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Heterogeneous Fleet Location Routing Problem for Waste Management: A Case Study of Yogyakarta, Indonesia

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Abstract

The design of waste supply chain networks has been a challenge in the area of coordinated waste management systems, particularly in Indonesia, where hundreds of nodes need to be handled. Previous studies of waste management in Indonesia mainly focused on routing, leaving out strategic aspects such as location. By contrast, recent literature proposes location routing problem (LRP) approach to attain the global optimum of an integrated system. Therefore, this study applies the LRP to the design of a waste supply chain network in the Special Region of Yogyakarta, Indonesia. The developed model considers two types of fleets to determine depot locations, waste-based power plant locations (act as final disposal site), service allocations, and associated routes, to minimize the total costs. The model is verified using CPLEX. A greedy algorithm is employed to solve the problem consisting of 849 nodes. Results and implications are discussed in this paper.

Keywords: Waste management system, location routing problem, heterogeneous vehicles.

1. Introduction

Municipal waste collection is a challenge faced by nearly all countries. The volume of waste generated by a certain region is proportional to the number of its inhabitants, as in the case of the Special Region of Yogyakarta (DIY hereinafter), Indonesia, which was explained by Mulasari et al. [22]. Notably, Central Bureau of Statistics of Special Region of Yogyakarta [8] showed that the total population of DIY in 2009 was 3,426,637, which increased to 3,594,954 in 2013. Meanwhile, Mulasari et al. [22] investigated that the volume of waste during final disposal site in 2009 was 7 kilotons, which increased to 14 kilotons in 2013. The phenomenon of the increasing volume of waste in DIY demands a massive and comprehensive waste management system. In one of its articles, Regional Regulation No. 10 (2012) of Yogyakarta [27] mentioned that the purpose of waste management is to utilize waste as a resource. One of the planned efforts by the government of DIY is to apply Swedish technology to establish a waste-based power plant. The plan has not been realized because it needs considerable preparation and analysis of various factors, which was explained by Handito [16]. Currently, the waste management system in DIY is still done separately between five districts. Each vehicle collects waste in its designated district and unloads the waste at its own final disposal site. Meanwhile, generating electricity requires a considerable volume of waste obtained from the five districts in DIY.

A technical analysis of waste processing using the waste-based power plant in DIY have been conducted by researchers from Bandung Institute of Technology [3] in 2007. However, no analysis related to power plant system design for a long-term planning has been conducted. Once a power plant facility is established, waste from each district is transported to the facility to meet the electricity conversion needs. Therefore, an appropriate design of a waste collection network is required. Simchi-Levi et al. [29] asserted that network configuration is one key issue in supply chain management. However, three decisions, namely, strategic, tactical, and operational decisions, are involved in the supply chain management based on a given time frame. Chopra and Meindl [9] and Simchi-Levi et al. [29] explained that facility location determination is a strategic decision, whereas vehicle distribution route determination is an operational decision. The analysis of decision making in distribution network design is often done independently. However, Watson-Gandy and Dohrn [32] investigated that determining facility location without considering the route may yield a suboptimal solution. By contrast, solving the facility location and routing problems simultaneously using an approach called location routing problem (LRP) can yield a good result. In waste management systems, determining both the facility location and vehicle route could address the need for a coordinated waste supply chain network.

Nagy and Salhi [23] and Prodhon and Prins [24] reviewed that in recent years, various types of LRPs have been investigated and applied to a wide variety of fields, such as waste collection. Although several studies of waste LRP have been conducted, nearly all of them only considered the commercial type of waste collection in their models. Meanwhile, in Toth and Vigo [31], two other types of waste collection, namely, residential collection and rollon-rolloff problem, were presented.

This study uses the LRP approach to deal with a real waste management system in DIY, Indonesia. The specified facility locations are the depot, which is the start and end point of vehicles, customers, and the waste-based power plant (power plant hereinafter). Power plant in this study acts as the final disposal site. The vehicle routes include the truck traversing the route from the depot to the customer, unloading the waste in the opened final disposal site, and returning to the depot. Different from previous studies, the current work considers the commercial and rollon-rolloff as types of waste collection. Therefore, the fleet is considered heterogeneous, with dump trucks used for commercial and arm roll trucks used for the rollon-rolloff type. Each truck has its own capacity, specific procedure for waste collection, and traveling time limitations.

A new mathematical model is proposed to determine the depot locations, final disposal site, service allocations, and associated routes. The goal of the model is to minimize the total cost, which consists of facility costs (establishment of depots and final disposal sites), vehicle fixed costs, and travel costs. The model is parameterized using empirical data acquired from a field study and secondary data. The model is implemented to some instances and verified using CPLEX.

Since LRP is an NP-hard problem, a greedy algorithm is proposed to solve the problem. The greedy algorithm has been widely used in various problem applications, such as vehicle routing problems by Mat et al. [21]. Moreover, Buhrkal et al. [7] and Markov et al. [20] employed greedy algorithm within their proposed algorithm to solve the waste collection problem but they only considered the commercial type for collecting the waste.

The remainder of this paper is structured as follows: Section 2 summarizes the related literature, particularly that on LRP, to deal with the waste management case. Section 3 presents a mathematical model of LRP for the waste management case in this study. Section 4 explains the solution structure and the proposed greedy algorithm to solve the problem. Section 5 describes the computational study in detail. Finally, Section 6 presents the conclusions of the study and suggestions for future research.

2. Literature Review

The early study of waste management by Beltrami and Bodin [4] was developed with the concept of the vehicle routing problem. An algorithm using the Clarke and Wright heuristic method was developed in their study to determine the optimal route of municipal waste collection in New York.

The concept of the vehicle routing problem has been used to aid decision making at the operational level, at which point the depot serving as the start and end points of trucks, customers, and final disposal locations have been determined. The prior studies on the waste collection vehicle routing problem described here employed either exact methods or heuristic techniques. The exact branch and bound method was used by Fooladi et al. [13] to optimize truck routes with the assumption that the depot location is the same as the final disposal site. Heuristic methods were employed by Teixeira et al. [30] and Buhrkal et al. [7], along with additional variables, such as periodic waste collection and time windows, respectively.

Apart from waste collection route determination, other prior studies, such as Eiselt and Marianov [10], Eiselt and Marianov [11] and Jabbarzadeh at al. [17], focused on the determination of final disposal sites. These studies were based on the facility location problem, in which the decision is taken at the strategic level, as explained by Han and Ponce-Cueto [15].

Over time, the separate decision on facility location and route determination often yielded suboptimal solutions, as explained by Watson-Gandy and Dohrn [32]. Thus, LRP research emerged and its application has grown rapidly. For example, the LRP has been actively applied in waste management research.

A mathematical LRP model for hazardous waste was proposed by Alumur and Kara [1], Boyer et al. [6], and Samanlioglu [28] and solved by an exact method using CPLEX solver. These studies considered homogeneous and uncapacitated vehicles, such that a vehicle may load as many units of waste as desired. The exact ε-constraint method was proposed in Ghezavati and Beigi [14] to solve the multi-echelon reverse logistics network problem by considering some attributes, such as time windows and heterogeneous and capacitated vehicles, as a novelty. Given the NP-hard nature of the LRP, heuristic methods have been proposed to solve practical instances instead of exact methods.

The metaheuristic genetic algorithm (GA) was employed by Ardjmand et al. [2] to deal with the waste LRP for hazardous materials. The fleet was assumed to be homogeneous and uncapacitated. A hybrid GA, as a modification of the GA, was proposed by Wichapa and Khokhajaikiat [33] to solve the multi-objective waste LRP. The study considered homogeneous but capacitated vehicles. The proposed method was verified by comparing it with hybrid goal programming. Metaheuristic non-dominated sorting genetic algorithm (NSGA-II) and multi-objective particle swarm optimization (MOPSO) were proposed by Farrokhi-Asl et al. [12] to handle the waste LRP with heterogeneous and capacitated vehicles. The objective functions were to minimize the costs and maximize the distance between customers and final disposal sites. The solutions obtained by these methods were compared, and the findings showed that NSGA-II outperformed MOPSO. The same method comparison was proposed by Rabbani et al. [26] to solve the three-objective waste LRP. NSGA-II was also proposed by Rabbani et al. [25] to handle the waste LRP with heterogeneous and capacitated vehicles, and it was then compared with decomposition methods.

3. Problem Description

Two types of trucks used to collect waste from customers are considered in this study. Each type of truck has its own capacity and limited allowable traveling time for each route. Therefore, the fleet is considered heterogeneous. Moreover, the waste collection process varies between trucks.

Figure 1: Dump truck (left) and arm roll truck (right).

The first type of truck, that is, a dump truck, serves customers through the commercial type of waste collection. A dump truck has a fixed container that cannot be replaced (see Figure 1). Each dump truck starts its journey from a depot and collects waste from the locations of regular customers. After collecting waste according to its capacity and time constraints, the dump truck proceeds to the opened final disposal site. Finally, the dump truck returns to the depot where it started its travel. The second type of truck, that is, arm roll truck, serves customers through the rollon-rolloff type of waste collection. The arm roll truck has an empty replaceable container attached to it (see Figure 1). Each arm roll truck starts its journey from a depot with an empty container and travels toward the locations of customers to switch the loaded container with an empty container. The arm roll truck brings the loaded container to the opened final disposal site to unload the waste. Then, the arm roll truck continues its service according to its time constraint. Finally, the arm roll truck returns to the depot where it started its travel. The waste collection process by dump truck and arm roll truck is illustrated in Figures 2 and 3.

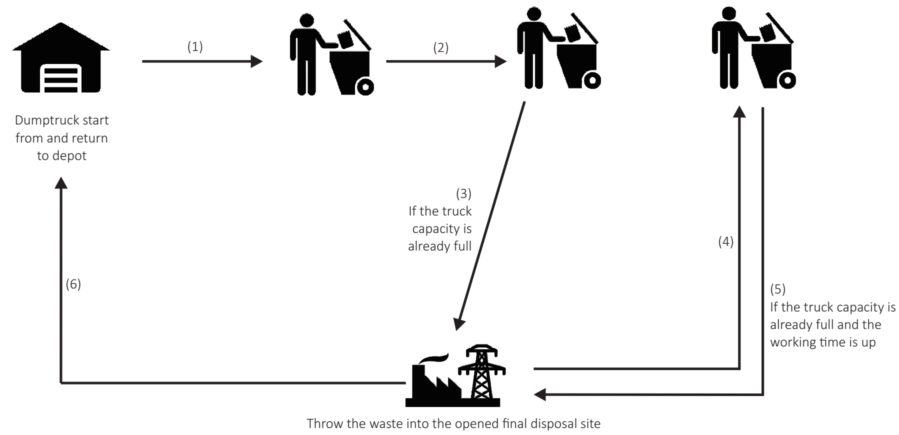

Figure 2: Dump truck service.

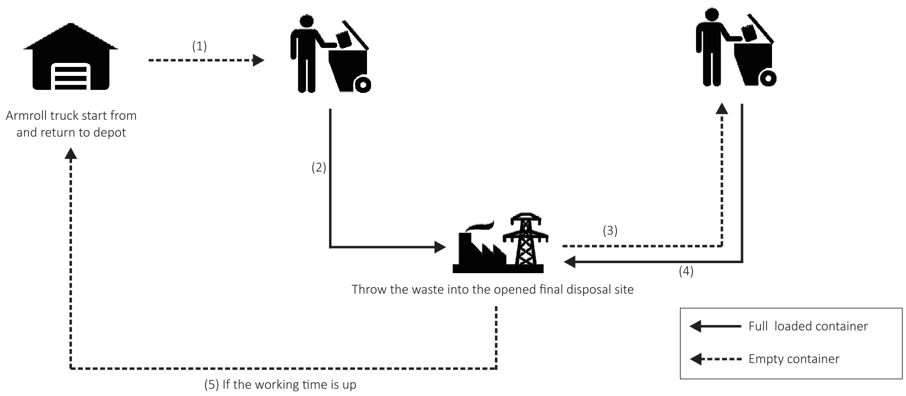

Figure 3: Arm roll truck service.

The proposed model is formulated as a single-objective mixed-integer programming model with the objective of minimizing the total cost. Fixed costs are associated with opening a depot and a final disposal at potential locations. Transportation costs are associated with vehicle fixed costs and travel costs, which are proportional to the fuel costs based on the distance traveled by the vehicle. We aim to determine the location of depots and final disposal sites, as well as vehicle routes, simultaneously. For modeling purposes, the depot and final disposal site candidates are duplicated.

3.1. Problem Assumptions

The assumptions used to develop the model are as follows:

1. The demand (volume of waste) of each customer is known and deterministic.
2. The customer locations are known.
3. The vehicle capacity is limited.
4. The vehicles are heterogeneous (dump truck and arm roll truck).
5. Each customer is served by only one type of vehicle.

3.2. Notations

Sets:

V	$V^d \cup V^{cr} \cup V^{cn} \cup V^f \cup V'^d \cup V'^f$ Set of nodes.
V^d	Set of potential depots.
V'^d	Set of potential depot duplications.
V^{cr}	Set of regular customers (served by the dump truck).
V^{cn}	Set of container customers (served by the arm roll truck).
V^f	Set of potential final disposal sites.
V'^f	Set of potential final disposal site duplications.
S	$\begin{cases} 0, & \text{if the fleet type is dump truck,} \\ 1, & \text{if the fleet type is arm roll truck.} \end{cases}$
K	$\{1, 2, \ldots, K\}$ Set of vehicles.

Parameters:

d_{ij}	Distance between nodes i and j.
t_{ij}	Travel time between nodes i and j.
h_{sk}	Fixed cost associated with using vehicle $k \in K$ of fleet $s \in S$.
c_{sk}	Variable cost of vehicle $k \in K$ of fleet $s \in S$ per unit of distance.
q_i	Demand of each node $i \in V$.
cap_{sk}	Maximum capacity of vehicle $k \in K$ of fleet $s \in S$.
cap_d	Maximum capacity of depot $i \in V^d$ that accommodates the vehicles.

H	Maximum allowable time to serve customers in each route.
FD_i	Fixed cost of opening a depot in potential location $i \in V^d$.
FP_i	Fixed cost of opening a final disposal site in potential location $i \in V^f$.
M	Large value.

Decision variables:

x_{ijsk}	If vehicle $k \in K$ of fleet $s \in S$ serves route (i,j), then $x_{ijsk} = 1$; otherwise, $x_{ijsk} = 0$.
z_{isk}	If vehicle $k \in K$ of fleet $s \in S$ is allocated to customer node $i \in V^{cr} \cup V^{cn}$, then $z_{isk} = 1$; otherwise, $z_{isk} = 0$.
o_i	If depot $i \in V^d$ is opened in potential location V^d, then $o_i = 1$; otherwise, $o_i = 0$.
y_i	If final disposal site $i \in V^f$ is opened in potential location V^f, then $y_i = 1$; otherwise, $y_i = 0$.
U_{isk}	Continuous variable representing the load of vehicle $k \in K$ of fleet $s \in S$ just after leaving node $i \in V$.
T_{isk}	Continuous variable representing the time consumed by vehicle $k \in K$ of fleet $s \in S$ just after leaving node $i \in V$.

3.3. Mathematical Formulation

The problem is formulated as follows:

$$\begin{aligned} \text{Minimize total cost} = &\sum_{s=0}\sum_{k\in K}\sum_{j\in V^{cr}}\sum_{i\in V^d} h_{sk}x_{ijsk} + \sum_{s=1}\sum_{k\in K}\sum_{j\in V^{cn}}\sum_{i\in V^d} h_{sk}x_{ijsk} \\ &+ \sum_{s=0}\sum_{k\in K}\sum_{j\in V}\sum_{i\in V} c_{sk}d_{ij}x_{ijsk} + \sum_{s=1}\sum_{k\in K}\sum_{j\in V}\sum_{i\in V} c_{sk}d_{ij}x_{ijsk} \\ &+ \sum_{i\in V^d} FD_i o_i + \sum_{i\in V^f} FP_i y_i. \end{aligned} \tag{3.1}$$

Subject to

$$\sum_{s=0}\sum_{k\in K}\sum_{i\in V\setminus V'^d\cup V^{cn}} x_{ijsk} = 1 \qquad \forall\, j \in V^{cr} \tag{3.2}$$

$$\sum_{s=1}\sum_{k\in K}\sum_{i\in V\setminus V'^d\cup V^{cr}\cup V^{cn}} x_{ijsk} = 1 \qquad \forall\, j \in V^{cn} \tag{3.3}$$

$$\sum_{i\in V\setminus V'^d\cup V^{cn}} x_{ijsk} = \sum_{i\in V\setminus V^d\cup V^{cn}} x_{jisk} \qquad \forall\, j \in V^{cr}\cup V^f\cup V'^f,\ s=0, k\in K \tag{3.4}$$

$$\sum_{i\in V\setminus V'^d\cup V^{cr}\cup V^{cn}} x_{ijsk} = \sum_{i\in V\setminus V^d\cup V^{cr}\cup V^{cn}} x_{jisk} \qquad \forall\, j \in V^{cn},\ s=1, k\in K \tag{3.5}$$

$$\sum_{i\in V^d}\sum_{j\in V^d\cup V'^d} x_{ijsk}=0 \qquad \forall\ s\in S,k\in K \tag{3.6}$$

$$\sum_{i\in V\setminus V'^d} x_{ijsk}=z_{jsk} \qquad \forall\ j\in V^{cr}\cup V^{cn},\ s\in S,k\in K \tag{3.7}$$

$$\sum_{k\in K}\sum_{s\in S}\sum_{j\in V^{cr}\cup V^{cn}} x_{ijsk}\le cap_i o_i \qquad \forall\ i\in V^d \tag{3.8}$$

$$\sum_{i\in V}\sum_{j\in V} t_{ij}x_{ijsk}\le H \qquad \forall\ k\in K,s\in S \tag{3.9}$$

$$T_{isk}=0 \qquad \forall\ k\in K,s=0,i\in V^d \tag{3.10}$$

$$T_{isk}+t_{ij}-M(1-x_{ijsk})\le T_{jsk} \quad \forall\ i\in V\setminus V'^d\cup V^{cn}, j\in V\setminus V^d\cup V^{cn},\ s=0,k\in K \tag{3.11}$$

$$U_{isk}\le cap_{sk} \qquad \forall\ k\in K,s=0,i\in V^{cr} \tag{3.12}$$

$$U_{isk}=0 \qquad \forall\ i\in V^d,s=0,k\in K \tag{3.13}$$

$$U_{isk}+q_j-M(1-x_{ijsk})\le U_{jsk} \qquad \forall\ i,j\in V^{cr},s=0,k\in K \tag{3.14}$$

$$q_j\le\sum_{s=0}\sum_{k\in K}U_{jsk}\le\sum_{s=0}\sum_{k\in K}cap_{sk} \qquad \forall\ j\in V\setminus V^d\cup V^{cn} \tag{3.15}$$

$$U_{isk}+q_j-M(1-x_{ijsk})\le U_{jsk} \quad \forall\ i\in V\setminus V'^d\cup V^{cn}, j\in V^{cr},\ s=0,k\in K \tag{3.16}$$

$$Mx_{ijsk}-M\le U_{jsk} \quad \forall\ i\in V\setminus V'^d\cup V^{cn}, j\in V'^d\cup V^f\cup V'^f, s=0,k\in K \tag{3.17}$$

$$\sum_{i\in V^d}\sum_{j\in V^{cr}\cup V^{cn}} x_{ijsk}\le 1 \qquad \forall\ k\in K,s\in S \tag{3.18}$$

$$\sum_{j\in V^f\cup V'^f}\sum_{i\in V'^d} x_{jisk}\le 1 \qquad \forall\ k\in K,s\in S \tag{3.19}$$

$$x_{ijsk}\le o_i \qquad \forall\ i\in V^d,j\in V^{cr}\cup V^{cn},k\in K,s\in S \tag{3.20}$$

$$x_{ijsk}\le o_j \qquad \forall\ i\in V^f\cup V'^f,j\in V'^d,k\in K,s\in S \tag{3.21}$$

$$\sum_{s\in S}\sum_{k\in K}\sum_{i\in V^d}\sum_{j\in V^{cr}\cup V^{cn}} x_{ijsk}=\sum_{s\in S}\sum_{k\in K}\sum_{i\in V^f\cup V'^f}\sum_{j\in V'^d} x_{ijsk} \tag{3.22}$$

$$\sum_{s\in S}\sum_{k\in K}\sum_{i\in V^d\cup V^{cr}\cup V^{cn}} x_{ijsk}\le 1 \qquad \forall\ j\in V^f\cup V'^f \tag{3.23}$$

$$\sum_{i\in V^d}\sum_{j\in V^{cr}\cup V^{cn}} Mx_{ijsk}\ge\sum_{i\in V^f\cup V'^f}\sum_{j\in V^{cr}\cup V^{cn}} x_{ijsk} \qquad \forall\ k\in K,s\in S \tag{3.24}$$

$$M\sum_{i\in V^d}\sum_{j\in V^{cn}} x_{ijsk}\ge\sum_{i\in V^{cn}}\sum_{j\in V^f\cup V'^f} x_{jisk}+\sum_{i\in V^f\cup V'^f}\sum_{j\in V^{cn}} x_{ijsk} \quad \forall\ k\in K,s=1 \tag{3.25}$$

$$\sum_{i\in V^d\cup V^{cn}} x_{ijsk}-\sum_{i\in V^{cn}\cup V'^d} x_{jisk}=0 \qquad \forall\ j\in V^f\cup V'^f,k\in K,s=1 \tag{3.26}$$

$$\sum_{i\in V^f} x_{ijsk}y_i\le 1 \qquad \forall\ j\in V^{cn},k\in K,s=1 \tag{3.27}$$

$$\sum_{i\in V^f} x_{ijsk}y_i \leq 1 \qquad \forall\ j \in V'^d, k \in K, s = 1 \tag{3.28}$$

$$\sum_{s\in S}\sum_{k\in K}\sum_{j\in V^f\cup V'^f}\sum_{i\in V^d} x_{ijsk} = 0 \tag{3.29}$$

$$\sum_{s\in S}\sum_{k\in K}\sum_{j\in V'^d}\sum_{i\in V^{cr}\cup V^{cn}} x_{ijsk} = 0 \tag{3.30}$$

$$\sum_{i\in V^d} o_i \geq 1 \tag{3.31}$$

$$\sum_{i\in V^f} y_i \geq 1 \tag{3.32}$$

$$x_{ijsk} \leq y_j \qquad \forall\ i \in V^{cr} \cup V^{cn}, j \in V^f \cup V'^f, k \in K, s \in S \tag{3.33}$$

$$o_i \geq o_j \qquad \forall\ i \in V^d, j \in V^d \cup V'^d \tag{3.34}$$

$$y_i \geq y_j \qquad \forall\ i \in V^f, j \in V^f \cup V'^f \tag{3.35}$$

$$x_{ijsk} = 0 \qquad \forall\ i \in V, k \in K, s \in S \tag{3.36}$$

$$x_{ijsk} = \{0,1\} \qquad \forall\ i,j \in V, k \in K, s \in S \tag{3.37}$$

$$z_{isk} = \{0,1\} \qquad \forall\ i \in V^{cr} \cup V^{cn}, k \in K, s \in S \tag{3.38}$$

$$y_i = \{0,1\} \qquad \forall\ i \in V^f \tag{3.39}$$

$$o_i = \{0,1\} \qquad \forall\ i \in V^d \tag{3.40}$$

$$U_{isk} \geq 0 \qquad \forall\ i \in V, k \in K, s \in S \tag{3.41}$$

$$T_{isk} \geq 0 \qquad \forall\ i \in V, k \in K, s \in S \tag{3.42}$$

Objective (3.1) of this problem is to minimize the total cost, which consists of the fixed costs of the dump truck and arm roll truck, the travel costs for each type of truck, depot opening costs, and final disposal site opening costs. Constraints (3.2) and (3.3) ensure that for each type of vehicle, each of its customer is visited exactly once. Constraints (3.4) and (3.5) ensure that if one vehicle enters one node, this vehicle should leave that node. Constraint (3.6) prohibits traveling between depots. Constraint (3.7) determines the relationship between two types of decision variables. Constraint (3.8) guarantees that the number of vehicles that depart from a depot do not exceed the depot capacity. Constraints (3.9) to (3.11) satisfy the time limitations of a vehicle while serving all customers in each route. Constraints (3.12) considers the dump truck capacity in each route. Constraints (3.13) to (3.15) are the modified lifted MillerTuckerZemlin sub-tour elimination constraints for the dump truck [18]. Constraints (3.16) and (3.17) ensure the continuity of the waste collection process of the dump truck. Constraints (3.18) to (3.21) ensure that each operating vehicle starts and ends at the same opened depot. Constraint (3.22) guarantees that the vehicle coming out of the depot returns to the same depot from the final disposal site. Constraint (3.23) ensures that the final disposal site node is only visited once as the real node. Constraint (3.24) ensures that the final disposal site is visited only if a route from the depot exists. Constraints (3.25) to

(3.28) identify the flow of the arm roll truck. Constraint (3.29) prohibits the vehicle from moving from the depot to the final disposal site directly. Constraint (3.30) prohibits the vehicle from moving from the customers to the depot before visiting the final disposal site. Constraint (3.31) specifies that at least one depot is opened as the starting point. Constraint (3.32) indicates that at least one final disposal site must be opened as the final destination of waste collection. Constraint (3.33) prevents the vehicle from visiting any final disposal site candidate that is not opened. Constraints (3.34) and (3.35) ensure that the decision variables of the opening depot and final disposal site are only for the real nodes. Constraint (3.36) prohibits self-routing. Constraints (3.37) to (3.42) specify the ranges of the variables.

4. Methodology

A greedy algorithm is proposed to solve the waste LRP in this study. A greedy algorithm is a constructive heuristic algorithm, in which a solution for a problem is constructed step by step following a particular procedure until a feasible solution is obtained, as examined by Mat et al. [21].

In this study, the route starts from the depot node. The greedy algorithm is utilized to determine the customer closest to the depot that needs to be served by comparing all distances from the depot to a number of customers of the dump truck or arm roll truck.

The solution for each truck type is illustrated using different structures. Structure of solution for dump truck consists of a set of V^d depots denoted by $\{1, 2, \ldots, V^d\}$, a set of V^{cr} customers denoted by $\{V^d + 1, V^d + 2, \ldots, V^d + V^{cr}\}$, and a set of V^f disposal sites denoted by $\{V^{cn} + 1, V^{cn} + 2, \ldots, V^{cn} + V^f\}$. While for arm roll truck consists of a set of V^d depots denoted by $\{1, 2, \ldots, V^d\}$, a set of V^{cn} customers denoted by $\{V^{cr} + 1, V^{cr} + 2, \ldots, V^{cr} + V^{cn}\}$, and a set of V^f disposal sites denoted by $\{V^{cn} + 1, V^{cn} + 2, \ldots, V^{cn} + V^f\}$. Figures 4 and 5 illustrate the solution structures for the dump truck and arm roll truck, respectively. Figure 6 provides a visual illustration of the waste collection network corresponding to the solution structures in Figures 4 and 5. The instance utilized to illustrate the solution structure has 5 potential depots (V^d), 18 dump truck customers (V^{cr}), 7 arm roll truck customers (V^{cn}), and 5 potential disposal sites (V^f).

2	7	9	32	11	10	8	32	2	6	12	13	32	2	5	16	15	17	21	33	5	19	14	33	5	18	20	33	22	23	33	5	1	3	4

Figure 4: Example of solution structure for a dump truck.

2	25	32	24	32	28	32	2	26	32	27	32	2	5	30	33	29	33	5	1	3	4

Figure 5: Example of solution structure for an arm roll truck.

The solution construction using a greedy algorithm is described as follows.

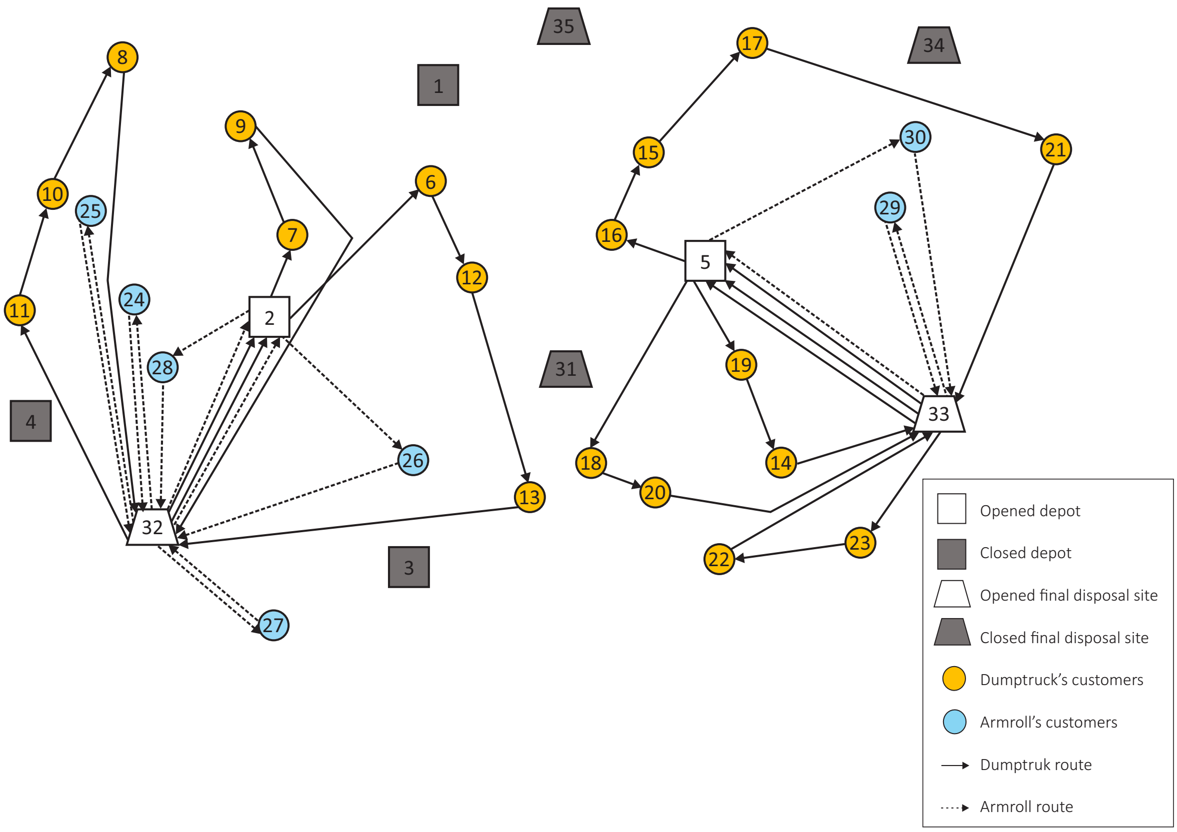

Figure 6: Visual illustration of solution structure.

Step 1: Calculate the distance from the depot to each customer. Each depot has a list of its customers from the closest to the farthest.

Step 2: Let V^d be the set of unused depots, and let cc(i) represent the number of unassigned customers with the closest depot to depot i in V^d. Select the depot with the largest cc value to be processed in the subsequent step.

Step 3: Let V^{cr} and V^{cn} be the sets of unassigned customers of the dump truck and arm roll truck (for depot), respectively. Assign customers in V^{cr} and V^{cn} to the selected depot in Step 2. Check whether adding the subsequent customer violates the capacity of the depot; if yes, stop the process, in which case the depot is not considered anymore. Remove the assigned customer from V^{cr} and V^{cn}.

Step 4: Use different procedures for each type of truck:
For the dump truck: Construct a TSP route for customer V^{cr} assigned to the selected depot. The route starts from and ends at the selected depot. When adding the subsequent customer will violate the vehicle capacity constraint, terminate the route by inputting the nearest final disposal site.

For the arm roll truck: Construct a rollon-rolloff route by inputting the customer V^{cn} assigned to the selected depot. The route starts from and ends at the selected depot. After inputting the customer V^{cn} once, input the nearest final disposal site. When adding the subsequent customer will violate the total time travel constraint, terminate the route by inputting the original depot node.

Step 5: If V^{cr} and V^{cn} are not empty yet, go back to Step 1; otherwise, terminate the process, and start the calculation for the objective function.

The proposed greedy algorithm is tested on a small instance to assess its performance. The result is then compared with the CPLEX result to determine whether the approach is verified. Then, the instances are scaled up to assess the effectiveness of the proposed greedy algorithm by comparing its results with those obtained by CPLEX. These calculations will be further discussed in the subsequent section.

5. Computational Study

The proposed greedy algorithm is implemented in Microsoft Visual C++ 2017 and run on a PC with an Intel Core i7-7490 CPU at 3.60 GHz and 16 GB of RAM under the Windows 7 Professional.

5.1. Test instances

Seven datasets are used to implement the model. The data are adopted from the real dataset in DIY, Indonesia. The first dataset contains 17 instances. The number of potential depots V^d ranges from 1 to 5, the dump truck customers V^{cr} vary between 6 and 10, the arm roll customers V^{cn} vary between 11 and 15, and the number of potential final disposal sites V^f vary between 16 and 17. Then, the data are scaled up to 37, 57, 107, 307, and 507.

Finally, the model is applied using the last dataset, which is the entire real dataset of the waste management system in DIY, Indonesia (Figure 7). Waste is generated from 842 nodes, defined as customer nodes, consisting of 738 dump truck customers and 104 arm roll truck customers. Five potential locations are generated for the depot, and two potential locations are generated for the power plant. The potential depot locations are determined using the existing depots, whereas the potential power plant locations are selected by considering the available land area. To clarify (once again), the power plant term in this study refers to the final disposal site as defined in general mathematical model in Section 3. For this instance, we follow the real assumption, which only requires one power plant opened to run the system. Therefore, Equation (32) becomes equal to 1.

5.2. Computational results

We assess the effectiveness of the proposed greedy algorithm in this study by testing the previously mentioned datasets. We then compare the obtained results with the

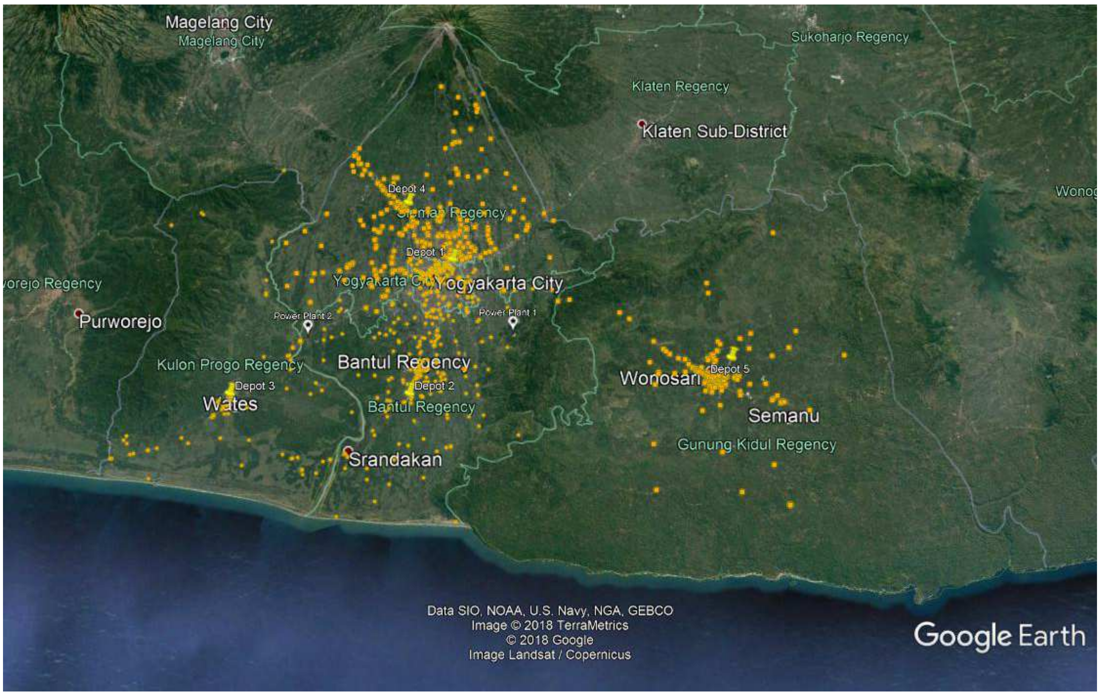

Figure 7: Location map of waste management in DIY.

CPLEX results within five-hours limit. The comparison of the results of CPLEX and the proposed greedy algorithm is presented in Table 1. Table 1 shows that CPLEX can obtain the optimal solution with a low total cost for 17 nodes as the smallest instance. However, the computational time of CPLEX is slower than that of the proposed greedy algorithm. CPLEX fails to generate a feasible solution for instances with 107849 nodes, whereas the proposed greedy algorithm solves all of them. The failure of CPLEX in finding solutions within five-hours limit may be attributed to the number of virtual nodes in the model that makes the model unresolvable with CPLEX.

Table 1: Comparison of CPLEX and the proposed greedy algorithm.

Nodes	CPLEX						Greedy algorithm					
	CPU (s)	Dump truck	Arm roll	Depot	Disposal	Total cost (IDR)	CPU (s)	Dump truck	Arm roll	Depot	Disposal	Total cost (IDR)
17	35.82	1	1	1	1	1,710,138,021	0.17	1	1	1	1	1,710,138,485
37	18,000	2	2	1	1	1,720,388,136	0.38	1	2	1	2	2,715,343,653
57	18,000	3	2	1	1	1,725,716,191	0.59	2	3	1	2	2,725,584,372
107	18,000	N/A	N/A	N/A	N/A	N/A	0.95	3	4	1	2	2,736,051,689
307	N/A	N/A	N/A	N/A	N/A	N/A	2.65	9	15	1	2	2,823,463,990
507	N/A	N/A	N/A	N/A	N/A	N/A	6.32	16	15	1	2	2,859,384,259
849	N/A	N/A	N/A	N/A	N/A	N/A	24.47	18	17	1	1	1,880,455,494

We obtain a solution using the proposed greedy algorithm for the real case in DIY, Indonesia. By modifying the model to fulfill the need to establish only one power plant, we show that the greedy algorithm requires 18 dump trucks and 17 arm roll trucks. The vehicles start and end at the opened depots, which is depot 1, with the final destination being power plant number 1 as the opened power plant, acts as the final disposal site.

6. Conclusions and Future Research

This study introduced the heterogeneous fleet LRP for waste management and formulated a mathematical model for the problem. The mathematical model can be utilized to obtain an exact solution, but it is limited to solving small-scale instances. This study applied the model to solve a real waste management system in DIY, Indonesia, consisting of hundreds of nodes. A heuristic greedy algorithm is utilized to solve the problem.

The proposed greedy algorithm was tested with several size of instances to evaluate its performance in comparison with that of CPLEX. The experimental results indicate that the proposed greedy algorithm outperforms CPLEX in terms of computational time, particularly in solving the real dataset. CPLEX fails to solve large-scale instances within five-hours limit, including the real dataset.

For future research, other algorithms may be utilized to solve this problem, and the results can be compared with those of the greedy algorithm. Moreover, since greedy algorithm is only a constructive algorithm, future research may propose improvement algorithm to improve the solution of greedy algorithm as the initial solution. Future studies may also consider other practical variables, such as a modified number of objective functions and the addition of time windows, so that the model could be extended to real applications. The research undertaken can provide other benefits for the parties involved and the community.

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