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OPTIMIZATION OF MEDAN CITY WASTE TRANSPORTATION SYSTEM USING MULTIPLE-TRIP VEHICLE ROUTING PROBLEM (MTVRP) MODEL AND SIMULATED ANNEALING

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ABSTRACT

Medan generates approximately 2,000 tons of waste daily, yet only 800 tons are successfully transported to landfills, indicating significant inefficiencies in waste transportation. This study addresses the issue by applying the Vehicle Routing Problem with Multiple Trips (VRPMT) combined with the Simulated Annealing (SA) algorithm to optimize waste transport operations. The VRPMT model allows each vehicle to make multiple daily trips, enhancing fleet utilization while ensuring that all service points are visited, vehicle capacities are not exceeded, and vehicles return to the depot after each trip. The study focuses on Tegal Sari Mandala II (TSM II), Medan Denai, a densely populated neighborhood with narrow roads that require bestari pedicabs for flexible waste collection. Data includes waste collection points, vehicle capacities, transport frequencies, and operational costs. The SA algorithm begins with a random route solution, then iteratively evaluates and improves it by minimizing total distance and cost. It also avoids local optima through a controlled temperature reduction process. Results demonstrate significant improvements: total travel distance was reduced from 12,500 meters to 8,646 meters (a 30.8% reduction), and operational costs decreased from IDR 12,000 to IDR 8,946 (a 25.5% reduction). On average, each bestari pedicab completed two daily trips, maximizing capacity utilization and minimizing penalty costs. The system integrates a structured database and Google Maps API for route visualization, enhancing planning and monitoring. Overall, this approach contributes to more efficient, cost-effective, and environmentally friendly waste transportation. It supports climate action goals and provides a scalable, replicable model for sustainable urban waste management in other regions facing similar logistical challenges. However, this study has some limitations. The VRPMT model was applied only in a neighborhood with a limited vehicle type, which may reduce its generalizability to broader urban areas with more complex logistics. Also, the Simulated Annealing algorithm settings were manually tuned and not benchmarked against other metaheuristic methods. Future studies could improve the model by considering dynamic traffic conditions, integrating real-time data, or testing hybrid optimization approaches to enhance its effectiveness and adaptability.

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1. INTRODUCTION

Waste is one of the environmental problems that requires serious attention due to its potential negative impacts on public health and environmental sustainability. In densely populated urban areas, unmanaged waste can block drainage systems, trigger flooding, disrupt traffic flow, and become breeding grounds for disease vectors such as mosquitoes and rats. These conditions contribute to the spread of infectious diseases, air and water pollution, and a decline in overall quality of life. According to a global report, waste generation is projected to increase by up to 70% by 2050 if no urgent measures are taken [1]. These facts highlight the urgent need for effective and sustainable waste management solutions. According to Law No. 18 of 2008, waste is defined as the residual material from daily human activities or natural processes in solid form. As the population in an area increases, the volume of waste produced also rises significantly. Changes in consumption patterns and lifestyles have further worsened the situation, resulting in increasingly complex types of waste [2]. Medan City, one of Indonesia's major cities, faces serious waste management challenges. In 2023, the city generated approximately 2,000 tons of waste per day. However, only 800 tons were successfully transported to the final disposal site (TPA), leaving around 1,200 tons potentially unmanaged [3]. According to data from the Medan City Central Statistics Agency (BPS), several sub-districts are the most significant contributors of waste, including Medan Helvetia (35,366.67 tons/year), Medan Sunggal (31,004.13 tons/year), and Medan Kota (30,632.08 tons/year). A significant increase in waste volume was also recorded at the Terjun TPA in October 2023, one of Medan's main waste management sites [4].

Before determining route optimization as a primary solution, several alternative waste management strategies should be considered. These include improving waste collection schedules to align with generation patterns and promoting waste separation at the source to reduce transport volume [5], increasing the number and capacity of waste collection vehicles [6], and enhancing coordination between municipal authorities and private waste management operators [7]. A more efficient waste transportation system is urgently needed to address these challenges. One solution is determining the optimal transportation routes to minimize operational costs and travel time [8]. Beyond economic benefits, route optimization also contributes to environmental sustainability. Reducing travel distance and vehicle operation time can lower fuel consumption and minimize greenhouse gas emissions, such as carbon dioxide (CO_2) [9]. This helps reduce air pollution and supports efforts to mitigate climate change, a pressing global concern [10]. In urban waste management, an eco-friendly transportation system contributes to creating a healthier and more sustainable urban environment. Transporting waste from collection points to vehicles and then to the landfill is a critical component of the waste management system. Determining the optimal transportation route significantly impacts fleet efficiency, fuel use, and travel time.

MySQL Document Store enables the development of both SQL-based and NoSQL-style applications, eliminating the need for a separate non-relational database [11]. It supports using relational data and JSON documents within a unified platform, enhancing integration and flexibility across various data-driven environments [12]. In modern transportation systems, especially in urban waste management, operational data such as collection points, vehicle capacities, trip schedules, and optimized routes are essential for efficient service [13]. MySQL, an open-source relational database system, is widely used to store and manage this structured data. Its ability to handle spatial data makes it suitable for mapping and route planning applications. A study showed that using real-time data, such as the fill levels of waste bins, can help dynamically adjust collection routes. This leads to more efficient waste collection and reduced environmental impact [14].

Several Indonesian cities have implemented various approaches to optimize waste transportation routes. For instance, Banyumas Regency has applied the Greedy Algorithm to determine the most efficient route. As noted in [15], "the shortest route for transporting waste is to go to the final disposal site in Tipar and return to the starting point at the Banyumas Environmental Office, covering a total distance of 53 km," which indicates an improvement in operational efficiency. Implementing the Vehicle Routing Problem (VRP) using the Savings Method in northern Bandung has optimized waste transportation routes. This approach improved the efficiency of route planning and service delivery by comparing routing techniques, including the Nearest Neighbor method, to identify the most effective alternative [16]. In Tegal Regency, Dijkstra's Algorithm has been utilized to optimize waste transportation routes. The method has effectively reduced operational costs and carbon emissions, promoting more sustainable waste management practices [17].While numerous studies have concentrated on classical VRP models, more advanced variants, such as the Vehicle Routing Problem with Multiple Trips (MTVRP), have received relatively limited attention despite their practical significance in real-world logistics [18]. The VRP is an optimization model that seeks to minimize travel distance and operational costs while considering constraints such as vehicle capacity and service requirements [19]. Among the various VRP variants, the Capacitated Vehicle Routing Problem (CVRP) integrates vehicle capacity constraints into the route planning process. Accounting for these constraints has enhanced logistical efficiency and reduced operational cost [20]. This model, which accounts for fuel consumption and demand uncertainty, has improved logistical efficiency and reduced operational costs [21]. MTVRP is a variant of the VRP that allows vehicles to perform more than one trip within a single planning horizon. This approach is particularly advantageous in urban logistics contexts, as returning to the depot for reloading enhances resource utilization and improves distribution efficiency [22].

This study applies the MTVRP model to optimize Medan's waste transportation system. The model enables the fleet to make multiple trips daily, maximizing transportation capacity without increasing the number of vehicles. In addition to reducing costs and travel time, MTVRP implementation also decreases the frequency of inefficient trips, thus directly lowering vehicle emissions and promoting environmentally friendly waste management. This approach supports the achievement of Sustainable Development Goals (SDGs), particularly those related to climate action and urban environmental quality [23].

Simulated Annealing (SA) has been widely acknowledged as an effective metaheuristic for addressing complex vehicle routing problems, primarily due to its ability to efficiently explore large solution spaces and avoid entrapment in local minima [24]. Recent research has demonstrated the successful application of SA in an omnichannel vehicle routing context, achieving superior solution quality and computational efficiency performance compared to existing algorithms [25]. By applying this method, the waste transportation system in Medan is expected to become more efficient, cost-effective, and environmentally sustainable, while positively contributing to urban environmental management.

2. RESEARCH METHODS

This study utilizes the VRPMT approach to optimize the waste transportation system in Medan City. VRPMT is an extension of the VRP model that allows vehicles to make more than one trip within the planning period. To obtain optimal solutions, this study also applies the SA optimization algorithm.

2.1 Vehicle Routing Problem with Multiple Trips (VRPMT) Model

The VRPMT was introduced to more accurately represent real-world logistics operations by allowing vehicles to complete multiple trips within a single planning horizon. This added flexibility facilitates more efficient vehicle utilization, particularly in environments with high demand or limited capacity. A recent study by Wu et al. demonstrated the effectiveness of an Iterated Local Search-based heuristic for solving the VRPMT with multiple time windows, emphasizing its capability to navigate complex solution spaces and avoid local optima [26]. The VRPMT is an extension of the classical VRP that allows vehicles to perform more than one trip within a single planning horizon. This capability enhances operational flexibility and efficiency, particularly in logistics and waste transportation contexts, where vehicles may need to return to the depot to reload before proceeding to the following route. The model is commonly formulated as:

$$min \sum_{k=1}^{M} \sum_{t=1}^{T} \sum_{i=0}^{N} \sum_{j=0}^{N} c_{ij} . x_{ijkt} \quad (1)$$

where

M : Number of vehicles available

T : Maximum number of trips a vehicle can make

N : Number of service points (TPS, customers, etc.)

c_{ij} : Travel costs from point i to point j (distance, time, or fuel costs)

x_{ijkt} : Binary variables

x_{ijkt} : 1 if vehicle k on trip t takes the route from point i to point j

x_{ijkt} : 0 if there is none

A recent study implemented this multi-trip model to optimize waste classification and collection in Shanghai, showing that allowing multiple trips improves route balance and reduces total travel distance, thereby contributing to system efficiency and sustainability [27].

2.2 Optimization of Waste Collection Routing Using the Simulated Annealing (SA) Approach

Waste collection routing is optimized using the Simulated Annealing (SA) approach, which aims to minimize the total travel distance and avoid exceeding vehicle capacity limits for each pickup route. The systematic optimization steps are explained as follows:

1. Data Acquisition and Preparation

   The initial step begins with reading and preparing data from the existing trajectory system database, consisting of:

   a. Waste collection point locations, each with location identity, geographic coordinates (X, Y), and waste wight (kg)

   b. Depot location that serves as the starting and ending point of each route

   c. Maximum capacity of each pickup vehicle

   d. Number of available vehicles

2. Distance Matrix Construction

   From the coordinates of each point, the Euclidean distance between points is calculated using the formula:

$$d(i,j) = \sqrt{(x_i - x_j)^2 + (y_i - y_j)^2} \quad (2)$$

   The distances between all pairs of points are stored in a symmetric distance matrix, which is then used in the evaluation of total route distance.

3. Initial Solution Initialization

   An initial solution is created by arranging a route for each vehicle based on heuristic observations of spatial proximity between points. Each route starts and ends at the depot, and waste collection points are added while considering the vehicle's capacity. All pickup points must be served exactly once.

4. Objective Function Formulation

   The objective function consists of two main components:

   Total Route Distance:

$$Total\ Distance = \sum_{r \epsilon R} \sum_{i=0}^{n_r} d(p_i, p_{i+1}) \quad (3)$$

   Capacity Violation Penalty, imposed if the accumulated load in a route exceeds the maximum capacity C:

$$Penalty_r = \sum_{i=1}^{n} max(0, \mu_i - C) x\alpha \quad (4)$$

   Where α is the penalty constant.

   The total objective function to be minimized is defined as:

$$Cost = Total\ Distance + \sum_{r \epsilon R} Penalty_r \quad (5)$$

5. Simulated Annealing Parameter Initialization

   The initial parameters of Simulated Annealing are defined as:

   a. Initial temperature (Initial Temperature) T_0

   b. Cooling rate (Cooling Rate) α

   c. Minimum temperature (Minimum Temperature) T_{min}

6. Iterative Simulated Annealing Process

   The optimization process is carried out iteratively with the following steps:

   a. Generate a candidate solution from the current solution using techniques such as point swapping (swap), point relocation (reinsertion), or segment reversal (2-opt).

   b. Evaluate the objective function of the candidate solution.

   c. Acceptance condition:

      i. If the candidate has a lower cost, accept it as the new solution.

      ii. If it has a higher cost, accept it with probability:

$$P = e^{-\Delta/T}$$

      where Δ is the cost difference between the candidate and current solution.

   d. Cooling is performed with the formula:

$$T_{next} = T\ x\ \alpha$$

   e. The process continues until the temperature drops below T_{min} or the maximum number of iterations is reached.

7. Best Solution Selection

   Throughout the iteration process, the best solution (with the lowest cost) is stored and updated. Once the algorithm stops, this best solution is considered the optimal route.

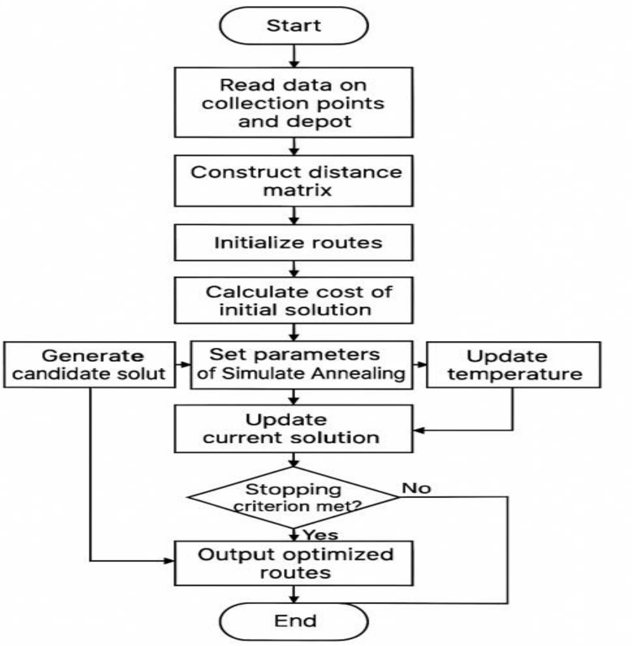

Figure 1. Flowchart of the Simulated Annealing Algorithm for Waste Collection Route Optimization

Figure 1: Flowchart of the Simulated Annealing (SA) algorithm for waste collection route optimization. The process begins with data input and distance matrix construction, then initializes a feasible route solution. Candidate solutions are generated and evaluated using a cost function that includes travel distance and capacity constraints. An acceptance criterion based on cost difference and temperature governs solution transitions. The procedure iterates until a termination condition is met.

3. RESULTS AND DISCUSSION

This study was conducted in Tegal Sari Mandala II (TSM II), in the Medan Denai District of Medan City. The area was chosen due to its high population density and significant daily waste volume, making it a suitable case for testing the effectiveness of a waste transportation system using the VRPMT model. TSM II covers approximately 0.87 km² and has a population of 20,016, resulting in a density of about 23,007 people per km² [28]. Daily waste generation in the area reaches around 6 m³ [29]. Due to narrow roads and densely packed residential areas, waste collection in TSM II relies on bestari pedicabs, capable of navigating small alleys. The data collected includes the coordinates of waste collection points, daily waste volume at each point, transportation frequency, and accessibility conditions. Additional data were also gathered, such as the number of pedicabs, their transport capacity, operational costs, working hours, and the maximum number of trips per day. A distance matrix and estimated travel times between collection points were developed to support route optimization, along with service time constraints and penalties for exceeding capacity or time limits.

The VRPMT model allows each vehicle to make multiple daily trips, enabling it to return to the depot and begin a new route if necessary. This improves system flexibility and optimizes fleet utilization. The SA algorithm was used to determine the most efficient routes, known for its ability to explore a broad solution space and avoid getting trapped in local minima. SA begins with a random solution and iteratively improves it by minimizing total operational cost, travel distance, and time. The integration of VRPMT and SA improves cost efficiency and travel time and reduces fuel consumption and carbon emissions, offering a more environmentally sustainable solution. Through this systematic approach, the study successfully developed a waste transportation system that is more effective, efficient, and adaptable to the logistical challenges of densely populated urban areas such as TSM II. The effectiveness of the proposed VRPMT model integrated with the SA algorithm was evaluated using key performance indicators, including total travel distance, operational cost, and vehicle utilization—the optimized solution reduced travel distance from 12,500 meters to 8,646 meters, achieving a 30.8% reduction. Similarly, operational costs decreased from IDR 12,000 to IDR 8,946, representing a 25.5% reduction. The model also enabled each bestari pedicab to perform an average of two daily trips, compared to a single trip under the conventional VRP model, indicating improved fleet efficiency. These quantitative improvements confirm the model's effectiveness in addressing the logistical challenges of urban waste collection. Additionally, integrating the Google Maps API and real-time data inputs supports dynamic route planning and responsiveness in the field, reinforcing the system's practical applicability. This study designs a web-based application to optimize waste transportation using the VRPMT model and SA as an optimization algorithm. This application is designed using PHP, HTML, JavaScript, and MySQL to solve the problem of optimizing waste transportation routes in Medan City.

In addition, the application incorporates a dynamic input interface that supports real-time updates on waste generation points, vehicle availability, and road network conditions. This ensures the optimization process remains responsive to daily operational changes and unforeseen disruptions such as traffic congestion or vehicle breakdowns. The system's adaptability enables waste management authorities to make timely, data-driven decisions, thereby enhancing the responsiveness and resilience of collection operations. By integrating spatial data with real-time operational inputs, the application ensures alignment between strategic planning and real-world conditions, ultimately improving the efficiency and sustainability of urban waste transportation.

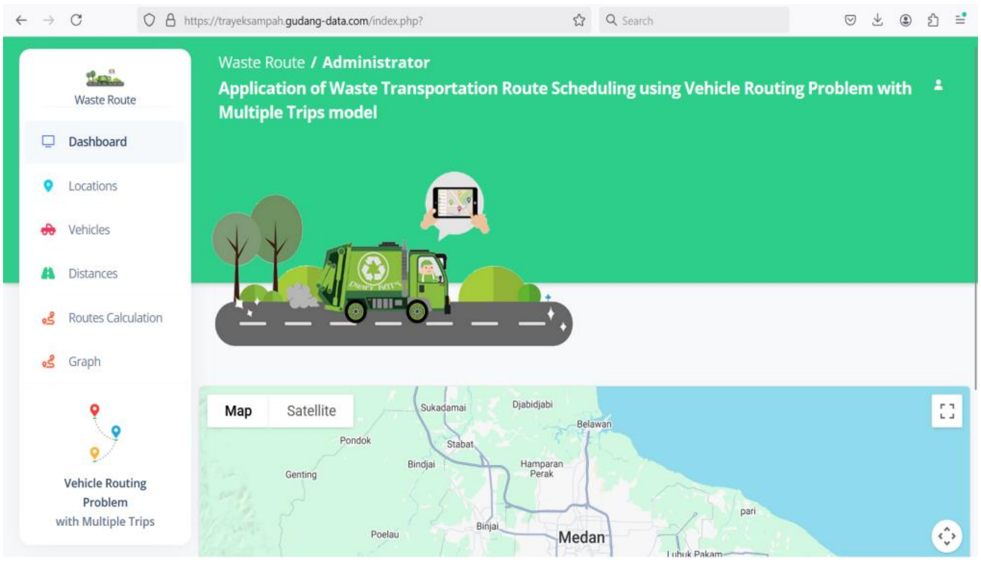

Figure 2. Interface Display of the Waste Transportation Route Scheduling Application Based on the Vehicle Routing Problem with Multiple Trips (VRPMT) Model

Figure 2 illustrates a web-based application to support efficient waste transportation system management in the Medan City area and its surroundings. With interactive map features and intuitive menus, this application allows waste managers to monitor fleets, calculate optimal routes, and improve operational efficiency by applying the VRPMT model.

MySQL Database Design for Waste Transportation Management

MySQL is a database management system for storing and managing data related to waste transportation in Medan City. This database includes information about waste collection points, the capacity of the Bestari pedicab fleet, optimal transportation routes, and other operational data that support the analysis and optimization of the transportation system. The location dataset stores information about waste collection points, depots, and other relevant operational locations. Key attributes include geographic coordinates (latitude and longitude), initial waste load, remaining load after collection, location type, and associated district code. This dataset is critical in spatial modeling and forms the foundation for route optimization processes.

The distance dataset records the distances between location pairs, including the starting and destination points, measured in kilometers. This data is essential for calculating the most efficient travel paths, estimating travel time and operational costs, and supporting algorithms to generate optimized vehicle routes. The vehicle dataset contains information about all operational fleets, particularly the *Bestari* pedicabs used for waste collection. A unique code, operational district, name, or ID, and transport capacity identify each vehicle. This dataset supports effective fleet management, route assignment, and load balancing, especially in areas with narrow roadways and high population density. The route dataset summarizes each trip, including the assigned vehicle, total distance traveled, and the total waste load collected. This information is vital for evaluating trip efficiency, identifying usage patterns, and enhancing future route planning based on historical performance data. The route step dataset logs each stop along a specific route. It includes the order of visits, location ID, amount of waste collected at each stop, and the remaining load capacity afterward. This dataset enables detailed tracking of vehicle movements and is essential for route visualization and performance analysis. The admin dataset manages user authentication and access privileges within the system. It stores account details such as usernames, encrypted passwords, and access levels. This structure ensures that only authorized personnel can access, manage, or modify sensitive data, thereby preserving the integrity and security of the system.

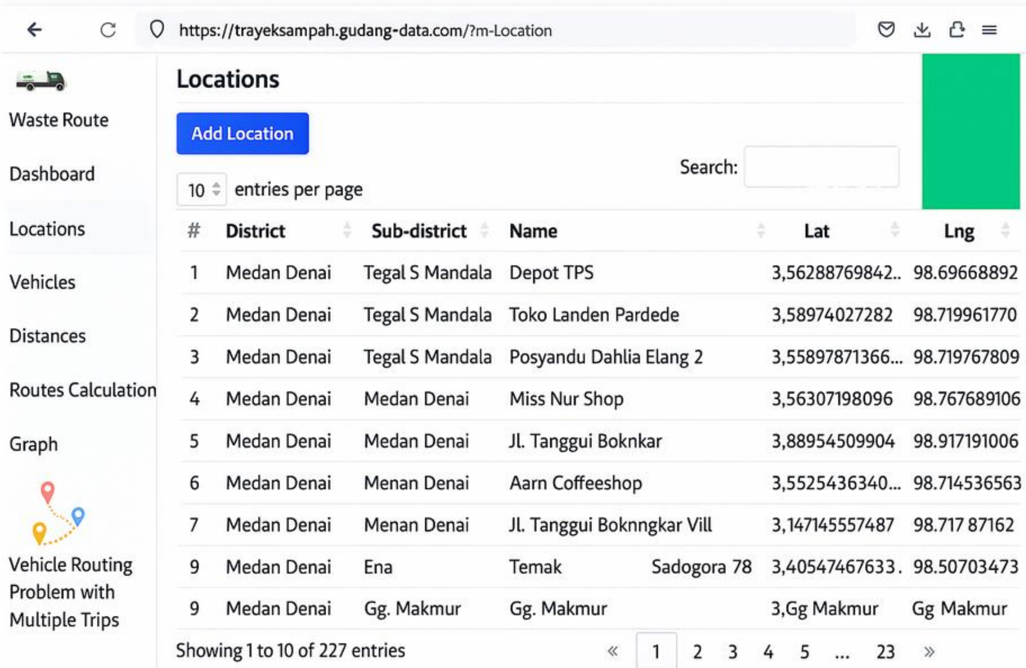

Figure 3. Data Display of Waste Collection Points in Tegal S Mandala II Sub-district Medan Denai District

Figure 3 shows the interface of the *Waste Route* application, which is used to manage and schedule waste transportation routes based on the VRPMT model. The main screen features a table displaying data on waste collection points in Medan Denai District, specifically Tegal Sari Mandala II Village. Each row in the table includes information on the district, village, name of the waste collection point, and geographic coordinates (latitude and longitude) to facilitate accurate mapping. The registered locations cover a range of site types, including TPS depots, public facilities (e.g., Posyandu Dahlia Elang 2), business premises (e.g., Landen Pardede Store, Azam Coffeeshop, Mie Holic & Nasi Goreng Seafood 78), as well as roads and alleys (e.g., Jl. Tangkuk Bongkar, Gg. Makmur).

On the left side of the interface, a navigation menu provides access to several core features such as Dashboard, Locations, Vehicles, Distances, Route Calculation, and Graph. The currently selected Locations feature allows users to manage waste collection points, including viewing and editing location details. A Search bar is available in the top-right corner of the table, enabling users to locate entries by name or sub-district quickly. A pagination control at the bottom of the table indicates that 227 location records are available for user access. This application is a decision support tool designed to optimize waste transportation routes by considering factors such as the shortest travel distance and vehicle load capacity. Ultimately, it helps maximize the operational efficiency of the waste collection fleet.

The *Vehicle Management* module of the web-based application enables administrators to manage critical vehicle data related to waste collection operations, including district, sub-district, driver name, and vehicle capacity. It provides *Edit* and *Delete* functionalities for efficient record maintenance and a *Search* bar and pagination controls to facilitate streamlined data access and navigation. The interface is designed for usability, allowing seamless interaction even for users with limited technical expertise. Data validation mechanisms are implemented to reduce input errors and ensure record consistency. The system enhances operational planning and supports responsive, data-driven decision-making by maintaining accurate and current vehicle information. This module plays a vital role in fleet management and significantly optimizes waste transportation routes in Medan City.

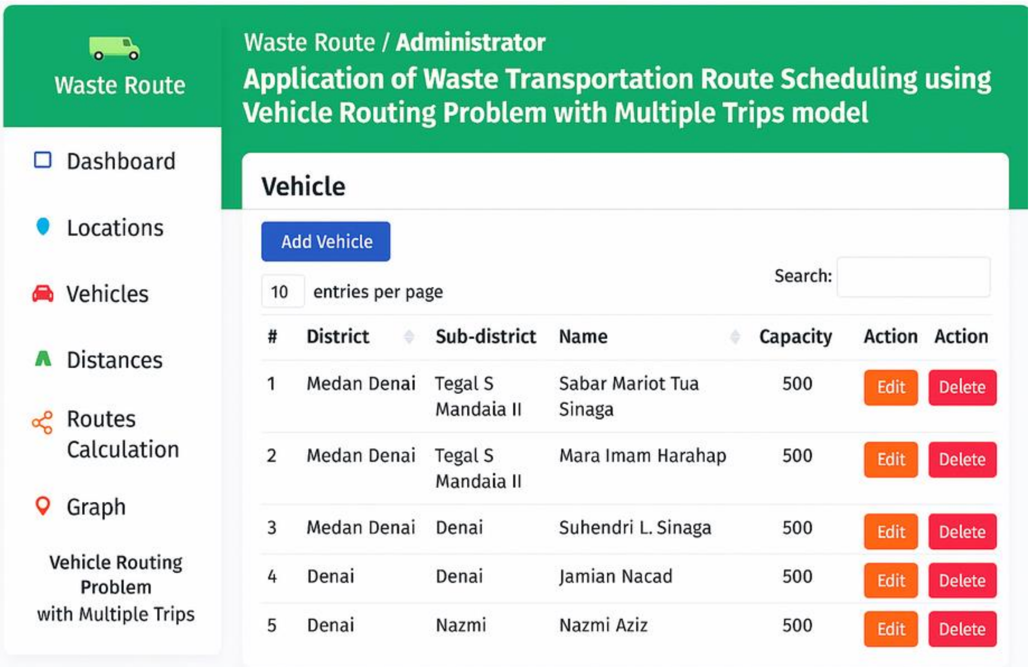

Figure 4. Vehicle Management Page in the Waste Transportation Route Scheduling Application

Figure 4 shows the Vehicle page in the *Waste Transportation Route Scheduling* application, which uses the VRPMT model. This page displays a list of vehicles used for waste transport in Medan Denai District, including information such as district, village, driver's name, and vehicle capacity. Each vehicle has a capacity of 500 units. Drivers like Sabar Mariot Tua Sinaga, Mara Imam Harahap, and Suhendri L. Sinaga are listed for Tegal Sari Mandala II. At the same time, Jamian Nadeak, Nazmi Aziz, and Roni are assigned to the Denai area. The Action column includes Edit and Delete buttons to manage vehicle data. Search and pagination feature also help users easily find and view records. This page helps administrators manage the vehicle fleet more efficiently to support adequate waste transportation in the area.

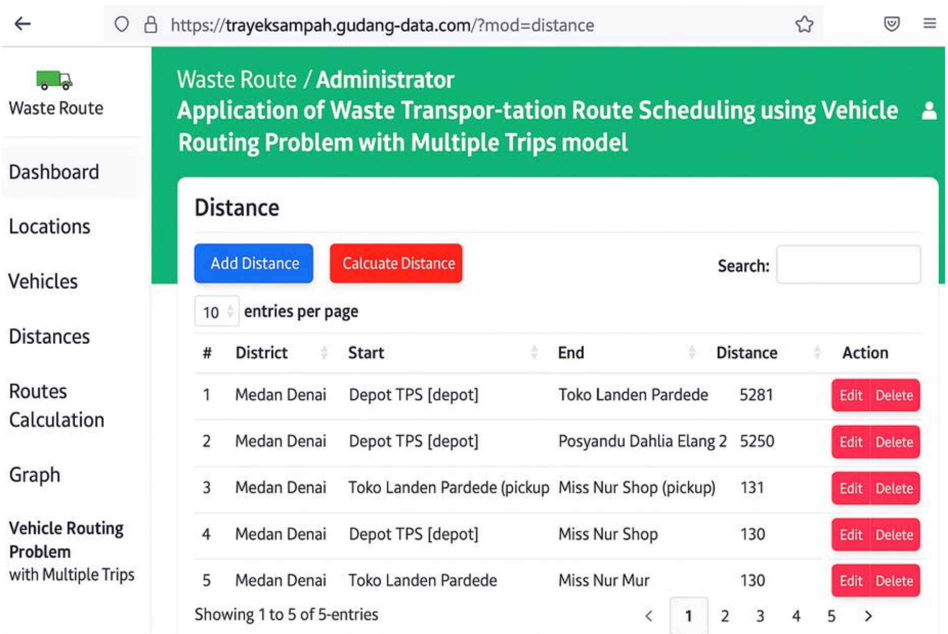

Figure 5. Distance Page Display on the Waste Transportation Route Scheduling Application

Figure 5 shows the Distance page in the Waste Transportation Route Scheduling application based on the Vehicle Routing Problem with Multiple Trips. This page displays data on the distance between waste transportation points in Medan Denai District

- Vehicle : Sabar Mariot Tua Sinaga
  1. Distance : 8646 m
  2. Cost : 8946
  3. Routes :
     1. Pickup : Depot TPS (Load : 0, Distance : 0, Penalty : 0, Cost : 0)
     2. Pickup : Toko Landen Pardede (Load : 100, Distance : 5281, Penalty : 0, Cost : 5281)
     3. Pickup : Posyandu Dahlia Elang 2 (Load : 237, Distance : 31, Penalty : 0, Cost : 31)
     4. Pickup : Miss Nur Shop (Load : 33, Distance : 100, Penalty : 0, Cost : 100)
     5. Pickup : Jl. Tangguk Bongkar (Load : 416, Distance : 130, Penalty : 100, Cost : 230)
     6. Pickup : Azam Coffeshop (Load : 207, Distance : 345, Penalty : 0, Cost : 345)
     7. Pickup : Jl. Tangguk Bongkar VIII (Load : 327, Distance : 972, Penalty : 100, Cost : 1072)
     8. Pickup : Ternak (Load : 375, Distance : 281, Penalty : 0, Cost : 281)
     9. Pickup : Mie Holic & Nasi Goreng Seafood 78 (Load : 128, Distance : 300, Penalty : 100, Cost : 400)
     10. Pickup : Gg. Makmur (Load : 13, Distance : 1153, Penalty : 0, Cost : 1153)
     11. Pickup : Day Florist Medan (Load : 162, Distance : 53, Penalty : 0, Cost : 53)

Figure 6. View of the Optimal Route for Waste Transportation in TSM II Subdistrict

- Vehicle : Mara Imam Harahap
  1. Distance : 6223 m
  2. Cost : 6623
  3. Routes :
     1. Pickup : Depot TPS (Load : 0, Distance : 0, Penalty : 0, Cost : 0)
     2. Pickup : Gg. Kilang (Load : 315, Distance : 3842, Penalty : 0, Cost : 3842)
     3. Pickup : Ayam Penyet Madura (Load : 54, Distance : 36, Penalty : 0, Cost : 36)
     4. Pickup : RM Minang Pesisir (Load : 480, Distance : 123, Penalty : 100, Cost : 223)
     5. Pickup : Hendhy's Bakery & Cake Shop (Load : 286, Distance : 79, Penalty : 0, Cost : 79)
     6. Pickup : Kopi 19 & AY'S Vape (Load : 454, Distance : 50, Penalty : 100, Cost : 150)
     7. Pickup : Komplek Denai Avenue (Load : 144, Distance : 474, Penalty : 0, Cost : 474)
     8. Pickup : Jl. Pasar 8 (Load : 320, Distance : 802, Penalty : 0, Cost : 802)
     9. Pickup : Gg. Galon (Load : 166, Distance : 152, Penalty : 100, Cost : 252)
     10. Pickup : SRC Toko Ridwan (Load : 20, Distance : 547, Penalty : 0, Cost : 547)
     11. Pickup : Gg. Amal (Load : 274, Distance : 42, Penalty : 0, Cost : 42)
     12. Pickup : Dicky bakso 2 daging lembu asli (Load : 234, Distance : 76, Penalty : 100, Cost : 176)

Figure 7. View of the Optimal Route for Waste Transportation in TSM II Subdistrict

Figure 6 and Figure 7 present the results of route optimization based on two primary parameters: total travel distance and total operational cost. An explanatory note at the top indicates that scheduling begins with an initial route, which is optimized by minimizing travel distance and applying penalties. A fixed penalty of 100 units is imposed for each occurrence where the load exceeds the vehicle's maximum capacity of 500 liters. The interface displays a summary table containing key metrics, including total distance (in kilometers), total cost (in standardized units), and vehicle utilization efficiency. Users can quantitatively evaluate the impact of operational constraints, particularly capacity violations, on overall route performance. This output provides an objective foundation for comparing alternative routing strategies across operational scenarios.

Figure 6 shows the results of route optimization based on total travel distance and operational cost. The system applies a penalty of 100 units for each 10-liter overload, beyond the vehicle capacity limit of 500 liters. To provide a more quantitative view of how the optimization is performed.

Example of Route Evaluation

One of the optimized routes in Tegal Sari Mandala II consists of 7 steps:

1. Depot $\rightarrow A = 1{,}2\ km$
2. $A \rightarrow B = 0.7\ km$
3. $B \rightarrow C = 0.9\ km$
4. $C \rightarrow D = 1.0\ km$
5. $D \rightarrow E = 0.8\ km$
6. $E \rightarrow F = 1.1\ km$
7. $F \rightarrow Depot = 1.4\ km$

The total travel distance is:

$$D = 1.2 + 0.7 + 0.9 + 1.0 + 0.8 + 1.1 + 1.4 = 7.1\ km \quad (6)$$

with a cost rate of IDR 1.200 per km, the total operational cost is:

$$C = 7.1\ x\ 1.200 = IDR\ 8.520 \quad (7)$$

If the waste collected in this trip is 560 liters, the overload is 60 liters (i.e., 6 units over the 500-liter capacity). With a penalty of 100 units per 10-liter excess

$$P_{overload} = 6\ x\ 100 = 600\ units \quad (8)$$

Thus, the total cost becomes:

$$Z = 8.520 + 600 = 9.12 \quad (9)$$

Simulated Annealing: Acceptance Probability Calculation

In the early stages of the Simulated Annealing (SA) algorithm, a worse solution may be accepted with a certain probability to escape local minima. The probability of acceptance is calculated using the following equation:

$$P = exp\left(-\frac{\Delta Z}{T}\right) \quad (10)$$

where:

1. ΔZ is the increase in the objective value
2. T is the current temperature

Numerical example

Assume the current solution has an objective value of:

$$Z_{current} = 8.750 \tag{11}$$

A new (worse) solution is generated with:

$$Z_{new} = 8.900 \tag{12}$$

The increase in cost is:

$$\Delta Z = 8.900 - 8.750 = 150 \tag{13}$$

Assume the current temperature:

$$T = 500 \tag{14}$$

Then the acceptance probability is:

$$P = exp\left(-\frac{150}{500}\right) = exp(-0{,}3) \approx 0.7408 \tag{15}$$

The acceptance probability is approximately 74.08%. This implies that if a random number $r \in [0,1]$ is generated and $r \leq 0.7408$, the worse solution will be accepted. This mechanism enables the algoritm to escape local optima and increases the likelihood of reaching a global optimum as the temperature decreases over time.

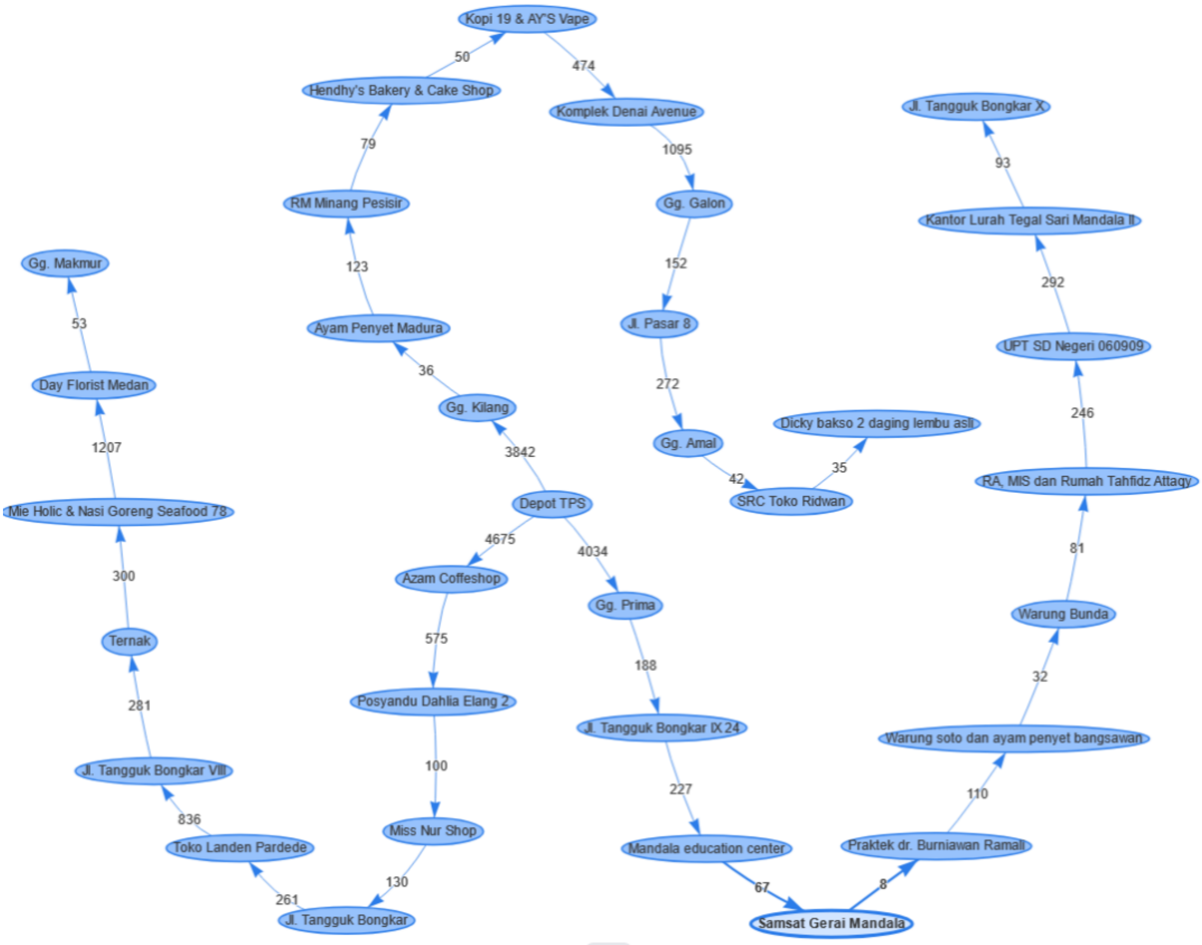

Figure 8. Visualization of the Waste Transportation Route Network in TSM II sub-district

Figure 8 presents a visualization of the waste transportation route network graph generated by the VRPMT system. Each node in the graph represents a waste collection point, such as depots, markets, shops, schools, and other locations within the Medan Denai area. The lines connecting the nodes indicate possible routes for waste collection vehicles, with distance values (in meters) shown along each path.

This graph illustrates the connectivity between collection points and highlights the optimal paths to minimize total travel distance and operational costs. Several key nodes—such as "TPS Depot", "Pasar 8", "Gg. Amal", and "Jl. Tangguk Bongkar"—serve as central hubs that link multiple other locations. The system also reveals high-density collection clusters and provides alternative routes that can be used if obstacles occur in the field. This visualization supports waste transportation managers in understanding the overall network structure, identifying strategic collection points, and optimizing routes to improve time and cost efficiency. Additionally, the graph helps identify potential congestion areas, shortest paths, and vulnerable points in the waste collection network.

4. CONCLUSION

This study demonstrates that the application of the Vehicle Routing Problem with Multiple Trips (VRPMT), integrated with the Simulated Annealing (SA) algorithm, provides an effective solution for optimizing waste transportation in densely populated urban areas such as Tegal Sari Mandala II, Medan. Compared to conventional single-trip VRP models, the proposed approach significantly reduces total travel distance (30.8%) and operational costs (25.5%), while improving fleet utilization by enabling multiple trips per vehicle per day. Integrating a structured database and the Google Maps API supports route planning, monitoring, and visualization, enhancing system practicality in real-world conditions. In addition to operational gains, the system contributes to environmental sustainability by minimizing fuel consumption and emissions, supporting broader climate action goals. However, its current applicability is limited to contexts involving homogeneous vehicle types and narrow road networks, and the SA parameters were manually tuned without benchmarking against other metaheuristic methods. Future work should explore the model's adaptability in more complex urban environments, integrate real-time traffic data, and evaluate hybrid optimization approaches. These findings confirm that the MTVRP model, compared to conventional VRP models, is more effective in optimizing waste transportation routes under urban logistical constraints.

AUTHOR CONTRIBUTIONS

Faridawaty Marpaung: Conceptualization, Funding Acquisition, Methodology, Project Administration. Arnita: Formal Analysis, Writing – Original Draft. Sri Dewi: Data Curation, Software. Marlina Setia Sinaga: Investigation, Visualization. Eri Widyastuti: Writing - Review and Editing. All authors discussed the results and contributed to the final manuscript.

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CONFLICT OF INTEREST

The authors declare that no conflicts of interest exist in this study.

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