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Enhancing Recycling Collection Point Coverage in Seremban City, Malaysia: A Comprehensive Study on Adapting Integer Linear Programming Models with Fixed Capacity Levels

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ABSTRACT

This study introduces an integer linear programming (ILP) model as an effective strategy to address the problem of facility location and allocation. The implemented model incorporated the concept of covering and finding optimal sites for facility locations to effectively satisfy demand at its optimum level. Identifying strategic and optimal locations for recycling bins, essential for maximizing the effectiveness of recycling initiatives, remains an area that requires substantial improvement, particularly within the context of Malaysia. The study used a mathematical model based on the Maximal Expected Covering Location Problem, with modifications including a fixed capacity level for each recycling facility. The model is applied to households in Seremban, the capital city of Negeri Sembilan in Peninsular Malaysia. The results indicate that three recycling facilities successfully covered the demand locations based on the performance of the modified model.

Keywords: Covering model, facility locations, recycling, waste management

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INTRODUCTION

Municipal solid waste (MSW) is commonly defined as daily trash and garbage, which includes waste from households, businesses and institutional sources but does not include industrial, construction, or hazardous waste (Hemidat et al., 2022). The amount of waste has grown massively worldwide in recent decades, mainly due to increased urbanization and industrialization. MSW

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must be collected regularly, recycled, or treated and disposed of properly to maintain healthy and sanitary living conditions and have less impact on the environment.

Kaza et al. (2018) estimate that by 2050, there will be 3.40 billion tonnes of waste produced globally, with each person producing between 0.11 and 4.54 kilograms per day on average. Malaysia is the third-largest ASEAN waste producer after Singapore and Brunei, producing 1.17 kilograms per person daily and increasing by 5.19% between 2015 and 2020 (Ghani, 2021). By 2030, these landfills are expected to reach their full capacity as 89% of MSW is sent to landfills (Yong et al., 2019). Despite increased waste segregation activity, Malaysian waste generation is at a high volume (Rangga et al., 2022), indicating that a mechanism for sustainable waste management is urgently required in Malaysia. The practice of waste segregation is an essential step in fostering recycling. However, in the current context, as public engagement in waste separation remains insufficient, over 80% of recyclable waste in Malaysia continues to be improperly disposed of, exacerbating environmental challenges (Daim & Mohamed Radhi, 2023).

Recycling contributes to environmental preservation, resource efficiency, and the general well-being of present and future generations by tackling waste creation holistically. It is also part of the sustainable development goal (SDG) 12, i.e., substantially reducing waste generation through prevention, reduction, recycling and reuse (3Rs), which must be achieved by 2030 (United Nations Environment Programme, 2023). Specifically, target 12.5 (Substantially reduce waste generation) of SDG 12 aims to "substantially reduce waste generation through prevention, reduction, recycling and reuse by 2030." Recycling also underpins the concept of zero-waste management.

Malaysia's current recycling rate is 31.5%, and the government plans to increase it to 40% by 2025 (Shakil et al., 2023). Although Malaysia's recycling rates have increased dramatically over the years, the need to cater to household waste is extremely important. Recycling practice must be part of their moral norm to encourage separation-at-source activity among householders (Razali et al., 2019). However, Malaysia still lacks of recycling infrastructures (Mustafa et al., 2022; Rodzi et al., 2023), which is an obstacle to the Malaysian community to practice recycling (Tiew et al., 2019). This is a particularly challenging problem for the local authority to solve, given the sporadic nature and restricted route options of households, especially within an urban congested area. Moreover, strategically located recycling facilities are believed to reach target users and effectively encourage recycling behavior (Azri et al., 2023; Rodzi et al., 2023).

Studies concerned about determining the strategic and optimal locations for recycling bins for more impactful results in recycling efforts, particularly in Malaysia, still lack of mathematical models to improve recycling facilities' location. Recently, mathematical programming models and set-covering location methodologies have become less common. Nevertheless, these techniques continue to retain significant importance across a variety of sectors.

Past Studies Covering Models of Recycling Facility Location

Standard covering models are based on *demand*-based objective functions. The covering concept occurs when a decision-maker strives to maximize a specific amount of demand within pre-specified distances (or travel times) between facilities and demand points. Problems with coverage arise in many real-life situations where location-specific services are unable to satisfy demand outside pre-specified coverage regions (Blanco & Gázquez, 2023). There were renowned basic covering-like models, the Location Set Covering Model (LSCM) and the Maximal Covering Location Problem (MCLP). The LSCM, introduced by Toregas et al. (1971), focuses on identifying the minimum number of facilities and their optimal locations to ensure complete coverage, whereby all demand points are served by at least one facility (Sitepu et al., 2019). In contrast, the MCLP, developed by Church and ReVelle (1974), aims to maximize the population coverage within a specified service distance by strategically locating a fixed number of facilities (Wang et al., 2021).

Several studies have applied mathematical programming (MP) models rooted in the covering conceptual framework to solve location-allocation problems, including identifying strategic locations and determining the optimal number of recycling facilities. Much recent work in utilizing a set covering framework was proposed by Zaharudin et al. (2024) for recycling facility locations and bin allocations. While some numerical analyses were presented, the study has yet to be applied to real-life cases. Additionally, Zaharudin et al. (2023) solved drop-off points for recyclable materials in a satellite city in Malaysia. The proposed model aims to maximize demand coverage by identifying the optimal sites for recycling drop-off points and determining the appropriate number of containers to be installed at these locations. Rosni et al. (2022) and Jamiron et al. (2021) modified a variant of the covering model, namely, the maximum expected covering location problem (MEXCLP) model of Daskin (1983) to position to identify and distribute recycling bins in Malaysia. However, both studies focused on different urban areas that exhibit varying levels of complexity in terms of route networks. Both studies utilized calibration values obtained from Shuib and Zaharudin (2011) to determine the allocation of recycling containers based on the likelihood of bin utilization. Rosni et al. (2022) do not restrict the allocation of containers at each chosen facility, while Jamiron et al. (2021) subsequently relaxed this constraint. On the other hand, Wang et al. (2021) introduced an element of uncertainty into the MCLP to determine the optimal location for a recycling facility in Tongji, China. The model incorporates the cost of service to characterize the uncertainty in demand variation. Meanwhile, Cubillos and Wøhlk (2020) proposed a bi-objective model that integrates cost elements to address the location and routing problem. The purpose is to identify the optimal locations for recyclable drop-off facilities in five specific regions of Denmark.

Certain types of waste, such as electronic waste (e-waste), batteries, and waste cooking oil (WCO), can also be recycled, but a diligent handling process is required. Therefore, collecting these recyclable materials is of utmost importance due to their hazardous and detrimental environmental effects. Sari et al. (2021) investigated the Yogyakarta e-waste network system to determine the quantity and spatial distribution of collection facilities, as well as the optimal transportation route for e-waste disposal. A study on selecting the optimal WCO collection points was conducted by Hartini et al. (2021). The authors used the MCLP model to locate the WCO collection point within Semarang, Indonesia. As a recyclable material, batteries encompass certain types that are classified as hazardous. Guan and Yang (2020) developed a bi-objective linear programming model to effectively identify the optimal placement of recycling facilities for power battery waste. The model takes into account the adverse social effects, which are directly proportional to the quantity of transport power batteries located between the facility nodes. Table 1 provides a summary of selected prior studies that focus on recycling facility location and allocation.

Table 1
Summary of the selected past study covering models of recycling facility location

Authors (year)	Objective Functions	Capacity Integration	Application To Real-Life Problem	Case Study Area
Guan and Yang (2020)	Minimize adverse social effects of battery recycling based on transport distance	✓	Power battery recycling	-
Cubillos and Wøhlk (2020)	Minimize the cost of facility location	✓	Recycling drop-off facilities	Denmark
Sari et al. (2021)	Minimize the total cost of the number of facilities to be established	-	E-waste collection and transportation	Yogyakarta, Indonesia
Hartini et al. (2021)	Maximize coverage for waste cooking oil (WCO) collection	-	Waste cooking oil collection	Semarang, Indonesia
Wang et al. (2021)	Maximize coverage of demand under uncertain demand variations	✓	Recycling facility location	Tongji, China
Jamiron et al. (2021)	Maximize expected coverage of demand locations	✓	Recycling bin location and allocation	Johor Bahru, Malaysia
Rosni et al. (2022)	Maximize expected coverage of demand locations	-	Recycling bin location and allocation	Seremban, Malaysia
Zaharudin et al. (2023)	Maximize the overage of recyclable waste	✓	Recycling drop-off points	Nilai, Malaysia
Zaharudin et al. (2024)	Maximize expected coverage of recyclable waste	✓	Recycling facility location and bin allocation	-

Table 1 highlights that while significant progress has been made in research on recycling facility location and container allocation, only two studies have explicitly prioritized expected recyclable waste generation as their primary focus. This underscores the need for greater emphasis on the coverability of recyclable waste generated. Addressing this research gap is vital for enhancing the efficiency of waste management systems by optimizing the utilization of existing facilities. Establishing new facilities often entails substantial financial costs and land requirements, which may not always be feasible.

This study introduces an ILP model to address the critical challenge of facility location and allocation within the context of recycling collection points. Incorporating the concept of covering, the ILP model seeks to identify optimal locations for recycling collection facilities to efficiently meet demand levels. A fixed capacity level is introduced in the ILP model to ensure full coverage of demand locations. The set capacity subsequently determines the bin allocations. We applied the proposed method to the urban area of Seremban using data from Rosni et al. (2022) through parameter calibration techniques to achieve optimal results.

MATERIALS AND METHODS

The framework in this paper describes the proposed study, referencing the MEXCLP model for the variables and outlining the objective functions, parameters, decision variables, and constraints of the existing covering model. The mathematical model for locating recycling facilities in this study adapts the model proposed by Rosni et al. (2022). By adopting this model, the paper aims to leverage its proven reliability and effectiveness in addressing the specific requirements of recycling facility location and capacity assessment. This paper has both modified and employed reliability measures, and it currently utilizes these adapted measures to assess a fixed capacity level simultaneously.

The application involved implementing a real-world case study. First, a case study of the recycling facilities in Seremban, Negeri Sembilan, was chosen. Second, the model was applied using data from Rosni et al. (2022). However, due to limited data, a weight is assigned to represent capacity levels. If actual capacity data is available, this weight can be adjusted. Third, the optimal solution for a recycling facility location was identified by calibrating the parameters and using the CPLEX solver.

There were variables for the formulation of a mathematical model. Thus, assume a network with a set of nodes (*N*) and arcs (*A*), namely as a graph, *G* = (*N*, *A*). Let a set of demand, $D = \{d_i\}$, where $i = 1, 2, \ldots, n$ and a set of facilities., $j = 1, 2, \ldots, m$, be located at these nodes, with travel times between nodes being the weight for the arcs, i.e., t_{ij}. Let the maximum travel times between these nodes be defined as *T*. A parameter, namely the s_{ij}, is the value to one of $t_{ij} \leq T$, and zero otherwise. In the proposed ILP model, two decision variables are introduced. First, the x_j that is a binary variable assigned a value of 1 if site *j* is activated (i.e., a facility is located at site *j*) and 0 otherwise. Second, the y_{ij} is the binary variable, whose value is 1 if demand at location i is covered with j facilities and 0 otherwise. The main objective of the proposed model is presented by [1], which maximizes the total demand served by activated recycling facilities.

$$\text{Maximize} \quad \sum_{i}^{n}\sum_{j}^{m} d_i\, x_j \qquad [1]$$

Subject to:

$$\sum_{j=1}^{m} s_{ij}\, x_j \geq 1; \qquad \forall i = 1,2,\dots,n \qquad [2]$$

$$y_{ij} \leq s_{ij}\, x_j; \qquad \forall i = 1,2,\dots,n;\ \forall j = 1,2,\dots,m \qquad [3]$$

$$\sum_{i=1}^{n} y_{ij} \geq x_j; \qquad \forall j = 1,2,\dots,m \qquad [4]$$

$$\sum_{i=1}^{n} d_i y_{ij} \leq q_j\, x_j; \qquad \forall j = 1,2,\dots,m \qquad [5]$$

$$\sum_{j=1}^{m} x_j \leq \sigma; \qquad [6]$$

$$x_j, y_{ij} \in \{0,1\}; \qquad \forall j = 1, 2,\dots,m;\ \forall i = 1,2,\dots,n \qquad [7]$$

Constraints of the proposed mathematical model are shown from [2] until [7]. Constraint [2] ensures that the demand at location *i* is served by the nearest activated recycling facility at site *j*, addressing the accessibility issue. To assign the demand from location *i* to the activated facility at location *j*, Constraint [3] is introduced, ensuring alignment with the proximity requirement specified in Constraint [2]. Constraint [4] guarantees that all demands within the proximity of the facilities are assigned to at least one operational site, ensuring the availability of services to all demand locations. To confirm that facilities can accommodate the assigned demand, Constraint [5] is implemented, ensuring that all facilities have sufficient capacity levels, q_j. Additionally, Constraint [6] sets an upper limit on the number of activated recycling facilities, restricting them to a maximum of σ locations. Lastly, Constraint [7] defines the domains of the decision variables, providing the necessary structure for solving the model.

The proposed method is grounded in the set covering framework, with the constraints designed to address the practical challenges of real-life recycling facility location and allocation problems, particularly in inadequate or less favorable locations. Furthermore, a capacity constraint is incorporated into the model to ensure that each facility has sufficient capacity to meet the assigned demand.

Implementation Process: Data Collections and Parameters Setting

Seremban is a densely populated region situated in the southern region of Malaysia. There are approximately 630,299 people residing in 221,529 households within 93.5 thousand square kilometers. Figure 1 depicts the geographic area of Seremban, visually denoted by the color red.

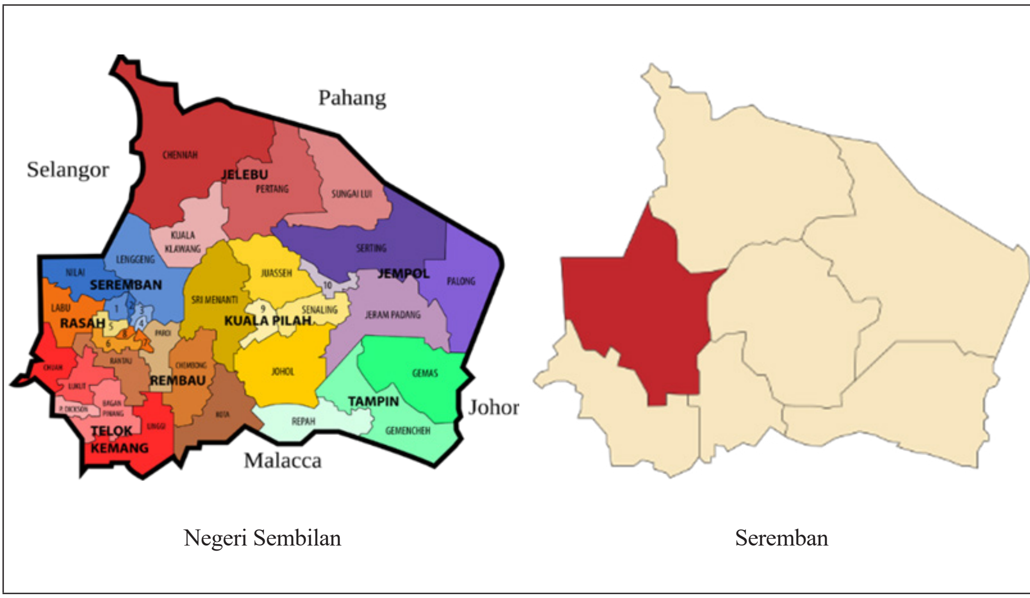

Figure 1. The area of study is Seremban, Malaysia

Figure 2 is the study area that was extracted from Rosni et al. (2022), with the number of households in area (i) being six and five potential locations for the recycling facilities (j). The potential location facilities consist of three shopping centers, one community center and one petrol center, namely, AEON Mall in Seremban 2 (j=1), Pall Mall in Seremban (j=2), CenterPoint in Seremban (j=3), Petronas Petrol Station in Senawang (j=4), and Youth and Sports Complex in Paroi (j=5). These locations can be depicted in the form of a graph network. Figure 2 also depicts an illustration of the interconnectedness between the demand locations and the potential locations for recycling facilities. The interconnectedness is measured by the travel distance between locations i and j, which is measured in minutes using Google Maps. This study assumed there is no traffic congestion along the routes and that these locations are always accessible to the public at any time on all days.

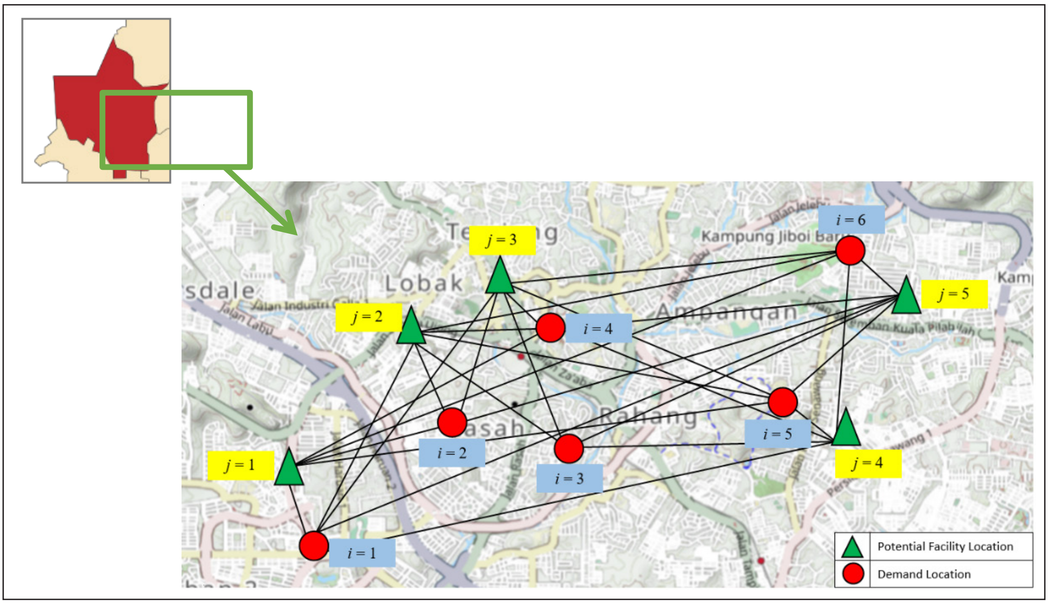

Figure 2. Area of study and network between demand locations and potential facility locations

The amount of waste generated in Seremban was approximated using the average number of persons per household. According to Ghani (2021), the mean waste generation rate for individuals in Malaysia is reported to be 1.17 kilograms per day. This means that for the Seremban area, almost 737,450 kilograms of waste are produced, or almost 3 kilograms per household per day. Currently, the Malaysian government is targeting a recycling rate of 40% for the entire nation. Hence, it is assumed that all users will actively participate in recycling practices that align with the established rate. The term "demand" can be interpreted as the expected amount of recyclable waste generated within a given household area. The data are shown in Table 2.

Table 2
Amount of demand and estimated recyclable waste generation

Household Area (*i*)	**1**	**2**	**3**	**4**	**5**	**6**	**TOTAL**
Expected amount of waste generation (kilograms/day)	60229	20885	12136	12668	36182	17610	159710
Expected recyclable waste generations (kilograms/day)	24092	8354	4855	5067	14473	7044	63884

Table 2 presents the data regarding waste generation amounts in various household areas (i), assuming a daily waste generation rate of 3 kilograms per household. Based on the figures in Table 2, it is possible to make an estimation regarding the generation of recyclable waste. Even though more than 80% of recyclable waste is found in landfills (Baba-Nalikant et al., 2023), for this study, we estimate the amount of recyclable waste generation by using the Malaysian government's target of 40% recycling rates. From this target, it is estimated that the amount of recyclable waste generated by households is almost 64,000 kilograms. The highest expected amount of recyclable waste is at $i = 1$. This is anticipated because the area consists of the household area of Seremban 2. Meanwhile, the least expected amount of recyclable waste is generated at area $i = 3$ since the area consists of a commercial area.

The remaining parameter values, including T, q_j, and σ, can be found in Table 3. The values of T are selected based on the permissible travel times between each demand location and each potential facility location. We randomly choose 10, 13, and 17 minutes to encompass the full spectrum of allowable travel durations. The parameter denotes the fixed potential capacity allocation of each recycling center q_j. In general, the values are gathered from the municipalities. However, due to limited data availability, we allocate a weight, denoted as δ, to the q_j, which signifies the dimensions of the recycling facility's capacity level. However, the weightage can be relaxed if the capacity data is known.

Table 3
List of parameter values

T	δ	q_j	σ
10, 13, and 15 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 units	1–5 units

Subsequently, the acquired total capacity is evenly distributed among all prospective recycling establishments situated at location j. In this study, the total expected quantity of waste generated is estimated at 63,884 kilograms. To analyze the impact of varying capacity levels, the parameter δ, which serves as the multiplier for the capacity, is set to values ranging from 1.0 to 3.0, incrementing by 0.5 in each iteration. This approach allows for a systematic evaluation of the model's performance under different capacity scenarios. For example, if the value of $\delta = 1.5$, then the total capacity of all facilities amounts to 95,826 kilograms, resulting in an average of 19,165.2 kilograms per facility. Meanwhile, the values of parameter σ are systematically varied from 1 to 5 units, representing the range of permissible recycling facility locations to be operating in the study area. The maximum value of 5 indicates the maximum number of locations of potential recycling facilities. Table 4 presents the indices that we use to test the proposed model. The proposed model is solved using CPLEX 20.0 on a personal computer with a 3.2 GHz processor and 16 GB of RAM.

Table 4
List of data values

Total Expected Waste (kg)	Capacity Multiplier, δ	Total Capacity of All Facilities (kg)	Average Capacity per Facility (kg)	Maximum Number of Facility Locations, σ
63,884	1.0	63,884	12,776.8	5
	1.5	95,826	19,165.2	
	2.0	127,768	25,553.6	
	2.5	159,710	31,942	
	3.0	191,652	38,330.3	

RESULTS AND DISCUSSION

This study identifies the optimal locations for the recycling facilities based on the results obtained using CPLEX solver. This involved calibrating the parameters and running the model to find the optimal solutions. The validation and verification processes confirmed the reliability and effectiveness of the changes to the variable models. This paper successfully provides a robust and reliable framework for locating recycling facilities and assessing their capacity levels.

For this study, the value of the objective function is measured with the variations of travel times between the facility and the demand locations (T) being T = 10, 13, and 17 minutes, the maximum number of operational facilities (σ) and the capacity multiplier (δ). We discovered that even though capacity multiplier (δ) increases, the objective function value remains unaffected because 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 3. The figure shows 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, it incurs greater costs or significantly impacts system performance. At the same time, the objective function value remains stable regardless of T and δ; the number of operating facilities changes with these constraints. A detailed analysis of operational facilities based on T, σ, and δ is provided in Table 5.

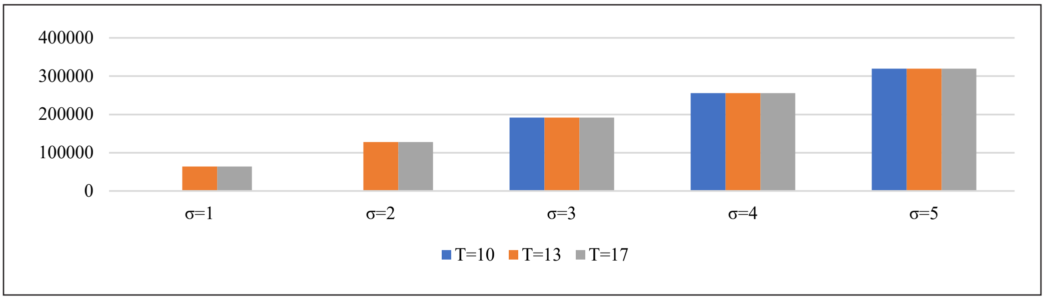

Figure 3. Variation of objective function values based on the values of T, σ, and δ

Table 5 presents the total number of demand locations covered based on the variations of travel times between the facility and demand locations (T), the maximum allowance of operational facilities (σ) and the weight of the capacities level (δ). Table 4 presents the total number of demand locations covered based on the variations of travel times between the facility and demand locations (T), the maximum allowance of operational facilities (σ) and the weight of capacities level (δ). As observed, when T is 10 minutes, 100% of demand locations are covered when a maximum of three facilities are operational. Notably, as the T increases, the percentage of demand locations that can be covered is consistently below 100%, except when T is equal to 13 minutes, and the weight assigned to the capacity level is 3.0. As the weightage values (δ) assigned to the capacity level increase, the corresponding percentage of covered demand locations also increases. However, the increase would reach a threshold covering level, which further increases in δ do not guarantee that more demand locations can be covered. For example, from Table 5, when δ is 3.0 units, and T is at 13 minutes, 100% of the covering level can be reached. However, not all demand locations are covered when the δ is 2.5 units. This happens because the model prioritized facilities that can handle a greater amount of demand over the location of demand (i.e., the i). Instead, when the values of the maximum allowance of operational facilities (σ) increase, the total locations of demand covered also increase. This implies that the model exhibits less sensitivity towards the values of T and δ, and instead, has greater emphasis on the values of σ.

Table 5
The number of demand locations covered based on T, σ, and δ

T	**σ**	**δ**				
		1.0	**1.5**	**2.0**	**2.5**	**3.0**
10	1	-	-	-	-	-
	2	-	-	-	-	-
	3	2	4	3	6	6
	4	3	5	4	6	6
	5	3	5	4	6	6
13	1	2	1	1	1	1
	2	1	4	1	1	1
	3	2	1	1	4	4
	4	2	4	2	4	4
	5	3	4	3	5	6
17	1	1	1	1	1	1
	2	1	1	1	1	1
	3	2	1	1	1	1
	4	2	4	1	1	1
	5	3	4	4	5	4

The results presented in Table 5 demonstrate that the proposed model effectively identifies the optimal locations for recycling facilities, ensuring that the demand can be served at its maximum possible level. Based on the results, to get full coverage of demand locations, it is necessary to establish three recycling facilities with a weightage of δ is 2.5 units of capacity expansion, all of which should be located within a travel time, T is 10 minutes. The locations of the selected recycling facilities are depicted in Figure 4.

Based on Figure 4, the star-shaped icon represents the optimal location for a recycling facility computed using the proposed model, i.e., the ILP with covering approach. Therefore, the three optimal locations of the facility that have been identified are AEON Mall in Seremban 2 (j=1), Pall Mall in Seremban (j=2), and CenterPoint in Seremban (j=3). As shown, the demand locations 1 (i=1) are designated to the facility at location 1 (j=1), and the demand locations 2 (i=2) are assigned to the facility at location 2 (j=2). Demand locations 3, 4, 5, and 6 (i=3, i=4, i=5, i=6) are allocated to the facility at location 3 (j=3). From these results, clearly, all demand locations are assigned to one facility, and it is expected that all recyclable waste will be covered.

The proposed ILP model illustrated that increasing the number of operating recycling facilities will improve the level of service. Additionally, for the area chosen as the case study, the model explicitly demonstrates that an increase in travel time from the demand area to the recycling facility location and capacity expansion would not guarantee an improvement in the amount of recyclables collected. Therefore, even with minimal adjustments, the local municipality may improve its recycling service by adding more operational facilities within its jurisdiction.

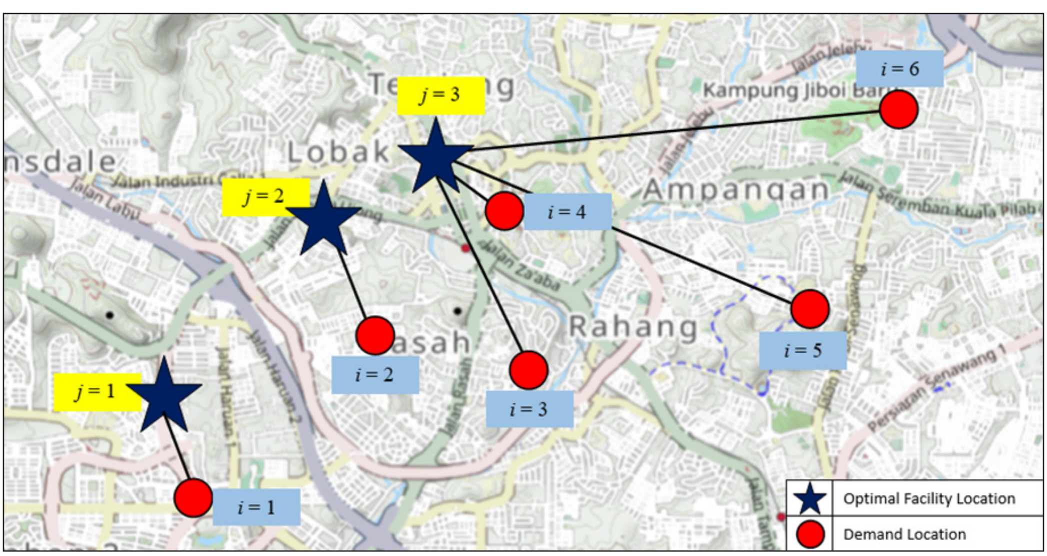

Figure 4. Three optimal facility locations with demand location assignments

The proposed model effectively captures the interaction between the expected amount of collected recyclables, facility capacity, service level, and user travel times. Changes in any of these variables are adequately accounted for within the proposed model. Therefore, it is imperative for decision-makers to implement suitable strategies to optimize users' coverage levels while ensuring optimal service delivery.

CONCLUSION

This study contributes to advancing sustainable regional waste management practices by offering a formal framework for optimizing recycling infrastructure and coverage. An ILP model with a covering concept was proposed to determine the optimal locations for a collection of recycling facilities while considering their restricted capacity levels. We utilized the data from Seremban, Malaysia, extracted from Rosni et al. (2022). Based on the results, to get full coverage of demand locations, it is necessary to establish three recycling facilities with a weightage of 2.5 units of capacity expansion ($\delta = 2.5$), all of which should be located within a travel time of 10 minutes ($T = 10$). On the other hand, there is a clear correlation between the total locations of demand covered and the maximum allowance of operational facilities provided in the model. As the value of the allowance expands, so does the total number of locations covered. This suggests that the model is more sensitive to changes in the maximum allowance of operational facilities (σ) than to changes in capacity level (δ) or maximum travel time (T).

This study addresses Malaysia's challenge of insufficient recycling infrastructure by introducing an ILP model to optimize the location and allocation of recycling bins. It fills a research gap in using mathematical programming and maximally covering locations' problems for this purpose, aiming to enhance recycling efforts in the country. For future work, it is suggested that demand clustering techniques be implemented as the initial step so that potential locations can be selected based on the cluster's centroid. This approach also implies that a system for collecting recyclable waste can be implemented once the locations of recycling facilities have been identified. One possible method for achieving this is to use the dynamic element to determine the inconsistency of waste generation over time.

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REFERENCES

Azri, S., Ujang, U., & Abdullah, N. S. (2023). Within cluster pattern identification: A new approach for optimizing recycle point distribution to support policy implementation on waste management in Malaysia.

Waste Management & Research: The Journal for a Sustainable Circular Economy, *41*(3), 687-700. https://doi.org/10.1177/0734242X221123489

Baba-Nalikant, M., Syed-Mohamad, S. M., Husin, M. H., Abdullah, N. A., Mohamad Saleh, M. S., & Abdul Rahim, A. (2023). A Zero-Waste Campus Framework: Perceptions and practices of university campus community in Malaysia. *Recycling*, *8*(1), 21. https://doi.org/10.3390/recycling8010021

Blanco, V., & Gázquez, R. (2023). Fairness in maximal covering location problems. *Computers and Operations Research*, *157*(May), 106287. https://doi.org/10.1016/j.cor.2023.106287

Church, R., & ReVelle, C. (1974). The maximal covering location problem. *Papers of the Regional Science Association*, *32*(1), 101-118. https://doi.org/10.1007/BF01942293

Cubillos, M., & Wøhlk, S. (2020). Solution of the maximal covering tour problem for locating recycling drop-off stations. *Journal of the Operational Research Society*, *72*(8), 1898-1913. https://doi.org/10.1080/01605682.2020.1746701

Daim, N., & Mohamed Radhi, N. A. (2023). Separating waste at source to boost recycling rate. *New Straits Times*. https://www.nst.com.my/news/nation/2023/03/888284/separating-waste-source-boost-recycling-rate

Daskin, M. S. (1983). Maximum Expected Covering Location Model: Formulation, properties and heuristic solution. *Transportation Science*, *17*(1), 48-70. https://doi.org/10.1287/trsc.17.1.48

Ghani, L. A. (2021). Exploring the municipal solid waste management via MFA-SAA approach in Terengganu, Malaysia. *Environmental and Sustainability Indicators*, *12*, 100144. https://doi.org/10.1016/j.indic.2021.100144

Guan, Q., & Yang, Y. (2020). Reverse logistics network design model for used power battery under the third-party recovery mode. *Proceedings - 2020 16th International Conference on Computational Intelligence and Security, CIS 2020*, 293-297. https://doi.org/10.1109/CIS52066.2020.00069

Hartini, S., Puspitasari, D., & Utami, A. A. (2021). Design of waste cooking oil collection center in Semarang City using maximal covering location problem: A finding from Semarang, Indonesia. *IOP Conference Series: Earth and Environmental Science*, *623*(1), 012100. https://doi.org/10.1088/1755-1315/623/1/012100

Hemidat, S., Achouri, O., Fels, L. El, Elagroudy, S., Hafidi, M., Chaouki, B., Ahmed, M., Hodgkinson, I., & Guo, J. (2022). Solid waste management in the context of a circular economy in the MENA Region. *Sustainability (Switzerland)*, *14*(1), 480. https://doi.org/10.3390/su14010480

Jamiron, N. F. H., Sarif, N. A. S., Abdul Rahman, N. S., & Zaharudin, Z. A. (2021). Establishing recycling bins location and allocation for sustainable urban municipalities of Johor Bahru in Malaysia. *International Journal of Academic Research in Economics and Management Sciences*, *10*(3), 459-472. https://doi.org/10.6007/IJAREMS/v10-i3/11344

Kaza, S., Yao, L. C., Bhada-Tata, P., & Van Woerden, F. (2018). What a Waste 2.0: A global snapshot of solid waste management to 2050. In *What a Waste 2.0: A Global Snapshot of Solid Waste Management to 2050*. World Bank. https://doi.org/10.1596/978-1-4648-1329-0

Mustafa, M. A. S., Mohd Noor, N. H., Mohd Saharom, N. A., & Shamsol Kamal, N. S. S. (2022). Understanding Malaysian household waste separation: An extended theory of planned behaviour. *Malaysian Journal of Sustainable Environment*, *9*(1), 19. https://doi.org/10.24191/myse.v9i1.17285

Rangga, J. U., Ismail, S. N. S., Rasdi, I., & Karuppiah, K. (2022). Waste management costs reduction and the recycling profit estimation from the segregation programme in Malaysia. *Pertanika Journal of Science and Technology*, *30*(2), 1457-1478. https://doi.org/10.47836/pjst.30.2.34

Razali, F., Weng Wai, C., & Daud, D. (2019). A review of Malaysia solid waste management policies to improve recycling practice and waste separation among households. *International Journal of Built Environment and Sustainability*, *6*(1–2), 39-45. https://doi.org/10.11113/ijbes.v6.n1-2.381

Rodzi, Z. M., Hazri, A. N., Mohd Azri, N. A. S., Sharul Rhmdan, N. D. F., Zaharudin, Z. A., & Uttunggadewa, S. (2023). Uncovering obstacles to household waste recycling in Seremban, Malaysia through Decision-Making Trial and Evaluation Laboratory (DEMATEL) analysis. *Science and Technology Indonesia*, *8*(3), 422-428. https://doi.org/10.26554/sti.2023.8.3.422-428

Rosni, M. Z., Ishak, M. I., Mohd Shah, A. Z., & Zaharudin, Z. A. (2022). Location-Allocation Model of recycling facilities – A case study of Seremban, Malaysia. *International Journal of Academic Research in Economics and Management and Sciences*, *11*(1), 56-69. https://doi.org/10.6007/IJAREMS/v11-i1/12119

Sari, D. P., Masruroh, N. A., & Asih, A. M. S. (2021). Extended maximal covering location and vehicle routing problems in designing smartphone waste collection channels: A case study of Yogyakarta Province, Indonesia. *Sustainability*, *13*(16), 8896. https://doi.org/10.3390/su13168896

Shakil, N. S. M., Azhar, N. A. Z. M., & Othman, N. (2023). Solid waste management in Malaysia: An overview. *Information Management and Business Review*, *15*(1(I)SI), 86-93. https://doi.org/10.22610/imbr.v15i1(I)SI.3410

Shuib, A., & Zaharudin, Z. A. (2011). TAZ_OPT: A goal programming model for ambulance location and allocation. *2011 IEEE Colloquium on Humanities, Science and Engineering*, 945-950. https://doi.org/10.1109/CHUSER.2011.6163878

Sitepu, R., Puspita, F. M., Romelda, S., Fikri, A., Susanto, B., & Kaban, H. (2019). Set covering models in optimizing the emergency unit location of health facility in Palembang. *Journal of Physics: Conference Series*, *1282*(1), 012008. https://doi.org/10.1088/1742-6596/1282/1/012008

Tiew, K. G., Basri, N. E. A., Deng, H., Watanabe, K., Zain, S. M., & Wang, S. (2019). Comparative study on recycling behaviours between regular recyclers and non regular recyclers in Malaysia. *Journal of Environmental Management*, *237*(February 2019), 255-263. https://doi.org/10.1016/j.jenvman.2019.02.033

Toregas, C., Swain, R., ReVelle, C., & Bergman, L. (1971). The location of emergency service facilities. *Operations Research*, *19*(6), 1363-1373. https://doi.org/10.1287/opre.19.6.1363

United Nations Environment Programme. (2023). *The Sustainable Development Goals Report 2023: Special Edition*. https://unstats.un.org/sdgs/report/2023/The-Sustainable-Development-Goals-Report-2023.pdf

Wang, Z., Duan, Y., & Huo, J. (2021). Maximal covering location problem of smart recycling infrastructure for recyclable waste in an uncertain environment. *Waste Management & Research: The Journal for a Sustainable Circular Economy*, *39*(2), 396-404. https://doi.org/10.1177/0734242X20967090

Yong, Z. J., Bashir, M. J. K., Ng, C. A., Sethupathi, S., Lim, J. W., & Show, P. L. (2019). Sustainable waste-to-energy development in Malaysia: Appraisal of environmental, financial, and public issues related with energy recovery from municipal solid waste. *Processes*, *7*(10), 676. https://doi.org/10.3390/pr7100676

Zaharudin, Z. A., Shuib, A., Hadianti, R., & Rodzi, Z. M. (2023). Towards sustainable city: A covering model for recycling facility location-allocation in Nilai, Malaysia. *Science and Technology Indonesia*, *8*(4), 570-578. https://doi.org/10.26554/sti.2023.8.4.570-578

Zaharudin, Z. A., Shuib, A., Hadianti, R., & Rodzi, Z. M. (2024). A preliminary model for recycling facility location-allocation problem. *AIP Conference Proceedings*, *2895*(1), 70001. https://doi.org/10.1063/5.0193367