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ORIGINAL ARTICLE

Analysing medical waste transportation using periodic vehicle routing problem for Surabaya public health facilities

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Abstract
Medical waste management is crucial in densely populated urban areas of developing nations. The disposal of biohazardous medical waste requires strict monitoring due to potential environmental and public health risks. In developing countries, several constraints present as challenges to medical waste disposal, including inaccessible biohazardous disposal plants, limited in-facility biohazardous waste storage, government regulation, and cost. Surabaya, Indonesia's second-largest city, experiences these challenges. Currently, the Surabaya Health Department (SHD) relies on third-party waste processing vendors to handle infectious waste from 63 health facilities due to hazardous waste disposal only being permitted at the provincial level. In addition, waste collection occurs monthly for most health facilities, with a regulated 14-day storage period to prevent accumulation which contradicts the minimum 25-kg threshold that third-party vendors implement. This study utilizes Surabaya's context to develop an effective medical waste disposal and transportation strategy and logistics using the Periodic Vehicle Routing Problem (PVRP). Results indicate that the 14-day storage requirement benefits SHD and vendors, improving operational efficiency and mitigating risks. Compliance with storage regulations reduces travel distances compared to scenarios without storage requirements. This study's methodology applies to developing countries exhibiting similar constraints and acts as a guideline to develop similar medical waste disposal strategies.

Keywords Periodic Vehicle Routing Problem · Optimization · Medical waste · Waste management

Introduction

In many developing countries, medical or hazardous waste management is poorly regulated [1, 2]. Medical waste, which includes waste generated from healthcare facilities, laboratories, and other sources that may contain infectious materials [3–5], demands serious attention due to its potential to spread contagious diseases, especially during the COVID-19 era. Some examples of the categories of medical and healthcare waste is elaborated upon in Table 1. Poor medical waste management can lead to infections, environmental pollution, and public health hazards. Despite these severe risks, critical infrastructure such as hazardous autoclaves and incinerators remains significantly lacking in these regions.

On Java, Indonesia's most populous island with over 150 million residents [6, 7], only 17 companies are licensed to treat hazardous waste, including medical waste [8]. Nationwide, only around 120 hospitals operate their own incinerators [9], leaving the bulk of medical waste management to private companies. However, these companies often struggle to handle the waste, especially during peak periods such as the COVID-19 pandemic [10–12]. This shortage of treatment facilities highlights a larger issue of hazardous waste management in Indonesia.

In Surabaya, the second-largest city in Indonesia located in East Java and home to 4.1 million residents, the problem is even more pressing. The city lacks a government-owned hazardous waste incinerator, and the nearest privately-owned facility is located approximately 300 km away. Despite these challenges, Surabaya remains committed to becoming an eco-city, having received the prestigious *Adipura Kencana Paripurna* Award recognizing its waste management efforts.

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Table 1 Categories of healthcare waste

No	Type	Descriptions and potential risks
1	Sharps	Waste entailing risk of injury
2	Waste entailing risk of contamination	Waste containing blood, secretions or excreta entailing a risk of contamination
	Anatomical waste	Body parts, tissue entailing risk of contamination
	Infectious waste	Waste containing large quantities of material, substances or cultures entailing the risk of propagating infectious agents
3	Pharmaceutical waste	Spilled/unused medicines, expired drugs and used medication receptacles
	Cytotoxic waste	Expired or leftover cytotoxic drugs, equipment contaminated with cytotoxic substances
	Waste containing heavy metals	Batteries, mercury waste (broken thermometers or manometers, fluorescent or compact fluorescent light tubes)
	Chemical waste	Waste containing chemical substances: leftover laboratory solvents, disinfectants, photographic developers and fixers
4	Pressurized containers	Gas cylinders, aerosol cans
5	Radioactive waste	Waste containing radioactive substances: radionuclides used in laboratories or nuclear medicine, urine or excreta of patients treated

The city strives to comply with national medical waste management regulations, underlining its commitment to public health and environmental sustainability.

Alagöz and Kocasoy [13–15] highlight that waste collection and transportation can account for 80–95% of the total cost of managing solid waste, emphasizing the need to optimize these processes. In Surabaya, the situation is complicated by inadequate infrastructure, which struggles to handle the increasing volume of medical waste, particularly during health crises. In addition, Indonesian law limits the storage of medical waste at healthcare facilities to 14 days [16–18] making frequent and reliable waste collection essential [5, 19–22]. However, logistical constraints often hinder compliance with this regulation, exacerbating health risks [23, 24].

This paper presents a study conducted in Surabaya to address the challenges of medical waste collection, transportation, and disposal in accordance with national standards. Unlike previous research that used hypothetical data [25–28], this study is based on real data collected from healthcare facilities across the city. The research applies the Periodic Vehicle Routing Problem with Time Windows (PVRPTW) model to optimize medical waste logistics. While previous studies like those by Noreña-Zapata et al. [29] and Wang et al. [30] have applied similar models to urban and solid waste management, this study's focus on medical waste fills a critical gap in the literature. Furthermore, it relies on empirical data from the Surabaya Health Department (SHD), strengthening the credibility and relevance of the proposed solutions.

The solutions proposed in this research have been validated and implemented by the Surabaya City Agency for Health, demonstrating real world effectiveness. This research balances the interests of multiple stakeholders, including the SHD and private waste management vendors, providing actionable recommendations [20, 31–33]. The study also mirrors advanced optimization models from developed nations like China, where regulatory enforcement and structured planning are critical [34, 35].

The PVRPTW model is particularly well-suited for this research as it manages the complexities of medical waste management and logistics, balancing multiple constraints—such as time windows, vehicle capacities, and storage limits—must be balanced. Unlike simpler routing models [27, 34, 36], PVRPTW integrates these constraints to optimize routes for cost efficiency while ensuring regulatory compliance [37]. By scheduling routes over multiple periods, the model accommodates fluctuating demands and irregular collection schedules, resulting in balanced workloads, improved resource utilization, and reduced operational costs [38–44].

This study demonstrates a strong link between the identified background challenges and the chosen methodology. It contributes to both theoretical and practical domains by offering real-world solutions to critical public health issues. The PVRPTW model's adaptability ensures its relevance not only for Surabaya but also for broader applications in medical waste management across developing countries.

Materials and methods

Literature review

The Periodic Vehicle Routing Problem (PVRP) and its extensions, such as the PVRPTW, are becoming increasingly prevalent in logistics and waste management research. However, their application to medical waste management, particularly in developing countries like Indonesia, remains limited. Most studies focus on general logistics or solid waste management, with few recent works (2015–2020) addressing the specific complexities of PVRP in medical waste logistics. Much of the existing literature relies on research from around 2010, highlighting a gap in more contemporary studies [23, 45, 46].

Efforts in Indonesia have largely focused on other optimization models, such as Vionanda et al.'s multi-objective optimization of medical waste costs and incineration [46]. Similarly, studies by Yustina et al. on improving government supervision and Hutajulu et al. on hospital policies do not incorporate PVRP models [23, 47]. Globally, studies such as Liang's review of recycling networks and Dwipayanti and Wijana's analysis of waste trends in Bali also overlook the use of PVRP in their methodologies [35, 48]. This points to a significant gap in applying PVRP models to medical waste logistics, especially in developing nations, where resource constraints and regulatory inconsistencies are common.

Another underexplored area is the integration of real-world constraints, such as public health and safety regulations, into PVRP models. Recent research emphasizes the need for more advanced models, especially during public health crises like the COVID-19 pandemic [49]. While some models have addressed infectious and non-infectious waste during emergencies, they have not incorporated PVRP frameworks [50–53]. Furthermore, technologies like IoT and blockchain, though promising for enhancing waste management, are not yet fully integrated into PVRP models, presenting an opportunity for future studies [54–59].

This study aims to address these gaps by applying the PVRPTW model to optimize medical waste transportation in Surabaya. This paper offers a unique contribution by using empirical data from the SHD, validating the model's practicality. In addition, it explores the balancing of objectives between stakeholders—such as the SHD and private waste vendors—through scenario analysis, providing actionable recommendations. This approach mirrors advanced models seen in studies from developed nations, but with a focus on addressing the logistical challenges unique to developing countries like Indonesia [23, 60].

A. *Generation* The generation of hospital waste varies not only between the countries but also within the same country due factors such as type of establishment, the utilization of reusable items, and the daily treatment rate. Despite the importance of waste generation data for effective management systems, many hospitals do not routinely record such data [61]. Waste generation in Asian countries range from 0.08 – 5.34 kg bed-day-1 [61], with Indonesia exhibiting a lower rate at 0.75 – 1 kg bed-day-1 [62, 63]. Quantifying different waste types can be conducted through interviews or direct waste generation measurement within the facilities [64].
B. *Segregation* Waste segregation, the process of separating and categorizing waste for recycling purposes, stands as a crucial phase in waste management protocols [65]. Ideally, segregation should occur at the point of waste generation, whether in medical facilities like patient rooms, operating theatres, or laboratories. A commonly employed segregation method is the "three-bin system" [66], which separates non-hazardous waste, potentially infectious waste, and used sharps into separate containers. While developed countries, rigorously enforce rules regarding waste segregation, several studies highlight non-compliance to these protocols and best practices. Factors contributing to these shortcomings include limited resources, low awareness, inadequate staff training, and lack of comprehensive record-keeping [61].
C. *Storage* Once the waste has been segregated, it proceeds to temporary storage. Storage facilities must undergo regular sanitation and maintain a controlled temperature to ensure safety before the medical waste is then transferred to a main storage facility [66]. Storage duration should be minimized, and proper bio-hazard warning signs must be prominently displayed to mitigate risks and prevent accidents. However, reports indicate that only a limited number of hospitals in developing countries possess adequate storage facilities [67, 68]. Moreover, hazardous waste should not be retained for extended periods [69]. Best practices for medical waste storage encompasses several steps. Sharps can be safely stored in cardboard safety boxes at room temperature. However, other infectious waste requires refrigeration at temperatures no higher than 3 – 8°C if storage exceeds 1 week. According to Chartier et al. [66] and ICRC [70], unless a refrigerated storage room is available, storage times for infectious waste (time gap between generation and treatment) should not exceed 48 h.
D. *Off-site transport* Off-site transport involves the transportation of healthcare waste from a healthcare facility onto public roads and should adhere to national regulations. In the absence of such regulations, authorities may consult recommendations provided by the United Nations regarding the transportation of dangerous goods [71]. Chartier et al. [66] outline several requirements for the vehicle used to transport hazardous waste to minimize the risk of accidents and spillages. These include ensuring appropriate vehicle size, implementing a secure system for load restraint during transportation, and equipping the vehicle with cleaning kits. Refrigerated containers may be utilized if storage times exceed recommended limits or if transportation durations are prolonged.

Before dispatching hazardous waste off-site, transport documentation, such as a consignment note, must be prepared and carried by the driver. This note acts as a control mechanism for waste transportation. The consignment note should include essential information and details encompassing waste classes, waste sources, pick-up date, destination, driver name, and number of containers/weight/volumes [66]. The weight of waste is particularly pertinent for commercial treatment or third-party operators who invoice healthcare facilities for waste services rendered.

In this study, waste collection and transportation were handled by third-party vendors, with one of the primary vendors being PT XYZ, located in Surabaya, East Java. PT ABC operates a fleet of 127 transport units dedicated to medical waste collection across multiple regions, including West Java, Central Java, East Java, Bali, Nusa Tenggara Timur (NTT), and Lombok. Their extensive operational range enables them to manage large volumes of waste, including compliance with the 14-day maximum storage duration as required by PMK No. 7 Tahun 2019. This collaboration between the SHD and third-party vendors like PT XYZ plays a crucial role in ensuring the city's adherence to national waste management regulations.

This paper focuses on the final step of the typical process, off-site transportation. Capacity and time window constraints are crucial considerations reflecting real-world dynamics. Each health facility possesses its waste generation rate, while the vendor's vehicle is limited by its specific capacity. Moreover, both health facilities and vendors operate within defined working hours, unable to collect waste beyond these times. Given the one-year contractual agreement between the SHD and the hazardous waste processing vendor, this research incorporates a periodic scope into the vehicle routing problem model. Routing is not a one-time event but rather occurs multiple times over an extended period.

Medical waste management transportation procedures have been predominantly modelled as a Vehicle Routing Problem (VRP) [72]. This approach is shown to optimize distribution centre transportation efficiency while servicing a geographically dispersed set of customers using vehicle fleets [27]. Various VRP variants have been explored, tailored to specific problem contexts such as VRP with time windows, VRP with capacity constraints, the Green VRP, dynamic VRP, and the inventory routing problem, each with distinct characteristics in their objective functions or system constraints [73].

Gaur and Fisher [74] optimized a vehicle routing and delivery scheduling problem of a supermarket chain in the Netherlands using periodic inventory routing (IRP) and determining when each store needs to be replenished from a central distribution center. Similarly, the PVRP closely aligns with IRP, involving multiple visits to customers within a planning horizon, determining optimal sequences of visits and vehicle routes for each day [75]. Furthermore, IRP and PVRP can be integrated as demonstrated by Rusdiansyah and Tsao [76] in the vending machine supply chains study under a vendor-managed inventory (VMI) scheme. Variants of PVRP can be categorized based on constraint concerning (i) visit planning (e.g., varying frequencies and restrictions on certain days), (ii) demand types (constant or variable), and (iii) the vehicle characteristics [77].

PVRP operates at the interface of tactical and operational planning, merging traditional VRP with temporal planning, often addressed through two-phase solution methods. Beltrami and Bodin [78] proposed two approaches, one involving route development followed by day assignment and the other involving customer assignment followed by route optimization for each day. The second approach is commonly used in research, such as Baptista et al. [79] where the approach to the VRP is an extension of the assignment problem with a routing component. The primary objective of PVRP is to minimize total travel distance, as it directly impacts costs. PVRP mainly comprises the Capacitated Vehicle Routing Problem with Time Windows (CVRPTW) and a clustering procedure, often with modifications to suit the specific context.

CVRPTW objective functions

$$Min\, Z = \sum_{i=0}^{NN} \sum_{j=0}^{NN} \sum_{k=1}^{NV} l_{ijk} \times d_{ij} \tag{1}$$

The CVRPTW focuses on optimizing a single route for a specific day without considering interrelationships between routes. The objective of the vehicle routing algorithm is to minimize the total distance travelled by the fleet of vehicles from the centralized depot to various health facilities, as defined in the object function. In the function, l_{ijk} represents a decision variable indicating whether arc i,j is traversed by vehicle k. it takes a value of 1 if the arc is visited and 0 if not. NN denotes the total number of nodes, and NV signifies the number of vehicles used. When the value of l_{ijk} equals 1, it is multiplied by d_{ij}; which represents the distance between nodes i and j. The arc length between nodes i and j is the model input, while l_{ijk} is the decision variable. By constructing routes that minimize total travel distance, the model generates a list of nodes visited by each vehicle to cover all available nodes within the designated time window for that day.

CVRPTW constraints

$$\sum_{i=0}^{NN} l_{ij} = \sum_{i=0}^{NN} l_{ij} \quad for\, all\, j \tag{2}$$

$$\sum_{i=0}^{NN} l_{ij} = 1 \quad for\, all\, j \tag{3}$$

$$C - \sum_{j=1}^{NN} \left\{ Qj \sum_{i=0}^{NN} l_{ij} \right\} \geq 0 \tag{4}$$

$$\sum_{j=1}^{NN} l_{0jk} = 1 \tag{5}$$

$$\sum_{i=1}^{NN} l_{0ik} = 1 \tag{6}$$

$$u_i - u_j + C \times l_{ij} \leq C - Q_j \quad for\, all\, i,j \tag{7}$$

$$Q_i \leq u_i \leq C \quad for\, all\, i \tag{8}$$

$$A_j = A_{j-1} + S_{j-1} + t_{j-1,j} \tag{9}$$

$$A_j = Max\left\{E_j, A_{kj-1} + S_{j-1} + t_{j-1,j}\right\} \tag{10}$$

$$w_j = Max\left\{0, E_{j-1} - A_{kj-1} - S_{j-1} - t_{j-1,j}\right\} \tag{11}$$

$$A_j \leq L_j \tag{12}$$

$$A_{k0} \geq 0 \tag{13}$$

$$\sum t_{j-1,j} + \sum w_j + \sum S_j \leq H \tag{14}$$

Constraint (2) ensures that flow of vehicles entering and exiting node j remains balanced. Constraint (3) specifies that each node's demand must be entirely satisfied by exactly on visitation. Constraint (4) restricts the number of nodes visited to not exceed capacity. This introduces Constant C, which represents the maximum capacity or load the vehicle can carry in a single route. The value of *C* ensures that the vehicle's load remains within its capacity after servicing each node. Similarly, Constant Q refers to the demand or load at each node *j*, which is the amount of waste to be collected. These constraints are critical for ensuring vehicles are not overloaded when making collections. Further, constraint (5) and (6) ensure that each vehicle starts and ends its route at the depot, modeled by the binary decision variables l_{0jk} and l_{0ik} which indicate whether a vehicle travels from the depot to a node or back to the depot after visiting a node. Constraint (7) is a bus-tour elimination constraint and capacity constraint. Constraint (8) mandates that a vehicle's load does not surpass its capacity after visiting customer i. Constraint (9) formulates the arrival time at node j. Constraint (10) permits the vehicle to wait until the node becomes available if it arrived before the working time begins. Constraint (11) calculates the waiting time at node j. Constraint (12) ensures that the arrival time at node j does not exceed the end of time windows. Constraint (13) is a non-negativity constraint. Lastly, Constraint (14) ensures that medical waste pick-up from health facilities does not exceed the working duration.

Methodological framework

Choosing the most suitable method

The PVRPTW model has been selected for this study because it effectively addresses the complexities involved in medical waste management. Medical waste collection must adhere to strict regulations, including the 14-day storage limit imposed by Indonesian law, making PVRPTW an ideal solution for optimizing both routes and regulatory compliance.

Advantages of PVRPTW:

- *Handling multiple periodic visits:* The PVRPTW model is particularly suitable for scenarios requiring regular waste collection, such as medical waste management, where hazardous materials must be collected periodically to prevent storage overflows and ensure compliance with regulations [80]. Unlike standard vehicle routing models, PVRPTW optimizes routes across multiple periods, reducing travel distances and increasing vehicle efficiency. This ability to manage deliveries over time is crucial for industries with periodic service needs, ensuring regulatory adherence while maintaining cost efficiency [26, 31, 81].
- *Incorporating time windows:* Time windows are an essential aspect of waste collection, particularly for medical facilities that operate within specific hours. PVRPTW accounts for these time window constraints, ensuring that waste is collected within the designated time frames without disrupting the day-to-day activities of healthcare providers [41, 82]. By aligning collection schedules with facility hours, the model reduces the risk of exposure to hazardous materials and ensures timely compliance, especially in time-sensitive scenarios like pandemics [3, 24].
- *Optimization over extended periods:* The PVRPTW model's ability to plan over extended periods allows for a comprehensive approach to route optimization, balancing workloads and maximizing vehicle utilization over days or weeks. By consolidating trips and reducing idle time, this model enhances overall efficiency [40, 83–85]. In addition, heuristic algorithms such as local search strategies further improve cost-efficiency by minimizing unnecessary travel and optimizing resource use, mak-

ing the PVRPTW model highly effective for long-term logistical planning [40, 84].

- *Scenario analysis flexibility:* PVRPTW offers the flexibility to model different scenarios under various operational conditions, including regulatory, logistical, and capacity constraints [86]. It can simulate the effects of varying storage durations and pickup frequencies, optimizing routes to meet both cost and regulatory requirements [87–89]. Advanced optimization techniques like General Variable Neighborhood Search (GVNS) enhance solution quality, making PVRPTW adaptable to complex real-world scenarios [90].
- *Balancing cost & compliance:* A key strength of the PVRPTW model is its ability to balance cost efficiency with regulatory compliance. By integrating legal constraints, such as the 14-day storage limit, into the optimization process, PVRPTW ensures that solutions are not only financially viable but also compliant with legal standards [80, 89–91]. This approach reduces the risk of non-compliance, which could lead to fines or penalties, while ensuring that waste collection operations are sustainable in the long term [92, 93].

The integration of time-sensitive constraints, regulatory requirements, and periodic scheduling makes PVRPTW an invaluable tool for optimizing medical waste management logistics, particularly in regions with strict compliance standards like Surabaya, Indonesia.

PVRPTW Model

Figure 1 illustrates the entire process of the PVRPTW model. Initially, input data are assigned. Subsequently, the daily waste record data are examined to determine if it is set to a daily time interval. In reality due to the inconsistencies of data recording between health facilities input standardization is required. To standardize the model input a conversion to daily basis data is necessary for a more precise time horizon. To achieve this, the daily waste generator algorithm is employed to split the waste data into smaller time intervals, constructed from the monthly basis data.

The medical waste generation data used in this study were obtained primarily from secondary data provided by the SHD. This dataset encompasses the amount of waste generated across various healthcare facilities within Surabaya. Although this secondary data offered a comprehensive overview, further validation was conducted to ensure its accuracy. We performed field verification by cross-checking the reported waste generation figures with six randomly selected public healthcare facilities. This dual approach of using both secondary data and on-site validation helped ensure data accuracy and reliability for the study.

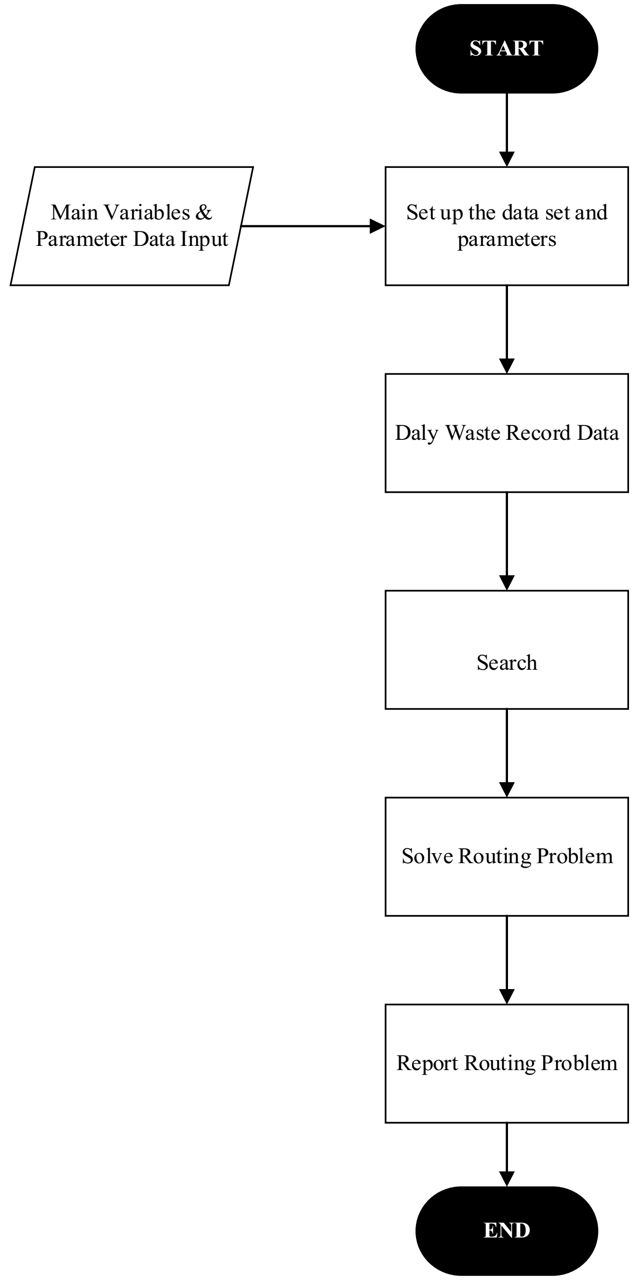
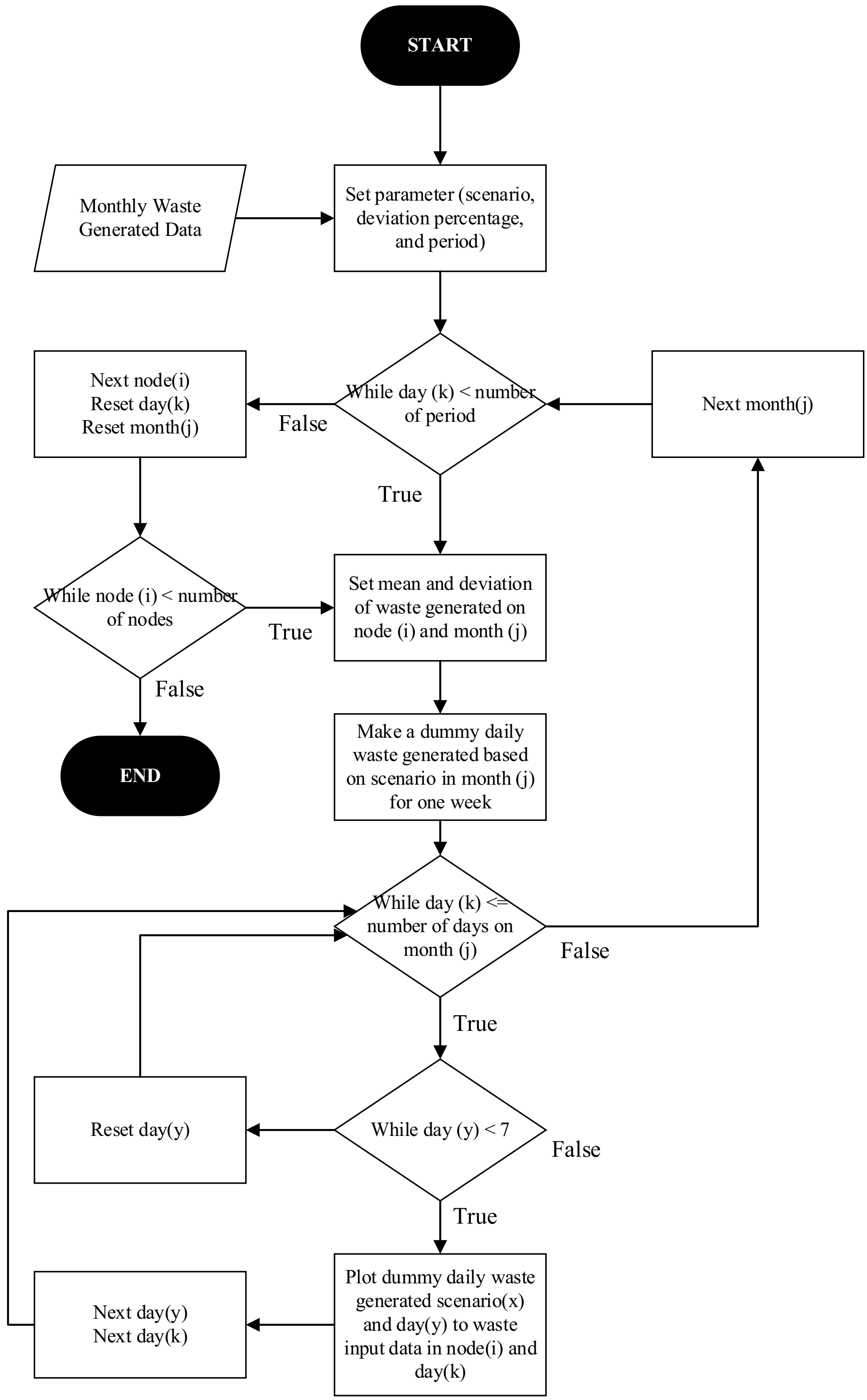


Fig. 1 Conceptual model of PVRPTW

The algorithm is required to convert the monthly data into daily data, dividing the medical waste transportation across each day of the month. A recognizable pattern emerges in waste generation during regular operational days, resembling a “V-shape” distribution rather than a flat curve, with medical waste generation dropping to 0 on Sundays. Due to the inconsistent nature of waste distribution information recorded by healthcare facilities for 1 week in this research, no quantitative parameters exist. Instead, distribution patterns are categorized into incline, decline, and flat patterns. The monthly waste values are calculated based on the mean and deviation, with these parameters varying for each month and node. For instance, Node 1 might have a mean of 3 in January, but this value could change to 5 in February, depending on the monthly waste data. In addition, the mean values between nodes may differ as each node will have distinct monthly waste generation rates. The waste values are plotted for 365 days across all 63 nodes and presented in Fig. 2.

Fig. 2 Waste generation algorithm



To optimize the transportation of medical waste between the 63 public health facilities involved in this study, an accurate calculation of travel distances was necessary. A distance matrix was developed using Google Maps, which provided real-time data on the shortest driving distances between each pair of facilities. This matrix consists of a 63×63 array, where each entry represents the shortest route distance between two facilities. The use of Google Maps allowed for up-to-date road information and the most efficient routes, considering traffic conditions and other relevant factors that could affect transportation times. The Google Map view of Surabaya health facilities is shown in Fig. 3.

After generating the distance matrix, it became a key input for the PVRPTW model, ensuring the routing optimization was grounded in realistic distance measurements. With the accurate distances in place, the next step involved converting the waste data for each facility into daily values. A visit configuration search was conducted to determine the optimal pickup schedules for each facility. This process accounted for factors such as waste volume, regulatory requirements, and operational constraints to ensure efficient and compliant waste collection.

Visit configuration search is initiated to determine when waste pickups will occur at each node. This search is conducted using a heuristic method. Each day, the emitted waste is accumulated and stored in cold storage. This accumulation continues daily. The decision to pick up waste is based on three termination conditions:

1. accumulated waste at a node exceeds cold storage capacity;
2. accumulated waste at a node exceeds recommended storing duration;
3. at the end of the period, the waste must be picked up to ensure no residual waste.

When at least one of these conditions is met, waste is picked up on that day. The amount picked up equals the cumulative waste at the node from the last pickup day until the current day, resetting the cumulative waste value to zero. Once the visit configuration is established, nodes requiring collection on a specific day are grouped into clusters. Multiple clusters may exist in one period and each cluster is treated as a single CVRPTW. The next step involves determining the routing solution by assigning vehicles' routes on an immediate need basis. This means each node must be served as quickly as possible or immediately, based on its need which is indicated by a collection request. For example, if the visit configuration for a customer in 1 week is 0-1-0-0-1-0-0, the node will only be visited on Tuesday and Friday. Nodes which indicate no need (0 value) will not be visited on that day. This Visit Configuration Algorithm is presented in Fig. 4.

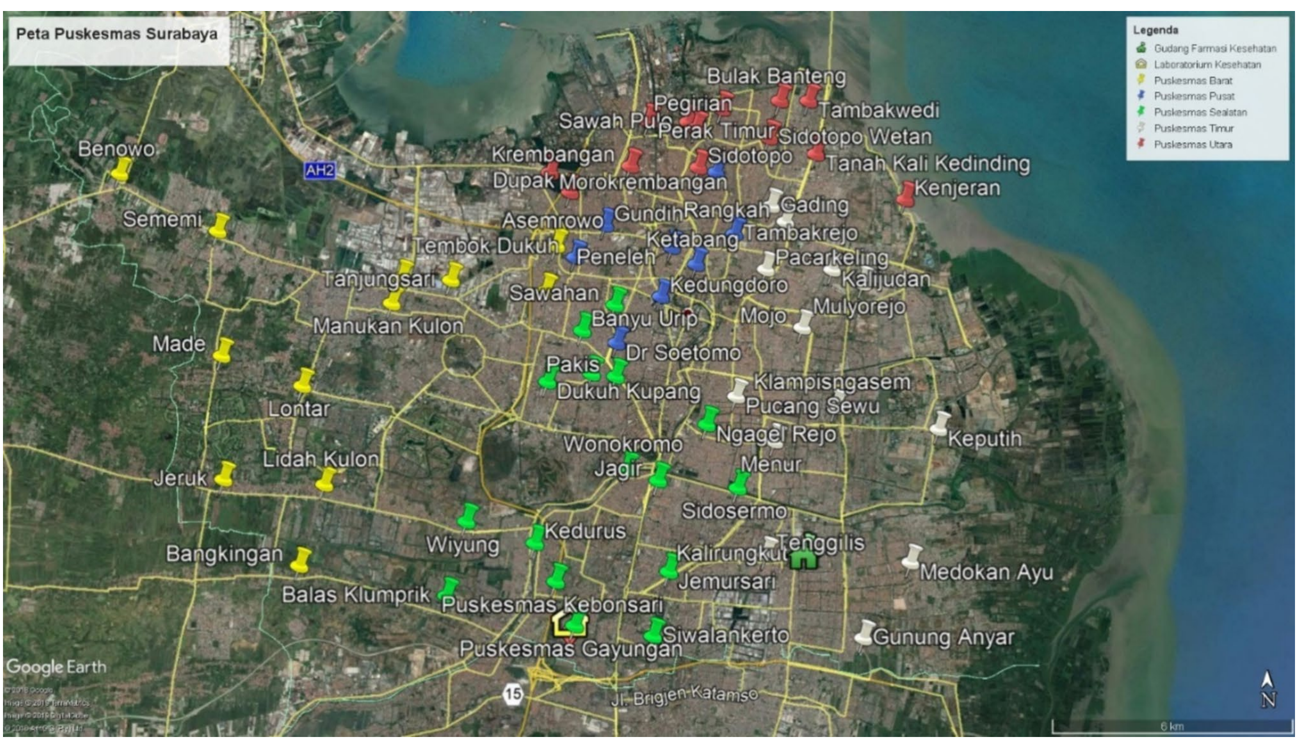


Fig. 3 Google Maps view of surabaya health facilities

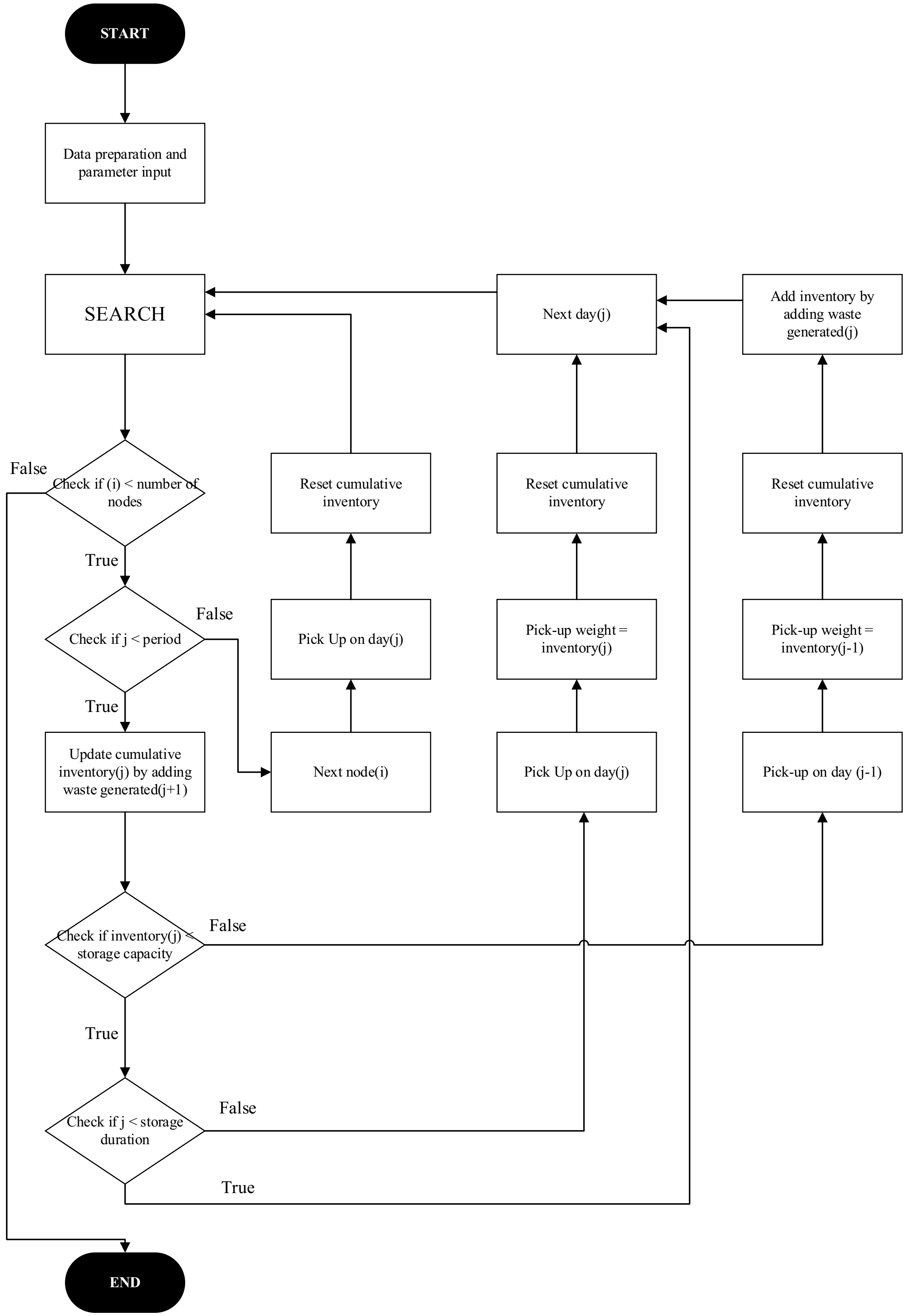


Fig. 4 Visit Configuration Algorithm

Regarding the vehicle capacity and operational hours for waste collection, the data was acquired through on-site interviews with personnel at public health facilities. During these interviews, facility staff indicated the type of trucks typically used for waste collection. Based on this information, vehicle specifications were sourced from online databases to ensure that the model accurately reflected real-world conditions. The operational hours followed the standard schedules of public health facilities, ensuring that the PVRPTW model took into account typical working hours for waste pickups.

After the comprehensive calculations are complete, critical variables are analysed. This includes site selection, route formation, total weight, and the total distance travelled. These variables are essential for further analysis and interpretation.

Data and result accuracy validation

To ensure the accuracy and reliability of the model and its results, two key validation steps were undertaken.

First, direct surveys were conducted at six randomly selected public health facilities. These surveys provided detailed insights into the real-world patterns of waste generation, including variations due to facility size, types of services provided, and seasonal fluctuations in patient numbers. These data points were critical to ensure that the waste generation patterns used in the model accurately mirrored actual conditions. In addition, these surveys explored the frequency of vendor pick-ups and compliance with the 25-kg collection threshold and 14-day storage regulation. This allowed the model to capture the operational realities of medical waste management in Surabaya.

Second, stakeholder validation was performed through direct engagement with the SHD. SHD management was consulted to confirm that the cost estimates and operational strategies generated by the model were not only theoretically sound but also aligned with the practical experiences of those responsible for medical waste management. This feedback confirmed that the model's outcomes are relevant and applicable in real-world contexts, ensuring a robust validation process.

Results and discussion

Inputs and variables

Input variables are submitted into the model to begin the analysis and calculations. These input variables are determined based on the existing factors observed and collected in the field as well as information collected from vendors and healthcare facilities as depicted in Table 2.

After general input data have been established, distance matrix was determined. The Distance Matrix consists of the locations of 63 health facilities, determined by examining the pairwise combinations among them. To create this matrix, Google Maps is utilized to find the shortest route between each pair of health facilities. For instance, the distance from Facility B to Facility A may be determined to be 14.7 kms. It's important to note that distances between locations are not symmetrical; therefore, the distance from A to B may differ from the distance from B to A. This matrix serves as essential input data for solving vehicle routing problems and plays a pivotal role in determining optimal pickup routes based on minimizing distances.

This study utilizes two sets of waste generation data as inputs for the model. Data for Year 1 and Year 2 waste generation were collected and processed from the SHD. Both annual datasets are utilized to evaluate the performance of alternative solutions and routing decisions, allowing for a comparison of their effectiveness across different waste generation scenarios.

Table 2 General input data

Required data		Value	Unit
General input data	Number of node(s)	63	Node(s)
	Number of day(s) in one period	365	Day(s)
	Facility's open time	390	Minute(s)
	Facility's close time	1020	Minute(s)
	Facility's estimated service time	30	Minute(s)
	Storage's capacity	36	Kilogram(s)
	Vehicle's weight capacity	700	Kilogram(s)
	Vehicle's average speed	40	km/hour
	Vendor's open time	0	Minute(s)
	Vendor's close time	1440	Minute(s)
Scenario settings	Waste pattern scenario	Variable	-
	Percentage of deviation	Variable	%
	Storage's maximum storing duration	Variable	Kilogram(s)

Scenario development will take into account the interests of both SHD and the waste processing vendors, where it encompasses three key aspects: general, distance, and total cost scenarios. This approach acknowledges the priorities of every party as the conflicting legislation necessitates collaboration between the private and public stakeholders and accommodation of the fluctuating needs and requirements. The vendors aim to minimize travel distance for waste collection while maximizing service costs. Conversely, SHD seeks to minimize waste collection costs. The scenarios are explored in Table 3.

The two distance scenarios determined for this study take into account the time that medical waste is stored in health facility cold storage, starting from the initial time of disposal. Currently, medical waste is collected by vendors once the cold storage unit is full, ensuring that the waste exceeds the vendor's desired collection threshold of 25 kg. This threshold is based on the typical storage capacity of healthcare facilities, ensuring that waste is stored safely without overcrowding and that hazardous materials remain in appropriate conditions until collection. However, with the introduction of new national regulations—such as Indonesia's PMK No. 7 Tahun 2019—medical waste must now be collected within 14 days to mitigate public health and environmental risks associated with prolonged storage of hazardous waste.

Therefore, two sub-scenarios for storage duration are considered: the existing condition (collection once the cold storage is full and exceeds the 25-kg threshold) and the 14-day storage duration mandated by PMK No. 7 Tahun 2019. The 14-day storage duration balances allowing healthcare facilities sufficient time to accumulate waste without overwhelming their storage capacities, while also ensuring that potentially infectious materials are not stored for prolonged periods, reducing the risk of contamination and ensuring compliance with public health regulations.

Table 3 Scenario list and configuration

Classification	Scenario	Variables	Description
General scenario	Waste generation pattern	Incline	Increasing waste generation over time, reflecting growing services or patient load in 1 week
		Decline	Decreasing waste generation throughout the week, potentially due to piling up patients in Monday
		V-shaped	Waste decreases then increases in 1 week, simulating fluctuations or recovery phases
		Flat	Constant waste generation, used as a baseline for comparison due to its simplicity
	Percentage of deviation	15%	Low variability of waste generation to test system resilience under different conditions
		25%	Medium variability of waste generation to test system resilience under different conditions
		35%	High variability of waste generation to test system resilience under different conditions
Distance scenario	Maximum storage duration	Comply with rules (14 days max)	Ensures waste is collected within the 14-day regulatory limit, testing compliance and efficiency
		Existing practices (pick up only after cold storage is full)	Reflects current practices, where waste is collected based on storage capacity rather than fixed schedules
Cost scenario	Payment scheme	Per Kilogram	Charging by weight, incentivizing waste reduction and efficient management
		Per one-site pick	Flat fee per collection visit, encouraging facilities to optimize waste before requesting pick-up
		Per route	Costs spread across an entire route, providing equitable expense distribution and enhancing cost predictability
	Average collection weight per site	Threshold	Collection occurs only after a minimum weight threshold is met, ensuring economic viability of trips
		Average	Represents typical collection weights, serving as a benchmark
		Maximum	Tests system limits by collecting the maximum possible weight per site, evaluating capacity and cost-effectiveness

Regarding the cost scenario, two sub-scenarios are identified: payment system and average collection weight per site. For the payment system, vendors typically charge the SHD based on the weight of waste collected and treated. This study explores alternative payment systems that may benefit both parties. The “per pickup site” system charges a fixed cost for each pickup, irrespective of weight or distance travelled. Conversely, the “per route” system charges a fixed cost for each vehicle dispatched, regardless of the number of facilities visited, weight collected, or distance travelled.

The “Average Collection Weight per Site” parameter is crucial for calculating total costs under different payment systems. Three sub-scenarios are considered: threshold, average, and maximum. The threshold value is fixed at 25 kg, aligning with the existing pickup conditions. The average value reflects the average weight collected for each distance scenarios, while the maximum value represents the highest weight collected, which may vary between scenarios.

Results

The PVRPTW model was employed to analyze various scenarios aimed at optimizing medical waste collection in Surabaya City. The model was run multiple times using two different sets of waste data inputs (Year 1 and Year 2). The results across 24 scenarios for distance and 256 scenarios for cost were evaluated, focusing on key parameters such as the total number of site pickups, total routes, distance traveled, and average vehicle utilization.

Distance scenario results

The first analysis focused on the distance traveled and vehicle utilization across different scenarios (see Appendix 1 and Appendix 2). The scenarios were differentiated by waste-deviation patterns (Incline, Decline, V-Shape, and Flat) and storage durations (with or without a maximum duration of 14 days as mandated by *PMK No. 7 Tahun 2019*). As shown in Table 4, the results indicated that scenarios with a 25% waste deviation, an Incline waste pattern, and a 14-day maximum storage duration yielded better average vehicle utilization and the lowest distance traveled, suggesting that these parameters are optimal for minimizing operational costs.

The Year 2 waste data generally resulted in higher values for all parameters compared to Year 1, reflecting the increased waste generation and collection requirements. The model confirmed that strict adherence to the 14-day storage duration, while increasing operational costs due to more frequent collections, remains critical to compliance with regulatory standards and the reduction of public health risks.

Cost scenario results

The cost analysis further reinforced the findings from the distance and utilization study. Scenarios were analyzed for their impact on total costs, with particular focus on how waste pattern, storage duration, and payment systems influenced the overall cost (see Appendix 3and Appendix 4). Table 5 below summarizes the cost results for Year 1 and Year 2 waste data under various configurations.

The cost analysis showed that scenarios with a 14-day storage duration and higher waste-deviation percentages generally resulted in higher total costs. However, these scenarios are necessary for compliance with health regulations, highlighting the trade-off between cost efficiency and regulatory adherence.

Combined analysis of distance and cost

To better understand the interaction between the interests of the Surabaya City Council for Health (focused on minimizing costs) and waste management vendors (focused on minimizing distance), the total cost and total distance traveled were analyzed together.

Table 4 Distance scenario results

Year	Scenario	Storage duration	Waste pattern	Deviation	Total routes	Distance (km)	Avg. utilization
Year 1	2	14 days	Incline	25%	188	9325.3	19%
Year 2	10	14 days	Incline	25%	246	12,081.4	23%

Table 5 Cost scenario results

Year	Scenario	Storage duration	Waste pattern	Deviation	Payment system	Cost (IDR Mn)	Implication
1	4	No maximum	Incline	15%	Threshold value	303.19	Cheapest
1	159	14 days	Incline	35%	Maximum weight	1290.73	Most expensive
2	169	No maximum	Incline	35%	Per-route	460.35	Cheapest
2	87	14 days	Incline	35%	Maximum weight	1431.17	Most expensive

The analysis revealed that:

- No maximum storage duration resulted in higher total distances (9867.96 km for Year 1, 13,864.47 km for Year 2) but lower costs.
- Fourteen-day storage duration resulted in shorter distances (9353.5 km for Year 1, 12,160 km for Year 2) but higher costs.

The most expensive scenarios involved the 14-day storage duration, a per-one-site pick payment system, and maximum weight picked per site. Conversely, the cheapest scenarios featured no maximum storage duration, a per-route payment system, and threshold weight picked per site. These findings suggest that while minimizing costs is a priority, ensuring compliance with regulatory requirements is essential for public health and environmental safety.

Analysis

The analysis revealed that a 14-day storage duration resulted in a reduction in total distance traveled compared to scenarios with no maximum storage duration, regardless of whether the data was from Year 1 or Year 2. In addition, the 14-day storage duration led to fewer total routes formed but more sites picked, while no maximum storage duration resulted in the formation of numerous total routes and the picking of many full sites. The waste pattern and deviation scenarios had little impact on the total distance traveled. However, there were differences between the results obtained using the Year 1 and Year 2 waste input data, with the latter showing higher values for total distances traveled, total routes formed, and entire sites picked.

Furthermore, the analysis indicated a correlation between total distance traveled, total routes formed, total sites picked, total weight, and average utilization. Specifically, higher total distances traveled and fewer total routes formed were associated with higher numbers of entire sites picked and lower average utilization. This suggests that many routes were not maximized, leading to lower average utilization. This study does not prove quantitatively the precise variable that impacts these relationships. One contributing factor to the high distance traveled is the underutilization of vehicle capacity, as indicated by the average utilization metric. High average utilization signifies that the vehicle's capacity is being fully utilized.

Implementing a 14-day storage duration benefits the hazardous waste processing vendor the most, as it results in a smaller total distance traveled compared to scenarios with no maximum storage duration. Given that the vendor is primarily concerned with the total distance traveled in medical waste transport and treatment, transportation cost becomes a significant operational cost driver.

The total cost is influenced by factors such as the average weight selected per route, the total weight of the waste, and the average size per route. When comparing scenarios, it was found that using no maximum storage duration resulted in a lower total cost compared to scenarios with a 14-day storing duration. Both scenarios chose no maximum storing duration as the most cost-effective option. However, it is important to note that scenarios with no maximum storing duration tend to incur relatively higher costs compared to those with a 14-day storing duration. Despite this, both scenarios with a 14-day storing duration were deemed the most expensive in terms of total cost. For the SHD, cost is a critical parameter. They prioritize cost over factors such as total traveled distance and average vehicle utilization. Therefore, from a cost perspective, the optimal scenario settings involve using no maximum storing duration, along with both "per route" and "per pickup site" payment systems, and maintaining an average weight of 25 kg per site.

Consequently, the preferred choice is a 14-day maximum storage duration. Under this condition, the most cost-effective scenario involves implementing a per-kilogram payment system. Notably, this payment method does not take into account the average weight picked per site.

In the context of distance scenario settings, average utilization tends to be low. This is primarily due to operational constraints during working hours. Often, the vehicle is unable to collect waste within the designated time frame, as it exceeds the health facilities' operating hours. In addition, while the expected weight capacity may be 700 kg, operational limitations mean that routes can only accommodate up to 400 kg of waste. To improve average utilization, adjustments are being made to factors such as health facility time windows, service time, average vehicle speed, and vehicle capacity.

Among the various scenarios tested, the highest average utilization was observed under the condition of 14-day storage duration and utilizing waste data from 2018. To enhance efficiency further, adjustments were made, including reducing service time from 30 to 15 min, extending working hours from 06:30–17:00 to 05:00–22:00, and decreasing vehicle capacity from 700 to 300 kg. Interestingly, vehicle average speed did not significantly impact average utilization.

Reducing service time notably affected average utilization, particularly in scenarios with a 14-day storage duration. This adjustment led to a tendency to accommodate more nodes in fewer routes, resulting in routes with more nodes compared to scenarios with no maximum storage duration. Consequently, vehicles had to pick up more nodes to meet capacity or time window constraints, particularly affecting routes terminated by time window constraints. Thus, reducing service time significantly impacted the efficiency of the 14-day storage duration scenario.

Furthermore, reducing vehicle capacity had a significant impact on average utilization across all conditions. A vehicle capacity of 300 kg yielded the highest average utilization due to the formula used for calculating utilization. Lower vehicle capacity reduced the expected weight to be picked, thereby increasing the average utilization percentage.

In analyzing the factors influencing average utilization, vehicle capacity emerged as the most significant, followed by service time and adjustments to working hours. Notably, vehicle average speed did not significantly affect average utilization. This information suggests that the vendor could benefit from using smaller vehicles, reducing operational fuel costs, and minimizing investment expenses.

If the vendor were to reduce service time by 50% (from 30 to 15 min), it would yield mutual benefits for both parties. With shorter service times, the vendor could collect waste from more facilities in a single route, while health facilities would experience shorter wait times for waste collection, allowing staff to focus on other productive activities.

The integration of total distance travelled and total cost parameters are crucial for understanding their interaction and making recommendations that align with the interests of both the SHD and waste treatment and transport vendors. The vendor seeks to minimize the total distance travelled while maximizing the total cost incurred by SHD for waste treatment and transportation services. Conversely, SHD aims to minimize the total cost incurred.

The scenario involving a 14-day maximum storage duration, a per pickup site payment system, and maximum weight picked per site settings leads to shorter distances travelled but results in the highest total cost. This scenario is advantageous for the vendor. Conversely, scenarios with no maximum storage duration, a per pickup site payment system, and threshold weight picked per site settings lead to the lowest total cost, making them favourable for SHD. However, due to regulations stipulating that waste stored using cold storage must not exceed fourteen days, SHD must opt for the 14-day storing duration scenario, which also benefits the vendor by reducing the distance travelled compared to scenarios with no maximum storage duration.

Within the 14-day storing duration scenario, the per kilogram payment system yields the cheapest total cost, while the per pickup payment system and maximum weight picked per site settings result in the highest total cost. If SHD prioritizes compliance with the 14-day storing duration over cost constraints, any payment system and average weight picked per site are acceptable. However, the research scope emphasizes the importance of considering the payment system and average weight picked per site in cost analysis.

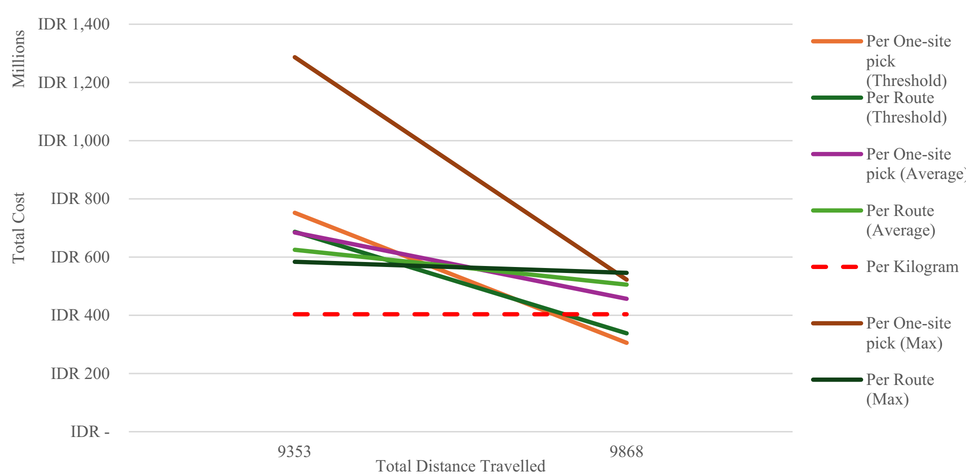
In conclusion, opting for a 14-day storage duration benefits both SHD and the vendor. It allows SHD to comply with regulations while reducing the total distance travelled, thus benefiting the vendor. The choice of payment system and average weight picked per site within this scenario requires careful consideration based on cost analysis. Figure 5 illustrates the relationship of total cost and the travel distance for each sub-scenario.

Conclusions

The primary aim of this research was to develop a model tailored to address the Medical Waste Transportation case for the Surabaya Department of Health (SHD), providing insights into the optimal decision-making process for medical waste treatment and transportation contracts. Optimization is a necessity to develop a solution to improving medical waste collection and transportation efficiency while ensuring compliance with national policies that contradict the needs of the municipality and require SHD to contract third-party vendors.

The PVRPTW model extends the Capacitated Vehicle Routing Problem with Time Windows (CVRPTW) to accommodate longer planning periods rather than single-day

Fig. 5 Total cost toward total distance travelled



vehicle routing. It is composed of two primary algorithms—the Visit Configuration Algorithm and the CVRPTW Constraints—and a supporting daily waste generator algorithm that transforms monthly waste data into daily figures. These algorithms work together to optimize node clustering, establish routine pickup schedules, and ensure that waste management operations adhere to both municipal requirements and national health regulations.

The model has the potential to assist both SHD and hazardous waste processing vendors in reaching mutually beneficial solutions. The research conducted experiments under various conditions or scenario settings, including waste pattern, waste-deviation percentage, maximum storage duration, average weight picked per site, and payment system. The findings suggest that while waste patterns and deviation percentages have minimal impact on total distance traveled or cost, the 14-day storage duration and per kilogram payment system strike the most efficient balance between regulatory compliance and operational costs.

Beyond these findings, this research offers important policy implications for optimizing waste collection routes and improving medical waste management practices in Surabaya and other urban environments. By employing the PVRPTW model, municipalities can reduce total travel distances, fuel consumption, and overall operational costs. Implementing such models city-wide will allow municipal governments to manage waste collection more efficiently, redirecting budget savings to other critical areas of public service.

Adherence to the 14-day maximum storage duration, as mandated by PMK No. 7 Tahun 2019, is critical to prevent health risks and environmental contamination. While adjusting storage durations and thresholds may enhance efficiency, strict regulatory compliance remains non-negotiable, ensuring public safety. This research suggests that more frequent waste collections may be necessary for larger facilities, even though it may lead to increased operational costs. Government support—through technical assistance or financial incentives—can help facilities adhere to these regulations, ensuring safer healthcare environments.

While this study focuses on Surabaya, the PVRPTW model's flexibility allows for scalability and adaptation to other cities facing similar challenges. National policymakers could establish frameworks for broader adoption, ensuring that waste management practices improve nationwide through standardized models and guidelines.

In summary, the adoption of the 14-day storage duration in conjunction with the PVRPTW model offers a robust solution for medical waste management, ensuring compliance with regulatory standards while optimizing operational efficiency and cost-effectiveness. The implications of this research extend beyond Surabaya, offering valuable lessons for cities across Indonesia and other developing countries facing similar medical waste management challenges.

While this study provides valuable insights into optimizing medical waste management in Surabaya, several future issues need to be addressed to ensure the long-term sustainability and adaptability of these practices. Futureresearch should focus on addressing several emerging challenges in medical waste management to ensure long-term sustainability. With increasing waste generation due to population growth and healthcare expansion, scalable solutions such as advanced forecasting models, waste reduction, recycling, and energy recovery technologies are critical. Regulatory adaptability is also essential, requiring flexible strategies that can adjust to evolving laws. Integrating digital technologies like GIS, blockchain, and IoT for route optimization and real-time monitoring offers opportunities for efficiency. Finally, circular economy approaches, including recycling and waste-to-energy conversion, present potential environmental and economic benefits, contributing to sustainable waste management systems.

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