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Sustainable waste solutions: Optimizing location-allocation of 3R waste management sites in Gondokusuman, Yogyakarta, Indonesia through multi-maximal covering location approach

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ABSTRACT

Developing a Multi-Maximal Covering Location Model (MMCLM) for waste management in Gondokusuman Sub-district, Yogyakarta, Indonesia, is urgently needed. The closure of the Piyungan landfill has resulted in the need for additional Reduce, Reuse, and Recycle Waste Management Sites (3R-WMSs) to reduce waste that the landfill cannot accommodate. The primary objective of this model is to optimize the location and allocation of demand volume nodes, representing the resident population, to a specific set of 3R-WMS. These demand nodes are located at different distances from 3R-WMSs, including high and low coverage areas. The research in the Gondokusuman Sub-district employed MMCLM with facility capacity constraints and was developed using mixed integer linear programming methodology. The study identified five optimal locations for a 3R-WMS establishment that comprehensively cover all demand nodes (15301) and population clusters (45903) in the sub-district, including both high (5085) and low coverage areas (10216). This research represents a significant step forward in developing a sustainable environment by ensuring easy access to reducing, reusing, and recycling-based waste management facilities for residents.

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1. Introduction

At present, solid waste management is a significant concern in the Special Region of Yogyakarta. The insufficient facilities and supporting infrastructures to manage urban waste effectively are the core problems. Thus, Yogyakarta landfills are overwhelmed to handling the overtly arriving waste volume. The Yogyakarta City Government, through its decree Number 658/8312, finally decided to close Piyungan Landfill, the biggest landfill in Yogyakarta due to its inability to manage the huge amount of waste generated by the residents of Yogyakarta and its surrounding areas [1]. The closure has resulted in the increase in illegal waste disposal and the accumulation of wastes in various locations, primarily along city roads. This condition potentially harms the city population with a higher risk of disease outbreaks and environmental pollution. Therefore, it is urgent to take action to develop a comprehensive waste management strategy including waste sorting, recycling, composting, efficient waste collection and transportation, and proper management and disposal. Adopting a comprehensive waste management strategy is crucial in reducing the negative impact of waste problems on human health and the environment [2]–[7].

Given the increasing challenges, the government of Yogyakarta must take concrete measures to address this issue effectively. Ensuring adequate facilities and infrastructures is critical to promoting a healthy urban environment. One of many instrumental approaches to dealing with urban waste problems is building Reduce, Reuse, and Recycle Waste Management Sites (3R-WMSs). 3R-WMSs will play a significant role in improving the effectiveness of waste management practices. Several factors that emphasize the importance of 3R-WMS development involve, but are not limited to, the following:

- Reducing the huge amounts of waste that end up in landfills.
- Increasing public awareness on the importance of good waste management.
- Strengthening the reduce, reuse, and recycle (3R) culture [8]-[9].

In addition, 3R-WMSs also will positively impact the local economy by creating jobs and supporting the growing recycling industries. Thus, 3R-WMSa are not merely a place to manage waste but also a foundation in realizing a clean, vibrant, and sustainable environment. Beside ensuring environmental sustainability for future generations, this effort will create a healthier and more sustainable future.

However, building 3R-WMSs accessible to the whole population faces significant challenges, including limited available land and high construction costs. Scientific research have indicated that improving the accessibility of waste collection points to residents can ease their daily waste disposals [10]. A strategic approach proposed for achieving this objective is the systematic waste collection from each household. Waste disposal systems close to households, including roadside or door-to-door collections, provide convenience to the households in their waste disposals, making them more favorable to households. Ideally, waste management facilities should be within walking distance of the households [11]. However, this is not always the case, as waste picking trucks may unable to collect waste from all households or from the communal waste collection sites. This problem has been identified in a study by Leteriel et al. [8], who looked at curbside waste collection in Renca, Santiago, Chile. Rossit et al. [12] has also conducted another study to reduce the investment costs, enhance waste-bin coverage, and improve accessibility to waste disposal facilities. Establishing 3R (Reduce, Reuse, Recycle) based waste management systems that are easily accessible to the public before disposing the wastes to landfills has been proven to be more efficient. In addition to supporting the growing recycling industries, this approach also has been observed raising public awareness on waste management.

To overcome this challenge, researchers have conducted numerous studies to decide the best locations of the infrastructure [13]-[14]. The Maximal Covering Location Model (MCLM), a mathematical method for public health service planning introduced by Church and Revelle [15], is preferred by many researchers to identify the most suitable locations for providing sufficient services to specific population groups. The aim of MCLM is to maximize the coverage of planned service facilities under certain available budget, thereby possibly serving the largest parts of a population.

In many contexts, suitable locations are frequently decided using operations research (OR) techniques [14], [16]–[20]. This approach aims to seek the most optimal placement for facilities, such as recycling plants and waste collection centers. This formulation considers several factors, including demand nodes, location and transport costs, and other relevant elements, while accounting for various constraints in the system, such as facility capacity, available budget, the extend of service area, and the level of demand satisfaction. In addition, OR approach needs designing and implementing algorithms, such as commercial, heuristic, and metaheuristic solvers, to obtain the most precise solutions to the optimization challenge. The solutions can then function as a basis for decision-making [9], [17], [21]–[23].

MCLM-related research and developments have found its applications in various contexts, beyond the field of public health. Ghiani et al. [24] developed an integer programming model to aid decision making processes concerning the location of unsorted waste collection sites in a residential city, altogether with the capacity of bins to be provided at each collection site. The study by Shariff et al. [21] proposed the application of MCLM to assess health facilities in a district in Malaysia. In this study, there is a discussion on facility capacity constraints, which are formulated as capacitated maximal covering locations. They also proposed a novel approach that adopts a genetic algorithm to check the coverage rate of existing facilities within the allowed distance, which the Malaysian government has set. Muren et al. [16] designed a Balanced MCLM for bike-sharing system in a large city in China. In this model, the concept of equilibrium was introduced to address the imbalanced service levels at various locations. Study by Yang et al. [25], applied Continuous MCLM to optimize vehicle or boat locations close to service centers so that the vehicles or boats can be efficiently deployed during natural disasters such as storms, floods, and earthquakes. Ospina et al [26] developed the maximal covering bicycle network model to build a bicycle network aiming to increase cyclists' coverage while reducing the total cost of building bicycle infrastructure. Rosni et al. [27] proposed a model for the allocation of recycling facilities in Seremban urban area, Malaysia, using a classical method of facility locations while considering their capacity. Medina et al. [28] developed MCLM with accessibility indicators and mobile units to expand service coverage and optimize accessibility indicators at the service area of facilities. Another study by Zhuo and Yan [10] has developed a Multi-Maximal Covering Location Model (MMCLM) to address the challenge of determining waste collection site allocations by considering the level of community satisfaction while taking into account site capacities and distances from municipal services.

Based on the above discussion, the objective of this study is to develop an MMCLM to optimize the location of 3R-WMSs. Although this study uses the same MMCLM concept used by Zhuo and Yan [5], it is novel as it presents significant variations in the characteristics of the MMCLM by incorporating Pirkul and Schilling's model [29]. The primary objective of this study is to maximize the allocation of a given facility within a given distance and facility capacity to a demand (population). The model was then tested in Gondokusuman Sub-district, Yogyakarta, Indonesia, a sample area that needs attention in waste management. Therefore, an optimization model approach was used to determine the allocation of waste collection sites to households.

This research makes several significant contributions to improving waste management systems. Firstly, it develops a decision tool based on an MMCLM that can optimize and enhance waste management practices. Secondly, recommendations and policy suggestions are provided for government entities to promote sustainable household waste management at a larger scale. Developing the decision tool and policy recommendations are systematic, while community participation is crucial for the implementation and long-term fundamental change. Together, these integrated contributions address sustainable waste management from many different angles.

2. Method

In this section, we outline the procedures during the data collection and the stages of the MMCLM development. Fig. 1 illustrates the methodological approach employed by this study to determine the population's location and prospective locations for 3R-WMS facilities. The objective is to secure the best possible area coverage. In this section, we also describe the data acquisition procedure by detailing the data sources, collection techniques, and processing procedures. Further, we present the procedures for developing the MMCLM, which involve defining variables, formulating the objective function, and applying constraints while designing the model.

2.1. Defining Study Location

According to Fig. 1, the determination of 3R-WMS location candidates in the Gondokusuman Sub-district followed several important steps. The first step was collecting shapefile (map) data of

Gondokusuman Sub-district geographic, infrastructure, social and demographic data. This information was the basis for understanding the area geography, infrastructure, social and demographic conditions that could influence the development of 3R-WMSs.

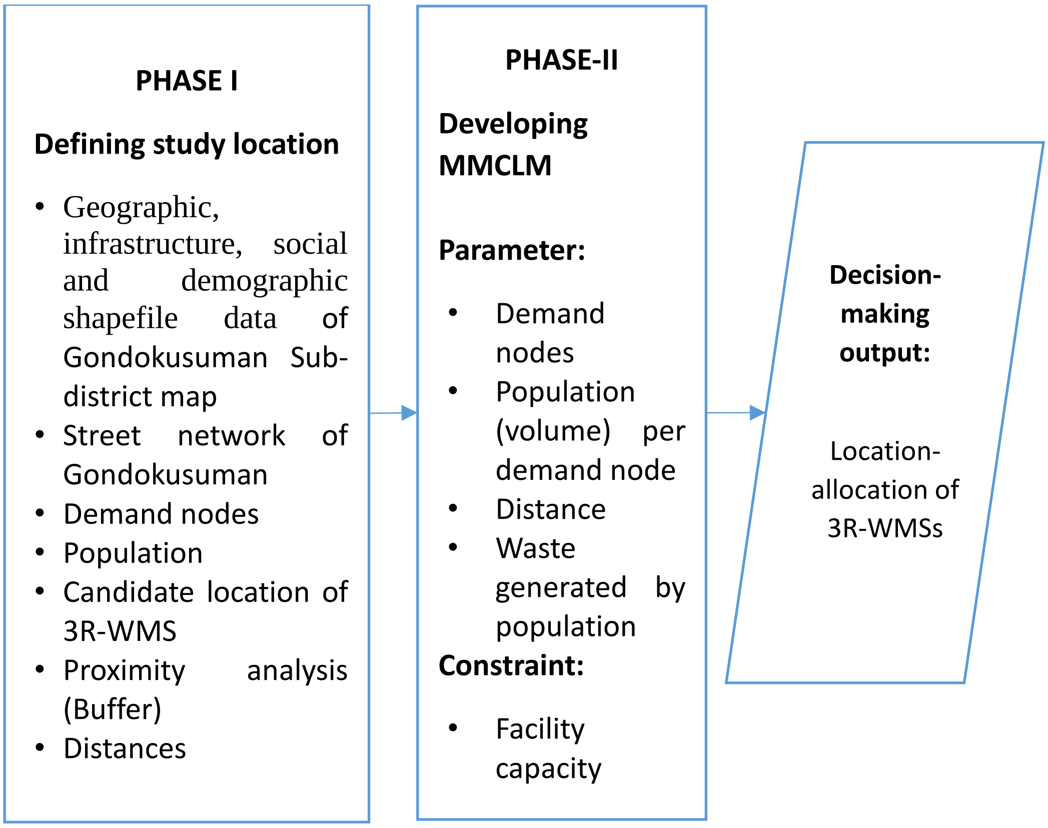

Fig. 1. The general research methodology

The second step was analyzing the street network in Gondokusuman Sub-district. The analysis was necessary to determine the accessibility of 3R-WMS locations to ensure that residents and waste collection vehicles could easily access them. In this way, the establishment of 3R-WMSs could be carried out efficiently and without logistical obstacles.

The next step was determining the demand points. In this case, resident population data at each demand point must be obtained. The demand points were determined using Polygon Midpoint processing feature available in the OpenStreetMap. This information was critical to ensure that 3R-WMSs are placed in areas of needs, taking into account population density and distribution.

Further, this study required average resident population data at each demand point. This information helped in calculating the population volume to be served by each 3R-WMS. After that, 3R-WMS location candidates were selected based on land availability. This was done through searching using Google Maps to determine the coordinates (latitude and longitude) of locations that met these requirements.

After obtaining the demand point data and the coordinates of each 3R-WMS, the data was then integrated. This process involved combining information from different sources to create a comprehensive and accurate representation of the population distribution and potential locations of 3R-WMSs in Gondokusuman Sub-district. Buffer analysis was then performed using ArcGIS. This analysis helped evaluate the coverage area of each 3R-WMS to the points of need. The coverage area values were determined based on the easiest access distance for residents to collect their household wastes to 3R-WMSs. The results of this analysis categorized the coverage area into low and high coverages, providing guidance for better 3R-WMS placement.

2.2. Developing MMCLM

Following the geographical and physical identification of Gondokusuman, a simplified and modified MMCLM was developed to identify potential 3R-WMS locations, focusing on the ease of access to the facilities. This approach reflects a significant innovation in waste management. Ease of access was assessed by calculating the area that could be covered by the proposed facilities. The main objective of the proposed MMCLM is to maximize the coverage of 3R-WMSs to serve the resident population, taking into account the distance factor. This approach considered not only the population, but also the available access routes to the facilities from different demand points. The result of the model was the most optimal (shorter and more accessible distances) set of 3R-WMS facilities, designed to serve larger population, with varying degrees of coverage. This study developed the MMCLM based on previous research by Pirkul and Schilling [29] and Zhuo and Yan [10]. Pirkul and Schilling [29] focused on maximizing population coverage through location planning, but their models only considered a uniform distance threshold when calculating covered demands. They did not account for variability in access distances to facilities which is important in the real-contexts. On the other hand, Zhuo and Yan [10] did incorporate multi-varied distances into their optimization formulation, for maximizing customer satisfaction. However, their objective did not ensure complete coverage and demand fulfillment to the entire population.

To overcome these limitations, the MMCLM developed in this study combined both study considerations – modeling multiple non-uniform access distance thresholds for more representative coverage calculations and optimizing location-allocation decisions to maximize total covered demand. In this computation, variations in the accessibility of waste disposal facilities were carefully considered, providing a solution to the waste management challenges in Gondokusuman Sub-district area. The following Eq. (1) – Eq. (5) are the formulations of the MMCLM:

$$\text{Maximize} \sum_{h=H} \sum_{i\epsilon I} \sum_{j\epsilon J} a_{ijh} v_i y_{ij} \tag{1}$$

Subject to

$$\sum_{j\epsilon J} x_j = T \qquad \forall\, j \in J \tag{2}$$

$$\sum_{j\epsilon J} y_{ij} \leq 1 \qquad \forall\, i \in I \tag{3}$$

$$y_{ij} \leq x_j \qquad i \in I, j \in J \tag{4}$$

$$\sum_{i\epsilon I} y_{ij}\, v_i w_i \leq k_j \qquad \forall\, j \in J \tag{5}$$

$$x_j, y_{ij} \in \{0, 1\}$$

where,

I : Set of demand points that represent buildings, indexed by i.

J : Set of facility potential locations, indexed by j.

H : Set of coverage distance values D for the high-level and low-level coverage of all facility potential locations, given the index h.

Parameter

T : Number of facilities to be built.

v_i : Demand volume (number of populations) at point i.

w_i : Waste volume generated by a resident at node i.

k_j : The number of waste (ton) capacity at facility j

D_h : The radius coverage parameter (D) in each category h, in both high-level and low-level coverage.

d_{ij} : Distance from demand point i to facility j.

$$a_{ijh} = \begin{cases} 1 & \text{If the } d_{ij} \leq D_h, \\ 0 & \text{Otherwise} \end{cases}$$

Binary Variables

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

$$y_{ij} = \begin{cases} 1 & \text{If } i \in I \text{ is assigned in site } j \in J, \\ 0 & \text{otherwise} \end{cases}$$

The objective of the model in Eq. (1) is to maximize the population assigned to a facility within both the high-level coverage and the low-level coverage. Eq. (2) defines the limit of the total number of facilities to be built no more than T. Eq. (3) assigns demand point i to one facility. Eq. (4) restricts the demand node i to be assigned only when facility j is allocated. Eq. (5) limits the waste generated by the population in a single facility. Moreover, this research developed the MMCLM using Microsoft Excel, a systematic modeling tool for organizing data and formulas, with the additional use of the OpenSolver add-in. This add-in efficiently facilitated the use of Mixed-Integer Linear Programming (MILP) techniques directly from the Excel. This combination quickly and accurately produced optimal solutions in the face of complex facility allocation associated with MMCLM problems.

3. Results and Discussion

This section presents the results of placing 3R-WMSs and the allocation of population to the locations of 3R-WMS-based waste management facilities according to the approach described in Fig. 1..

3.1. Result of defining study location

The identification of study location as input for the MMCLM approach involved a number of important steps. First, Gondokusuman Sub-district geographic, infrastructure, social and demographic shapefile data were obtained from OpenStreetMap and then integrated into ArcGIS analysis platform. In the ArcGIS, a street network is a set of geometric and attribute data that represents the street structures. The street networks in ArcGIS were used diversely and covered a wide range of spatial analysis and planning applications. With these shapefiles and street network information, it was possible to identify various access points, such as homes, businesses, or schools, and calculate the distances of these points to other locations. Fig. 2 shows the resulting map of Gondokusuman Sub-district, providing a visual representation of the street structures relevant to location analysis. Next, the population data associated with the demand points was retrieved from OpenStreetMap. This data was inferred from the number of buildings (polygon), with demand point identified as the center of the polygon. To simplify, one demand point was assumed to represent a family of three. In the process of integrating the OpenStreetMap data into the ArcGIS software, a total of 15,301 demand points were identified, shown by green dots in Fig. 3.

The population data played a critical role in calculating the distance from demand points to potential 3R-WMS locations. With accurate coordinates, this research used geospatial algorithms to calculate the optimal distance between each demand point and the potential 3R-WMS locations. This step was crucial in the development of MMCLM, as it aims to minimize travel distance and improve the efficiency of waste management in Gondokusuman Sub-district. Therefore, ArcGIS provided a valuable database for compiling accurate and detailed information needed to test and validate the MMCLM under development. Next, potential locations for the establishment of a 3R-WMS waste management systems using data from OpenStreetMap (OSM) and ArcGIS were identified. These data allowed the identification of areas with high population density, an important criterion in determining the optimal location for 3R-WMSs. The results of this location determining process are shown in Fig.

4, where there are eight potential locations T, selected and marked with blue polygon points. These sites provide a solid basis for the development of 3R-WMS facilities in Gondokusuman Sub-district.

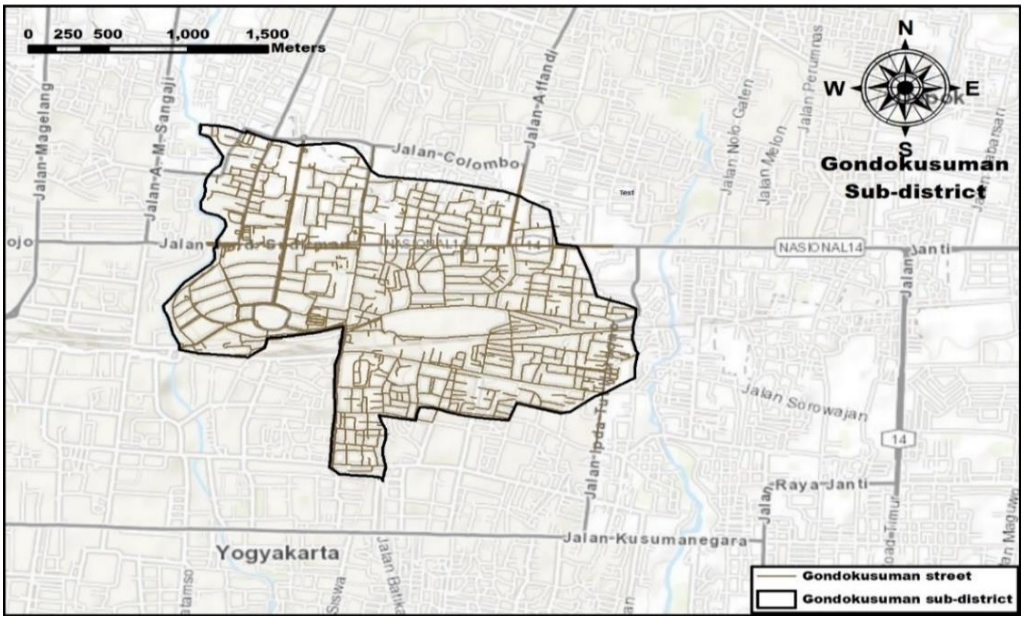

Fig. 2. Map of Gondokusman Sub-district of Yogyakarta

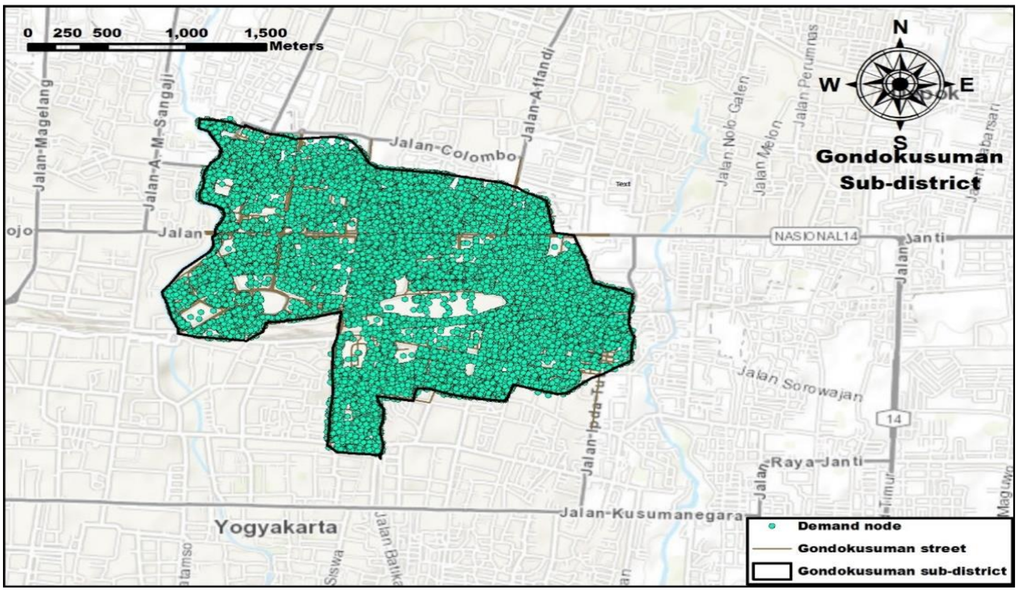

Fig. 3. Distribution map of demand points

In addition to population density, other factors such as the available vacant land and environmental aesthetics were also taken into consideration when determining the potential locations of 3R-WMSs. These factors were evaluated using Google Maps, which involved rigorous spatial analysis to identify locations that met the technical requirements. Available vacant land took into account several aspects, including area, level of accessibility, and land ownership by the Yogyakarta City Government. Meanwhile, the aesthetic value of the environment was taken into account to ensure that the projected 3R-WMSs do not only efficiently support waste management, but also support the beauty and harmony of the surrounding environment and the environmental sustainability goals of Gondokusuman Sub-district. After that, eight potential 3R-WMS locations, T were evaluated based on the coverage area for high level coverage (500 meters) and low-level coverage (1000 meters), as visually shown in Fig. 5.

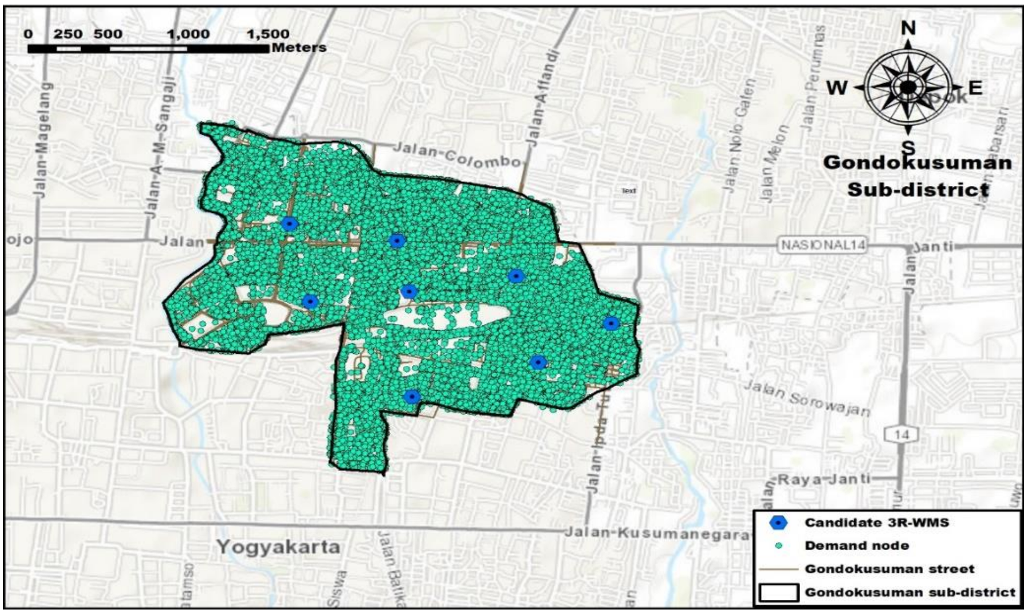

Fig. 4. Eight potential candidates of 3R-WMSs

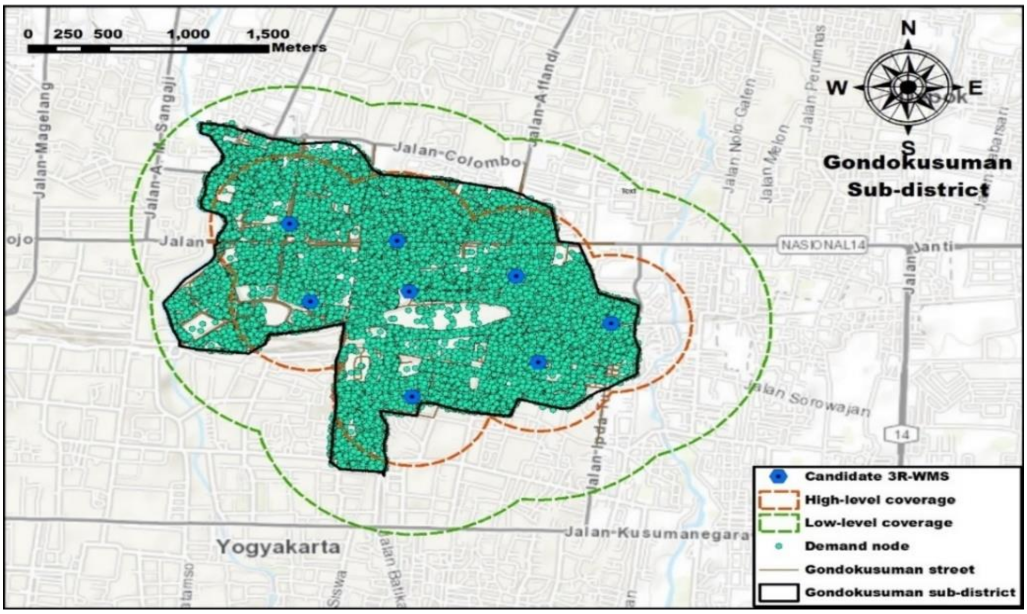

Fig. 5. Proximity analysis result of eight potential candidates of 3R-WMSs for high level coverage (500m) and low-level coverage (1000m)

In Fig. 5, the high-level coverage area is represented by orange circles, while the low-level coverage area is represented by green circles. Interestingly, this distance measurement was not only based on physical aspects, but also based on the ability of residents to reach the 3R-WMSs within a reasonable time. Determining the locations of the 3R-WMS took into account not only geographical factor, but also demographic factor, particularly the number of populations. These two factors are very important in ensuring the operational efficiency of the 3R-WMS facilities so that they can be reached by all residents. The analysis also considered the distance and travel time from the points of demand to the 3R-WMS locations, taking into account various travel methods such as walking, bicycling, or motorcycling. By implementing strict time constraints, such as six minutes, two minutes, and one minute for high coverage, and twelve minutes, three minutes, and two minutes for low coverage, the analysis ensured that 3R-WMS facilities are accessible by all segments of the population. By utilizing the data and analysis features provided by ArcGIS software, the determination of potential 3R-WMS locations in Gondokusuman Sub-district becomes more accurate and efficient, with positive implications for waste management and the welfare of the local community.

Based on Fig. 5, the results of the buffer proximity analysis at high-level of coverage (500 meters) and low-level (1000 meters) show that all demand points or populations in Gondokusuman Sub-district are covered by the 3R-WMSs. At the high level of coverage, with a distance of 500 meters, almost the entire populations are visually covered by the facilities. Meanwhile, at the low level of coverage, with a distance of 1000 meters, the entire populations of Gondokusuman Sub-district are visually covered, even beyond the administrative boundaries of the sub-district. This shows that the placement of the 3R-WMS locations identified by the buffer proximity analysis is able to provide optimal coverage for the entire population of the sub-district. This will ensure that this waste management system meets not only all needs but also goes beyond expectations, bringing significant benefits to the local community and its environment.

3.2. Result of multi-maximal covering location model

After extracting geographic data related to demand points and 3R-WMS candidate locations using ArcGIS software, this data was then incorporated into the MMCLM. The results of the map analysis show the population I in Gondokusuman Sub-district are 15,301 points, with the distance matrix data d_ij measuring the distance between each demand point (i) and the candidate location point (j). In addition, the 3R-WMSs facility have a coverage of 500 meters (high level) and 1000 meters (low level). The distance values between demand points and 3R-WMS locations are classified based on the 500 or 1000-meter coverage. Each demand point has a population volume with v_i, which is equal to 3 people. In addition, the capacity of the 3R-WMS facility is set to k_j = 10 tons per day, while each person at the demand point generates w_i waste weighing 0.7 kg or 0.0007 tons per day. Referring to these data, the results of the MMCLM approach described by Eq. (1) can detail the optimal strategy for assigning the population in the 3R-WMS facility as shown in Table 1. Note that the MMCLM calculation process in Microsoft Excel, which was supported by OpenSolver Add-in, required a computer with certain specifications. For optimal calculation performance, a computer with an Intel(R) Core(TM) i5-10500H processor at 2.50GHz and 8GB of RAM was required. Table 1 shows the data for the scenario of increasing the number of 3R-WMS points versus the number of demand points and population.

Table 1. Location of the built 3R-WMS against changing values of T=1 to T=8

T	**Selected Candidate 3R-WMS**								**Total waste in selected facility (ton)**
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	
1	0,00	0,00	0,00	10,00	0,00	0,00	0,00	0,00	10,00
2	10,00	0,00	0,00	10,00	0,00	0,00	0,00	0,00	20,00
3	0,00	10,00	0,00	10,00	0,00	10,00	0,00	0,00	29,99
4	10,00	6,48	0,00	10,00	0,00	5,60	0,00	0,00	32,08
5	10,00	7,86	4,89	0,00	0,00	5,49	0,00	3,89	32,13
6	8,40	4,94	3,70	0,00	0,00	2,78	2,74	9,57	32,13
7	7,97	4,38	3,25	2,42	0,00	3,24	2,27	8,60	32,13
8	4,63	5,11	3,62	2,67	2,06	2,94	3,96	7,14	32,13

It is important to note that each demand point in this table represents 3 family members. Analysis of the data shows that as the number of 3R-WMS points increases, the coverage of demand points and population increases significantly. For example, when there are 5 or more 3R-WMS points, all demand points and populations can be fully covered. However, it should be noted that the coverage values vary at different 3R-WMS point levels. At the 5th 3R-WMS point, there are two coverage categories – "high" with 5085 points (15255 population) and "low" with 10216 points (30648 population).

Meanwhile, at the 6th 3R-WMS point, the high coverage increase to 5244 points (15732 population), while the low coverage are 10057 points (30171 population).

The analysis of the 7th and 8th 3R-WMS points revealed an interesting dynamic: the allocation of new demand point results in a decrease in high coverage and an increase in low coverage. Although all demand points and populations remain covered, the change in allocation significantly affects the coverage pattern. This emphasizes the importance of understanding local needs and demand distribution to efficiently optimize the waste collection system. With this understanding, demand point and population management strategies can be adjusted to provide optimal service to the community. Identifying more strategic points and increasing public awareness of waste management policies could also improve the system's overall effectiveness. Table 2 confirm that the capacity of each facility is limited to an average of 10 tons. However, Table 3 provides a more detailed picture of the amount of waste that can be accommodated by each facility selected based on the analysis results.

A detailed analysis of Table 3 shows that the MMCLM value increases significantly when the number of 3R-WMS points reaches T=5. This finding indicates that at this level, the addition of 3R-WMS points positively impacts the economic optimization of the distribution of demand points to waste collection facilities. However, it should be noted that the MMCLM value remains stable from T=6 to T=8, with a constant value of 45903. It can be inferred that at T=5 all demand points and populations will have been fully covered, which is consistent with the results in Table 1, so the additional 3R-WMS will not add any benefit in terms of reducing costs or improving the efficiency of demand point distribution. This analysis shows that the optimal number of 3R-WMS points that should be established is five (at locations 1, 2, 3, 6, and 8), each with an average capacity of 10 tons. With the number, the needs of all demand points and the population can be optimally fulfilled, creating an efficient and effective operation.

It should be noted that this estimated amount of waste includes the results of assigning demand points to the selected 3R-WMS points. Although there is a capacity limit of 10 tons in the MMCLM approach, the optimization results show variations in the estimated amount of waste for each selected 3R-WMS. This analysis provides important insights for Gondokusuman Sub-district government, enabling them to plan the construction of 3R-WMSs that fit with the predetermined capacity while taking into account the estimated amount of waste to be handled by each facility. With a deeper understanding of these waste load projections, the government can manage the development budget more efficiently and effectively, ensuring that the established facilities can meet the needs of the community while minimizing environmental impacts.

3.3. Policy recommendation

The analysis shows that establishing five 3R-WMS points that covers all demand points provides essential managerial insights in the government's efforts to build a sustainable environment. Optimizing the right number of points is the strategic basis for effective and sustainable waste management. By ensuring that every demand point is covered, the government will successfully optimize the distribution of waste collection facilities. This decision provides multiple benefits: first, it reduces the environment's vulnerability to waste pollution and ensures the cleanliness of the area; and second, it reduces the economic and social impacts that may arise from uncontrolled waste accumulation.

A thorough understanding of the optimal capacity of each 3R-WMS facility is the key in development planning. By considering the 10-ton capacity that has been determined, the government can plan the allocation of waste collection facilities efficiently and effectively. In this context, optimal selection of the number and location of collection points will optimize resource utilization and reduce wastage. Proper management of facility capacity allows for sustainable planning of facility maintenance and development, keeping the infrastructure operating at its optimal capacity.

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Table 2. Analysis of the relations between the number of waste collection points and demand and population coverage

Number of 3R-WMS point *T*	**Number of demand nodes covered**			**Number of demand nodes not covered**	**Number of populations covered**			**Percentage of coverage (%)**			**Not covered**
	High-level coverage	**Low-level coverage**	**Total covered**		**High-level coverage**	**Low-level coverage**	**Total covered**	**High-level coverage**	**Low-level coverage**	**Total covered**	
1	1442	3319	4761	10540	4326	9957	14283	9,42%	21,69%	31,12%	68,9%
2	2986	6536	9522	5779	8958	19608	28566	19,52%	42,72%	62,23%	37,8%
3	5587	8696	14283	1018	16761	26088	42849	36,51%	56,83%	93,35%	6,7%
4	5026	10250	15276	25	15078	30750	45828	32,85%	66,99%	99,84%	0,2%
5	5085	10216	15301	0	15255	30648	45903	33,23%	66,77%	100,00%	0,0%
6	5244	10057	15301	0	15732	30171	45903	34,27%	65,73%	100,00%	0,0%
7	4881	10420	15301	0	14643	31260	45903	31,90%	68,10%	100,00%	0,0%
8	5031	10270	15301	0	15093	30810	45903	32,88%	67,12%	100,00%	0,0%

Table 3. Location of the established 3R-WMS against changing values of T=1 to T=8

Number of 3R-WMS point *T*	**Established 3R-WMS candidate**	**MMCLM value**
1	4	14283
2	1, 4	28566
3	2, 4, 6	42849
4	1, 2, 4, 6	45828
5	1, 2, 3, 6, 8	45903
6	1, 2, 3, 6, 7, 8	45903
7	1, 2, 3, 4, 6, 7, 8	45903
8	1, 2, 3, 4, 5, 6, 7, 8	45903

Calculating capacity of each facility in handling waste volume is valuable information in designing a sustainable waste management strategy. By understanding the projected waste load to be addressed by each 3R-WMS, the government can appropriately allocate budgets, ensuring that the facilities are built not only according to the needs of the community, but also are able to address additional waste volume in the future. In addition, waste estimation also provides better insights into consumption trends and people's disposing behavior, enabling the government to design more effective education and awareness programs.

In managing the 3R-WMSs, the government needs to consider a long-term strategy to ensure their sustainability. Effective management must be carried out side by side with continuous monitoring and evaluation of the facility performances. By regularly monitoring the waste stream, the government can better understand the composition and the sources of wastes, and develop targeted reduction and recycling programs. Many programs can be implemented, including, not limited to, introducing incentives for residents sorting many types of wastes at their homes, and imposing higher tariffs for the unsorted wastes.

Environmentally, ongoing lifecycle assessments should track sustainability metrics such as greenhouse gas emissions, resource consumption and disposal rates to inform progressive policies and processes that minimize environmental impacts [30]. Investing in the transformation of waste into clean energy or developing markets for recycled products can support this effort [31], [32].

Socially, an inclusive approach should involve all stakeholders, from informal waste pickers, households to private operators, in a collaborative manner [33]. Building local capacity through training programs, providing fair wages and supporting working environments, and partnering with corporations/NGOs helps to develop empowered formal workforces. Community participation should be encouraged through education [34], social campaigns and incentives to encourage sustainable waste management behaviors [35]–[40].

The integration of economic viability, environmental protection and social progress are keys to the sustainable achievement of the 3R-WMS objectives. These recommendations provide a framework for continuous improvement as an adaptive and responsible system. Monitoring impacts across sustainability parameters, investing in cleaner solutions and keeping communities at the center will be critical to success.

4. Conclusion

In the context of waste management in Gondokusuman Sub-district, Yogyakarta, this research makes an important contribution by developing a multi-maximal covering location model to support the establishment of 3R-WMSs. The results show that the establishment of five 3R-WMSs is an optimal solution that covers all demand points and population clusters in the sub-district, including high and low coverage areas. This successful implementation reflects an important step towards achieving a sustainable environment.

Optimizing the number of 3R-WMS by considering the capacity of the facility according to the volume of waste generated by the population provides deep insight into future facility planning and the required budget. By integrating the MMCLM model, the government and relevant stakeholders can make smarter resource allocation decisions to build efficient and sustainable waste management facilities. The model's emphasis on recycling, reuse, and waste reduction not only creates easy access to facilities for residents, but also supports a paradigm shift in society toward more environmentally friendly behaviors.

Thus, the results of this study not only provide a basis for effective waste management in Gondokusuman Sub-district, but also provide valuable insights for the development of similar strategies in other locations. Environmental sustainability and community welfare are the top priorities; and the MMCLM model, together with optimal implementation of the 3R-WMS, can be a concrete step toward achieving these goals. By continuously integrating scientific knowledge and practical experience, these steps pave the way for a clean, healthy, and sustainable environment for all residents of Gondokusuman Sub-district and surrounding communities.

An important aspect that can be the focus of future research is to incorporate budget constraints into the MMCLM model. In addition, extending the research to a larger scale, especially to the entire city of Yogyakarta, will provide a deeper insight into the complexities of waste management in a larger urban context.

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