Short Communication:

Simulation and graph based optimization of urban waste transportation networks with CO_2 emission assessment: evidence from Ampenan district

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Abstract: *The increasing population in Ampenan District in Lombok Island has contributed to a continuous rise in municipal solid waste generation, requiring a more efficient waste transportation route planning system. Inefficient routing may increase travel distance, fuel consumption, operational costs, collection delays, and carbon emissions. This study applies Prim's algorithm as a minimum spanning tree approach to determine minimum-distance waste transportation networks and estimate the related CO_2 emissions in Ampenan District. Waste collection points and transportation paths were modeled as a weighted undirected graph, where vertices represent collection points and edges represent road distances between points. The waste transportation system involved four garbage trucks operating in four route groups. For each group, the total route distance was optimized using Prim's algorithm. The results show that the minimum route distance obtained for Group 1 was 3.279 km, Group 2 was 5.05 km, Group 3 was 6.45 km, and Group 4 was 3.20 km, resulting in a total optimized route length of 17.979 km. Based on an estimated diesel consumption rate of 0.143 L/km and an emission factor of 2.68 kg CO_2/L, the optimized routes require approximately 2.57 liters of diesel and generate around 6.89 kg CO_2 per operation. These findings indicate that Prim's algorithm can support the design of more efficient waste transportation networks by minimizing travel distance, fuel consumption, and associated emissions. This study contributes to urban waste management planning by providing a graph-based optimization model that can assist local governments in improving transportation efficiency and supporting more sustainable municipal waste services.*

Keywords: *Prim's algorithm; minimum spanning tree; waste transportation; route optimization; CO_2 emissions; Ampenan District*

Introduction

Municipal solid waste has become one of the major challenges in urban environmental management [1]. Rapid population growth, increasing human activities, changing consumption patterns, and limited residential space have contributed to the rising volume of waste generated in urban areas. If not managed properly, waste accumulation can cause environmental pollution, reduce urban sanitation quality, and create risks to public health. Therefore, an efficient waste management system is essential [2], particularly in the transportation stage, which directly affects operational costs, travel distance, fuel consumption, emissions, and service effectiveness.

In Ampenan District, waste transportation remains an important issue that requires systematic planning [3]. As part of Mataram City, this area is closely related to broader urban transportation and environmental challenges. Previous studies in Mataram City have shown that increasing vehicle volume contributes to carbon dioxide emissions [4], while traffic optimization using mathematical approaches can improve urban mobility efficiency [5]. These findings indicate that transportation management is not only related to mobility but also to environmental sustainability. Therefore, optimizing waste transportation routes is important to reduce unnecessary travel distance, fuel consumption, operational costs, and potential emissions.

Mathematics provides several methods that can be used to model and solve transportation optimization problems. One relevant approach is graph theory, which represents objects and their relationships in the form of vertices and edges. In the context of waste transportation, waste collection points can be represented as vertices, while the roads connecting these points can be represented as edges with certain weights, such as distance or travel time [6]. Through this representation, the transportation network can be analyzed more systematically.

Several algorithms in graph theory are commonly used to solve network and route optimization problems, including Dijkstra's algorithm, Bellman-Ford algorithm, Floyd-Warshall algorithm, and greedy-based algorithms. Among these methods, Prim's algorithm is widely used to construct a Minimum Spanning Tree [7], which connects all vertices in a weighted graph with the minimum total edge weight. Prim's algorithm works by selecting the edge with the smallest weight from the connected vertices and adding it step by step until all vertices are connected without forming a cycle. This makes the algorithm suitable for determining a minimum-distance network that connects all required waste collection points.

In this study, Prim's algorithm is applied to model the waste transportation network in Ampenan District. The transportation points are represented as vertices, while the distances between points are represented as weighted edges. The algorithm is then used to determine the minimum connecting network for each waste transportation group. This approach is expected to provide an alternative route-planning model that can support more efficient waste transportation services.

This study is limited to the analysis of transportation distance based on the available route network. Factors such as weather conditions, traffic congestion, road surface conditions, operational schedules, vehicle damage, and waste disposal activities at the final disposal site are not included in the analysis. Therefore, the results of this study should be understood as a graph-based minimum-distance network model rather than a complete operational simulation of waste transportation.

The contribution of this study lies in the application of Prim's algorithm to support waste transportation route planning in Ampenan District. The findings are expected to assist local government and related stakeholders in designing a more efficient, measurable, and data-based waste transportation system. In addition, this study may serve as a reference for further research that combines graph theory with broader operational factors, such as traffic conditions, vehicle capacity, collection schedules, fuel consumption, and carbon emission estimation.

Method

This study employed a descriptive quantitative approach to analyze the optimization of waste transportation routes using graph theory. The main objective was to determine the minimum route for waste transportation in order to reduce travel distance, travel time, operational costs, and potential environmental impacts. Prim's algorithm was applied to identify the optimal minimum route, and the results were evaluated through numerical simulation using Python-based software.

The research began with problem identification, which aimed to define the main focus of the study, namely the optimization of waste transportation routes in Ampenan District. This stage was important to ensure that the research focused on effective strategies for reducing travel distance and transportation time. In addition, this stage also identified several factors affecting the efficiency of waste transportation, including route networks, graph weights, and the locations of key nodes or waste collection points.

A literature review was then conducted by examining relevant journals, books, and previous studies related to waste transportation route optimization. The review focused on the application of graph theory in transportation problems, particularly the use of Prim's algorithm in determining a minimum spanning tree. This stage provided the theoretical foundation for modeling the transportation network and selecting the appropriate algorithm for route optimization.

The data used in this study were primary data obtained from the Environmental Agency of Ampenan District. The data included information on existing waste transportation routes, waste collection points, and the current conditions of waste management in the study area. These data were used as the basis for constructing the graph model and determining the most efficient waste transportation route.

In this study, the waste transportation route network was represented as a weighted graph. Each node represented a location or waste collection point, while each edge represented a connection between two locations. The weight of each edge indicated the distance or travel time between the connected locations. This graph representation enabled the waste transportation network to be analyzed mathematically using Prim's algorithm.

Prim's algorithm was implemented to determine the minimum spanning tree of the weighted graph. The algorithm works by gradually constructing a tree that connects all nodes with the minimum total edge weight and without forming any cycle. Formally, let G be a weighted graph with nnn vertices, and let T denote the minimum spanning tree to be constructed. The steps of Prim's algorithm are described as follows (Siang, 2002):

1. Initially, T is an empty graph.
2. Select an arbitrary vertex $v \in V(G)$, and add v to $V(T)$.
3. Remove v from $V(G)$ as follows:
$$V(G) = V(G) - \{v\}.$$
4. For $i = 1,2,\cdots,n-1$, perform the following steps:
   a. Select an edge $e \in E(G)$ and $e \notin E(G)$ that satisfies the following conditions:
      i. The edge e is incident to one vertex in T and does not form a cycle.
      ii. The edge e has the smallest weight among all edges incident to vertices in T. Let w be the endpoint of e that has not yet been included in T.
   b. Add e to $E(T)$ and add w to $V(T)$:
$$E(T) = E(T) \cup \{e\}$$
$$V(T) = V(T) \cup \{w\}$$
   c. Remove w from $V(G)$, as follows:
$$V(G) = V(G) - \{w\}$$

Thus, Prim's algorithm constructs a minimum spanning tree by repeatedly selecting the minimum-weight edge that connects a vertex already included in the tree to a vertex not yet included, while ensuring that no cycle is formed.

The analysis was performed using Python through the Google Colab platform. The NetworkX library was used to model and analyze the weighted graph, while Matplotlib was used to visualize the route network and the resulting minimum spanning tree. The simulation results were then evaluated to determine the effectiveness of Prim's algorithm in optimizing waste transportation routes based on distance or travel time. The findings were used to formulate recommendations for improving the waste transportation route system in Ampenan District and for supporting more efficient waste management strategies.

Result and Discussion

Based on data obtained from previous research, four dump trucks are used to transport waste in Ampenan District. Therefore, Ampenan District can be divided into four areas according to the available waste transportation trucks. The division of areas based on waste transportation trucks is presented in Table 1.

Table 1. Area division based on waste transportation trucks

Node	x Coordinate	y Coordinate	Group
1	-8.570353318793	116.072539798898	4
2	-8.554428866205	116.073882471227	4
3	-8.563510816164	116.072583326300	4
4	-8.561744402823	116.073828340161	4
5	-8.565205851578	116.074297475822	4
6	-8.572301862104	116.077627153737	1
7	-8.576915005793	116.075829223780	2
8	-8.592829240419	116.076685708820	2
9	-8.584746052946	116.075255107708	2
10	-8.574221462105	116.077791199436	1
11	-8.574081445211	116.077294841343	1
12	-8.574490937297	116.077377665453	1
13	-8.572254787768	116.078173159677	1
14	-8.575998090463	116.077961813667	1
15	-8.579010321519	116.091147308126	3
16	-8.581303197764	116.086941590084	2
17	-8.588596679042	116.085035884182	2
18	-8.580291636298	116.083667949984	2
19	-8.568786613821	116.083774187711	3
20	-8.563796129170	116.103540764768	3
21	-8.568597581466	116.079186200949	3
22	-8.565535244895	116.093103094460	3
23	-8.567160932802	116.083353622326	3
24	-8.566140152835	116.0775804054948	4

Notes: 1: Ampenan Beach; 2: Saleh Sungkar St.; 3: H. Moh. Ruslan St.; 4: H. Ahyar Abduh St.; 5: Kembung St.; 6: Niaga 2 St.; 7: Ragi Genap St.; 8: Arya Banjar Getas St.; 9: Skip St.; 10: Energi 1 St.; 11: Gurami St.; 12: Energi 2 St.; 13: Yos Sudarso St.; 14: Malomba St.; 15: Langko St.; 16: R. Soeprapto St.; 17: Panji Tilar Negara St.; 18: Majapahit St.; 19: Koperasi St.; 20: Ex Airport Roundabout; 21: Banda St.; 22: Adi Sucipto St.; 23: Blongas St.; 24: Kebon Roek Market

After the area was divided into groups according to the waste transportation trucks, distance matrices between transportation nodes were prepared for each group. These matrices can also be referred to as adjacency matrices.

Table 2. Distance matrix for Group 1

Group 1	6	10	11	12	13	14
6	0	0.75	0.55	0.70	0.70	0.80
10	0.75	0	0.084	0.11	0.35	0.23
11	0.55	0.084	0	0.045	1000	0.45
12	0.07	0.11	0.045	0	0.95	0.17
13	0.07	0.90	1000	0.95	0	1.10
14	0.80	0.23	0.45	1.70	1.10	0

Table 3. Distance matrix for Group 2

Group 2	7	8	9	16	17	18
7	0	1.80	1.00	2.50	2.60	1000
8	1.80	0	1.20	3.30	1.30	1000
9	1.00	1.20	0	2.50	2.00	1.90
16	2.50	3.30	2.50	0	0.85	0.70
17	2.60	1.30	2.00	0.85	0	1.10
18	1000	1000	1.90	0.70	1.10	0

Table 4. Distance matrix for Group 3

Group 3	15	19	20	21	22	23
15	0	3.90	3.20	3.90	1000	4.00
19	3.90	0	1000	0.55	1.10	0.30
20	3.20	1000	0	7.00	1.20	1000
21	3.90	0.55	7.00	0	2.30	0.65
22	1000	1.55	1.20	2.30	0	1.20
23	4.00	1.10	1000	1000	1.20	0

Table 5. Distance matrix for Group 4

Group 4	1	2	3	4	5	24
1	0	2.30	1.00	1.60	1.00	1.10
2	2.30	0	1000	1.10	1.40	1.40
3	1.00	1000	0	0.30	0.35	1.90
4	1.60	1.10	0.30	0	0.80	0.80
5	1.00	1.40	0.35	0.80	0	0.45
24	1.10	1.40	1.90	0.80	0.45	0

In the matrices above, each entry i, j represented by a row and a column, shows the travel distance from node v_i to node v_j, and vice versa. Routes that are not adjacent are assigned a very large weight, namely 1000, while the unit used is kilometers (km).

The minimum route for waste transportation in Ampenan District was then identified. The approach involved the implementation of Prim's algorithm using the Python programming language. Prim's algorithm helps determine the shortest connection that links all waste transportation points, such as temporary collection points or residential collection points, with the minimum total distance. This can reduce travel time and fuel costs. Thus, the best solution to the problem was obtained by applying Prim's algorithm to each group, as shown in Table 6.

Table 6. Minimum route for waste transportation

Group	Edges	Route Length
1	11-10, 6-11, 11-12, 10-13, 12-14	3.279 km
2	9-8, 7-9, 17-16, 8-17, 16-18	5.05 km
3	23-19, 15-20, 19-21, 20-22, 22-23	6.45 km
4	3-4, 3-5, 5-24, 4-2	3.20 km

Figure 2 presents an example of a minimum spanning tree visualization for Group 4, with a route length of 3.20 km.

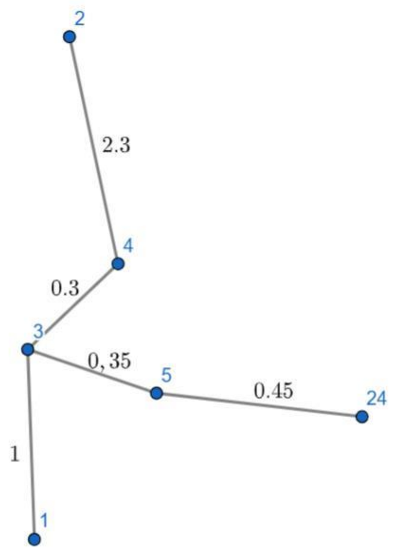

Figure 2. Visualization of the shortest route for Group 4

The minimum spanning trees for Groups 1 to 4 represent the shortest waste transportation routes for each group. Group 1 has a route length of 3.279 km, while Groups 2, 3, and 4 have minimum waste transportation routes of 5.05 km, 6.45 km, and 3.20 km, respectively.

Based on operational estimates from recent transportation and waste management studies, a compactor truck with a carrying capacity of around 5 tons and an average fuel efficiency of 7 km per liter consumes approximately 8.57 liters of diesel for a 60 km round trip. This is equivalent to a fuel consumption rate of about 0.143 L/km [8]. This value was used as a conservative estimate to assess the environmental impact of the optimized waste transportation routes.

The minimum spanning tree analysis produced the shortest transportation routes for four waste collection groups. The optimized route length for Group 1 was 3.279 km, while Groups 2, 3, and 4 had route lengths of 5.05 km, 6.45 km, and 3.20 km, respectively. Overall, the total optimized route length across all groups was 17.979 km.

By applying the fuel consumption rate of 0.143 L/km, the optimized routes are estimated to consume approximately 2.57 liters of diesel for one complete transportation cycle across the four groups. Using the standard diesel emission factor of 2.68 kg CO_2 per liter, the estimated total emission is approximately 6.89 kg CO_2 per operation. These findings indicate that route optimization using the minimum spanning tree approach can contribute to lower fuel consumption and reduced carbon emissions by eliminating unnecessary travel distance.

Group 3 generated the highest estimated fuel use and CO_2 emissions because it had the longest optimized route, at 6.45 km. Conversely, Group 4 had the shortest route, at 3.20 km, resulting in the lowest estimated fuel consumption and emissions. This difference shows that route length, node distribution, and network structure affect the environmental performance of waste transportation.

Overall, the optimized routes obtained through Prim's algorithm demonstrate the potential of graph-based route planning to reduce travel distance, diesel use, and greenhouse gas emissions. This result supports previous studies showing that efficient route design is an important strategy for achieving more sustainable urban waste collection systems [9, 10, 11]

Conclusion

This study optimized waste transportation routes in Ampenan District by dividing the service area into four groups based on the number of available waste transportation trucks. Prim's algorithm was applied to determine the minimum spanning tree for each group, representing the shortest connected transportation route. The results show that the optimal route lengths were 3.279 km for Group 1, 5.05 km for Group 2, 6.45 km for Group 3, and 3.20 km for Group 4. The application of the minimum spanning tree approach successfully identified the shortest route for each group, indicating its potential to reduce travel distance, transportation time, fuel consumption, and operational costs. Therefore, Prim's algorithm can be considered an effective method for supporting more efficient and sustainable waste transportation planning in Ampenan District.

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Author Contributions

Conceptualization, C.S.M. and A.I.U.; methodology, T.H. and A.U.; software, T.K. and A.I.U.; validation, C.S.M., T.H., and A.U.; formal analysis, C.S.M.; investigation, A.I.U.; resources, T.H.; data curation, T.K.; writing—original draft preparation, C.S.M. and A.I.U.; writing—review and editing, T.H., A.U., and T.K.; visualization, T.K.; supervision, T.H. All authors have read and agreed to the published version of the manuscript.

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Conflicts of Interest

The authors declare no conflict of interest.

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