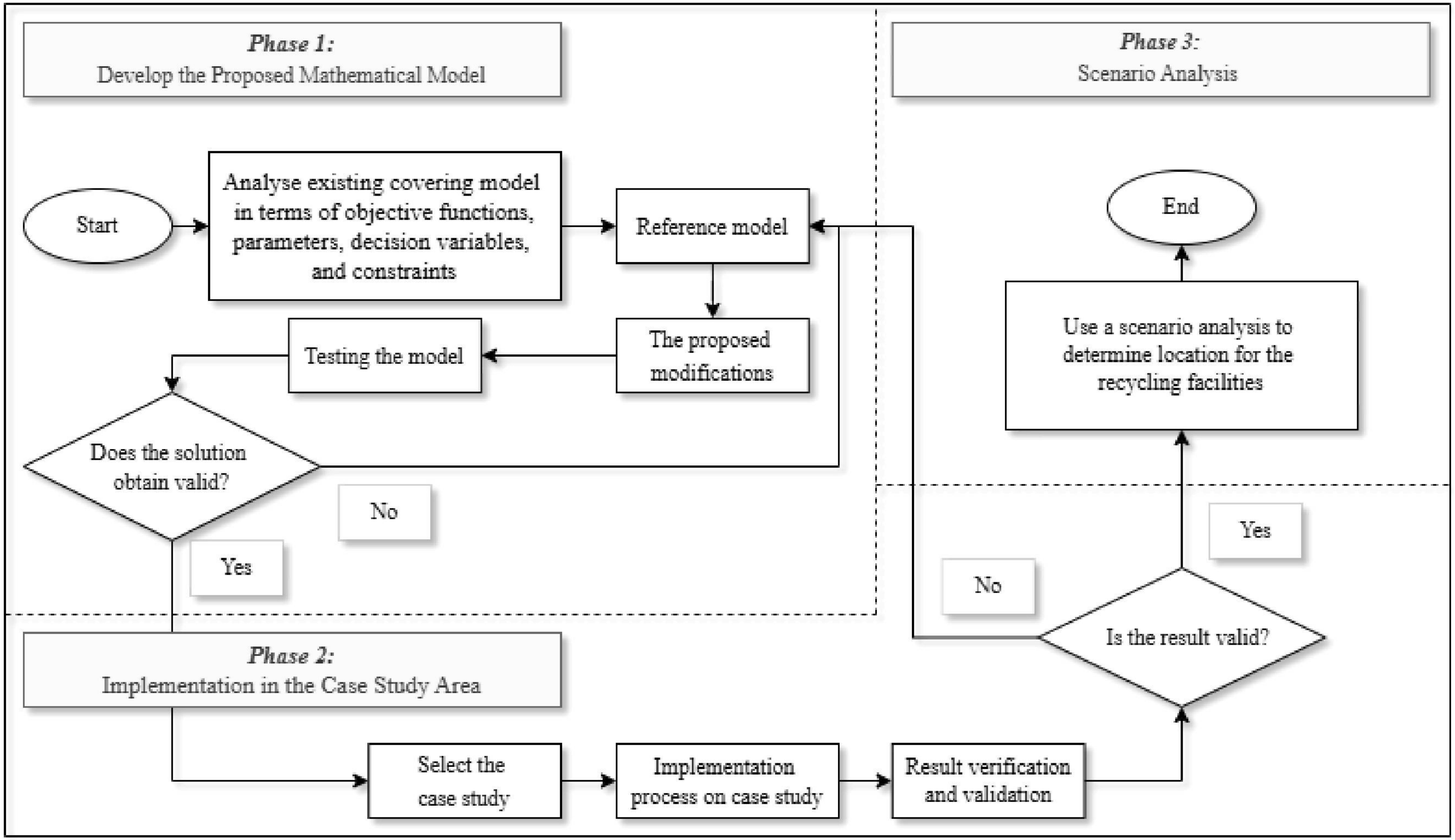


Figure 3.1 Framework of Research Works

3.2.1 Phase 1: Develop the Proposed Mathematical Model

Phase one begins with an analysis of the existing covering model, including its objective function, parameters, decision variables, and constraints. A reference model is then established to support further improvements. Modifications are applied to refine the model. The phase ends with testing the proposed model to evaluate its performance.

3.2.1.1 Step 1: Analyse the Existing Covering Model in Terms of Objective Functions, Parameters, Decision Variable, and Constraints

In this step, the analyses from Chapter 2 were used to propose modifications to the reference model. Particular attention was given to studies employing a covering-based conceptual framework to tackle location-allocation problems, including the identification of strategic sites and the determination of the optimal number of recycling facilities. Table 3.1 summarizes the selected studies.

Table 3.1
Summary of the Selected Studies

Details		**Authors**				
		[1]	**[2]**	**[3]**	**[4]**	**Present**
Objective function	Maximises the amount of demand covered	✓	✓	✓		
	Minimise the overall cost			✓	✓	
	Maximise the amount of generated waste collected					O
Decision variables	The number of recycling bins or containers	✓	✓	✓		O
	Recycling facility location			✓	✓	O
	Location of demand that will be covered by the allocated bins	✓	✓	✓	✓	O
Constraints	Maximum number of operating facilities	✓	✓	✓	✓	O
	Maximum number of containers/bins	✓	✓		✓	
	Maximum capacity of facility/container/bin	✓	✓		✓	O
	Minimum facility service rate				✓	O
Parameters	Demand location	✓	✓	✓	✓	O
	Recycling bin location	✓	✓	✓	✓	O
	Distance between the demand location and the recycling bin location	✓	✓	✓	✓	O
	Number of recycling bin locations at each facility	✓		✓	✓	O
	The busyness level of having bins at each recycling bin location	✓		✓		
	Fixed cost of locating a facility at the node recycling facility location		✓			
	Capacity Level of Recycling Facilities		✓		✓	O
	Overall Service Rate of the Operating Facilities				✓	O

Table 3.1 presents a comprehensive optimization model for recycling systems, aiming to simultaneously maximize demand coverage and the volume of waste collected. Unlike previous studies that focus solely on either coverage or cost minimization, this model integrates both strategic and operational considerations. Decision variables include the number and location of recycling bins and facilities. Constraints address the maximum number of operating facilities, container capacities, and minimum service rates. Parameters encompass demand and bin locations, distances between them, facility busyness levels, fixed facility costs, and overall service performance.

As can be concluded, the proposed model offers a more integrated and comprehensive approach to recycling system optimization compared to previous studies. By simultaneously addressing demand coverage and waste collection, and incorporating a broader set of decision variables, constraints, and parameters, the model enhances both operational efficiency and service effectiveness in recycling infrastructure planning.

3.2.1.2 Step 2: Reference Model

This research employs the variation of MEXCLP established by Rosni et al. (2022). The authors applied Daskin's (1983) concept of busyness to address the location problem of recycling facilities. Their approach focuses on optimizing operational coverage by determining the optimal number of recycling containers. The definitions of each index, parameter, and decision variable used in this study follow the framework established in their model.

Notation – Sets, Parameters, and Decision Variables

Sets:

i = the set of demand locations $\{i = 1, 2, 3, \dots , n\}$

j = the set of potential recycling bin locations $\{j = 1, 2, 3, \dots , m\}$

k = the set of recycling bin locations located at each location j $\{k = 1, 2, 3, \dots, K\}$

Parameters:

D = maximum travel distance between demand i and recycling bin location j

σ = maximum recycling bin locations in the selected area of study

d_i = the number of demands at location i

$dist_{ij}$ = distance between demand i and recycling bin location j

a_{ij} = $\begin{cases} 1, \text{ if } (dist_{ij}) \leq D \\ 0, \text{ if } (dist_{ij}) > D \end{cases}$

q_{jk} = idle level of having k bins at each recycling bin location j

Decision Variables:

x_j = $\begin{cases} 1, \text{if the recycling bin is located at } j \\ 0\text{, otherwise} \end{cases}$

y_{ik} = $\begin{cases} 1, \text{if the demand at location } i \text{ is covered with } k \text{ bins} \\ 0\text{, otherwise} \end{cases}$

Model Formulation:

$$\text{Maximize } Z = \sum_{i}^{n} \sum_{j}^{m} \sum_{k}^{K} d_i q_{jk} y_{ik} \tag{3.1}$$

subject to:

$$\sum_{k}^{K} y_{ik} - \sum_{j}^{m} a_{ij} x_j \leq 0\,;\ \forall i = 1,2,\dots,n \tag{3.2}$$

$$\sum_{j=1}^{m} x_j \leq \sigma \tag{3.3}$$

$$\sum_{k}^{K} y_{ik} \leq 1\,;\ \forall i = 1,2,\dots,n \tag{3.4}$$

$$x_j, y_{ik} = \{0,1\}\,;\ \forall j = 1,2,\dots,m;\ \forall k = 1,2,\dots,K \tag{3.5}$$

Rosni et al. (2022) proposed a model with an objective function (3.1) that aims to maximize the amount of demand at i that is met by the chosen facilities j, where j is allocated with k bins. The model is subject to four constraints, presented by the inequalities of (3.2) - (3.5). Inequalities (3.2) ensure that the location's demand can reach at least one operational recycling facility within the specified travel time thresholds. However, the number of operating recycling facilities within the specified study area is limited to σ locations, as indicated by inequalities (3.3). Meanwhile, the demand at location i must be covered by at most k recycling bins, as constrained by (3.4). The inequalities also guarantee the availability of sufficient bin capacity to meet demand at the location i. Inequalities (3.5), on the other hand, indicate the decision variable characteristics, i.e., either zero or one value. One of the parameters is the idle level (q_{jk}) that was imposed by the Rosni et al. (2022) is adopted from Shuib and Zaharudin (2011). The idle level is defined in equation (3.6), as follows:

$$q_{jk} = 1 - (b_j)^k, \forall j = 1,2, \dots, m \tag{3.6}$$

According to Rosni et al. (2022), the b_j is defined as the rate of busyness of a facility of location j to comprise the demand at all location i. The b_j is calculated based on the following equation:

$$b_j = \frac{\sum_{i=1}^{n} d_i a_{ij}}{\sum_{i=1}^{n} d_i} \tag{3.7}$$

The value b_j is raised to the power of k, representing the capacity rate of recycling facility j for k bins, i.e., $(b_j)^k$. This formulation indicates that the occupancy rate of recycling facility j increases exponentially with the growth of the number of bins k. The value of q_{jk} is determined by subtracting the result of equation (3.7) from one, indicating the idle rate of facility j at a given k bin.

Rosni et al. (2022) proposed a mathematical model that utilises indirect calculations to determine the optimal location for the facility and the optimal distribution of bins. Their model would require the computation of the idle rate as a component of the model's inputs, resulting in increased computational inefficiency and time consumption. Additionally, their model calculates the number of bins based on the potential demand to be served by the recycling facility at location j. This implies that the bins are treated as incapacitated, which is practically unrealistic. In practical applications, bins come in various sizes, designed to efficiently serve a specific amount of demand. Therefore, it is essential to consider the bin's capacity to accurately determine the optimal coverage level of a recycling facility. For these reasons, a new approach is required to simultaneously calculate the number of bins. The process is discussed in the following step.

3.2.1.3 Step 3: The proposed modifications

This research focuses on determining the optimal location for operating recycling facilities and the optimal allocation of recycling containers. To achieve this, modifications were proposed, particularly to enable the simultaneous determination of optimal container allocation within the mathematical model. A fixed capacity level for containers was introduced, defined by the amount of recyclable waste that can be collected or covered at a facility location. By contrast, Rosni et al. (2022) concentrated on the number of households that a facility can serve. The fixed capacity is also used to allocate the optimal number of on-site containers. Although container capacity may vary depending on the spatial availability at each facility, it is assumed that organizations choose to procure uniform-sized containers and increase the number of containers as needed, rather than acquiring containers of varying sizes. Moreover, the proposed mathematical model does not constrain all demand at location i to be served by a single operational facility, as indicated by Rosni et al. (2022). Rather, it stipulates that demand may be distributed among many recycling facilities within their accessibility.

For implementing the fixed capacity level of a recycling container, several modifications have been proposed regarding parameters and decision variables, resulting in alterations to the objective functions and constraints. The objective of the proposed mathematical model remains consistent with that of Rosni et al. (2022), specifically to maximize the expected demand covered by the operational recycling facility locations. Additionally, instead of focusing on demand location, this research defines the demand at location i, i.e., d_i is the amount of recyclable waste at location i. A new binary decision variable, y_{ij}, introduces a difference in the mathematical representation of the objective function. The variable y_{ij} is defined by the capability to serve the demand of location i by the recycling facility at location j. The summary of the notations of the proposed method is as follows.

The proposed modifications can be observed in equations (3.8) to (3.12). The objective function (3.8) of the proposed mathematical model is defined as maximizing the amount of recyclable waste collected at all recycling facility locations.

$$\text{Maximize} \sum_{i}^{n} \sum_{j}^{m} d_i y_{ij} \tag{3.8}$$

The modification was also made to ensure the constraints fit the capacity level within the mathematical model. The constraint (3.9) ensures that each demand location i, representing recyclable waste, has accessibility to at least one operating recycling facility located at site j, provided the travel time from i to j is within the maximum allowable limit. Specifically, for every i from 1 to n, the sum of the binary coverage indicators a_{ij} multiplied by the facility decision variables x_j, taken over all facility sites j from 1 to m, must be greater than or equal to one. Here, $a_{ij} = 1$, if the travel time from location i to site j is less than the maximum time, and $x_j = 1$, if a facility is located at site j. This formulation guarantees that each demand location is served by at least one accessible and operational recycling facility.

$$\sum_{j=1}^{m} a_{ij} x_j \geq 1 ;\ \forall i = 1,2, \dots, n \tag{3.9}$$

This constraint (3.10) ensures that recyclable waste from location i can only be assigned to site j if a facility is actually operating at that site. If no facility is located at j, then $x_j = 0$, and the right-hand side becomes zero, forcing y_{ij} to be zero. This formulation directly supports the objective of ensuring that the demand at location i has accessibility only to an active recycling facility at location j. This ultimately maintains logical consistency and operational feasibility in the allocation process.

$$y_{ij} \leq s_{ij} x_j ;\ \forall i = 1,2, \dots, n;\ \forall j = 1,2, \dots, m \tag{3.10}$$

This research introduces q_j, the fixed capacity level of a container at a recycling facility location j. This constraint (3.11) ensures that the total volume of recyclable waste assigned to facility j, aggregated from all demand locations, does not exceed the container's fixed capacity q_j. If no facility is located at site j, then $x_j = 0$, and the right-hand side becomes zero, preventing any waste from being assigned there. This formulation directly supports the operational requirement that each active recycling facility must be capable of overseeing the total assigned waste without exceeding its designed capacity. To guarantee that the operational recycling facility at location j has an adequate capacity level to accommodate the anticipated volume of recyclable waste from all locations i.

$$\sum_{i=1}^{n} d_i y_{ij} \leq q_j x_j \; ; \; \forall j = 1,2,\dots,m \tag{3.11}$$

This constraint (3.12) ensures that the total recyclable waste generated at each demand location i is fully allocated to one or more recycling facilities, without exceeding the combined available capacity provided by the assigned facilities. It reinforces the requirement that each demand location must be served adequately by operational facilities with sufficient capacity. This, in turn, supports the model's objective of ensuring accessibility and feasibility in waste allocation. To guarantee that the demand at location i is only assigned to recycling facilities that have sufficient capacity to accommodate its recyclable waste.

$$d_i \leq \sum_{j=1}^{m} y_{ij} q_j \; ; \; \forall i = 1,2,\dots,n \tag{3.12}$$

Imposing these constraints and conditions ensures comprehensive coverage of recyclable waste across all locations served by the recycling facilities at location j, thereby enhancing the existing waste recycling system. The full mathematical model is presented in Chapter 4.

3.2.1.4 Step 4: Testing the model

This section focuses on testing the proposed mathematical model using numerical experimentation, specifically, calibration procedures. Two datasets were used, namely, the randomly generated dataset and the dataset from Rosni et al. (2022).

i) Numerical Experimentation using Random Generated Dataset

The numerical dataset used in this research was randomly generated and includes demand values at each location *i*, fixed capacity levels for each facility *j*, and travel times between locations *i* and *j*. These data are provided in Appendix 2 and were designed to simulate realistic conditions for the case study. To assess the stability and performance of the model, this experiment was conducted by varying different parameters. The proposed model was assessed using various combinations of problem dimensions, including demand location (*I*) and facility location (*J*), which were set randomly. Additionally, factors such as distance between nodes, demand patterns, fixed facility capacities, and the maximum allowable number of facility locations were also randomized to evaluate their performance under different scenarios. For this testing, the distance between node *i* and node *j* is considered as the travel time between node *i* and node *j* (minutes). Table 3.2 provides a summary of these parameters.

Table 3.2
Summary of Parameter Settings for Numerical Experiments

Problem dimension ($I \times J$)	**Maximum travel times (T)**	**Recyclable waste generated at each i (d_i)**	**Capacity level of containers (q_j)**	**Number of operating recycling facilities (σ)**
10x10	5, 6, 7, 8, 9, and 10 minutes	Random between 10 to 100 kilograms	50, 60, 70, 80, 90, and 100 kilograms	1 – 10 units

Table 3.2 illustrates the parameters used for numerical experiments. For testing purposes, the problem dimension was established at 10 x 10. The maximum travel threshold between these nodes was randomly set to 5, 6, 7, 8, 9, and 10 minutes. The travel time from *i* to *j* differs from the travel time from *j* to *i*. These thresholds (*T*) represent the maximum allowable travel time between demand nodes and assigned

facilities, ensuring accessibility within a reasonable duration. The demand at each location was randomly assigned a value between 10 and 100 kilograms. The capacity level of the container (q_j) is established to range from 50, 60, 70, 80, 90, and 100 kilograms for each j, increasing by 10 kilograms with each iteration. The maximum allocation for the locations of operational recycling facilities (σ) is randomly selected within the range of 1 to 10 units, increasing by one unit per iteration. It is essential to note that most of these values were randomly selected for our research, with a deliberate effort to keep them as small as possible. This approach aimed to encourage the proposed model to minimize facility location and allocation while solving the system. For these experimentations, three tests were performed, which are outlined as follows:

a) Test 1: The impact of the maximum travel time thresholds (T) on the objective function value, the total quantity of recyclable waste that can be covered, and the total number of operating facilities, while keeping the capacity level of the container (q_j) and the maximum operational facility (σ) at a fixed value.
b) Test 2: The correlation between the capacity level of the container (q_j) with the objective function. The impact on the total quantity of recyclable waste that can be covered and the total number of operating facilities were also configured. The maximum operational recycling facility (σ) and travel times between locations (T) are defined as constants.
c) Test 3: The relationship between the maximum number of operational recycling facilities (σ) and the objective functions and total amount of recyclable waste to be covered. Meanwhile, the values for service capacity (q_j) and the threshold of travelling times between locations (T), remained unchanged.

For all tests, all constants were set at their maximum range values. For instance, the service capacity is consistently defined as 100 units, representing the maximum value within the established range. This approach ensures that the fixed parameters do not influence the outcomes, allowing the analysis to focus solely on the effects of the variables under investigation. Additionally, these values were randomly set to evaluate the performance of the proposed mathematical model.

ii) Numerical Experimentation using Data from Rosni et al. (2022)

The data from the main reference model of Rosni et al. (2022) is employed to evaluate the proposed mathematical model. It is essential to compare the performance of the proposed method with the reference model to evaluate and validate the proposed modifications and conduct benchmarking. Their research was also conducted in the Seremban area, but on a smaller scale, involving six household areas and five potential recycling facility locations. The dataset, provided in Appendix 3, contains the numerical values used for model input, including demand at each location *i*, fixed capacity levels for each facility *j*, and travel times between nodes *i* and *j*. Table 3.2 provides the rest of the data collected from the key reference model.

Table 3.3
The Parameters adopted from Rosni et al., (2022)

Maximum travel time (*T*)	**Serve as the multiplier for the capacity (δ)**	**The quantity of total capacity (q_j)**	**The number of operational facilities (σ)**
10, 13, and 17 minutes	1.0, 1.5, 2.0, 2.5, 3.0	12,776.8, 19,165.2, 25,553.6, 31,942, and 38,330.3 kg	1 – 5 units

Table 3.3 presents the maximum travel times (*T*) and other relevant data reported by Rosni et al. (2022), which serve as key inputs for evaluating transportation efficiency within the proposed model. Based on this dataset, the total expected quantity of waste generated is estimated at 63,884 kilograms, evenly distributed among all prospective recycling facilities located at node *j*, denoted as q_j. Since the reference model does not assign a fixed capacity value to each facility, capacity is calculated by multiplying a base value by the parameter, i.e., δ. The parameter δ is randomly varied from 1.0 to 3.0 kilograms, incrementing by 0.5 in each iteration, allowing for a systematic evaluation of the model's performance under different capacity scenarios. For instance, when δ = 1.5, the total capacity across all facilities amounts to 95,826 kilograms, resulting in an average of 19,165.2 kilograms per facility.

Additionally, the parameter σ is varied from 1 to 5 units to represent the number of permissible recycling facility locations operating within the study area. A maximum value of σ = 5 indicates the upper limit of potential facility locations considered in the model. In this research, the conventional representation of bin quantity (*k* = 1, 2, 3) is replaced with a capacity multiplier ($\delta = 1.0, 1.5, 2.0, 2.5, 3.0$) to more accurately capture variations in container capacity rather than merely the number of bins. This modification enables a more flexible and realistic assessment of the system's performance under different capacity scenarios. The proposed model is evaluated using three primary data components derived from Rosni et al. (2022): the demand location at i, the travel time from i to j, and the recycling facility location at j.

All model solution processes were executed using IBM CPLEX 20.0 on a computer equipped with an Intel Core i5-7200 processor (2.71 GHz) and 12 GB RAM. The results are then analyzed to determine their consistency and validity.

3.2.2 Phase 2: Implementation in the Case Study Area

This section outlines the specific geographic region that is identified based on criteria such as data availability, waste generation patterns, and logistical feasibility.

3.2.2.1 Step 1: Select the case study area

Figure 3.2 Regional Map of Seremban, Negeri Sembilan

In this research, Seremban, Negeri Sembilan, served as a case study for implementing the proposed mathematical model. The location of Seremban is presented in Figure 3.2. Seremban stands as a prominent urban centre within Malaysia, serving as the capital of Negeri Sembilan. Hence, Seremban exemplifies locales experiencing swift population growth, rendering it a viable candidate for comparative analysis in analogous urban settings. Its selection as a case study underscores its utility as a testing ground for evaluating the efficacy of methodologies deployed in this research endeavor.

3.2.2.2 Step 2: Implementation process on the Case Study

This section defines the population implementation in Seremban, Negeri Sembilan, which is located within the municipalities of the MBS. In the meantime, Google Maps is used to determine the shortest distance between these recycling facility locations and demand locations. The modified model was defined using the CPLEX solver software. Details for each of the collected data are explained in the following section.

In addition to the synthetic datasets, a real-world dataset from the Seremban area was utilized to enhance the practical relevance of the research. This dataset, detailed in Appendix 4, includes actual demand values at each location *i* represent as a, travel times between locations *i* and *j*, and fixed capacity levels for each facility *j*. Incorporating this dataset enables the model to be assessed under realistic conditions, supporting the validation of its applicability in real-world scenarios.

Figure 3.3 below visualizes the spatial distribution of demand location *i* and recycling facilities location *j* in Seremban. In the figure, the blue-shaded areas represent the demand locations, comprising a total of 315 households within the Seremban municipality, denoted as d = 315. The entire names of the households' areas are provided in Appendix 4. The red star marks the 12 locations of recycling facilities. Meanwhile, the yellow lines denote the transportation networks for all demand and facilities.

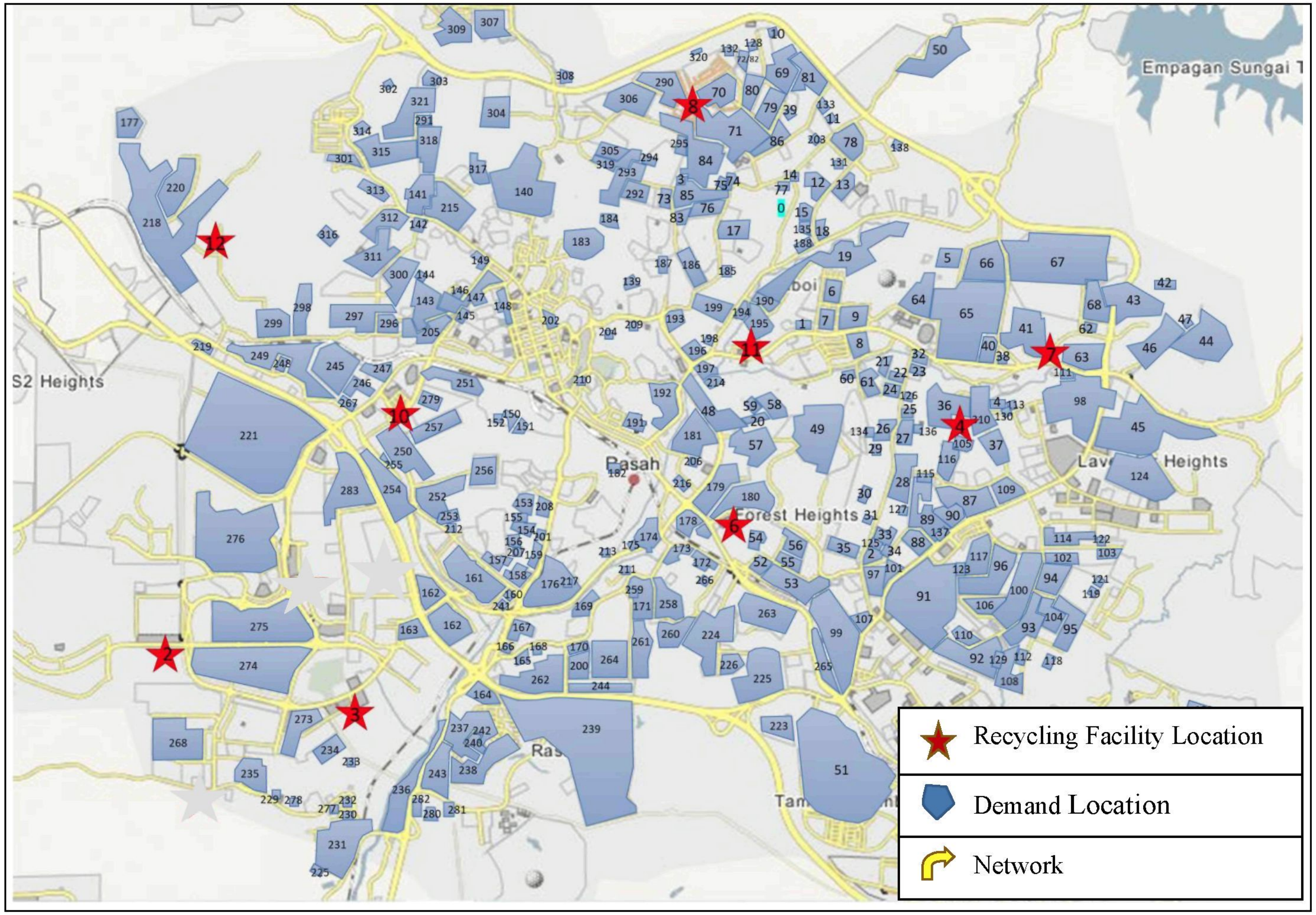


Figure 3.3 Geographic Location of the Case Study (Seremban)

Hence, to support the formulation of the proposed model, several key parameters are defined: i) d_i, representing the demand locations in Seremban; ii) J, denoting the locations of recycling facilities; iii) $trav_{ij}$, referring to the travel time in minutes between each demand location i and facility j; and iv) q_j, indicating the capacity level of containers at facility j, along with σ, the maximum number of recycling facilities that can be operated.

i) Demand Location in Seremban (d_i)

Table 3.4 provides the gathered statistics regarding the number of households, estimated population, estimated waste generation, and anticipated recyclable waste production. The estimated total population is 422,710, scattered among 315 household areas. According to the Seremban City Council, an average of 3.97 individuals per household generate approximately 473,435 kilograms of waste daily. Using the estimated recyclable waste proportion of 1.17 kilograms per capita per day, as reported by Imran et al. (2019), the recyclable waste generated by Seremban residents amounts to approximately 169,092 kilograms per day (Source: Malaysia Department of Statistics). In 2023, the state recycling rate was 35.38% (Nizam, 2024). Nonetheless, the proportion remains significantly below the Malaysian Government's target of achieving a 40% recycling rate by 2025.

Table 3.4
Data Collection in Seremban

Demand location, *i* (unit)	**Estimated populations (unit)**	**Estimated wastes (kilogram)**	**Estimated recyclable wastes, d_i (kilogram)**
315	422,710	473,435	169,092

An analysis employing calibration procedures was undertaken to derive optimal solutions. The parameter variations enabled a comprehensive examination of the impact of varying waste proportions on the optimization outcomes. Therefore, the primary focus of this research is the estimation of recyclable waste (measured in kilograms), which serves as a representation of demand.

ii) Recycling Facilities Location in Seremban (J)

The data regarding the existing recycling facilities within the Seremban area were obtained from the Negeri Sembilan KITARecycle website. As of 2024, there exist nine established recycling facilities in Seremban. In addition to the existing facilities, this research introduces three additional potential locations for recycling facilities. These locations were selected manually based on practical criteria, rather than through mathematical modeling. Although the locations were selected randomly, the decision was guided by practical criteria to ensure relevance and feasibility. These criteria included proximity to high-demand residential areas, minimal disruption to surrounding communities and the environment, and good road accessibility for waste collection operations.

This approach is supported by previous research that emphasizes the importance of strategic site selection based on local conditions. For example, Rosni et al. (2022) highlighted that recycling facilities should be located near areas with high waste generation and accessible infrastructure to improve collection efficiency. Similarly, guidelines from the National Solid Waste Management Department (JPSPN) recommend that new facility sites consider environmental impact, community acceptance, and operational practicality. Meanwhile, the location of these facilities is indicated in Table 3.5.

Table 3.5
The Recycling Facilities Location of Seremban (Negeri Sembilan KITARecycle)

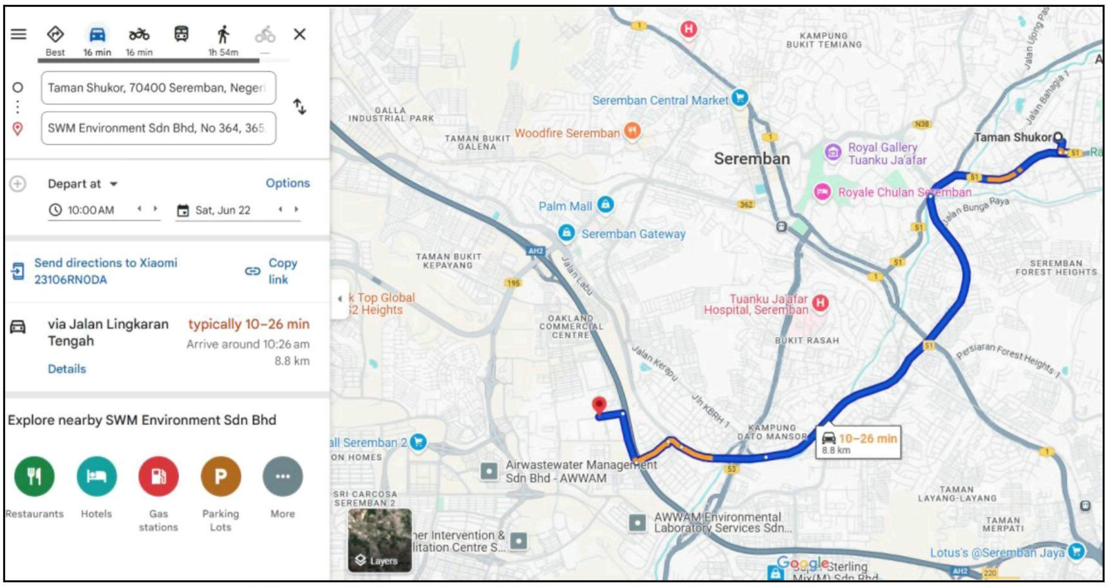
j	Recycling Facility Location	Facility
1	Solid Waste Management Environment Sdn. Bhd.	Existing
2	Sri Carcosa, S2	Existing
3	Taman Arowana Indah	Existing
4	Kampung Sentosa Jaya	Existing
5	Perpustakaan Awam Negeri Sembilan	Existing
6	Majlis Bandaraya Seremban	Existing
7	Taman Pasar Ampangan	Existing

j	Recycling Facility Location	Facility
8	Taman Sri Inai	Existing
9	Kalista 2	Existing
10	Marrybrown Pusat Perniagaan Oasis	Potential
11	Benteng Ampangan Diecast	Potential
12	99 Speedmart 1692 (NS) Galla Industrial Park	Potential

Table 3.5 outlines recycling facilities in Seremban, including Solid Waste Management Environment, Sri Carcosa of S2, Taman Arowana Indah, Kampung Sentosa Jaya, Perpustakaan Awam Negeri Sembilan, Majlis Bandaraya Seremban, Taman Pasar Ampangan, Taman Sri Inai, and Kalista 2. The addition of three potential recycling facility locations, Marrybrown Pusat Perniagaan Oasis, Benteng Ampangan Diecast, and 99 Speedmart 1692 (NS) Galla Industrial Park, was strategically implemented to increase the total number of facilities from nine to twelve, specifically to address underserved, high-demand areas lacking nearby access. This targeted expansion enhances spatial coverage, improves user convenience, and encourages greater public participation in recycling efforts. The decision is supported by findings from previous studies, such as the one published by Rosenthal and Linder (2021). This demonstrates that proximity to recycling bins significantly increases recycling behavior, especially when facilities are placed in accessible and visible locations. This is to ensure the goal of evaluating the coverage level of both existing and prospective recycling facility locations is met, thereby ensuring demand within the Seremban area is met.

iii) Travel Time ($trav_{ij}$) and Maximum Travel Time (T)

The distance based on the travel times (minutes) between specific locations (i and j) is collected from Google Maps. The application is configured to depart from location i to location j on weekends between 10:00 a.m. and 5:00 p.m. This timing is selected under the assumption that most householders are more likely to participate in the recycling process on weekends. The parameter T represents the maximum allowable travel time between a demand location and a recycling facility.



Taman Shukor, 70400 Seremban, Neger

SWM Environment Sdn Bhd, No 364, 365

Depart at

10:00AM

Sat, Jun 22

Send directions to Xiaomi 23106RNODA

via Jalan Lingkaran Tengah

typically 10–26 min

Arrive around 10:26 am

8.8 km

Explore nearby SWM Environment Sdn Bhd

Figure 3.4 Travel Times using Google Maps

Figure 3.4 displays the travel route between the demand location and the recycling facility location, using Google Maps. Based on the figure, Taman Shukor is chosen as the demand location, and Solid Waste Management Environment Sdn. Bhd. is the specified recycling facility location. To determine the travel routes between these locations, the "depart" section is set to 10:00 a.m., with a random date selected for analysis. In this case, Saturday was selected as the day for data collection. As displayed in Figure 3.4, the travel time typically ranges from 10 to 26 minutes. To account for potential delays, the longest travel time is assumed for users, i.e., 26 minutes. The process is repeated for the journey that starts at all demand locations to all other recycling facility locations.

The travel times are recorded and stored in Microsoft Excel. The overall travel distance can be observed in Appendix 4. Meanwhile, for computing optimal results for recycling facility locations in Seremban, the maximum travel time T is randomly set to 14, 20, 26, and 30 minutes.

iv) Capacity Level of a Facility (q_j) and Maximum Number of Operating Facilities (σ)

The capacity of a recycling facility is typically determined by the physical dimensions of the container. Since the dimensions and weights of recyclable items vary, this research assumes that items are deposited based on weight. This approach is crucial since the sizes of KITARecycle containers vary based on the spatial constraints associated with their specific locations. As a result, the fixed capacity level of a recycling facility at the location (q_j) was randomly set at 10,000, 20,000, and 30,000 kilograms. Then, the iterative procedure is used to identify the optimal solution within this predefined range.

Additionally, the parameter σ is systematically iterated from 1 to 12 units, indicating the permissible range for the number of operational recycling facility locations in the study area, as there are a maximum of 12 locations, including both existing and anticipated ones. Similarly, an iterative procedure is also utilized to identify the optimal solution within the specified range.

The summary of these parameter inputs for solving the recycling facility location and capacity allocation problems is presented in Table 3.6. There are related parameter inputs that can achieve optimal results for locating recycling facilities within the Seremban municipality. Thus, the outcomes of varying the rate of recyclable waste collection are utilized and further analyzed.

Table 3.6
The Parameters Adopted to Enhance the Present Research

Demand Location in Seremban (d_i)	**Capacity Level of a Facility (q_j)**	**Maximum Operating Facilities (σ)**	**Maximum travel time (T)**
169,092 kilograms	10,000, 20,000, and 30,000 kilograms	1 – 12 units	14, 20, 26, and 30 minutes

This would provide insights into service performance and pinpoint actionable measures to meet Malaysia's recycling rate objectives. The results focused on identifying the optimal locations for recycling facilities that minimize the number of operating facilities while ensuring maximum coverage of demand locations. Then, the results are further examined based on scenario testing, which is explained in the following phase.

The mathematical model was implemented using CPLEX through a custom-coded formulation. For full details of the coding structure and implementation, refer to Appendix 1. The solution procedures were solved using IBM CPLEX 20.0, running on a laptop with an Intel Core i5-7200 processor (2.71 GHz) and 12 GB of RAM.

3.2.2.3 Step 3: Result Validation and Verification

This step focuses on assessing the reliability and accuracy of the results obtained from the site selection process. Since the selection of potential recycling facility locations in this research was conducted manually based on practical criteria, validation and verification were carried out through the following approaches. To ensure the reliability and appropriateness of the selected facility locations, a structured validation and verification process was conducted. The summary of this process is presented in Table 3.7.

Table 3.7
Validation Methods Used in This Research

Validation Method	Description	Key Elements Assessed
Cross-Referencing with Existing Research	Compared selected locations with Rosni et al. (2022) to ensure consistency.	Proximity to demand, accessibility, environmental suitability
Coverage Improvement Analysis	Reviewed impact of the added facilities on system performance.	Demand points served, travel time reduction, underserved area coverage

Table 3.7 summarizes the validation and verification process conducted to ensure the reliability and suitability of the selected facility locations. Although the selection was conducted manually, it followed systematic spatial criteria and was supported by comparisons with previous studies. The proposed sites were assessed for accessibility, proximity to demand areas, and environmental impact, while improvements in coverage and travel time confirmed their overall effectiveness.

3.2.3 Phase 3: Scenario Analysis

The results were tailored to align with the needs and preferences of decision-makers by fine-tuning controlled parameters. A method of calibration was used to figure out what percentage of waste could be recycled at 90%, 70%, 50%, 30%, and 10%, with capacity levels of containers (q_j) set at 5,000, 10,000, and 20,000 kilograms. These percentages were applied to the estimated number of recyclable wastes at each location i (d_i) to simulate varying operational intensities. The full dataset for each scenario is provided in Appendix 6. The capacity of each facility was reduced from earlier test scenarios to reflect the expected decrease in recyclable waste volume. This adjustment ensures that the model remains realistic and aligns with actual waste generation patterns in the study area. By minimizing the required capacity, the proposed facility design becomes more cost-effective and easier to manage. This approach benefits local authorities by reducing infrastructure investment, optimizing resource allocation, and supporting more sustainable planning decisions. Using these scenarios, a cause-and-effect analysis was performed to determine optimal locations for recycling facilities and to allocate household areas accordingly. This strategy enables decision-makers to inform the optimization of the recyclable waste collection system in the Seremban municipality.

3.3 Summary

This chapter outlines a mathematical model approach for addressing the location and allocation of recycling facilities. The process consists of three phases, with the initial phase outlining the modifications to the key reference model established by Rosni et al. (2022). The proposed methodology was validated and verified by testing the enhanced model with a random dataset as well as data from the original Rosni et al. (2022) model. In the second phase, the enhanced model was implemented in Seremban, Negeri Sembilan, to determine optimal locations for recycling facilities with appropriate fixed capacity allocation. The details regarding the further experimentations based on scenario analysis were also outlined in the last phase. The following chapter analyzed and discussed the results obtained.

CHAPTER 4

RESULTS AND DISCUSSIONS

4.1 Introduction

This chapter presents and discusses the related results, structured according to the methodological framework. The results presented in this chapter were obtained using the CPLEX-based code detailed in Appendix 1. The initial section concentrated on the proposed mathematical model and its associated validation and verification results. The subsequent section presents the optimal location of recycling facilities within the case study area, i.e., Seremban, Negeri Sembilan. The final section presents the results of three scenario analyses, which provide insights and establish optimal strategies for utilizing recycling facilities for relevant stakeholders (users and authorities) through the application of parameter calibration approaches.

4.2 Result 1: The Proposed Mathematical Model

This section is divided into two sections, namely the proposed model that was modified from Rosni et al. (2022), and the numerical experimentations' results.

4.2.1 The Mathematical Model For Locating Recycling Facility Locations With Fixed Capacity

Details for the model are outlined as follows:

Notation – Sets, Parameters, and Decision Variables

Sets:

I = the set of demand locations where $\{i = 1,2,\ldots,n\}$

J = the set of recycling facility locations $\{j = 1,2,\ldots,m\}$

Parameters:

σ = The maximum number of operating recycling facilities is limited to σ locations

d_i = The number of recyclable wastes generated at location *i*

q_j = The capacity level of the container at each of the recycling facility location *j*

$trav_{ij}$ = The travel time between demand location *i* and recycling facility location *j*

T = The maximum travel time between the demand location *i* and the recycling facility location *j*

$$a_{ij} = \begin{cases} 1, \text{ if } (trav_{ij}) \leq T \\ 0, \text{ if } (trav_{ij}) > T \end{cases}$$

Decision Variables:

$$x_j = \begin{cases} 1, \text{if a facility is located at site } j \\ 0\text{, otherwise} \end{cases}$$

$$y_{ij} = \begin{cases} 1, \text{if demand at location } i \text{ is served with } j \text{ facilities} \\ 0\text{, otherwise} \end{cases}$$

Objective Function:

$$\text{Maximize} \sum_{i}^{n} \sum_{j}^{m} d_i y_{ij} \tag{4.1}$$

Subject to:

$$\sum_{j=1}^{m} a_{ij} x_j \geq 1\,;\ \forall i = 1,2,\ldots,n \tag{4.2}$$

$$a_{ij} x_j \geq y_{ij};\ \forall i = 1,2,\ldots,n; \forall j = 1,2,\ldots,m \tag{4.3}$$

$$\sum_{i=1}^{n} d_i y_{ij} \leq q_j x_j \text{ ; } \forall j = 1,2,\ldots,m \tag{4.4}$$

$$\sum_{j=1}^{m} y_{ij} q_j \geq d_i \text{ ;} \forall i = 1,2,\ldots,n \tag{4.5}$$

$$\sum_{j=1}^{m} x_j \leq \sigma \tag{4.6}$$

$$x_j, y_{ij} \in \{0,1\} \text{ ;} \forall i = 1,2,\ldots,n; \forall j = 1,2,\ldots,m \tag{4.7}$$

Equation (4.1) is a renumbered objective function of (3.6), indicating the maximum expected total collected recyclable waste served at demand location i that is covered with a recycling facility at location j. The proposed mathematical model constraints are presented by the constraints of (4.2)-(4.7). Constraint (4.2) ensures that recyclable waste at every demand location is served by at least one operating recycling facility at location j. Constraints (4.3) enforce feasible assignments between demand and recycling facility. Following the discussions in Chapter 3, the model has been adjusted to incorporate the fixed capacity. Constraints (4.4) ensure that the recyclable waste deposited by all users at each location j remains within the designated capacity. Simultaneously, constraints (4.5) establish a fixed capacity framework to ensure that the recyclable waste generated at location i can be accommodated across multiple recycling facilities. This demonstrates that the proposed model is capable of establishing a more efficient recycling waste system. Inequalities (4.6) set an upper limit on the total number of activated recycling facilities at most σ locations. The constraint also indicates the allowance of operating facilities within the research area. Finally, constraint (4.7) defines the domains of the decision variables used in the model.

The following section presents the results of the numerical experiments conducted to validate and verify the proposed mathematical model.

4.2.2 Numerical Experimentations' Results

This section presents the validation and verification outputs in two folds. Initially, the results presented in this chapter are based on the dataset detailed in Appendix 2, which includes the demand, capacity, and travel time parameters used in the model. These parameters are followed by the findings derived from Rosni et al. (2022).

4.2.2.1 Numerical Experimentation using Random Dataset

As described in Chapter 3, the dataset used for these experiments was generated randomly within predefined ranges for travel time, demand, container capacity, and facility allocation. The results for this part are presented according to the three tests conducted. All the tests were conducted to examine the relationship with objective function values, the total number of operating facilities, and the total demand locations that can be covered.

Test 1: Maximum travel time thresholds (*T*) versus objective function values, total demand locations that can be covered, and total number of operating facilities.

Table 4.1
Results of Test 1 – Correlation between Maximum Travel Time Thresholds (*T*), Objective Function Values, and Total Number of Operating Facilities (*x*)

Capacity level, q_j (kilograms)	Maximum number of operational facilities, σ	Maximum travel time, T (minutes)	Objective function	Total number of operating facilities (x)
100	10	5	-	-
		6	-	-
		7	369.2	7 ($x_1, x_2, x_4, x_5, x_7, x_9, x_{10}$)
		8	559.2	9 ($x_1, x_2, x_3, x_4, x_5, x_7, x_8, x_9, x_{10}$)
		9	661.2	10 ($x_1, x_2, x_3, x_4, x_5, x_6, x_7, x_8, x_9, x_{10}$)
		10	695.6	10 ($x_1, x_2, x_3, x_4, x_5, x_6, x_7, x_8, x_9, x_{10}$)

Table 4.1 presents the sensitivity analysis, which supports informed decision-making in practical scenarios. The maximum travel time (*T*) and the objective function were increased. The increase in the total amount of recyclable waste collected can be attributed to the expansion in both the number of operating facilities and the extent of demand coverage. As more facilities are activated within the network, a greater number of demand locations can be feasibly assigned, thereby enhancing spatial coverage and

accessibility. This leads to a higher volume of recyclable waste being captured, which explains the rise in the objective value. The sensitivity of the model to maximum travel time further influences this outcome, as relaxed constraints enable broader allocation and improved collection efficiency. There are outlines of the relationship between the maximum travel time thresholds (*T*), objective function values, and the number of operating facilities for a service capacity of 100 kilograms and a maximum of 10 operational facilities. As the maximum travel time threshold increases from 5 to 10 minutes, the objective function value also rises, indicating improved efficiency or cost-effectiveness. For instance, at $T = 7$, the objective function value is 369.2, and it increases to 695.6 at $T = 10$. Additionally, the number of operating facilities grows with higher travel time thresholds, starting from 7 facilities at $T = 7$ and reaching 10 facilities at $T = 9$ and $T = 10$. Throughout these scenarios, the total quantity of recyclable waste covered remains constant at 100 kilograms. This suggests that allowing more travel time enables the operation of more facilities, thereby enhancing overall efficiency while maintaining the same capacity level.

Test 2: Capacity level (q_j) versus objective functions values, total demand locations that can be covered, and the total number of operating facilities.

Table 4.2
Result for Test 2 – Correlation between Capacity Levels (q_j), Objective Function Values, and Total Number of Operating Facilities (x)

Maximum number of operational facilities, σ (units)	Travel time, *T* (minutes)	Capacity levels, q_j (kilograms)	Objective function	Total number of operating facilities (x)
10	10	50	389.2	10 $(x_1, x_2, x_3, x_4, x_5, x_6, x_7, x_8, x_9, x_{10})$
		60	493.2	10 $(x_1, x_2, x_3, x_4, x_5, x_6, x_7, x_8, x_9, x_{10})$
		70	539.6	10 $(x_1, x_2, x_3, x_4, x_5, x_6, x_7, x_8, x_9, x_{10})$
		80	604	10 $(x_1, x_2, x_3, x_4, x_5, x_6, x_7, x_8, x_9, x_{10})$
		90	658.8	10 $(x_1, x_2, x_3, x_4, x_5, x_6, x_7, x_8, x_9, x_{10})$
		100	695.6	10 $(x_1, x_2, x_3, x_4, x_5, x_6, x_7, x_8, x_9, x_{10})$

Table 4.2 presents a sensitivity analysis of the number of operational facilities under varying capacity levels while maintaining a maximum travel time of 10 minutes. The maximum operational facilities are consistently set at 10 for each scenario. As the capacity level increases from 50 to 100 kilograms, the performance values related to maximizing total recyclable waste covered also increase, indicating enhanced system performance. This increase suggests that the model can accommodate a greater volume of recyclable waste, thereby improving service coverage and resource utilization. This analysis demonstrates how changes in capacity level impact the objective function and supports more informed resource allocation decisions. The consistent operation of all 10 facilities across various capacity levels suggests a robust system capable of managing varying demands without compromising on performance.

Table 4.3
Total Number of Demand Locations Based on Calibration of Capacity Levels (q_j)

Operational Facilities (*j*)	**Total Number of Demand Locations (*i*)**					
	q_j=50	**q_j=60**	**q_j=70**	**q_j=80**	**q_j=90**	**q_j=100**
1	2	2	2	3	3	3
2	3	2	2	3	3	3
3	1	1	1	1	1	1
4	2	2	2	2	2	2
5	1	2	2	2	3	3
6	1	1	1	1	1	1
7	1	2	2	2	3	3
8	1	2	2	3	3	3
9	2	2	3	3	3	4
10	2	2	3	3	3	3

Table 4.7 illustrates a clear positive relationship between the capacity levels parameter q_j and the total number of demand locations (*i*) served by each operational facility (*j*). As the capacity levels increase from 50 to 100 kilograms, most facilities are

able to serve a greater number of demand locations. Facilities 1, 2, 5, 7, 8, 9, and 10 demonstrate a steady increase in the number of demand locations they serve. In contrast, facilities 3, 4, and 6 remain unchanged across various capacity levels, which may be due to their location or the maximum travel time required. These findings demonstrate that calibrating capacity levels (q_j) plays a critical role in enhancing facility performance and optimizing the model's ability to meet varying levels of demand efficiently.

Test 3: Maximum number of operational facilities (σ) versus objective function values, total demand locations that can be covered, and total number of operating facilities.

Table 4.4 presents data on capacity levels, travel time, maximum number of operational facilities, objective function values, and the specific facilities operated. It starts with capacity levels of 100 kilograms and a travel time of 10 minutes. The maximum operational facilities range from 1 to 10. For each level, the corresponding value for maximizing recyclable waste collected and the facilities in operation are listed. For instance, with four operational facilities, the objective function value is 363.6, and the facilities operated are x_2, x_5, x_7, and x_9. As the number of operational facilities increases, the objective function value also increases, reaching 695.6 when all 10 facilities are operated (x_1 through x_{10}). This progression illustrates the positive correlation between the number of operational facilities and the total amount of recyclable waste collected.

Table 4.4
Result of Test 3 – Correlation between Maximum Number of Operational Facilities (σ), Objective Functions, and Total Number of Operating Facilities (x)

Capacity levels, q_j (kilograms)	**Travel time, T (minutes)**	**Maximum number of operational facilities, σ (units)**	**Objective function**	**Total number of operating facilities (x)**
100	10	1	-	-
		2	-	-
		3	-	-
		4	363.6	4 (x_2, x_5, x_7, x_9)

Capacity levels, q_j (kilograms)	Travel time, T (minutes)	Maximum number of operational facilities, σ (units)	Objective function	Total number of operating facilities (x)
		5	446.8	5 (x_2, x_5, x_7, x_8, x_9)
		6	521.6	6 ($x_1, x_2, x_5, x_7, x_8, x_9$)
		7	587.6	7 ($x_1, x_2, x_5, x_7, x_8, x_9, x_{10}$)
		8	636.8	8 ($x_1, x_2, x_4, x_5, x_7, x_8, x_9, x_{10}$)
		9	669.2	9 ($x_1, x_2, x_4, x_5, x_6, x_7, x_8, x_9, x_{10}$)
		10	695.6	10 ($x_1, x_2, x_3, x_4, x_5, x_6, x_7, x_8, x_9, x_{10}$)

Table 4.5 presents the results of calibrating the maximum number of operational facilities (σ) from one to ten, with a maximum travel time of 10 minutes and capacity levels of 100 kilograms. Performance values related to maximizing total recyclable waste covered are reported only from four operational facilities onward. This indicates that measurable performance improvements begin at this point and continue as more facilities are added. Beyond this threshold, the objective function increases steadily, reflecting that improved recyclable waste coverage increases as additional facilities are introduced. The maximum number of operational facilities, denoted as σ, directly influences the total amount of recyclable waste collected under each scenario. As σ increases, more facilities are allowed to operate, enabling broader demand coverage and improved accessibility. This expansion enhances the system's ability to assign demand locations within acceptable travel time limits, resulting in a higher volume of recyclable waste collected. The model's sensitivity to σ demonstrates that increasing the facility allowance leads to better network performance, reflecting greater efficiency in resource allocation and service reach.

Table 4.5
Total Number of Demand Locations by Calibration of Maximum Travel Time (T)

Operational Facilities (*j*)	Total Number of Demand Locations (*i*)									
	T=1	T=2	T=3	T=4	T=5	T=6	T=7	T=8	T=9	T=10
1	-	-	-	-	-	3	3	3	3	3
2	-	-	-	3	3	3	3	3	3	3
3	-	-	-	-	-	-	-	-	-	1
4	-	-	-	-	-	-	-	2	2	2
5	-	-	-	3	3	3	-	3	3	3
6	-	-	-	-	-	-	-	-	1	1
7	-	-	-	3	3	3	3	3	3	3
8	-	-	-	-	3	3	3	3	3	3
9	-	-	-	4	4	4	4	4	4	4
10	-	-	-	-	-	-	3	3	3	3

Table 4.5 presents the variation in the number of demand locations served based on the number of operational facilities and the calibration maximum travel time (T). Following this, when fewer than four facilities are in operation, no demand locations are served, regardless of the travel time. This indicates that a minimum of four facilities is required to begin covering demand. As the number of operational facilities and travel time increase, coverage improves. However, the rate of improvement becomes smaller with each additional facility. In summary, using four or more facilities with sufficient travel time increases the number of locations covered and supports more effective planning of recycling infrastructure.

4.2.2.2 Numerical Experimentation using Data from Rosni et al. (2022)

This section presents the outcomes obtained using the proposed model, which utilises the data extracted from Rosni et al. (2022), as detailed in Appendix 3. The value of the objective function is randomly measured with the variations of travel times between facility and demand locations (T) being $T = 10$, 13, and 17 minutes, maximum number of operational facilities (σ) between 1 and 5 units, and capacity multiplier (δ) being 1.0, 1.5, 2.0, 2.5, and 3.0. As outlined in Chapter 3, the model uses capacity multipliers (δ) instead of bin quantities to evaluate performance across varying container capacities. It was observed that increases in the capacity multiplier (δ) do not affect the objective function value, as the total demand remains constant across all scenarios.

Meanwhile, the relationship between objective function values across the travel times (T) and the maximum number of operational facilities (σ) is presented in Figure 4.1. From the figure, it is discovered that across all T variations, the objective function consistently increases as σ rises. This trend indicates that as more facilities become operational or capacity levels increase, this results in greater costs or a significant impact on the system performance.

Although the objective function value remains unaffected by variations in the maximum travel time (T) and the service threshold (δ), these constraints significantly influence the number of facilities required to operate. Specifically, changes in T and δ alter the spatial and service feasibility of meeting demand, thereby affecting the number of facilities that must be operated to maintain system performance. This suggests that, although overall optimization outcomes may be stable, operational decisions are sensitive to the settings of constraints.

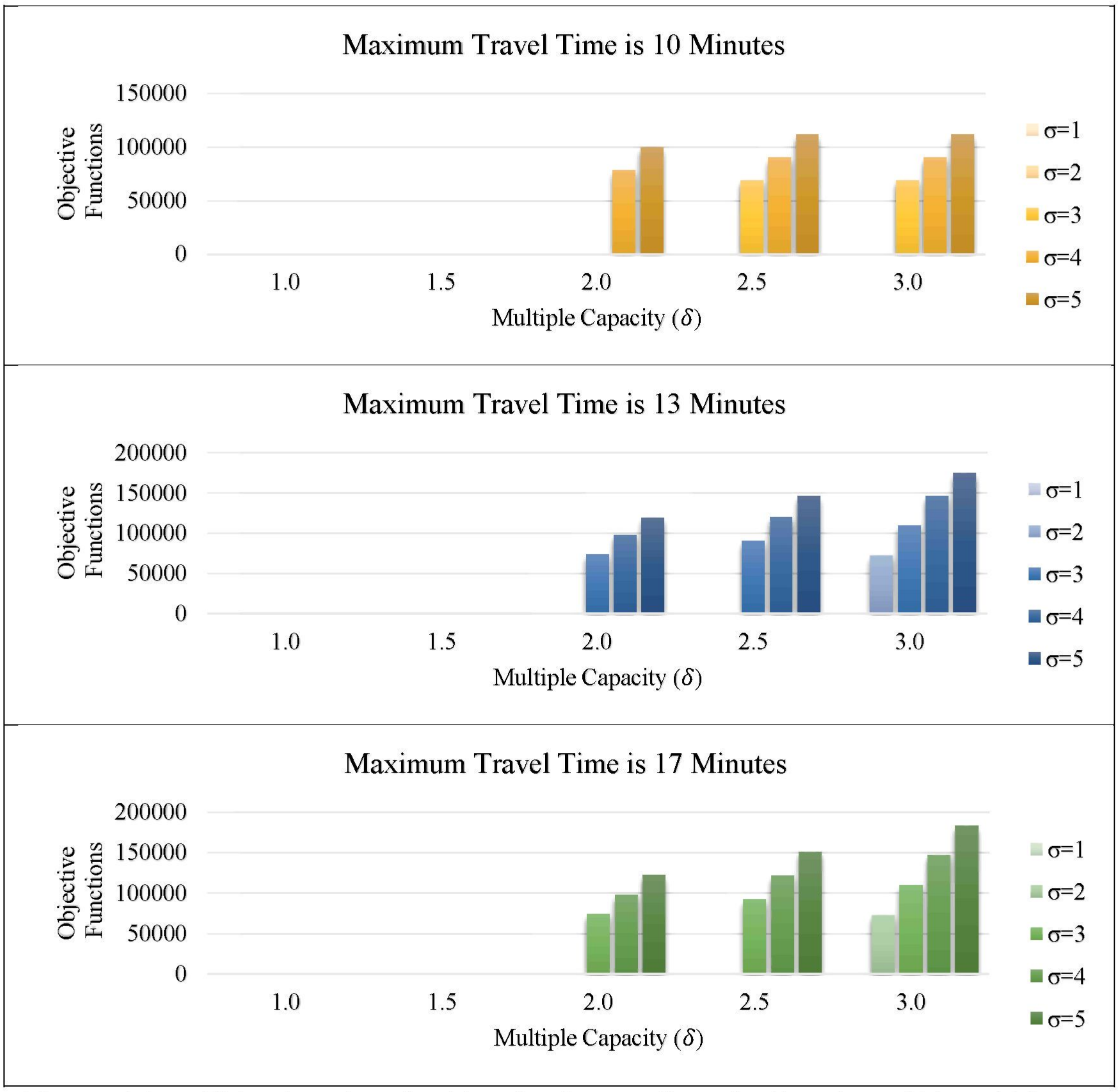


Figure 4.1 Objective Function Results Across Capacity Levels and Travel Times

This figure illustrates how variations in capacity multipliers (δ), maximum travel times (T), and the number of operating recycling facilities (σ) influence the performance of the objective function. The results reveal that objective values increase progressively with higher δ, longer T, and greater σ. At a travel time of $T = 10$ minutes, the model yields zero objective values for $\sigma = 1$ and $\sigma = 2$ across all capacity levels, indicating limited coverage. However, as σ increases to 3 or more, and δ reaches 2.0 or above, the model begins to generate positive outcomes. Furthermore, with extended travel times of $T = 13$ and $T = 17$ minutes, the system exhibits improved flexibility, achieving higher objective values even at lower capacity levels. The highest performance is observed at $T = 17$, $\sigma = 5$, and $\delta = 3.0$, confirming that increased logistical reach and facility availability significantly enhance system efficiency and coverage. This configuration represents the optimal balance between travel flexibility, operational capacity, and service scalability within the recycling system.

Table 4.6
Total Optimized Recycling Facility Locations across varying δ, T, and σ

Maximum travel time (T)	**Maximum number of operational facilities (σ)**	**Multiple capacity (δ)**				
		1.0	**1.5**	**2.0**	**2.5**	**3.0**
10	1	-	-	-	-	-
	2	-	-	-	-	-
	3	-	-	-	3	3
	4	-	-	4	4	4
	5	-	-	5	5	5
13	1	-	-	-	-	-
	2	-	-	-	-	2
	3	-	-	3	3	3
	4	-	-	4	4	4
	5	-	-	5	5	5
17	1	-	-	-	-	-
	2	-	-	-	-	2
	3	-	-	3	3	3
	4	-	-	4	4	4
	5	-	-	5	5	5

Table 4.6 presents the optimal number of recycling facility locations that can be fully operated under varying capacity multipliers (δ = 1.0 to 3.0), maximum travel times (T = 10, 13, and 17 minutes), and operational limits (σ = 1 to 5). At lower travel times (T = 10), no facilities are operable when σ = 1 or 2, regardless of capacity. However, when \sigma increases to 3 or more, and δ reaches 2.0 or above, the model begins to

generate positive outcomes. With extended travel times of $T = 13$ and $T = 17$ minutes, the system demonstrates improved flexibility, allowing facilities to operate at lower δ values.

The optimal system performance is observed when the maximum travel time (T) is set to 17 minutes, the number of operational facilities (σ) reaches 5, and the capacity multiplier (δ) is at 3.0. An extended travel time allows for greater flexibility in assigning demand locations to facilities, while higher capacity levels ensure that operational constraints are met without compromising service quality.

Among all the variables analyzed, the number of operational facilities (σ) emerges as the most influential factor. Incremental increases in σ consistently improve operability across various combinations of travel time and capacity settings, underscoring its critical role in system scalability and responsiveness. The spatial distribution of the optimal recycling facilities under these conditions is presented in Table 4.7.

Table 4.7
The Locations of the Selected Recycling Facilities (Based on Data Extracted from Rosni et al. (2022))

Facility Location (j)	**Facility Name**	**Demand Location (i)**
1	AEON Mall, Seremban 2	1
2	Palm Mall, Seremban	2
3	CenterPoint, Seremban	3, 4, 5
4	Petronas Petrol Station, Senawang	5, 6

Table 4.7 presents the locations of the selected recycling facilities, which were determined based on data extracted from Rosni et al. (2022), ensuring alignment with established spatial and operational criteria. AEON Mall (j_1), located in Seremban 2, is designated to serve the demand location (d_1), while Palm Mall (j_2) in Seremban is assigned to location (d_2). CenterPoint (j_3), also situated in Seremban, accommodates demand locations (d_3, d_4, and d_5), indicating a broader service coverage. Petronas Petrol Station (j_4) in Senawang is responsible for demand locations (d_5 and d_6), reflecting an overlap with CenterPoint (j_3) for location (d_5). Additionally, the figure

below presents the geographical distribution of recycling facility locations and their corresponding demand locations within the case study area.

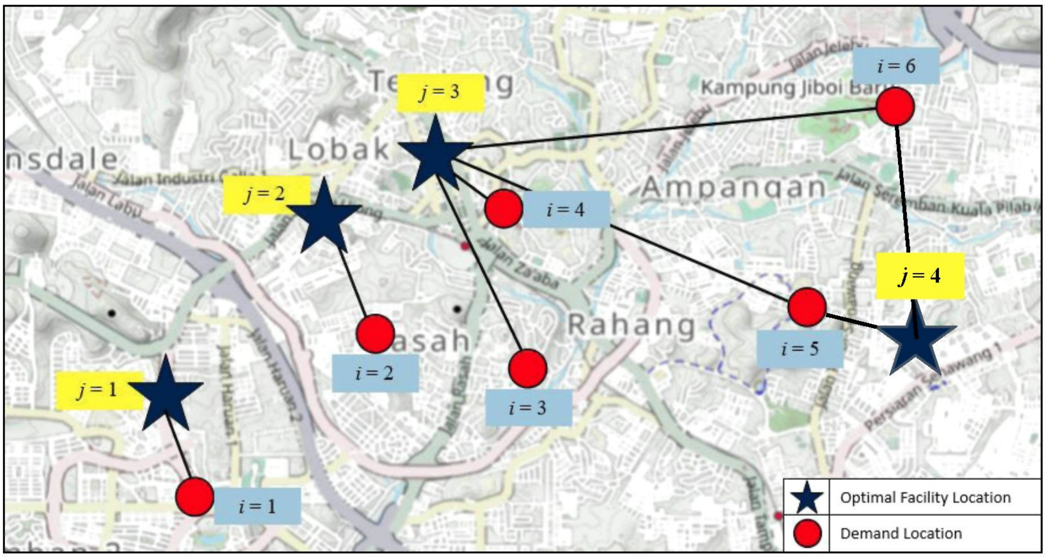


Figure 4.2 The Optimal Recycling Facility

Figure 4.2 illustrates the optimal locations of recycling facilities, represented by star-shaped icons, as determined by the proposed model using a BLP approach with a covering formulation. The results clearly indicate that all demand locations are successfully assigned to at least one facility, ensuring full coverage of recyclable waste within the study area. When compared to the findings of Rosni et al. (2022), which identified three optimal recycling facility locations, the proposed model demonstrates an improvement by identifying four optimal facilities. This enhancement reflects a positive outcome, indicating that the proposed model offers a more effective solution.

Furthermore, the numerical experiment suggests that adding more operational recycling facilities can significantly improve service levels. However, the model also indicates that increasing travel time or facility capacity alone does not always result in collecting more recyclables. These results suggest that local municipalities can improve recycling efficiency by focusing on increasing the number of facilities, even with slight changes. This confirms that the proposed model is a practical and reliable tool for planning recycling facility locations.

4.3 Result 2: Optimal Location of Recycling Facilities within Seremban, Negeri Sembilan

This section presents the results derived from the calibration procedures implemented on various proportions of the estimated recyclable waste to be collected in Seremban, Negeri Sembilan. The estimated recyclable waste dataset is presented in Appendix 4. The analysis of the objective function values for each iteration is based on the number of operational facilities, considering capacity levels, maximum travel times, and the proportion of recyclable waste generated at location *i*.

The results presented in Appendix 5 summarize the behavior of the objective function under varying operational constraints. Specifically, the analysis explores the impact of changes in maximum travel time (*T*) and maximum number of operational recycling facilities, while maintaining a fixed container capacity level at each facility location. These variations were applied to identify optimal trade-offs between service coverage and operational efficiency. The corresponding graph line of results is presented below, illustrating how the objective function fluctuates in response to adjustments in T and facility limits.

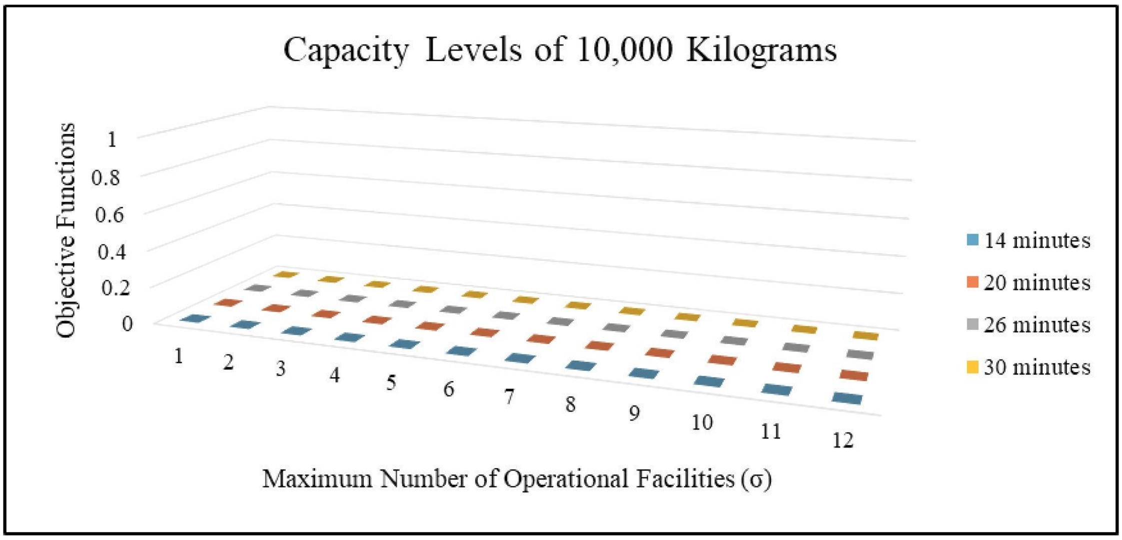


Figure 4.3 Objective Function Results for Varying σ and T at q_j (10,000 kilograms)

Figure 4.3 presents a graph illustrating the results of the objective functions for a capacity level of q_j = 10,000 kilograms, with variations in the maximum number of operational facilities (σ) from 1 to 12 and maximum travel times of 14, 20, 26, and 30 minutes. As displayed in the graph, the objective function yields no outcome across all combinations, as the capacity levels were insufficient to support coverage for the entire demand in the Seremban case study.

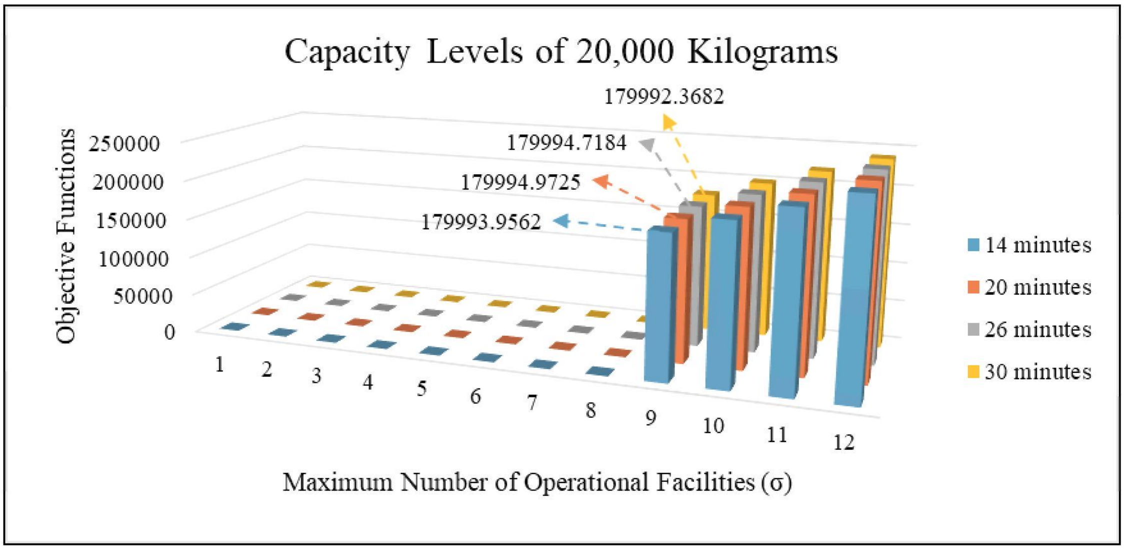


Figure 4.4 Objective Function Results for Varying σ and T at q_j (20,000 kilograms)

Figure 4.4 presents a graph of the objective function results for a scenario in which each facility location has a capacity of 20,000 kilograms. The results vary the maximum number of operational facilities (σ) from 1 to 12 and consider maximum travel times of 14, 20, 26, and 30 minutes. For facility counts ranging from $\sigma = 1$ to 8, the objective function yields no result, indicating that these configurations are insufficient to support the system under the given capacity. Starting from $\sigma = 9$, the objective function begins to produce positive values, which increase steadily as the number of facilities increases. The graph reflects this trend, showing flat lines for $\sigma = 1$ to 8 and a rising pattern from $\sigma = 9$ to 12 across all travel time thresholds. This pattern demonstrates that a minimum of nine operational facilities is required to activate the objective function and effectively utilize the 20,000 kilograms capacity, with longer travel times offering slight flexibility in coverage.

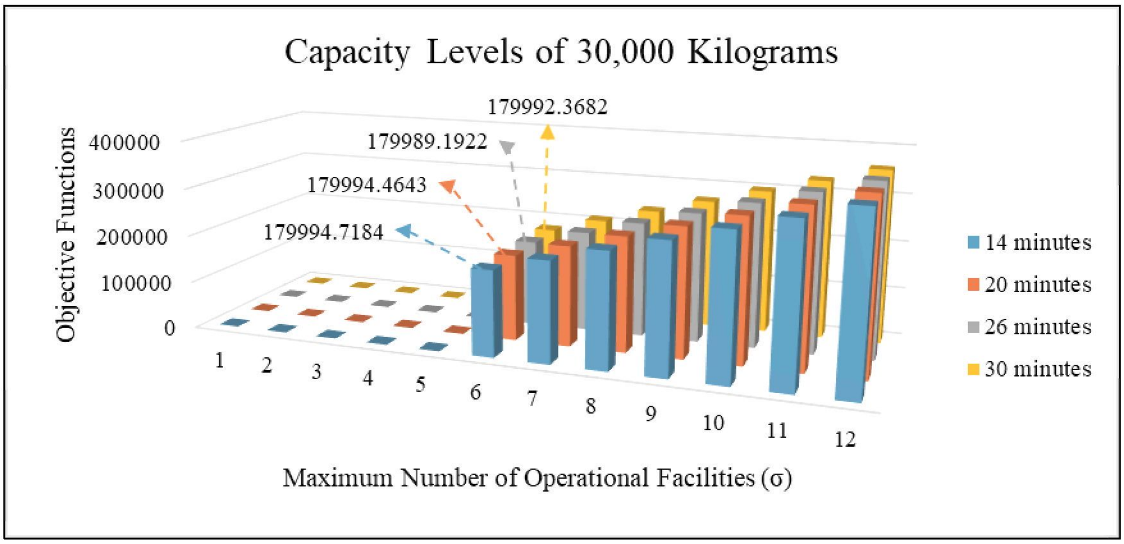


Figure 4.5 Objective Function Results for Varying σ and T at q_j (20,000 kilograms)

Figure 4.5 presents a line graph based on the objective function results for a facility capacity level of 30,000 kilograms. The analysis varies the maximum number of operational facilities (σ) from 1 to 12 and considers maximum travel times of 14, 20, 26, and 30 minutes. For σ values ranging from 1 to 5, the objective function values remain at zero, indicating that these configurations are insufficient to support the system under the given capacity. Starting from $\sigma = 6$, the objective function begins to produce positive values, which increase steadily as the number of facilities increases. The graph reflects this trend, showing flat lines for $\sigma = 1$ to 5 and a rising pattern from $\sigma = 6$ to 12 across all travel time levels. This indicates that at least six operational facilities are needed to utilize the 30,000 kilograms capacity effectively, with longer travel times providing slight improvements in coverage.

Table 4.8
Objective Function Values by Capacity Level and Number of Operational Facilities across varying Maximum Travel Times

σ	**14 minutes**			**20 minutes**			**26 minutes**			**30 minutes**		
	q_1	q_2	q_3	q_1	q_2	q_3	q_1	q_2	q_3	q_1	q_2	q_3
σ = 1	-	-	-	-	-	-	-	-	-	-	-	-
σ = 2	-	-	-	-	-	-	-	-	-	-	-	-
σ = 3	-	-	-	-	-	-	-	-	-	-	-	-
σ = 4	-	-	-	-	-	-	-	-	-	-	-	-

σ	14 minutes			20 minutes			26 minutes			30 minutes		
	q_1	q_2	q_3	q_1	q_2	q_3	q_1	q_2	q_3	q_1	q_2	q_3
σ = 5	-	-	-	-	-	-	-	-	-	-	-	-
σ = 6	-	-	179995	-	-	179994	-	-	179989	-	-	179992
σ = 7	-	-	209994	-	-	209994	-	-	209988	-	-	209993
σ = 8	-	-	239993	-	-	239993	-	-	239987	-	-	239992
σ = 9	-	179994	269992	-	179995	269992	-	179995	269986	-	179992	269991
σ = 10	-	199994	299991	-	199994	299992	-	199994	299985	-	199981	299990
σ = 11	-	219994	329990	-	219994	329991	-	219995	329984	-	219990	329988
σ = 12	-	239993	359989	-	239993	359990	-	239992	359989	-	239993	359990

Table 4.8 presents the system's performance under different configurations of the maximum number of operational facilities (σ), capacity levels (q_1= 10,000 kilograms, q_2 = 20,000 kilograms, q_3 = 30,000 kilograms), and a maximum of travel time (14, 20, 26, and 30 minutes). The table outlines that when the number of operational facilities is low, especially below six, the system cannot produce results. This is marked with a dash (–), meaning the model could not support the system under those conditions. At a capacity level of 30,000 kilograms, results begin to appear when six facilities are used. At 20,000 kilograms, results only appear when nine facilities are operating. Although both configurations, with six facilities at 30,000 kilograms and nine facilities at 20,000 kilograms, perform similarly, with a maximum travel time of 14 minutes, this research chose the 20,000 kilograms option.

The main reason is cost and service coverage. Using 20,000 kilograms facilities is more cost-effective than using larger 30,000 kilograms ones. Also, having nine facilities provides better access and more options for users than only six. Therefore, the selected configuration, with a 20,000-kilogram capacity level, a 14-minute maximum travel time, and nine operational facilities, offers a good balance between performance, cost savings, and user accessibility.

Table 4.9 illustrates the optimal locations of recycling facilities identified in this research, based on a maximum travel time of 14 minutes. It highlights the performance of different capacity levels and numbers of operational facilities, with the selected solution being a 20,000-kilogram capacity level and nine facilities. This solution comprises six existing recycling facilities and three potential new locations. The yellow highlights represent existing recycling facility locations in Seremban, while the green highlights indicate additional sites identified as potential recycling facility locations. The table below provides the names of each location included in the analysis.

Table 4.9
Names of Existing and Potential Optimal Facility Locations

j	Recycling Facility Location	Detail	Selection Status
1	Solid Waste Management (SWM) Environment	Existing	–
2	Sri Carcosa, S2	Existing	✓
3	Taman Arowana Indah	Existing	✓
4	Kampung Sentosa Jaya	Existing	✓
5	Perpustakaan Awam Negeri Sembilan	Existing	–
6	Majlis Bandaraya Seremban	Existing	✓
7	Taman Pasar Ampangan	Existing	✓
8	Taman Sri Inai	Existing	✓
9	Kalista 2	Existing	–
10	Marrybrown Pusat Perniagaan Oasis	Potential	✓
11	Benteng Ampangan Diecast	Potential	✓
12	99 Speedmart 1692 (NS) Galla Industrial Park	Potential	✓

Note: Facilities marked with "✓" indicate the final locations selected based on model optimization results and validation criteria such as accessibility, demand coverage, and feasibility, while "–" represents sites not included in the final selection.

Table 4.9 presents 12 recycling facility locations in Seremban evaluated in this research. Among these, nine locations were identified as optimal for operation under the selected configuration, which features a 20,000 kilograms capacity and a 14-minute maximum travel time. These include six existing facilities and three potential sites. The results show the inclusion of three potential sites: Marrybrown Pusat Perniagaan Oasis, Benteng Ampangan Diecast, and 99 Speedmart 1692 (NS) Galla Industrial Park. Adding these sites would further enhance service reach, particularly in areas previously underserved by existing facilities. In contrast, the locations not recommended for operation are the Solid Waste Management (SWM) Environment, Perpustakaan Awam Negeri Sembilan, and Kalista 2, as these locations do not contribute effectively to meeting system demand. The figure below presents the optimal recycling facility locations in Seremban. It provides an overview of the selected configuration within the case study area, highlighting the spatial distribution of facilities that best meet system performance under the defined parameters.

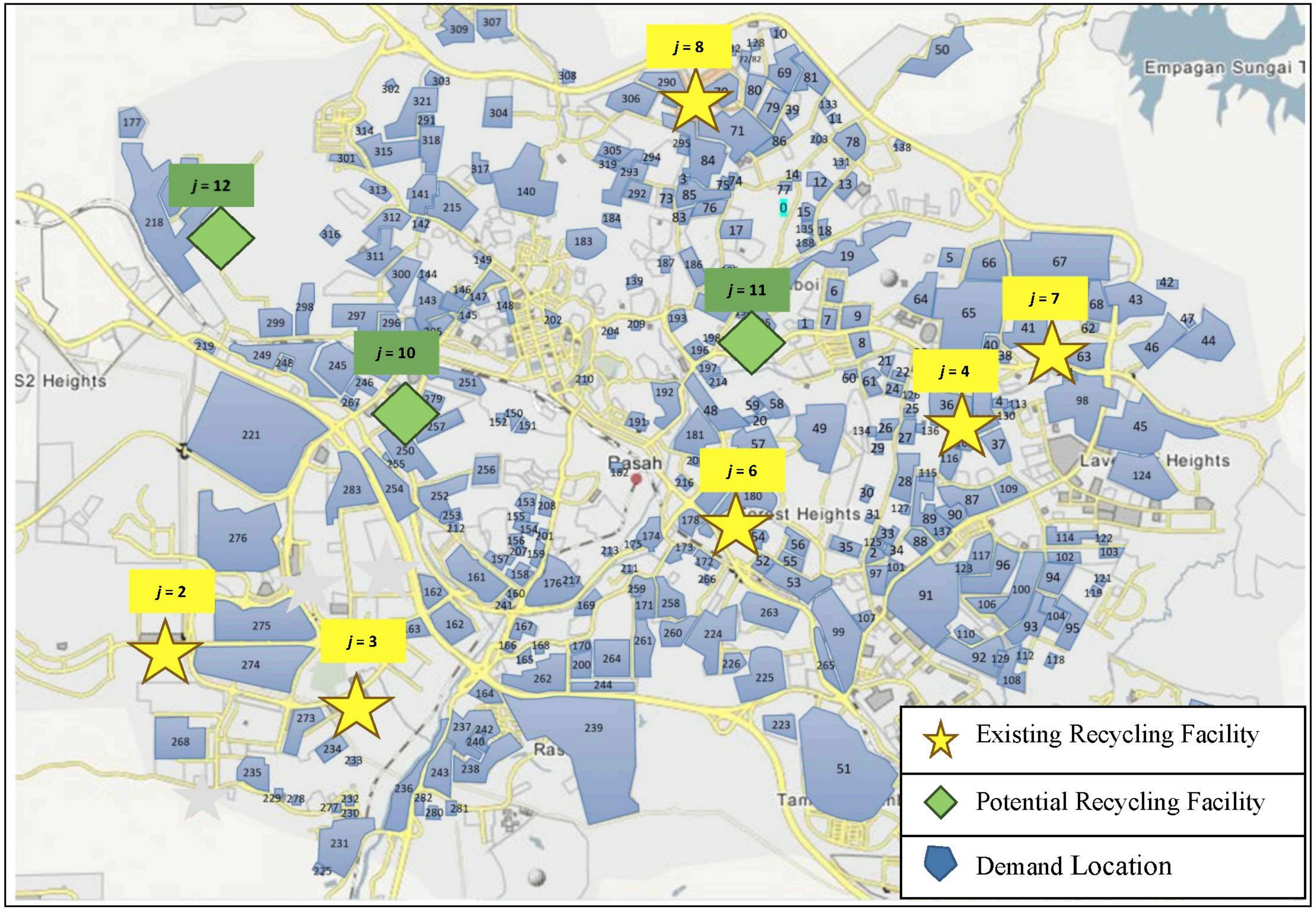


Figure 4.6 Optimal Facility Location Identified in the Case Study

Figure 4.6 presents the mapping of the case study area, showing the distribution of demand locations, existing recycling facilities, and potential facility sites. In the figure, existing facilities are represented by yellow stars, potential facilities by green diamonds, and demand locations by blue squares.

Table 4.10
Demand Coverage with Optimal Facility Location

Recycling Facility Location (*j*)	**Demand location (*i*)**	**Total Covered Demand Quantity at location *i***
2	6, 16, 57, 142, 153, 154, 155, 157, 158, 161, 176, 179, 205, 207, 224, 227, 234, 236,237, 240, 242, 245, 246, 247, 250, 251, 256, 262, 268, 278, 281, 290, 292	33
3	1, 3, 6, 7, 8, 9, 31, 48, 126 ,140, 144, 153, 159, 163, 168, 172, 173, 175, 181, 200, 210, 217, 219, 221, 222, 228, 229, 230, 233, 235, 249, 252, 253, 255, 260, 266, 267, 269, 271, 276, 280, 282, 283, 293	44
4	5, 19, 23, 36, 38, 42, 43, 49, 60, 66, 68, 75, 92, 93, 95, 103, 108, 110, 124, 133, 138, 139,164, 174, 188, 201, 209, 223, 225, 226, 287, 289, 306	33
6	2, 12, 26, 30, 40, 41, 51, 53, 55, 58, 61, 67, 76, 96, 97, 116, 121, 127, 130, 131, 137, 166,182, 212, 213, 220, 239, 270, 285, 308	30
7	1, 3, 4, 5, 6, 7, 8, 9, 13, 15, 17, 21, 22, 24, 25, 27, 28, 29, 33, 34, 37, 45, 47, 53, 54, 56, 63, 64, 65, 77, 88, 90, 91, 94, 101, 102, 104, 106, 107, 112, 113, 114, 117, 119,122, 123, 186, 189, 191, 192, 195, 203, 206, 207, 210, 211, 265, 288	58
8	2, 4, 15, 20, 24, 32, 39, 50, 59, 69, 70, 72, 79, 80, 81, 82, 83, 115, 128, 134, 141, 181, 185,187, 190, 196 ,198, 202 ,209, 241, 284, 300, 304, 307, 309	35
10	2, 4, 7, 15, 16, 18, 21, 22, 52, 71, 73, 74, 78, 85, 86, 89, 99, 125, 132, 136 ,148, 151, 155, 159, 170 ,184, 193, 194, 197, 204, 205, 208, 214, 216, 218, 231, 243, 257, 258, 259, 261, 272, 273, 275, 277, 286, 295, 301, 310, 312, 314	51
11	9, 10, 11, 14, 21, 27, 33, 35, 44, 46, 62, 87, 98, 100, 105, 109, 111, 118, 120, 129, 135, 145, 149, 177, 180, 210, 232, 238, 244, 248, 264, 291, 298, 299, 302, 303, 313, 315	38
12	6, 16, 20, 48, 57, 59, 84, 140, 141, 142, 143, 144, 145, 146, 147, 148,	56

Recycling Facility Location (j)	**Demand location (i)**	**Total Covered Demand Quantity at location i**
	149, 150, 151, 152, 153, 154, 155, 156 ,157, 158, 159 , 160, 161, 162, 164, 165, 166, 167, 168,169 , 170, 171, 172, 173 , 174, 175, 177, 178, 183, 199, 215, 254, 263, 274, 279, 294, 296, 297, 305, 311	

Figure 4.6 presents the mapping of the case study area, showing the distribution of demand locations, existing recycling facilities, and potential facility sites. In the figure, existing facilities are represented by yellow stars, potential facilities by green diamonds, and demand locations by blue squares.

Table 4.10 presents the optimal recycling facility that can cover a minimum of 30 demand locations and a maximum of 58 demand locations. The results indicate that the minimum coverage is at Majlis Bandaraya Seremban (j = 6) and the maximum coverage is at Taman Pasar Ampangan (j = 7). Consequently, the total coverage is 100%, with nine optimal facility locations, a travel time of 14 minutes, and a service capacity of 20,000 kilograms.

4.4 Result 3: Scenario Analysis

To assess the performance of the proposed model under varying demand conditions, a series of scenario-based experiments was conducted. These scenarios were designed using scaled estimates of recyclable waste levels at 90%, 70%, 50%, 30%, and 10% relative to the baseline. Each scenario represents a distinct level of service intensity, enabling the evaluation of the model's adaptability and robustness across a range of operational demands. The corresponding estimated number of recyclable wastes at each location i (d_i) for each scenario are presented in Appendix 6, providing a comprehensive foundation for the analysis that follows.

Figures 4.6 to 4.10 illustrate the relationship between the estimated proportion of recyclable waste to be collected (spanning from 10% to 90%), capacity levels (q_j) from 5,000 to 20,000 kilograms, maximum travel times (T) of 14, 20, 26, and 30 minutes, maximum operational facility allowances (σ) from one to twelve units, and the output of the proposed mathematical model, i.e., the objective function values.

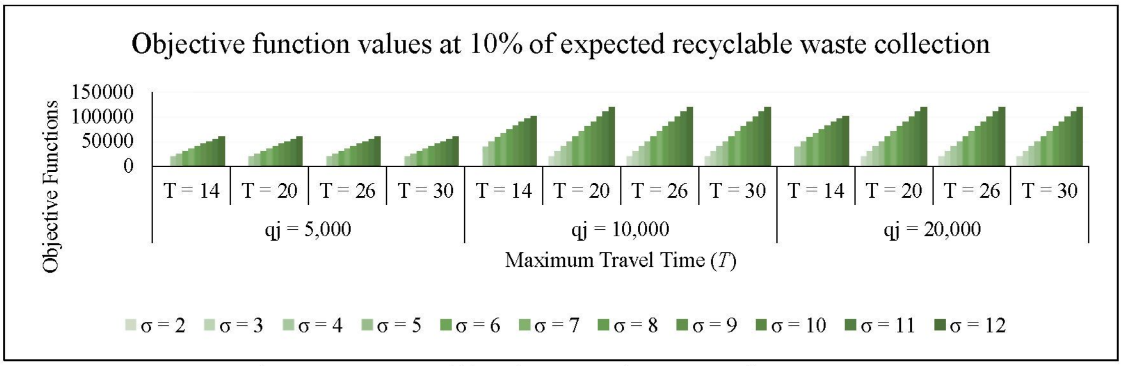


Figure 4.7 Calibration Service Capacity at 10%

Figure 4.7 illustrates the output of the proposed model when 10% of recyclable waste is expected to be collected. It clearly indicates that as σ and q_j increases, the objective function values also increase. This is mainly because more recyclables can be accommodated through the expansion of the allowance for operational recycling facilities and their respective capacity levels. Additionally, it is observed that having one facility is insufficient to cover 10% of recyclable waste. In contrast, the impact of T on the objective function values is minimal. For instance, when q_j is 10,000 and 20,000 kilograms, the objective function values demonstrate only slight increases as T rises from 14 to 20 minutes and remain unchanged from 20 to 30 minutes.

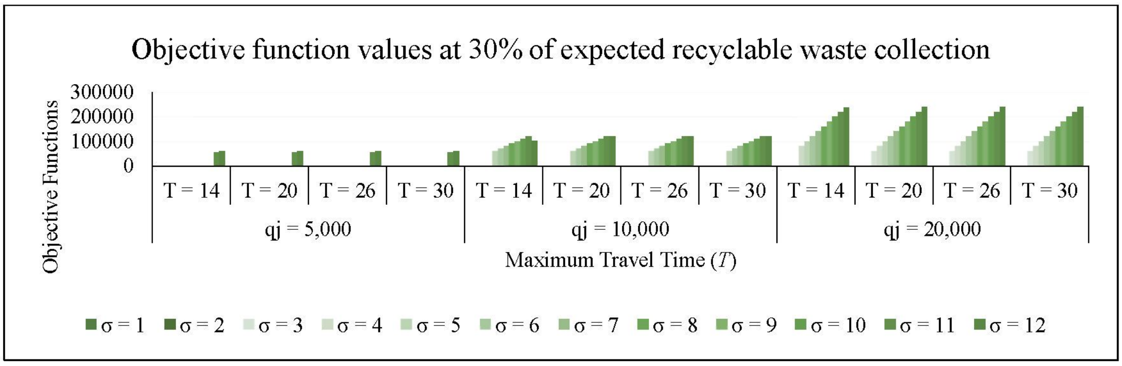


Figure 4.8 Calibration Service Capacity at 30%

Figure 4.8 examines scenarios in which 30% of recyclable waste is expected to be collected. Similar to Figure 4.6, calibration service capacity at 10%, the objective function values increase as both σ and q_j increase. From the figure, when q_j is at 5,000 kilograms, fewer facilities are operating across all T values, except when σ is 11 or 12 units. This is attributed to the fact that the lower capacity for covering recyclable waste requires additional facilities to operate in order to meet the collection target.

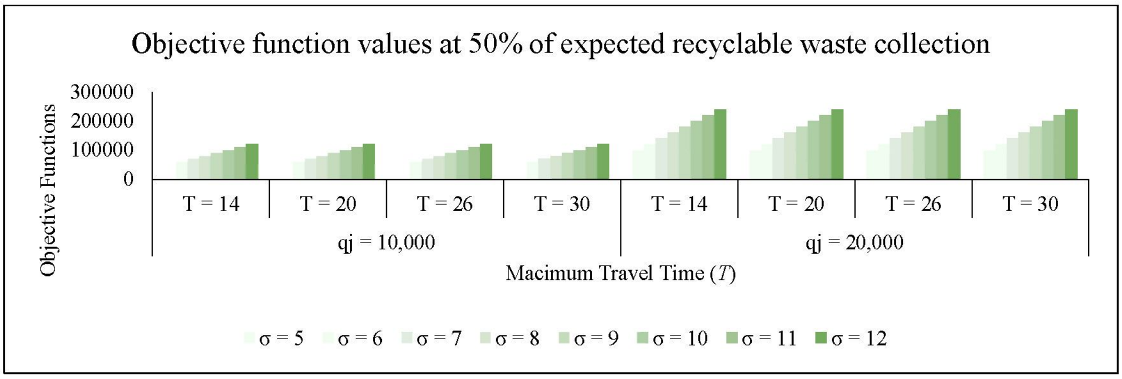


Figure 4.9 Calibration Service Capacity at 50%

Figure 4.9 displays the objective function values for scenarios when 50% of the recyclable waste is collected. From the figure, the objective function values become infeasible when q_j is set at 5,000 kilograms and σ is below 5 units. The analysis indicates that achieving a 50% collection rate of recyclable waste requires the operation of at least five facilities, each with a minimum capacity of 10,000 kilograms. It also indicates that the values of the objective function remain unchanged despite an increase in T.

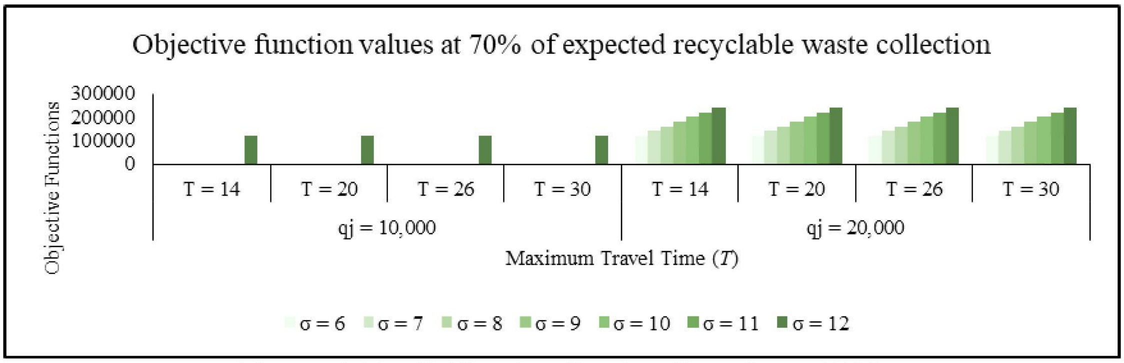


Figure 4.10 Calibration Service Capacity at 70%

Figure 4.6 presents the mapping of the case study area, showing the distribution of demand locations, existing recycling facilities, and potential facility sites. In the figure, existing facilities are represented by yellow stars, potential facilities by green diamonds, and demand locations by blue squares.

Table 4.10 illustrates the objective function values for collecting 70% of the generated recyclable waste. From the figure, when q_j is set at 5,000 kilograms, the solution becomes infeasible, indicating that the system cannot achieve 70% coverage with such limited capacity. Increasing q_j to 10,000 kilograms yields a feasible solution only when σ is at 12 units across all T values. However, as the capacity is further increased to 20,000 kilograms, the objective function values rise proportionally. This reflects the need for a greater number of operational facilities to accommodate the higher capacity allocation.

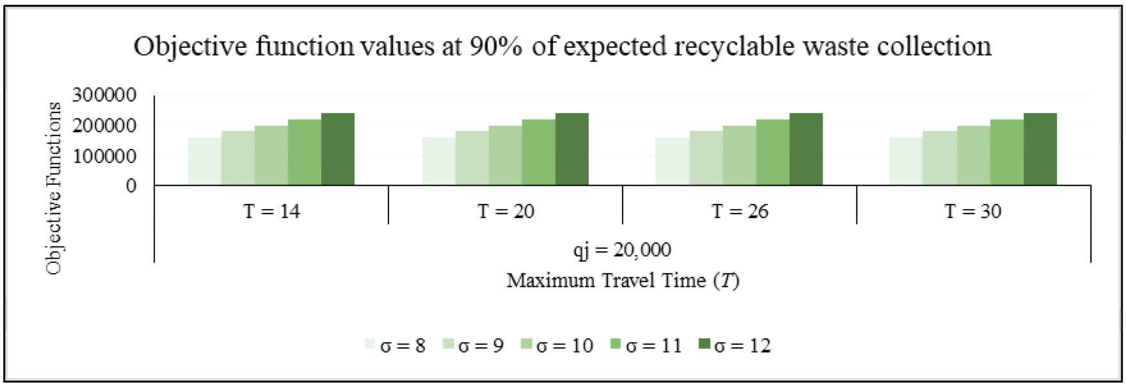


Figure 4.11 Calibration Service Capacity at 90%

From Figure 4.7 to Figure 4.11, it is evident that the objective function values vary significantly across different capacity levels and operational facility allowances, but remain relatively stable across all T values. Despite this consistency in T values, they provide valuable insights into the minimum travel time required to maintain feasible solutions. Indirectly, the proposed model is able to determine the minimum travel times required for users to access recycling facility locations. The findings further emphasize the significant influence of expanding the number of operational facilities and enhancing relative capacity in improving overall system availability and accessibility. This demonstrates a greater impact on performance outcomes compared to reductions in travel time alone. Although reductions in travel time may offer incremental benefits, it is the strategic augmentation of infrastructure and capacity that delivers the most significant improvements in service coverage and operational efficiency.

Table 4.11 provides detailed insights into the number of facilities required to be operational at various levels of expected recyclable waste collection. The table illustrates how higher waste collection targets necessitate a corresponding increase in the number of operational facilities. This ultimately reinforces the significance of aligning infrastructure planning with anticipated service loads to ensure sustainable and effective recycling operations.

Table 4.11

Minimum of Operational Facilities at Different Proportion Rates

Capacity level (q_j)	**Traveling Time (*T*) Minutes**	**Proportion of d_i**				
		90%	**70%**	**50%**	**30%**	**10%**
5,000	14	-	-	-	11	4
	20	-	-	-	11	4
	26	-	-	-	11	4
	30	-	-	-	11	4
10,000	14	-	12	9	6	4
	20	-	12	9	6	2
	26	-	12	9	6	2
	30	-	12	9	6	2
20,000	14	8	6	5	4	4
	20	8	6	5	3	1
	26	8	6	5	3	1
	30	8	6	5	3	1

Table 4.11 indicates the respective number of recycling facilities that can be operational at capacity q_j and proportion of expected recyclable waste collected. For a capacity of 5,000 kilograms, there are no recycling facilities that can serve at 90%, 70%, and 50% expected recyclable waste collection. However, at 30% demand, 11 recycling facilities are operational, and at 10% demand, four recycling facilities are operational. Then, for a capacity of 10,000 kilograms, no results are observed at a 90% expected recyclable waste collection rate. At 70% expected recyclable waste collection, 12 recycling facilities are operational, while at 50%, nine facilities are operational. At a 30% level, six recycling facilities are operational, and at a 10% demand, either two or four recycling facilities are operational. For the capacity of 20,000 kilograms, eight recycling facilities are operational at 90% expected recyclable waste collection, while six facilities are operational at 70% demand. At a 50% expected rate of recyclable waste

collection, five recycling facilities are operational. At a 30% level, either three or four recycling facilities are operational, and at a 10% expected recyclable waste collection rate, either one or four recycling facilities are operational. As expected, with greater capacity levels in facilities, a greater demand can be served.

Table 4.11 also presents a scenario where only one recycling facility is in operation, which may occur due to budget constraints. In this scenario, users are required to travel at least 20 minutes to access a recycling facility. Based on the data, to accommodate 10% of the recyclable waste, four facilities are required, each with a capacity of 5,000 kilograms. This requirement is reduced to two facilities with a capacity of 10,000 kilograms and one facility with a capacity of 20,000 kilograms. These figures indicate that longer travel times significantly reduce user participation in recycling activities, thereby lowering the number of facilities required to meet reduced demand. This variation illustrates that higher-capacity facilities can reduce the total number of sites needed to meet a given demand level. This low participation rate could negatively affect the state's overall recycling rate. Alternatively, to achieve a collection rate of at least 90% of recyclable waste, the municipality should operate eight recycling facilities. Under this configuration, users would travel no more than 14 minutes to access a facility, thereby enhancing accessibility and encouraging higher participation. The optimal facility locations were determined through scenario analysis, considering a 90% recyclable waste rate, a maximum travel time of 14 minutes, a facility capacity of 20,000 kilograms, and a limit of eight operational facilities. The resulting configuration, which represents the most efficient spatial arrangement under these constraints, is illustrated in Appendix 7.

4.5 Summary

This chapter presents the results and discussions, beginning with the proposed mathematical model for locating recycling facility locations with fixed capacity. It includes the results of numerical experiments conducted with three tests and additional experimentation using a random dataset. The chapter then addresses the optimal location of recycling facilities within Seremban, Negeri Sembilan. Furthermore, it provides a scenario analysis that includes optimal locations for recycling facilities from both user and authority perspectives. The chapter concludes with remarks on both scenarios.

CHAPTER 5
CONCLUSION

5.1 Introduction

This chapter presents the conclusion of the overall research objectives, the contributions made in this research, and recommendations for future research.

5.2 Conclusions

This research develops a modified mathematical model for optimizing the locations of recycling facilities, incorporating fixed capacity constraints and realistic service parameters. The literature review, model formulation, numerical experiments, and real-world implementation in Seremban aimed to identify effective strategies for facility allocation and user accessibility. The following conclusion summarizes the key findings, model validations, and practical implications derived from the various phases of this research.

Following this, this research identifies the key factors influencing the location of recycling facilities, with a specific focus on demand, space, location, recycling rate, and accessibility. A comprehensive review of existing studies revealed that most facility location problems (FLPs) have been addressed using mathematical models, particularly the covering location model. This model serves as the foundation for the secondary scope of the research. Additionally, several recycling facility location models were examined and categorized based on their objective functions, decision variables, and parameters. Further analysis of four selected research studies, selected for their relevance to the research scope, provided deeper insights into existing methodologies. From the literature review and article analysis, a significant research gap was identified. Therefore, the application of mathematical modeling, especially the covering location model, for solving recycling facility location-allocation problems remains limited. Furthermore, there is a noticeable lack of research focusing on improving recycling facility planning in Malaysia using such models. The detailed discussion of these findings can be observed in Chapter 2.

Following that, this research focuses on modifying an existing mathematical programming model for the facility location problem using Binary Linear Programming (BLP) to determine the optimal locations for recycling facilities. To achieve this, specific enhancements were proposed to allow for the simultaneous determination of optimal container allocation within the model. One of the key modifications involved the introduction of a fixed capacity level for recycling containers. The performance of the proposed modified mathematical model was evaluated through numerical experimentation, particularly via calibration procedures. Two datasets were employed for this purpose: a randomly generated dataset and an empirical dataset sourced from Rosni et al. (2022). The model was validated through three distinct tests, each examining the relationship between key input parameters and model performance. The first test analyzed the impact of varying maximum travel time thresholds (T) on the objective function value, total recyclable waste coverage, and the number of operating facilities. Meanwhile, the second test assessed how changes in service capacity (q_j) affected the same outcome measures. Moreover, the third test evaluated the influence of different maximum limits on operational recycling facilities (σ) on the model's outputs. The results from the experiments, particularly using the Rosni et al. (2022) dataset, confirmed that increasing the number of operational recycling facilities leads to improved service levels. These findings validate the model's applicability and reliability, demonstrating its potential as a decision-support tool for optimizing recycling facility planning under capacity and service constraints. Therefore, the modified model effectively integrates both location selection and fixed-capacity allocation, offering a more realistic and practical approach to planning recycling infrastructure. A detailed discussion of these findings is provided in Chapter 3.

This research enhanced the proposed model, which was applied to the Seremban area, enabling the determination of optimal recycling facility locations and the total amount of recyclable waste collected, based on real-world data and optimization techniques. The model was assessed using calibration procedures based on various proportions of estimated recyclable waste collected from the region. The results demonstrated that a service capacity of 10,000 kilograms was insufficient to produce feasible solutions, highlighting its inadequacy for effective implementation. In contrast, service capacities of 20,000 kilograms and 30,000 kilograms generated valid outcomes. The 20,000 kilograms capacity corresponded with four objective functions, while the 30,000 kilograms capacity supported six operational facilities. The findings revealed that a minimum operational capacity of 20,000 kilograms, combined with a processing time of 14 minutes, required a total of nine recycling facilities to ensure full-service coverage. Of these nine facilities, six were existing sites, namely Sri Carcosa, S2, Taman Arowana Indah, Kampung Sentosa Jaya, Majlis Bandaraya Seremban, and Taman Pasar Ampangan. At the same time, three were identified as potential facilities: Marrybrown Pusat Perniagaan Oasis, Benteng Ampangan Diecast, and 99 Speedmart 1692 (NS) Galla Industrial Park. Among these, the minimum demand coverage was observed at MBS, while the maximum was at Taman Pasar Ampangan. Overall, the implementation of the modified model in Seremban confirms its effectiveness in supporting data-driven planning for recycling facility allocation, providing practical solutions that align with capacity, demand, and travel time considerations. A detailed discussion of these results is provided in Chapter 4.

Furthermore, the objective was to propose optimal strategies for locating and allocating recycling facilities that would benefit both users and local authorities, utilizing scenario analysis techniques. This was achieved through scenario-based analysis and parameter calibration techniques designed to reflect real-world decision-making preferences. By simulating various scenarios, the model was calibrated to evaluate recycling collection rates at 90%, 70%, 50%, 30%, and 10%, across facility capacity levels (q_j) of 5,000, 10,000, and 20,000 kilograms. The findings revealed that a single facility is inadequate to support even a 10% recycling rate. For 30% waste collection, feasible solutions emerged at 5,000 kilograms capacities, particularly when the number of operational facilities (σ) reached 11 or 12. Achieving 50% collection required at least five facilities with a minimum capacity of 10,000 kilograms. For higher targets, a 70% collection rate was only feasible when q_j remained at 10,000 kilograms and $\sigma = 12$, while a 90% collection rate was only attainable with capacities of 20,000 kilograms and a minimum of eight operational facilities. The results emphasized that increasing facility capacity and the number of operational sites had a greater impact on improving service coverage and accessibility than merely reducing user travel times. Despite the optimized strategies, the model also estimated that only 10% of users are likely to participate in recycling activities, a factor that may limit overall system performance. Therefore, if the goal is to achieve a 90% recycling rate, it is recommended that at least eight facilities be operated, ensuring users do not travel more than 14 minutes to reach a recycling facility. Chapter 4 contains a comprehensive discussion of the results.

Therefore, this research successfully fulfilled its objectives through a structured and systematic methodology. The investigation began by identifying and analyzing key factors influencing the recycling facility location problem, including demand distribution, spatial limitations, site suitability, recycling rates, and accessibility through an extensive literature review. This approach established a solid foundation for understanding the underlying challenges. Building on this, the mathematical programming model was modified using Binary Linear Programming (BLP), resulting in an improved Facility Location Model with Fixed Capacity that effectively determines optimal facility placements. The model was then applied to the Seremban area, enabling the determination of both optimal recycling facility locations and the total amount of recyclable waste collected, based on real-world data and optimization techniques. Furthermore, scenario analysis techniques were employed to propose strategic solutions for facility location and allocation, offering practical benefits to users and local authorities. Collectively, the outcomes of this research provide a comprehensive framework for recycling facility planning and serve as a valuable reference for future policy development and decision-making.

In addition to achieving its objectives, this research makes important contributions to both theory and practical application. Theoretically, it enhances existing facility location models by introducing a new parameter: fixed capacity levels for each container at the recycling facility. This addition reflects real-world operational limits and improves the model's accuracy and relevance for urban planning. On the practical side, the model was assessed using actual data from the Seremban area, indicating its effectiveness in identifying optimal recycling facility locations and estimating the total amount of recyclable waste collected. The scenario analyses also provided useful strategies for local authorities to improve recycling systems and support sustainable waste management planning.

5.3 Recommendations

Based on the outcomes of this research, several pivotal recommendations are put forward to enhance both scholarly understanding and practical implementation in the optimization of recycling facilities. Future investigations should consider incorporating advanced methodologies such as Multi-Criteria Decision Analysis (MCDA), dynamic and adaptive capacity models, and big data-driven techniques, including machine learning, to improve decision-making processes under varying environmental and operational conditions.

From a practical standpoint, local authorities and waste management agencies are advised to implement the refined mathematical model developed in this research to optimize facility locations, taking into account realistic constraints such as fixed capacities and demand coverage. Scenario-based analyses and data-driven decision support tools should be utilized to enhance operational planning and responsiveness.

Additionally, future research should focus on financial sustainability and the impact of public behavior on recycling participation to ensure long-term success. Collectively, these recommendations aim to bridge the gap between theory and practice, providing a robust foundation for developing efficient, adaptive, and sustainable recycling systems in Malaysia and similar contexts.

5.4 Future Work

In this research, a fixed-capacity approach was employed to model recycling facility planning. However, future research should focus on developing dynamic models that can incorporate real-time adjustments in response to varying waste generation rates, seasonal fluctuations, and demographic shifts. Such models would enhance both the flexibility and applicability of facility planning under dynamic conditions. Additionally, the integration of big data analytics and machine learning techniques presents a promising avenue for forecasting waste generation patterns, estimating future demand for recycling facilities, and supporting automated, data-driven decision-making. These technologies have the potential to significantly improve the responsiveness and intelligence of planning frameworks. Furthermore, future investigations should include comprehensive cost-benefit analyses and financial modeling to evaluate the long-term economic sustainability of recycling facilities. It is also essential to examine the influence of public policies, governmental incentives, and inter-organizational collaborations on the implementation, efficiency, and viability of recycling infrastructure initiatives.

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APPENDICES

APPENDIX 1

Coding Formulation Mathematical Model

```
/*********************************************
 * OPL 20.1.0.0 Model
 * Author: User
 * Creation Date: 22 Dec 2023 at 6:04:43 pm
 *********************************************/

 int i=...; // Index of demand
 int j=...; // Index of recycling

 range demand=1..i; // Set of demand
 range facility=1..j; // Set of recycling

 // parameter

 int s[demand][facility]=...; // 0-1 value
 int F=...; // max of facilities
 float d[demand]=...; // Waste at location i
 float q[facility]=...; // Capacities at location j

 // variable

 dvar boolean x[facility];
 dvar boolean y[demand][facility];

 // model

 maximize sum (i in demand, j in facility) d[i]*y[i][j];

 subject to {

   forall (i in demand)
     sum (j in facility) s[i][j]*x[j] >= 1;

   forall (i in demand, j in facility)
     s[i][j]*x[j] >= y[i][j];

   forall (j in facility)
     sum (i in demand) d[i]*y[i][j] <= q[j]*x[j];

   forall (i in demand)
     sum (j in facility) y[i][j]*q[j] >= d[i];

     sum (j in facility) x[j] <= F;

 }
```

APPENDIX 2

Coding Formulation Calling Data

```
/*********************************************
 * OPL 20.1.0.0 Data
 * Author: User
 * Creation Date: 22 Dec 2023 at 6:04:43 pm
 *********************************************/

 i=315; // demand location
 j=12; // recycling facilities location

 F=1; // max of recycling facilities

 SheetConnection sheet("Data Collection (Latest).xlsx");

 d from SheetRead(sheet,"di_5"); // waste at node i
 q from SheetRead(sheet,"q_3"); // capacity at each j
 s from SheetRead(sheet,"sij"); // 0-1 value

 x to SheetWrite(sheet,"x");
 y to SheetWrite(sheet,"y");
```

APPENDIX 3

Numerical Random Dataset

Demand at i (d_i)

i	Estimated Household	Waste Estimated	Recyclable Estimated
1	28	68	27
2	79	59	24
3	39	75	30
4	82	81	32
5	31	73	29
6	91	50	20
7	13	85	34
8	16	78	31
9	54	42	17
10	62	66	26
	495	677	271

Fixed capacity levels at each facility at j (q_j)

j	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
q_1	50	50	50	50	50	50	50	50	50	50
q_2	60	60	60	60	60	60	60	60	60	60
q_3	70	70	70	70	70	70	70	70	70	70
q_4	80	80	80	80	80	80	80	80	80	80
q_5	90	90	90	90	90	90	90	90	90	90
q_6	100	100	100	100	100	100	100	100	100	100

Travel time demand location at i to recycling facility location at j ($trav_{ij}$)

i	j_1	j_2	j_3	j_4	j_5	j_6	j_7	j_8	j_9	j_{10}
1	18	19	13	14	5	13	21	13	22	29
2	6	19	16	21	24	21	5	9	17	22
3	16	20	18	15	13	22	5	14	25	20
4	30	6	29	8	5	9	23	29	11	29
5	12	9	20	20	8	19	7	29	8	7
6	7	13	28	12	24	24	24	8	10	5
7	15	18	22	16	18	29	7	8	21	25
8	5	10	18	15	8	26	13	14	19	21
9	19	5	22	5	14	28	19	24	8	9
10	14	17	8	20	20	29	25	19	7	15

APPENDIX 4

Numerical Data Rosni Random Dataset

Demand at i (d_i)

i	Demand	Estimated Recyclable Waste Generations
1	60229	24092
2	20885	8354
3	12136	4855
4	12668	5067
5	36182	14473
6	17610	7044
	159710	63884

Fixed capacity levels in each facility at j (q_j) with multiple capacities (δ)

δ	j				
	1	2	3	4	5
1	12776.8	12776.8	12776.8	12776.8	12776.8
1.5	19165.2	19165.2	19165.2	19165.2	19165.2
2	25553.6	25553.6	25553.6	25553.6	25553.6
2.5	31942.0	31942.0	31942.0	31942.0	31942.0
3	38330.3	38330.3	38330.3	38330.3	38330.3

Travel time demand location at i to recycling facility location at j $(trav_{ij})$

i	j				
	1	2	3	4	5
1	3	12	11	17	13
2	11	7	13	19	16
3	10	11	8	19	11
4	12	11	6	13	11
5	18	18	10	3	4
6	20	18	7	8	4

APPENDIX 5

Real-World Dataset At Seremban

Table of Demand at i (d_i)

i	Demand Location	Households (units)	Estimated Populations (units)	Estimated Wastes (kilograms)	Estimated Recyclable Waste (kilograms)
1	Taman Shukor	43	171	191	76
2	Taman Desa Kenanga Indah	30	119	133	48
3	Taman Villa Palma	56	222	249	89
4	Taman Seri Sentosa	28	111	124	44
5	Residensi Sigc	217	861	965	345
6	Gedung Lalang 162	198	786	880	314
7	Gedung Lalang 50	171	679	760	272
8	Taman Dato Wan	120	476	534	191
9	Taman Golf Height	91	361	405	145
10	Taman Bukit Nibong	129	512	574	205
11	Seremban Putra	1000	3970	4446	1588
12	Taman Desa Permai	159	631	707	252
13	Taman Perwira	160	635	711	254
14	Rumah Rakyat Sikamat 1	159	631	707	252
15	Taman Ujong Pasir	14	56	62	22
16	Taman Sri Pulai	86	341	382	137
17	Taman Angsana	45	179	200	71
18	Taman Kayu Manis	21	83	93	33
19	Kampung Jiboi	533	2116	2370	846
20	Taman Kekwa	343	1362	1525	545
21	Taman Negeri Ampangan	36	143	160	57
22	Taman Sri Landak	13	52	58	21
23	Taman Nz	46	183	205	73
24	Taman Sri Negeri	26	103	116	41
25	Taman Bougainvilla	22	87	98	35
26	Taman Bukit Kelana	73	290	325	116
27	Taman Melati Indah	34	135	151	54
28	Taman Kiambang Indah	72	286	320	114
29	Taman Desa Ros	346	1374	1538	549
30	Taman Sri Siantan	27	107	120	43
31	Taman Guru	152	603	676	241
32	Taman Desa Duranta	113	449	502	179
33	Taman Setia Hati	24	95	107	38
34	Taman Lily Sutera	26	103	116	41
35	Taman Rashidah Utama	53	210	236	84

36	Kampung Sentosa Jaya	138	548	614	219
37	Kampung Sentosa	388	1540	1725	616
38	Flat Casurina	237	941	1054	376
39	Ppr Paroi	390	1548	1734	619
40	Kampung Tok Dagang	115	457	511	183
41	Taman Cengal Utama	551	2187	2450	875
42	Taman Jemerlang	130	516	578	206
43	Taman Margosa	531	2108	2361	843
44	Kampung Melayu Panchor	23	91	102	37
45	Taman Sri Paroi	53	210	236	84
46	Rumah Murah Panchor	176	699	783	279
47	Kampung Panchor	415	1648	1845	659
48	Taman Nyior (A,B,C)	471	1870	2094	748
49	Seremban Forest Height	2388	9480	10618	3792
50	Taman Warisan Puteri	5479	21752	24362	8701
51	Taman Seremban Jaya	30	119	133	48
52	Taman Yoon Fook	60	238	267	95
53	Taman Tan Chee Hoe	161	639	716	256
54	Taman Seremban	136	540	605	216
55	Taman Seremban Baru	483	1918	2148	767
56	Taman Kian Kee	36	143	160	57
57	Taman Dusun Setia	864	3430	3842	1372
58	Taman Dato Shah Bandar	238	945	1058	378
59	Taman Sakura	99	393	440	157
60	Taman Bukti	407	1616	1810	646
61	Taman Bukti Setia	109	433	485	173
62	Taman Ampangan	311	1235	1383	494
63	Kampung Baru Paroi	58	230	258	92
64	Taman Pinggiran Golf	411	1632	1827	653
65	Taman Paroi Jaya	1233	4895	5482	1958
66	Taman Palma Jaya	176	699	783	279
67	Taman Panchor Jaya	1154	4581	5131	1833
68	Taman Sri Telawi	311	1235	1383	494
69	Taman Sikamat Utama	245	973	1089	389
70	Taman Jujur	650	2581	2890	1032
71	Taman Desa Rhu	1428	5669	6349	2268
72	Taman Sri Penaga Fasa 2	296	1175	1316	470
73	Taman Kurshiah	53	210	236	84
74	Taman Selaseh	59	234	262	94
75	Taman Sikamat Jaya	113	449	502	179
76	Taman Megaway	302	1199	1343	480
77	Kampung Baru Sikamat	246	977	1094	391
78	Taman Ampangan Jaya	1387	5506	6167	2203
79	Taman Pelangi	560	2223	2490	889

80	Taman Sri Inai	156	619	694	248
81	Taman College Height	909	3609	4042	1443
82	Taman Sri Penaga Fasa 1	135	536	600	214
83	Taman Pinang Gading	186	738	827	295
84	Taman Sri Pulai	522	2072	2321	829
85	Taman Desa Beringin	285	1131	1267	453
86	Taman Desa Kiara	318	1262	1414	505
87	Taman Sri Pagi	713	2831	3170	1132
88	Taman Rasa Sayang	236	937	1049	375
89	Taman Cempaka	364	1445	1618	578
90	Taman Cempaka 3	380	1509	1690	603
91	Taman Marida	981	3895	4362	1558
92	Taman Senawang Jaya	1427	5665	6345	2266
93	Taman Desa Anggerik	388	1540	1725	616
94	Taman Kobena	388	1540	1725	616
95	Taman Senawang Indah	372	1477	1654	591
96	Taman Satria	891	3537	3962	1415
97	Taman Sri Kasih	276	1096	1227	438
98	Taman Tasik Jaya	2689	10675	11956	4270
99	Taman Sri Mawar	670	2660	2979	1064
100	Taman Desa Dahlia	511	2029	2272	811
101	Taman Lily	156	619	694	248
102	Taman Teratai	255	1012	1134	405
103	Taman Desa Flora	68	270	302	108
104	Taman Widuri	415	1648	1845	659
105	Taman Sri Bayu	219	869	974	348
106	Taman Alamanda	458	1818	2036	727
107	Rumah Pangsa Senawang 2	632	2509	2810	1004
108	Taman Jasmin	1201	4768	5340	1907
109	Taman Matahari Height	404	1604	1796	642
110	Taman Kemuning	428	1699	1903	680
111	Taman Desa Jaya	288	1143	1281	457
112	Taman Jasmin Indah	412	1636	1832	654
113	Taman Tasik Jaya 2	412	1636	1832	654
114	Taman Desa Ixora	441	1751	1961	700
115	Taman Ros Mewah	693	2751	3081	1100
116	Taman Desa Orkid	406	1612	1805	645
117	Taman Desa Melor	466	1850	2072	740
118	Taman Jasmin Indah 2	328	1302	1458	521
119	Taman Matahari Indah	407	1616	1810	646

120	Taman Senawang Indah 2	38	151	169	60
121	Taman Mayang Sari	100	397	445	159
122	Taman Desa Flora 2	54	214	240	86
123	Taman Desa Melor Indah	38	151	169	60
124	Taman Lavender Height	1107	4395	4922	1758
125	Taman Seroja Indah	19	75	84	30
126	Taman Bourgainvillea Idaman	19	75	84	30
127	Taman Seri Kiambang	64	254	285	102
128	Laman Akasia	80	318	356	127
129	Taman Villa Beringin	60	238	267	95
130	Taman Tasik Jaya 2	16	64	71	25
131	Taman Seri Pandan	14	56	62	22
132	Taman Penaga Indah	72	286	320	114
133	Taman Kiara Indah	147	584	654	233
134	Taman Desa Ros	62	246	276	98
135	Rumah Rakyat Sikamat 2	200	794	889	318
136	Taman Sentosa Indah	26	103	116	41
137	Taman Cempaka 2	28	111	124	44
138	Villa Suria	35	139	156	56
139	Taman Dellinia	61	242	271	97
140	Taman Nee Yan	265	1052	1178	421
141	Taman Bukit Markisa	87	345	387	138
142	Taman Suria	35	139	156	56
143	Taman Permata	212	842	943	337
144	Taman Jed Villa	30	119	133	48
145	Rumah Pangsa Lobak	190	754	845	302
146	Ppr Lobak	468	1858	2081	743
147	Taman Saga	124	492	551	197
148	Taman Bukit Lemon	69	274	307	110
149	Rumah Pangsa Tun Dr Ismail	330	1310	1467	524
150	Taman Bukit Tembok	181	719	805	287
151	Taman Bukit Nenas	38	151	169	60
152	Taman Bukit Belimbing	21	83	93	33
153	Taman Lian	26	103	116	41
154	Taman Ban Aik	22	87	98	35
155	Taman Kelana Indah	42	167	187	67

156	Taman Limau Emas	119	472	529	189
157	Taman Klana Jubli	74	294	329	118
158	Taman Tuan Sheikh	24	95	107	38
159	Taman Ho	38	151	169	60
160	Taman Dato Abu Hanifah	134	532	596	213
161	Kampung Baru Rasah	484	1921	2152	769
162	Taman Bukit Chedang 1	530	2104	2357	842
163	Taman Bukit Chedang 2	832	3303	3699	1321
164	Taman Sungai Ujong	96	381	427	152
165	Taman Sri Puteh	30	119	133	48
166	Taman Mok Sum	57	226	253	91
167	Taman Happy	65	258	289	103
168	Taman Kasturi	28	111	124	44
169	Taman Ujong	73	290	325	116
170	Taman Sri Loop	156	619	694	248
171	Taman Kenari	28	111	124	44
172	Taman Sejahtera	53	210	236	84
173	Taman Star Light	140	556	622	222
174	Kampung Abok (Kampung Semarak)	103	409	458	164
175	Taman Abok Jaya	150	596	667	238
176	Kampung Datok Mansor	133	528	591	211
177	Taman Sri Pulasan	21	83	93	33
178	Taman Rahang	188	746	836	299
179	Taman Bidara	977	3879	4344	1551
180	Taman Merdeka Height	42	167	187	67
181	Taman Dusun Nyior	135	536	600	214
182	Taman Bukit Rasah	331	1314	1472	526
183	Kampung Bukit Temiang	58	230	258	92
184	Kampung Merbah	23	91	102	37
185	Taman Meranti Jaya	24	95	107	38
186	Taman England	76	302	338	121
187	Taman Desa Manggis	23	91	102	37
188	Taman Zaitun Indah	173	687	769	275
189	Taman Sena Jaya	16	64	71	25
190	Taman Sri Rambai	40	159	178	64
191	Taman Sri Rahang	159	631	707	252

192	Taman Bukit Nona	40	159	178	64
193	Taman Cermai Jaya	32	127	142	51
194	Taman Setia Jaya	30	119	133	48
195	Kampung Ismail	62	246	276	98
196	Taman Murugesu	54	214	240	86
197	Taman Lee Siew Joo	46	183	205	73
198	Taman Bukit Ampangan	46	183	205	73
199	Taman Sikamat	19	75	84	30
200	Taman Punca Emas	149	592	663	237
201	Taman Negeri	20	79	89	32
202	Taman Sim	21	83	93	33
203	Ampangan Blok B & C	138	548	614	219
204	Taman Negeri (Rasah)	122	484	542	194
205	Taman Koop	31	123	138	49
206	Taman Nyior Hijau	63	250	280	100
207	Taman Limau Emas Fasa 3	12	48	53	19
208	Taman Anggur Jaya	102	405	454	162
209	Off Jln Tuan Haji Said (Lake Height)	25	99	111	40
210	Vila Taman Tasik	8	32	36	13
211	Kampung Singh	61	242	271	97
212	Taman Permai Impian	502	1993	2232	797
213	Kampung Pasir	394	1564	1752	626
214	Taman Purba	42	167	187	67
215	Taman Bukit Delima	78	310	347	124
216	Taman Ming Hoe	63	250	280	100
217	Taman Ceri Indah	16	64	71	25
218	Taman Mutiara Galla	713	2831	3170	1132
219	Taman Harmonium Utama	130	516	578	206
220	Taman Bukit Kristal	288	1143	1281	457
221	Taman Bukit Kepayang	2477	9834	11014	3933
222	Taman Bukit Kepayang	15	60	67	24
223	Taman Senangin	329	1306	1463	522
224	Taman Layang-Layang	669	2656	2975	1062
225	Taman Merpati	361	1433	1605	573
226	Taman Seri Kamban Baru	268	1064	1192	426
227	Rumah Murah Mambau	50	199	222	79

228	Taman Kaloi Jaya	81	322	360	129
229	Taman Bukit Belida	117	464	520	186
230	Taman Mambau Height	110	437	489	175
231	Taman Mambau Baru	83	330	369	132
232	Taman Mambau Jaya	60	238	267	95
233	Taman Kerisi	139	552	618	221
234	Taman Arowana Indah	383	1521	1703	608
235	Taman Arowana Impian	558	2215	2481	886
236	Kampung Batu3 Mambau	167	663	743	265
237	Taman Harapan Baru	219	869	974	348
238	Taman Desa Rasah	489	1941	2174	777
239	Taman Rasah Jaya	4977	19759	22130	7903
240	Taman Merbok Ria	118	468	525	187
241	Taman Koperasi Guru Tamil	45	179	200	71
242	Taman Sri Rasah	153	607	680	243
243	Taman Kok Ann	45	179	200	71
244	Taman Bukit Nuri Indah	416	1652	1850	661
245	Taman Bukit Kaya	562	2231	2499	892
246	Taman Labu Utama	88	349	391	140
247	Taman Bukit Labu	153	607	680	243
248	Taman Seruling Jaya	41	163	182	65
249	Kampung Dato Mohd Said	175	695	778	278
250	Taman Permai	279	1108	1241	443
251	Taman Labu Jaya	236	937	1049	375
252	Taman Permai 2	1154	4581	5131	1833
253	Taman Permai 3	956	3795	4251	1518
254	Taman Oakland	225	893	1000	357
255	Taman Permai Jaya	20	79	89	32
256	Taman Bukit Kelisa	485	1925	2157	770
257	Taman Duyung	336	1334	1494	534
258	Taman Yoon Chan	122	484	542	194
259	Taman Bukit Blossom	414	1644	1841	657
260	Taman Sea	140	556	622	222
261	Taman Bunga Blossom	653	2592	2903	1037
262	Taman Thivy	851	3378	3784	1351
263	Kampung Baru Rahang	352	1397	1565	559

264	Taman Loop	141	560	627	224
265	Taman Bukit Emas	681	2704	3028	1081
266	Taman Sri Binjai	518	2056	2303	823
267	Taman Sri Labu	98	389	436	156
268	Seremban 2 - Seksyen G	4093	16249	18199	6500
269	Seremban 2 - Seksyen C	191	758	849	303
270	Seremban 2 - Seksyen H	690	2739	3068	1096
271	Seremban 2 - Seksyen K	892	3541	3966	1416
272	Seremban 2 - Seksyen F	950	3772	4224	1509
273	Seremban 2 -Seksyen E	720	2858	3201	1143
274	Seremban 2 -Seksyen D	1652	6558	7345	2623
275	Seremban 2 - Seksyen B	450	1787	2001	715
276	Seremban 2 - Seksyen A	786	3120	3495	1248
277	Taman Mambau Jaya	60	238	267	95
278	Taman Belida Indah	102	405	454	162
279	Taman Chemara Hills	267	1060	1187	424
280	Seremban 3 - Seksyen 1a	309	1227	1374	491
281	Seremban 3 - Seksyen 1b	213	846	947	338
282	Seremban 3 - Seksyen 3	69	274	307	110
283	Taman Oakland Fasa3	177	703	787	281
284	Taman Coral Height	676	2684	3006	1073
285	Taman Berlian Tropika	34	135	151	54
286	Taman Indah	387	1536	1721	615
287	Taman Temiang Jaya	370	1469	1645	588
288	Taman Rashibah Indah	263	1044	1169	418
289	Taman Suliana	144	572	640	229
290	Taman Baiduri	277	1100	1232	440
291	Taman Bukit Intan	1290	5121	5736	2049
292	Taman Jasper Jaya	488	1937	2170	775
293	Taman Bukit Galena	286	1135	1272	454
294	Taman Bukit Jed	1647	6539	7323	2615
295	Taman Bukit Mika	85	337	378	135
296	Taman Bukit Desa	99	393	440	157
297	Taman Sapphire	50	199	222	79
298	Taman Bukit Zamrud	611	2426	2717	970
299	Taman Pulai Perdana	244	969	1085	387
300	Taman Pulai Impian	320	1270	1423	508

301	Taman Desa Temiang	519	2060	2308	824
302	Taman Keng Wong	108	429	480	172
303	Taman Bukit Mutiara	799	3172	3553	1269
304	Taman Kwang Tong	71	282	316	113
305	Taman Makmor	128	508	569	203
306	Taman Templer	244	969	1085	387
307	Taman Dawn	115	457	511	183
308	Taman Kotamas	94	373	418	149
309	Taman Chip Aik	418	1659	1859	664
310	Taman Sri Amber	661	2624	2939	1050
311	Taman Jaya Emas	705	2799	3135	1120
312	Taman Bukit Sentosa	365	1449	1623	580
313	Taman Bukit Sarimban	193	766	858	306
314	Taman Bukit Penaga	57	226	253	91
315	Taman Bukit Berlian	125	496	556	199
Total			422710	-	169092

Travel time demand location at i to recycling facility location at j ($trav_{ij}$)

i	j											
	1	2	3	4	5	6	7	8	9	10	11	12
1	10	15	13	6	12	7	6	10	15	10	3	15
2	12	16	15	4	14	4	7	13	17	13	6	16
3	12	16	14	11	13	10	12	5	16	9	6	17
4	13	17	15	2	15	9	5	13	17	12	6	19
5	15	19	17	7	16	12	7	12	19	14	7	21
6	10	14	12	5	11	6	6	9	14	9	2	14
7	10	15	13	6	12	9	7	11	15	10	3	15
8	11	15	14	6	13	9	7	11	15	10	4	15
9	12	16	14	5	13	8	6	11	16	10	4	15
10	17	21	20	15	19	15	16	5	21	15	10	21
11	13	17	16	11	15	11	10	5	17	11	6	17
12	13	17	16	11	15	10	10	8	17	12	6	17
13	13	17	16	11	15	11	10	7	17	12	6	17
14	12	16	15	10	14	10	11	5	20	11	7	16
15	13	17	15	10	16	10	10	9	21	14	6	19
16	11	14	14	12	11	7	12	10	15	6	6	12
17	14	19	17	13	17	11	13	6	20	11	6	18
18	15	19	18	10	17	13	9	9	20	14	8	19
19	18	23	22	10	21	13	10	21	24	20	14	23
20	9	13	11	10	10	5	10	11	13	9	4	12
21	12	17	15	4	15	8	6	12	17	11	4	17
22	13	17	16	3	15	7	5	12	17	11	5	18
23	13	17	16	3	15	7	5	12	17	11	4	17
24	13	17	16	3	15	7	5	12	18	12	5	17
25	16	21	18	3	18	7	6	14	21	15	5	20
26	18	22	20	3	20	8	7	15	23	16	7	21
27	17	23	18	2	19	7	7	15	22	16	6	21
28	16	21	19	5	19	7	10	18	22	18	9	20
29	17	22	20	3	20	7	8	16	23	16	7	20
30	16	21	19	5	19	7	10	17	22	18	9	19
31	13	16	11	22	15	14	25	23	13	14	17	18
32	17	21	19	4	19	9	6	14	22	16	6	21
33	16	20	18	5	18	6	9	17	21	18	9	20
34	16	20	18	5	18	6	10	18	21	17	9	20
35	15	20	18	5	18	6	9	17	20	17	9	19
36	18	23	21	1	21	9	6	16	24	17	8	23
37	19	24	22	3	22	12	7	17	24	18	9	23
38	20	25	23	6	23	13	4	14	25	19	10	25
39	19	24	21	16	21	15	16	4	24	16	10	22
40	19	24	22	5	21	13	4	14	25	19	9	23

41	20	25	22	6	22	13	3	14	25	19	10	24
42	26	31	28	10	28	19	5	19	31	25	15	29
43	26	31	29	10	28	19	4	18	32	24	16	30
44	25	30	28	9	27	17	8	21	31	24	14	29
45	21	26	23	5	23	14	4	17	26	20	10	25
46	24	29	26	8	26	16	7	20	30	23	13	27
47	24	29	28	8	28	16	7	20	31	23	13	28
48	9	13	12	9	11	5	11	11	13	9	5	12
49	12	16	14	8	13	3	12	15	17	11	8	15
50	21	26	24	16	23	16	14	10	26	18	11	24
51	17	22	20	15	19	14	20	25	22	17	18	21
52	12	17	15	8	14	5	13	19	17	12	12	15
53	14	19	17	8	17	5	12	20	19	14	11	17
54	12	17	14	9	14	6	13	18	17	12	12	15
55	12	17	15	7	14	5	12	20	19	12	11	16
56	13	18	16	8	15	5	12	21	19	13	12	17
57	9	14	12	9	11	5	14	15	14	10	7	13
58	12	17	15	9	14	7	11	13	17	13	5	16
59	10	15	13	9	12	6	11	12	16	12	4	14
60	15	20	18	6	17	10	9	14	20	15	5	18
61	16	20	18	6	18	10	9	14	20	15	5	19
62	23	28	25	7	25	16	1	15	27	21	11	26
63	24	27	24	6	24	15	2	16	26	20	11	25
64	19	22	20	7	20	11	7	15	23	16	6	21
65	18	23	21	6	20	11	6	15	22	16	7	23
66	18	23	21	8	21	13	7	15	23	17	8	22
67	19	24	22	7	21	13	4	15	24	18	11	23
68	22	26	25	10	24	16	3	18	27	21	13	26
69	18	23	21	16	20	15	16	3	23	15	10	22
70	18	23	21	16	20	15	16	2	23	15	10	22
71	16	21	19	14	18	13	14	3	21	13	8	20
72	20	25	23	17	22	17	17	3	25	16	11	22
73	14	19	17	14	16	11	15	6	19	10	6	18
74	14	19	17	13	16	11	14	4	19	12	6	18
75	15	19	17	12	16	11	13	4	19	11	6	18
76	15	20	18	13	17	12	13	6	20	11	6	18
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78	17	22	20	11	19	13	10	7	22	14	8	22
79	18	23	21	16	20	15	15	3	24	15	10	21
80	19	24	22	16	21	15	15	1	25	16	10	22
81	20	25	23	17	22	17	16	5	25	16	11	23
82	20	25	23	17	22	17	17	3	25	16	11	22
83	14	19	17	15	16	11	14	6	20	11	6	18
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85	16	21	19	14	18	12	14	6	22	12	7	19

86	18	23	21	15	20	14	14	3	23	14	9	21
87	21	26	24	5	22	11	8	18	26	20	10	24
88	14	18	17	6	16	6	9	16	19	14	9	18
89	14	19	17	3	16	8	7	14	19	14	7	19
90	14	19	17	3	16	8	7	14	19	14	7	19
91	14	18	16	7	16	7	10	17	18	14	10	18
92	14	18	17	9	17	7	10	18	19	15	11	19
93	16	20	19	9	18	8	9	19	21	16	12	20
94	17	22	20	8	19	10	8	19	22	17	11	21
95	18	21	19	9	18	10	9	19	23	19	12	23
96	18	22	20	7	19	10	8	18	22	17	11	22
97	12	16	15	6	14	5	8	15	17	12	8	16
98	15	20	18	4	17	11	5	15	20	15	8	20
99	13	17	15	7	15	6	10	16	17	13	9	17
100	17	21	19	8	18	9	8	19	21	16	11	21
101	13	17	16	7	15	6	9	16	18	13	9	18
102	17	22	19	7	19	10	7	18	22	17	10	21
103	18	22	20	7	20	11	8	19	22	18	11	23
104	17	21	19	8	19	10	9	19	21	17	12	21
105	15	19	18	4	17	10	7	15	20	14	7	19
106	16	20	18	9	18	9	10	20	20	16	13	20
107	13	17	15	7	15	5	10	16	17	13	9	17
108	15	19	17	9	17	9	10	20	19	15	12	19
109	16	20	18	4	17	10	6	15	20	14	8	20
110	14	18	17	9	16	7	10	18	19	14	10	18
111	16	20	18	5	17	11	5	16	20	15	8	20
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113	14	18	16	3	16	9	6	13	19	13	6	18
114	17	21	19	6	18	10	8	17	21	17	10	21
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116	15	19	18	4	17	9	7	14	20	14	7	19
117	17	21	19	7	18	9	8	18	21	16	11	20
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121	18	23	21	10	20	12	10	19	23	18	13	22
122	18	22	21	8	20	11	8	18	22	18	11	22
123	18	22	20	8	19	10	9	18	22	18	12	21
124	18	25	20	8	19	12	7	17	22	17	10	21
125	12	17	15	4	14	4	7	13	17	13	6	16
126	12	16	14	3	14	5	5	11	16	11	4	16
127	14	18	17	5	16	6	8	14	19	14	7	18
128	17	22	20	15	19	15	16	4	22	15	10	20
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134	13	17	15	3	14	6	6	12	17	12	5	17
135	12	16	15	11	14	10	10	8	17	12	5	16
136	12	16	15	4	14	4	8	14	17	14	6	16
137	14	19	17	3	16	8	8	14	19	14	7	19
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163	2	6	4	13	4	7	15	14	6	6	9	9
164	6	11	8	14	9	8	16	16	9	9	10	11
165	5	10	8	14	8	7	15	15	9	8	9	10
166	5	11	8	12	7	6	14	14	10	9	8	10
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173	8	12	10	12	10	9	14	13	13	9	8	12
174	6	11	9	13	8	7	13	13	11	8	7	11
175	9	14	12	13	11	9	16	15	15	9	9	13

176	7	12	10	15	10	7	15	15	12	9	9	13
177	11	12	14	20	11	14	20	20	14	9	14	4
178	9	13	11	12	11	6	13	12	13	8	7	13
179	10	14	12	9	11	3	13	12	15	10	7	14
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185	11	15	13	9	13	9	10	6	16	9	4	15
186	14	18	16	12	17	10	13	7	18	10	5	17
187	13	17	15	12	15	8	13	8	18	9	6	17
188	11	15	14	8	13	9	8	6	15	10	4	15
189	12	16	15	11	14	9	14	17	16	12	11	16
190	11	15	13	7	13	9	8	8	15	10	4	15
191	9	13	12	11	11	5	11	11	13	7	5	14
192	12	17	15	12	15	6	14	13	18	8	7	16
193	11	16	14	11	13	7	11	10	17	10	4	16
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195	10	15	13	7	13	8	8	8	15	11	3	15
196	9	14	12	8	11	5	9	9	14	8	8	13
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198	13	16	14	10	15	8	11	8	17	10	3	15
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205	8	10	10	15	8	11	16	14	12	4	10	7
206	10	14	12	11	12	5	13	12	14	7	6	13
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208	12	16	14	15	14	9	19	14	17	7	10	15
209	13	19	16	13	14	9	15	9	19	7	6	15
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212	7	11	9	15	7	9	20	17	11	5	12	9
213	9	15	12	17	12	10	19	15	15	11	9	15
214	10	15	13	9	12	5	12	11	15	14	3	13
215	23	26	26	23	27	18	23	14	28	15	14	14
216	8	12	10	9	10	3	12	11	12	10	5	11
217	9	14	12	15	11	9	20	17	14	10	11	15
218	11	12	12	18	10	13	20	19	14	8	14	2
219	9	9	11	16	7	10	18	17	11	6	12	4
220	12	13	14	19	11	13	21	20	15	10	15	4

221	6	8	9	18	6	12	20	18	10	7	14	9
222	6	8	9	18	6	12	20	18	10	7	14	9
223	13	17	15	12	15	10	15	16	17	13	11	16
224	10	14	13	12	12	9	14	14	15	11	9	14
225	12	16	15	11	14	9	14	15	16	12	9	15
226	10	15	13	12	12	10	15	16	15	12	12	14
227	9	8	4	17	10	11	19	18	5	11	13	13
228	11	8	5	18	10	12	20	19	5	12	14	15
229	9	5	4	18	8	13	21	19	3	13	15	15
230	10	7	4	17	10	11	19	18	5	11	13	14
231	9	8	5	17	10	11	19	18	5	12	13	14
232	10	7	4	17	9	11	20	18	5	12	13	14
233	8	8	2	19	8	13	22	20	5	13	15	15
234	6	5	1	17	6	11	19	18	4	11	13	13
235	6	5	3	18	6	13	21	19	2	11	15	13
236	8	13	10	17	10	11	19	18	10	11	13	13
237	8	12	9	17	10	9	17	16	10	10	11	12
238	8	13	9	17	10	9	18	16	10	10	11	12
239	9	13	11	15	10	10	18	17	12	11	11	13
240	8	12	9	17	10	10	18	17	9	10	12	13
241	5	9	7	12	7	6	14	13	9	7	8	10
242	10	11	8	19	11	11	20	19	9	12	13	14
243	10	11	7	19	12	12	21	20	8	12	14	15
244	15	19	17	4	16	8	7	15	19	15	8	19
245	7	8	9	15	6	10	18	14	10	4	12	7
246	7	9	9	15	8	10	18	14	10	4	12	8
247	6	8	8	15	6	9	18	14	10	3	11	7
248	7	9	9	14	6	9	17	15	10	4	10	4
249	7	10	9	15	7	9	17	15	10	5	11	5
250	8	10	10	15	7	9	17	17	11	5	11	8
251	12	14	15	18	11	11	22	18	16	2	12	13
252	8	12	11	17	8	10	21	19	13	5	13	10
253	8	12	10	17	9	10	21	19	12	5	13	10
254	6	8	8	14	5	8	16	15	9	4	10	7
255	12	13	14	21	11	15	22	18	16	4	14	11
256	10	13	13	18	10	12	23	20	15	6	15	12
257	11	13	14	21	10	14	25	22	15	7	16	12
258	7	11	10	11	9	9	14	14	11	8	8	12
259	8	12	10	12	10	9	15	14	12	9	8	12
260	9	13	11	11	10	8	14	15	13	10	9	13
261	10	14	13	13	12	10	15	17	14	11	11	15
262	7	11	9	14	9	8	17	16	11	9	11	11
263	8	13	11	10	13	8	12	14	13	8	8	13
264	9	13	11	14	10	10	17	16	13	11	11	13
265	11	16	14	9	13	8	12	15	16	12	11	16

266	7	11	9	10	9	7	12	13	11	8	8	12
267	6	8	8	15	6	9	16	14	10	4	11	7
268	7	3	5	18	5	13	21	21	3	11	15	13
269	5	6	5	16	5	10	18	17	6	10	12	12
270	7	3	5	18	5	13	20	20	3	10	14	13
271	7	2	7	19	5	13	21	20	6	10	15	12
272	6	4	3	17	5	12	19	19	3	10	13	12
273	6	5	2	4	6	11	19	18	4	10	13	13
274	5	3	4	17	4	11	19	19	4	9	13	11
275	6	3	7	18	5	12	20	20	5	10	14	13
276	7	8	8	19	4	14	21	21	9	9	15	11
277	10	8	4	18	10	12	19	19	5	12	14	14
278	10	6	4	18	9	13	20	20	3	13	15	16
279	11	14	13	20	10	13	23	18	15	5	15	12
280	10	12	7	18	13	12	19	20	8	14	14	14
281	11	10	11	17	11	14	21	25	9	15	19	19
282	11	15	11	18	13	12	24	21	12	12	15	18
283	3	7	7	16	3	9	16	16	9	7	11	9
284	15	17	18	14	15	13	15	5	19	11	9	16
285	14	16	17	18	13	13	18	16	17	9	12	12
286	13	18	16	12	15	11	12	6	18	11	7	16
287	12	18	15	11	14	10	12	7	17	10	6	16
288	13	18	16	5	15	5	8	14	18	14	7	17
289	13	18	16	12	15	11	13	5	18	11	7	17
290	9	11	12	15	8	12	15	14	13	4	10	7
291	11	12	14	17	11	13	17	15	15	6	11	7
292	11	12	14	18	10	12	19	17	14	7	13	6
293	10	11	13	18	9	11	18	17	13	7	13	4
294	11	14	15	17	11	14	17	16	16	6	12	9
295	13	15	16	17	13	13	18	14	17	8	12	9
296	14	16	17	19	14	15	19	16	18	9	14	10
297	17	18	20	21	16	17	22	18	21	12	16	14
298	17	17	19	16	14	12	17	10	19	10	11	16
299	16	17	19	15	15	12	15	9	19	10	10	16
300	16	17	19	14	14	12	15	6	19	10	9	16
301	16	18	21	17	16	13	17	10	20	11	12	17
302	17	17	18	16	14	12	16	9	19	10	11	15
303	18	21	22	19	18	16	20	13	22	13	14	19
304	13	19	17	2	16	10	5	13	19	12	5	19
305	13	16	16	16	12	12	16	15	17	8	10	10
306	13	15	16	14	12	10	15	14	16	7	9	11
307	13	15	16	15	13	11	15	14	17	7	9	11
308	14	16	17	16	13	12	16	14	18	8	10	10
309	14	15	16	15	13	11	16	14	17	8	10	11
310	13	15	16	15	13	11	16	14	17	8	10	4

311	21	21	23	20	22	16	21	11	24	13	13	14
312	13	15	16	15	13	11	16	14	17	8	10	12
313	15	19	17	13	17	12	13	8	19	10	7	16
314	18	22	20	15	19	14	15	5	22	13	9	18
315	15	17	17	18	14	13	18	16	18	9	12	12

Fixed capacity levels each container at facility j (q_j)

	j											
q_j	1	2	3	4	5	6	7	8	9	10	11	12
1	10k	10k	10k	10k	10k	10k	10k	10k	10k	10k	10k	10k
2	20k	20k	20k	20k	20k	20k	20k	20k	20k	20k	20k	20k
3	30k	30k	30k	30k	30k	30k	30k	30k	30k	30k	30k	30k

APPENDIX 6

Results of Objective Functions Values Varying Maximum Travel Time (T) and Maximum Number of Operational Facilities (σ) with Fixed Capacity Levels (q_j)

Result: Capacity levels at 10,000 kilograms

Capacity levels (q_j)	Maximum number of operational facilities (σ)	14 minutes	20 minutes	26 minutes	30 minutes
10,000 kilograms	σ = 1	-	-	-	-
	σ = 2	-	-	-	-
	σ = 3	-	-	-	-
	σ = 4	-	-	-	-
	σ = 5	-	-	-	-
	σ = 6	-	-	-	-
	σ = 7	-	-	-	-
	σ = 8	-	-	-	-
	σ = 9	-	-	-	-
	σ = 10	-	-	-	-
	σ = 11	-	-	-	-
	σ = 12	-	-	-	-

Result: Capacity levels at 20,000 kilograms

Capacity levels (q_j)	Maximum number of operational facilities (σ)	14 minutes	20 minutes	26 minutes	30 minutes
20,000 kilograms	σ = 1	-	-	-	-
	σ = 2	-	-	-	-
	σ = 3	-	-	-	-
	σ = 4	-	-	-	-
	σ = 5	-	-	-	-
	σ = 6	-	-	-	-
	σ = 7	-	-	-	-
	σ = 8	-	-	-	-
	σ = 9	179993.9562	179994.9725	179994.7184	179992.3682
	σ = 10	199993.7363	199994.4986	199994.2445	199980.7782
	σ = 11	219994.0246	219994.0246	219994.7869	219989.8323
	σ = 12	239993.2966	239992.7885	239991.7722	239993.2966

Result: Capacity levels at 30000 kilograms

Capacity levels (q_j)	Maximum number of operational facilities (σ)	14 minutes	20 minutes	26 minutes	30 minutes
20,000 kilograms	σ = 1	-	-	-	-
	σ = 2	-	-	-	-
	σ = 3	-	-	-	-
	σ = 4	-	-	-	-
	σ = 5	-	-	-	-
	σ = 6	179994.7184	179994.4643	179989.1922	179992.3682
	σ = 7	209993.6264	209994.1346	209988.1002	209992.8642
	σ = 8	239992.7885	239993.2966	239987.0082	239991.7722
	σ = 9	269991.9506	269992.2046	269986.1702	269990.6802
	σ = 10	299991.1126	299991.6208	299985.0782	299989.5882
	σ = 11	329990.2747	329990.5288	329983.9862	329988.4962
	σ = 12	359988.6746	359989.945	359989.4368	359989.6909

APPENDIX 7

Scenario Demand Percentage at 90%, 70%, 50%, 30%, And 10%

Percentage rate of estimated recyclable wastes at i (d_i)

i	Percentage Rate of Estimated Recyclable Waste				
	90%	70%	50%	30%	10%
1	69	54	38	23	8
2	43	33	24	14	5
3	80	62	44	27	9
4	40	31	22	13	4
5	310	241	172	103	34
6	283	220	157	94	31
7	244	190	136	81	27
8	172	133	95	57	19
9	130	101	72	43	14
10	184	143	102	61	20
11	1429	1112	794	476	159
12	227	177	126	76	25
13	229	178	127	76	25
14	227	177	126	76	25
15	20	16	11	7	2
16	123	96	68	41	14
17	64	50	36	21	7
18	30	23	17	10	3
19	762	592	423	254	85
20	490	381	272	163	54
21	51	40	29	17	6
22	19	14	10	6	2
23	66	51	37	22	7
24	37	29	21	12	4
25	31	24	17	10	3
26	104	81	58	35	12
27	49	38	27	16	5
28	103	80	57	34	11
29	495	385	275	165	55
30	39	30	21	13	4
31	217	169	121	72	24
32	161	126	90	54	18
33	34	27	19	11	4
34	37	29	21	12	4
35	76	59	42	25	8
36	197	153	110	66	22
37	555	431	308	185	62

38	339	263	188	113	38
39	557	434	310	186	62
40	164	128	91	55	18
41	787	612	437	262	87
42	186	145	103	62	21
43	759	590	422	253	84
44	33	26	18	11	4
45	76	59	42	25	8
46	252	196	140	84	28
47	593	461	330	198	66
48	673	524	374	224	75
49	3413	2655	1896	1138	379
50	7831	6090	4350	2610	870
51	43	33	24	14	5
52	86	67	48	29	10
53	230	179	128	77	26
54	194	151	108	65	22
55	690	537	384	230	77
56	51	40	29	17	6
57	1235	960	686	412	137
58	340	265	189	113	38
59	141	110	79	47	16
60	582	452	323	194	65
61	156	121	87	52	17
62	444	346	247	148	49
63	83	64	46	28	9
64	587	457	326	196	65
65	1762	1371	979	587	196
66	252	196	140	84	28
67	1649	1283	916	550	183
68	444	346	247	148	49
69	350	272	195	117	39
70	929	723	516	310	103
71	2041	1587	1134	680	227
72	423	329	235	141	47
73	76	59	42	25	8
74	84	66	47	28	9
75	161	126	90	54	18
76	432	336	240	144	48
77	352	273	195	117	39
78	1982	1542	1101	661	220
79	800	622	445	267	89
80	223	173	124	74	25
81	1299	1010	722	433	144
82	193	150	107	64	21

83	266	207	148	89	30
84	746	580	414	249	83
85	407	317	226	136	45
86	454	353	252	151	50
87	1019	793	566	340	113
88	337	262	187	112	37
89	520	405	289	173	58
90	543	422	302	181	60
91	1402	1090	779	467	156
92	2039	1586	1133	680	227
93	555	431	308	185	62
94	555	431	308	185	62
95	532	414	295	177	59
96	1273	990	707	424	141
97	394	307	219	131	44
98	3843	2989	2135	1281	427
99	958	745	532	319	106
100	730	568	406	243	81
101	223	173	124	74	25
102	364	283	202	121	40
103	97	76	54	32	11
104	593	461	330	198	66
105	313	243	174	104	35
106	655	509	364	218	73
107	903	703	502	301	100
108	1716	1335	954	572	191
109	577	449	321	192	64
110	612	476	340	204	68
111	412	320	229	137	46
112	589	458	327	196	65
113	589	458	327	196	65
114	630	490	350	210	70
115	990	770	550	330	110
116	580	451	322	193	64
117	666	518	370	222	74
118	469	365	260	156	52
119	582	452	323	194	65
120	54	42	30	18	6
121	143	111	79	48	16
122	77	60	43	26	9
123	54	42	30	18	6
124	1582	1231	879	527	176
125	27	21	15	9	3
126	27	21	15	9	3
127	91	71	51	30	10

128	114	89	64	38	13
129	86	67	48	29	10
130	23	18	13	8	3
131	20	16	11	7	2
132	103	80	57	34	11
133	210	163	117	70	23
134	89	69	49	30	10
135	286	222	159	95	32
136	37	29	21	12	4
137	40	31	22	13	4
138	50	39	28	17	6
139	87	68	48	29	10
140	379	295	210	126	42
141	124	97	69	41	14
142	50	39	28	17	6
143	303	236	168	101	34
144	43	33	24	14	5
145	272	211	151	91	30
146	669	520	372	223	74
147	177	138	98	59	20
148	99	77	55	33	11
149	472	367	262	157	52
150	259	201	144	86	29
151	54	42	30	18	6
152	30	23	17	10	3
153	37	29	21	12	4
154	31	24	17	10	3
155	60	47	33	20	7
156	170	132	94	57	19
157	106	82	59	35	12
158	34	27	19	11	4
159	54	42	30	18	6
160	192	149	106	64	21
161	692	538	384	231	77
162	757	589	421	252	84
163	1189	925	661	396	132
164	137	107	76	46	15
165	43	33	24	14	5
166	81	63	45	27	9
167	93	72	52	31	10
168	40	31	22	13	4
169	104	81	58	35	12
170	223	173	124	74	25
171	40	31	22	13	4
172	76	59	42	25	8

173	200	156	111	67	22
174	147	114	82	49	16
175	214	167	119	71	24
176	190	148	106	63	21
177	30	23	17	10	3
178	269	209	149	90	30
179	1396	1086	776	465	155
180	60	47	33	20	7
181	193	150	107	64	21
182	473	368	263	158	53
183	83	64	46	28	9
184	33	26	18	11	4
185	34	27	19	11	4
186	109	84	60	36	12
187	33	26	18	11	4
188	247	192	137	82	27
189	23	18	13	8	3
190	57	44	32	19	6
191	227	177	126	76	25
192	57	44	32	19	6
193	46	36	25	15	5
194	43	33	24	14	5
195	89	69	49	30	10
196	77	60	43	26	9
197	66	51	37	22	7
198	66	51	37	22	7
199	27	21	15	9	3
200	213	166	118	71	24
201	29	22	16	10	3
202	30	23	17	10	3
203	197	153	110	66	22
204	174	136	97	58	19
205	44	34	25	15	5
206	90	70	50	30	10
207	17	13	10	6	2
208	146	113	81	49	16
209	36	28	20	12	4
210	11	9	6	4	1
211	87	68	48	29	10
212	717	558	399	239	80
213	563	438	313	188	63
214	60	47	33	20	7
215	111	87	62	37	12
216	90	70	50	30	10
217	23	18	13	8	3

218	1019	793	566	340	113
219	186	145	103	62	21
220	412	320	229	137	46
221	3540	2753	1967	1180	393
222	21	17	12	7	2
223	470	366	261	157	52
224	956	744	531	319	106
225	516	401	287	172	57
226	383	298	213	128	43
227	71	56	40	24	8
228	116	90	64	39	13
229	167	130	93	56	19
230	157	122	87	52	17
231	119	92	66	40	13
232	86	67	48	29	10
233	199	155	110	66	22
234	547	426	304	182	61
235	797	620	443	266	89
236	239	186	133	80	27
237	313	243	174	104	35
238	699	544	388	233	78
239	7113	5532	3952	2371	790
240	169	131	94	56	19
241	64	50	36	21	7
242	219	170	121	73	24
243	64	50	36	21	7
244	595	462	330	198	66
245	803	625	446	268	89
246	126	98	70	42	14
247	219	170	121	73	24
248	59	46	33	20	7
249	250	195	139	83	28
250	399	310	222	133	44
251	337	262	187	112	37
252	1649	1283	916	550	183
253	1366	1063	759	455	152
254	322	250	179	107	36
255	29	22	16	10	3
256	693	539	385	231	77
257	480	373	267	160	53
258	174	136	97	58	19
259	592	460	329	197	66
260	200	156	111	67	22
261	933	726	518	311	104
262	1216	946	676	405	135

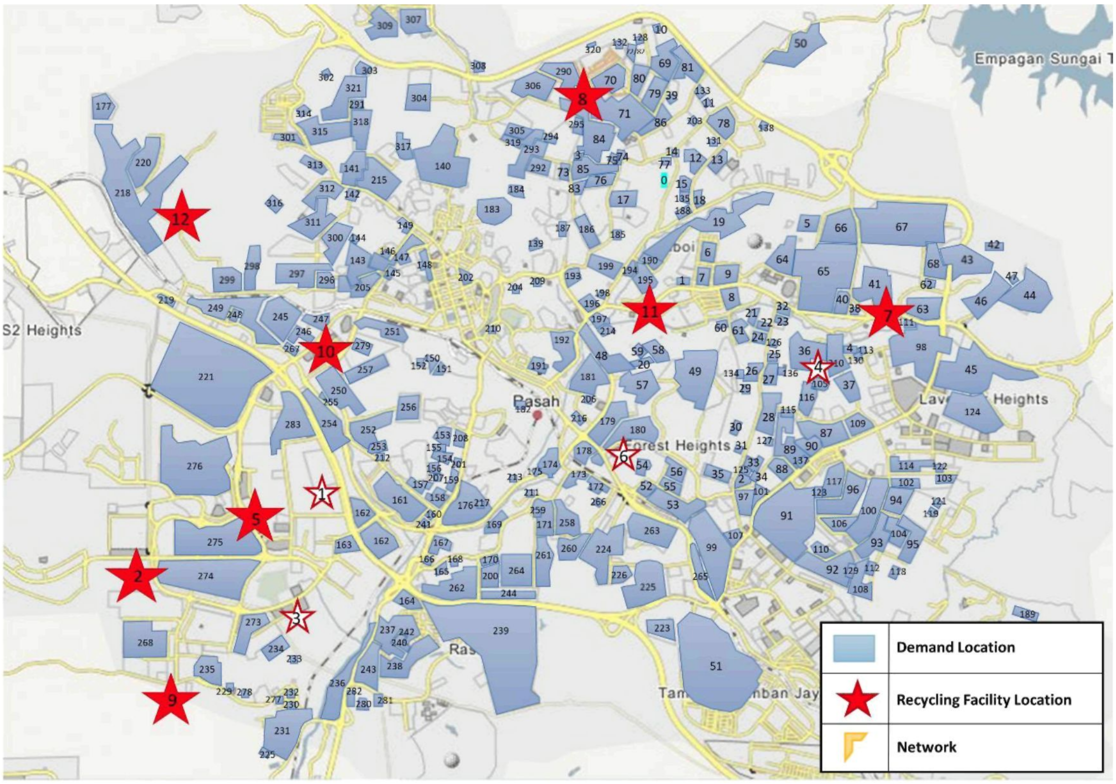
263	503	391	279	168	56
264	202	157	112	67	22
265	973	757	541	324	108
266	740	576	411	247	82
267	140	109	78	47	16
268	5850	4550	3250	1950	650
269	273	212	152	91	30
270	986	767	548	329	110
271	1275	992	708	425	142
272	1358	1056	754	453	151
273	1029	800	572	343	114
274	2361	1836	1312	787	262
275	643	500	357	214	71
276	1123	874	624	374	125
277	86	67	48	29	10
278	146	113	81	49	16
279	382	297	212	127	42
280	442	343	245	147	49
281	304	237	169	101	34
282	99	77	55	33	11
283	253	197	141	84	28
284	966	751	537	322	107
285	49	38	27	16	5
286	553	430	307	184	61
287	529	411	294	176	59
288	376	292	209	125	42
289	206	160	114	69	23
290	396	308	220	132	44
291	1844	1434	1024	615	205
292	697	542	387	232	77
293	409	318	227	136	45
294	2354	1831	1308	785	262
295	121	94	67	40	13
296	141	110	79	47	16
297	71	56	40	24	8
298	873	679	485	291	97
299	349	271	194	116	39
300	457	356	254	152	51
301	742	577	412	247	82
302	154	120	86	51	17
303	1142	888	634	381	127
304	101	79	56	34	11
305	183	142	102	61	20
306	349	271	194	116	39
307	164	128	91	55	18

308	134	104	75	45	15
309	597	465	332	199	66
310	945	735	525	315	105
311	1008	784	560	336	112
312	522	406	290	174	58
313	276	215	153	92	31
314	81	63	45	27	9
315	179	139	99	60	20
	152183	118364	84546	50728	16909

APPENDIX 8

The Optimal Recycling Facility Location on 90% Rate Demand At *i*

Number of operational facilities	Optimal recycling facility at location *j*	Name of recycling facility
1	j_2	Sri Carcosa, S2
2	j_5	Perpustakaan Awam Negeri Sembilan
3	j_7	Taman Pasar Ampangan
4	j_8	Taman Sri Inai
5	j_9	Kalista 2
6	j_{10}	Marrybrown Pusat Perniagaan Oasis
7	j_{11}	Benteng Ampangan Diecast
8	j_{12}	99 Speedmart 1692 (NS) Galla Industrial Park



AUTHOR'S PROFILE

Muhammad Zulhazwan Rosni obtained a Bachelor of Science (Hons.) Management Mathematics in 2018 from Universit Teknologi Mara (UiTM), Negeri Sembilan, and MSc in Mathematics (Research) on 2022 from Universiti Teknologi Mara (UiTM). His MSc thesis involves several methods in Facility Location Problem and Covering Problem includes Data Preprocessing, Regression, Classification and Variable Selection.

LIST OF PUBLICATION:

Muhammad Zulhazwan Rosni, Zati Aqmar Zaharudin, and Adibah Shuib. (2025) Enhancing Recycling Collection Point Coverage in Seremban City, Malaysia: A Comprehensive Study on Adapting Integer Linear Programming Models with Fixed Capacity Levels. (Published, a Pertanika Journal Science & Technology)

LIST OF ORAL PRESENTATION:

a) Best Presenter Award. Enhancing Recycling Collection Point Coverage in Seremban City, Malaysia: A Comprehensive Study on Adapting Integer Linear Programming Models with Fixed Capacity Levels. ICECT IV (International Conference on Engineering & Computing Technologies)