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COMPARATIVE ANALYSIS OF EXISTING AND OPTIMIZED ROUTES IN A NEW WASTE COLLECTION POINT (TPS) DESIGN SCENARIO IN BALIKPAPAN CITY USING THE SAVING MATRIX AND TABU SEARCH METHODS

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Abstract
Waste transportation is a critical stage in solid waste management that requires efficient route planning to minimize travel distance and improve operational effectiveness. In Balikpapan City, waste is transported from the temporary waste collection points (TPS) to the Manggar final processing site (TPA) along operational routes that have not been systematically optimized, resulting in excessive travel distances. This study applies the Clarke and Wright Saving Matrix method to generate an initial solution, which is subsequently refined using the Tabu Search algorithm. The results show that the total transportation distance for the 399 existing collection points was reduced from 2,297 km to 1,083 km, an efficiency gain of 52.84%, while accounting for the operation of 47 dump trucks. For the scenario involving 430 newly relocated collection points, the procedure produced a total distance of 2,250.34 km distributed across 76 routes. These findings are expected to serve as a consideration for the Balikpapan City Environmental Agency (DLH) in improving the efficiency of its waste transportation routes.

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Keywords:
Waste collection point; saving matrix; tabu search; waste transportation

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1. Introduction

Balikpapan City, located in East Kalimantan Province, covers an area of approximately 503.30 km² divided into six districts: Balikpapan Barat, Balikpapan Utara, Balikpapan Tengah, Balikpapan Selatan, Balikpapan Timur, and Balikpapan Kota [1]. As one of the buffer cities for the Nusantara Capital City (IKN), Balikpapan has undergone rapid growth in the residential, commercial, industrial, and service sectors. This growth has directly increased the population, economic activity, and demand for public services, including the solid waste management system. The geographic conditions of a region strongly influence the effectiveness of waste management, particularly during collection and transportation, because topography, road conditions, inter-location distances, and the distribution of service points determine vehicle travel time, the number of trips, fuel consumption, and the size of the fleet that must be operated [2].

Waste transportation is one of the crucial stages of the solid waste management system because it links the temporary waste collection points (TPS) with the final processing site (TPA). This stage requires careful planning so that waste can be collected in a timely manner and does not accumulate at the TPS. A transportation system that is not optimally designed leads to longer vehicle travel distances, extended operating times, higher fuel use, and rising operational costs. Moreover, delayed collection can degrade environmental quality, generate unpleasant odors, and disturb the comfort of communities living near TPS locations. The efficiency of transportation routes therefore becomes a highly important aspect of improving the quality of urban waste services.

According to data from the National Waste Management Information System (SIPSN), waste generation in Balikpapan City has shown a consistent upward trend from 2019 to 2024, rising from 458.62 tonnes per day to 540.69 tonnes per day [3]. This increase is driven by population growth, the expansion of residential areas, and rising economic activity. The growing waste volume must be matched by a transportation system capable of serving all TPS points effectively and efficiently. If service capacity is not increased, an imbalance will emerge between the amount of waste generated and the fleet's capacity to transport it.

Waste management in Balikpapan City currently relies on direct transportation from the TPS to the Manggar TPA using operational routes formed from field practice rather than systematic optimization [4]. This pattern renders each vehicle's route length inefficient, as overlapping paths, sub-optimal TPS visiting sequences, and under-utilized vehicle capacity persist. Consequently, the total daily travel distance increases, driving up fuel consumption, operational costs, and service time. If this condition continues, the effectiveness of waste services will progressively decline as annual waste generation grows.

Based on recapitulation data from the Balikpapan City Environmental Agency (DLH), the waste transportation fleet consists of 47 dump trucks and 33–34 arm roll trucks distributed across the six districts [4]. However, the distribution of this fleet is not yet fully balanced against the service demand in each area. Several districts have relatively more TPS than the available fleet capacity, forcing vehicles to make more trips per day. This imbalance among fleet size, TPS distribution, and vehicle capacity is one of the factors keeping transportation efficiency sub-optimal [5]. An optimization approach is therefore required to produce transportation routes with shorter travel distances without violating vehicle capacity limits.

The waste transportation routing problem can essentially be modeled as a Capacitated Vehicle Routing Problem (CVRP), namely the problem of determining vehicle routes with the objective of minimizing the total travel distance or distribution cost, where each vehicle has a fixed capacity limit. In a waste transportation system, each TPS is treated as a service point that must be visited exactly once before the vehicle returns to the TPA. Solving the CVRP exactly requires substantial computation time as the number of service points grows. Heuristic and metaheuristic methods are therefore widely used because they can produce good solutions within a relatively short computation time.

A variety of route optimization methods have been applied in previous studies. A Genetic Algorithm was used to optimize waste transportation routes in Yogyakarta while accounting for a multi-capacity fleet [6]. Ant Colony Optimization was applied to determine the shortest waste transportation route in Pekanbaru [7]. In addition, the Clarke and Wright Saving Matrix method has been widely used because it can form a good initial solution by merging pairs of service points according to the largest saving values [8][9]. To improve the quality of this initial solution, several studies have combined the Saving Matrix with metaheuristic algorithms such as Tabu Search, which explores neighbor solutions and thereby increases the likelihood of obtaining a better result [10], [11].

The Clarke and Wright Saving Matrix method was selected in this study because its computation process is simple, it is easy to implement, and it can produce a good initial solution for distribution problems involving a large number of service points. The Tabu Search algorithm is then used as an improvement heuristic through a swap mechanism between service points. The use of a Tabu List enables the algorithm to avoid revisiting identical solutions, allowing the search to explore the solution space more broadly. The combination of these two methods is thus expected to yield more efficient transportation routes than the existing operational condition. Unlike previous studies that generally focus only on optimizing routes under existing conditions, this study evaluates not only the transportation system currently applied in Balikpapan City but also a new relocated-TPS planning scenario as part of the future development of the waste service system. This approach provides insight into the transportation route requirements should the number of TPS increase as the urban area expands. The findings are therefore useful not only as an evaluation of existing conditions but also as a basis for planning a waste transportation system that is more adaptive to Balikpapan City's development.

Based on the foregoing, this study aims to (1) analyze the efficiency of waste transportation routes under the existing TPS conditions in Balikpapan City and (2) develop transportation routes for the new relocated-TPS

planning scenario using the Clarke and Wright Saving Matrix method refined with the Tabu Search algorithm within a Capacitated Vehicle Routing Problem (CVRP) framework. The results are expected to serve as a recommendation for the Balikpapan City Environmental Agency in improving the efficiency of the waste transportation system through a reduced total travel distance, more optimal fleet utilization, and the design of more effective routes to support sustainable waste services.

2. Method

A. Preliminary Study

The preliminary study is the initial stage carried out to obtain a comprehensive overview of the waste transportation system in Balikpapan City. Activities at this stage include field observation, problem identification, and a literature review related to solid waste management systems and vehicle route optimization methods. Observation was conducted to understand the operational conditions of waste transportation, the characteristics of the temporary waste collection points (TPS), the location of the Manggar final processing site (TPA), and the transportation route patterns applied by the Balikpapan City Environmental Agency. Various problems that reduce transportation efficiency were then identified, such as high total travel distances, limited vehicle capacity, and the absence of an optimization method in route planning. A literature review was also conducted on theories and previous studies concerning the Vehicle Routing Problem (VRP), the Capacitated Vehicle Routing Problem (CVRP), the Clarke and Wright Saving Matrix method, the Tabu Search algorithm, and the use of the Haversine formula in distance calculation. The results of this stage form the basis for formulating the research objectives, selecting the methods used, and structuring the overall research stages.

B. Data Collection

The data collection stage was carried out to obtain all information required for the route optimization process. The data used consist of primary and secondary data. Primary data were obtained through field observation to understand the operational conditions of waste transportation and to verify TPS locations. Secondary data were obtained from the Balikpapan City Environmental Agency, Statistics Indonesia (BPS), and the National Waste Management Information System (SIPSN). The collected data include the coordinates of all TPS and the Manggar TPA, the daily waste volume at each TPS, the number and capacity of the dump truck fleet, the existing transportation routes, and other supporting data related to the solid waste management system. All data were subsequently checked for completeness, standardized in format, and verified so that they could serve as the basis for data processing and route optimization.

C. Data Processing

The data processing stage was carried out to prepare all data for the optimization method. The TPS coordinates, originally obtained in Degree–Minute–Second (DMS) format, were first converted into Decimal Degrees (DD) so that they could be processed using the Python programming language. After conversion, a distance matrix among all TPS and the Manggar TPA was computed using the Haversine formula, which calculates distances from geographic latitude and longitude coordinates. The resulting distance matrix is symmetric, so the distance from TPS A to TPS B equals the distance from TPS B to TPS A. Data consistency was then checked and the distance matrix was compiled as the basis for calculating saving values in the Clarke and Wright Saving Matrix method and for evaluating solutions in the Tabu Search algorithm. This stage is highly important because the quality of the resulting data directly affects the accuracy of the route optimization.

D. Route Optimization Using the Clarke and Wright Saving Matrix

The optimization stage begins by applying the Clarke and Wright Saving Matrix method to form the initial solution for the waste transportation routes. At this stage, the saving value for each pair of TPS is calculated using the previously obtained distance matrix. The saving value indicates the distance saved when two TPS are combined

into a single route rather than served separately. All saving values are then sorted from largest to smallest as the basis for route construction. Pairs of TPS are merged incrementally while observing several operational constraints, including a maximum dump truck capacity of 4 tonnes, the requirement that a TPS can be merged only when it lies at the end node of a route, and the proximity of service areas so that the resulting routes are more efficient and realistic. In addition, each TPS may appear only once across all routes to avoid duplicated service. The output of this stage is an initial transportation solution with a shorter total travel distance than the existing condition while still satisfying all imposed operational constraints.

E. Analysis and Conclusion Drawing

The initial solution produced by the Clarke and Wright Saving Matrix method is then refined using the Tabu Search algorithm to obtain a higher-quality result. This study uses a swap operator, namely exchanging the positions of two TPS either within a single route or between routes. The search is performed iteratively over 100 iterations, in which each iteration generates a number of neighbor solutions that are evaluated according to the total travel distance using the Haversine distance matrix. Solutions yielding a shorter total distance while still satisfying the vehicle capacity constraint are accepted as the new current solution, whereas solutions that provide no improvement are rejected. To avoid re-evaluating identical solutions, each swap already performed is stored in the Tabu List. This mechanism allows the algorithm to explore the solution space more broadly and reduces the likelihood of becoming trapped in a local optimum. The final output of this stage is a set of transportation routes that have undergone refinement and thus achieve a higher level of efficiency than the initial solution.

F. Conclusion

The conclusion is the final research stage, which summarizes all analytical results obtained. At this stage, the effectiveness of applying the Clarke and Wright Saving Matrix and Tabu Search methods to optimize waste transportation routes in Balikpapan City is evaluated. The evaluation compares the optimized routes with the existing routes based on indicators such as total travel distance, the number of routes formed, vehicle capacity utilization, and the resulting efficiency. In addition, the new relocated-TPS planning scenario is analyzed to assess the method's ability to construct routes under broader service conditions. Based on this evaluation, conclusions are drawn regarding the success of the applied methods, together with recommendations for the Balikpapan City Environmental Agency to improve the efficiency of the waste transportation system. The resulting recommendations are expected to inform the planning of operational routes and the development of a more effective, efficient, and sustainable waste management system in the future.

G. Research Flow

The research flow provides a general overview of the entire research process from beginning to end. The flow adopted in this study is depicted in the flowchart shown in Figure 1. All stages were carried out with the aid of the Python programming language. The study began with the collection of TPS and TPA coordinate data, followed by distance matrix computation using the Haversine formula, initial route construction using the Clarke and Wright Saving Matrix method, solution refinement using the Tabu Search algorithm, and finally a comparative analysis of the efficiency between the actual routes and the optimized routes.

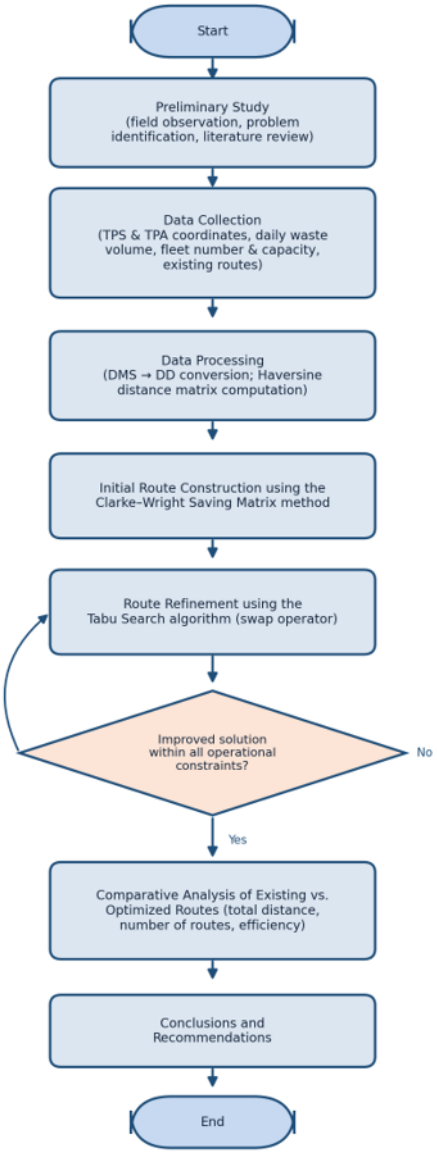

Figure 1. Research Flowchart

3. Result and Discussion

A. General Overview of the Research Data

This study uses data from 399 concrete temporary waste collection points (TPS) distributed across six districts in Balikpapan City as the main object of optimization. All of these TPS are served by 47 dump trucks that transport waste to the Manggar final processing site (TPA). The data used include the coordinates of each TPS, the daily waste volume, vehicle capacity, and the existing transportation routes obtained from the Balikpapan City Environmental Agency. The study focuses only on concrete TPS because this type has uniform operational characteristics and its entire transportation process uses dump trucks. Container TPS, by contrast, were excluded from the optimization because they are served by arm roll trucks, which have a different transportation system, operational mechanism, and vehicle characteristics from dump trucks. Separating the research objects in this way ensures that the optimization produces routes that are more representative of, and consistent with, actual

operational conditions, allowing the analysis to portray the transportation efficiency of the dump truck fleet more accurately.

B. Data Processing and Distance Matrix

The coordinates of each TPS obtained from the Balikpapan City Environmental Agency were initially in Degree–Minute–Second (DMS) format. To enable computational processing using the Python programming language, all coordinates were first converted into Decimal Degrees (DD) format. The converted coordinates were then used as input for computing the distance matrix among the TPS and between each TPS and the Manggar TPA using the Haversine formula. The Haversine formula was chosen because it computes the shortest distance between two points from their latitude and longitude coordinates on the earth's surface with good accuracy. The resulting distance matrix is symmetric, so the distance from TPS A to TPS B equals the distance from TPS B to TPS A. This matrix subsequently serves as the basis for calculating saving values in the Clarke and Wright Saving Matrix method and for evaluating distances in the Tabu Search algorithm. Based on the actual route data used by the 47 dump trucks, a total daily travel distance of 2,297 km was obtained. This value is used as the baseline and serves as the main reference for comparing the performance of the optimized routes. Accordingly, the efficiency gained from applying the proposed method can be measured quantitatively from the difference in total travel distance between the existing condition and the optimization result.

Table 1. Total Vehicle Distance for Existing TPS Transportation

Vehicle	Total Vehicle Distance (km)
Dump truck 1	68.5
Dump truck 2	39.6
Dump truck 3	40.1
…	…
Dump truck 47	79.2
Total distance	2,297

Table 2. Distance Matrix

TPS	0359	0360	0361	…	TPS
0359	0	0.40	0.73	…	11.3
0360	0.40	0	0.84	…	11.6
0361	0.73	0.84	0	…	11.9
…	…	…	…	…	…
TPA	11.3	11.6	11.9	…	0

C. Route Construction Using the Saving Matrix

The route construction process begins by calculating the saving value for each pair of TPS using the equation Sij = di0 + d0j − dij; all saving values are then sorted from largest to smallest to prioritize the merging of TPS pairs into a single route. A larger saving value indicates a greater potential reduction in travel distance if the two TPS are served in a single trip. Routes are then constructed incrementally while considering several operational constraints, namely a maximum dump truck capacity of 4 tonnes, the requirement that a TPS lie at the end node of a route to be merged, and the proximity of districts so as to produce more efficient and realistic paths. In addition, each TPS can be served only once, so no duplication occurs during route formation. This process yielded 51 transportation routes with a total travel distance of 1,083 km, a significant reduction compared with the existing condition. The number of routes produced is slightly larger than the available fleet of 47 dump trucks; however, this can still be accommodated through a trip-rotation system in which one vehicle serves more than one route per day. This demonstrates that the Clarke and Wright Saving Matrix method can produce an efficient initial solution while satisfying all operational constraints imposed in the study.

Table 3. Route Construction Using the Saving Matrix

Dump truck	Number of TPS	Total volume (t)	Total distance (km)
Dump truck 1	9	4	18.8
Dump truck 2	6	3.5	9.2
Dump truck 3	6	3.6	9.4
…	…	…	…
Dump truck 47	9	4	25.8

D. Refinement Using Tabu Search

The initial solution obtained from the Clarke and Wright Saving Matrix method was then refined using the Tabu Search algorithm with a swap operator to evaluate whether a more optimal route arrangement could be obtained. The optimization was performed over 100 iterations, in which each iteration swapped the positions of two TPS, either within the same route or between routes, thereby generating a set of neighbor solutions. The total travel distance of each swapped solution was recalculated and compared with the current solution. A new solution was accepted only if it produced a shorter total distance or met the predetermined criteria, while evaluated solutions were placed in the Tabu List to prevent repeated searching of identical solutions. Through this iterative process, only one route changed, with a total-distance reduction of 0.007 km, while the remaining routes stayed the same as in the initial solution. This very small improvement indicates that the solution generated by the Clarke and Wright Saving Matrix method was already very close to optimal, leaving relatively limited room for Tabu Search to explore. Nevertheless, the application of Tabu Search still plays an important role as a validation and refinement stage, as it confirms that no alternative route arrangement yields a shorter total travel distance while still satisfying all operational constraints, such as vehicle capacity and the established route structure. The combination of the two methods thus produces a solution that is not only efficient but also more reliable than using the Clarke and Wright Saving Matrix method alone.

Table 4. Refinement of Route Construction Using Tabu Search

Dump truck	Number of TPS	Total volume (t)	Total distance (km)
Dump truck 1	9	4	18.8
Dump truck 2	6	3.5	9.2
Dump truck 3	6	3.6	9.4
…	…	…	…
Dump truck 9	7	3.8	14.606
…	…	…	…
Dump truck 47	9	4	25.8

E. Comparison of Actual and Optimized Distances

A comparison between the existing routes and the routes optimized using Tabu Search was carried out as the final stage to evaluate the effectiveness of the methods applied in this study. The comparison used the total travel distance as the main indicator, because the distance traveled directly affects operating time, fuel consumption, and transportation cost. The analysis identifies the performance difference between the transportation system currently applied in the field and the optimized system obtained through the combination of the Clarke and Wright Saving Matrix and Tabu Search methods. In addition to comparing the total travel distance of each vehicle, the efficiency of each route was analyzed to determine the extent of the distance reduction achieved after optimization. Based on the data processing, all optimized routes exhibited positive efficiency values, so no single route had a longer travel distance than its existing counterpart. Overall, the total transportation distance was reduced from 2,297 km under

the existing condition to 1,083 km after optimization, yielding an efficiency of 52.84%. These results show that combining the Clarke and Wright Saving Matrix method as the initial-solution generator with Tabu Search as the refinement method can significantly improve the efficiency of the waste transportation system without violating the imposed operational constraints; the proposed method is therefore worth considering as an alternative for planning waste transportation routes in Balikpapan City.

Table 5. Comparison of Actual and Optimized Distances

No.	Vehicle	Actual distance (km)	Optimized distance (km)	Efficiency (%)
1	Dump truck 1	68.6	18.8	72.59
2	Dump truck 2	39.7	9.2	76.83
3	Dump truck 3	40.1	9.4	76.56
…	…	…	…	…
47	Dump truck 47	79.2	55.2	30.30

F. Data and Distance Matrix for the New TPS

In addition to analyzing the transportation conditions at the 399 existing TPS, this study also developed a transportation route scenario for 430 newly relocated TPS to anticipate the expansion of the waste service area in Balikpapan City. Increasing the number of TPS in this scenario portrays the future transportation requirements associated with population growth, residential development, and the widening of the service area. Consequently, the number of TPS in the relocation scenario is greater than in the existing condition, so new routes must be constructed to keep the transportation system running efficiently. The coordinate data for all relocated TPS were obtained in Degree–Minute–Second (DMS) format and then converted into Decimal Degrees (DD) using the same procedure as for the existing TPS data, so that they could be processed computationally using the Python programming language. The coordinates were then visualized using Google Maps to ensure that the distribution of TPS locations matched the planned service area and to facilitate verification of each point's position against the geographic conditions in the field. After validation, the distance matrix among all TPS and the Manggar TPA was computed using the Haversine formula, chosen for its good accuracy in calculating distances from geographic coordinates. The resulting distance matrix is symmetric — the distance from TPS A to TPS B equals the distance from TPS B to TPS A — making the calculation more consistent and efficient. This matrix was then used as the basis for calculating the saving value for each pair of TPS with the Clarke and Wright Saving Matrix method, which subsequently guided route construction for the new relocated-TPS scenario. All data processing stages were thus carried out systematically so that the resulting routes represent realistic operational conditions and can serve as an alternative for planning the waste transportation system in Balikpapan City in the future.

Table 6. Distance Matrix for the New TPS

TPS	1S	2S	3S	…	70B
1S	0	0.68	1.72	…	35.0
2S	0.68	0	2.13	…	34.9
3S	1.72	2.13	0	…	33.6
…	…	…	…	…	…
70B	35.0	34.9	33.6	…	0

G. Saving Matrix for the New TPS

The saving value for each pair of TPS in this scenario was calculated using the same Clarke and Wright equation as in the existing scenario, namely Sij = di0 + d0j − dij. All saving values were then sorted from largest to smallest, because the pair of TPS with the highest saving value offers the greatest potential distance saving when combined into a single route. Route grouping was performed incrementally while considering three main

constraints — a maximum vehicle capacity of 4 tonnes, the requirement that a TPS lie at the end node of a route, and the priority given to district proximity — identical to the approach used in the existing scenario. This process produced 76 transportation routes with a total travel distance of 2,250.34 km. The larger number of routes compared with the existing scenario (47 routes) is consistent with the broader TPS coverage, so it is reasonable that both the number of routes required and the total travel distance increase.

Table 7. Saving Matrix for the New TPS

	1B	2B	3B	…	70U
1B	0	27.399	27.024	…	7.962
2B	27.399	0	26.276	…	7.578
3B	27.024	26.276	0	…	8.102
…	…	…	…	…	…
70U	7.962	7.578	8.102	…	0

H. Refinement Using Tabu Search (New TPS Scenario)

The initial solution generated using the Clarke and Wright Saving Matrix method for the 430 newly relocated TPS scenario was then evaluated and refined using the Tabu Search algorithm to determine whether an alternative route arrangement could yield a shorter total travel distance. The optimization used the same parameters as in the existing TPS scenario so that the results of the two scenarios could be compared objectively. The algorithm was run for 100 iterations as the stopping criterion, applying a swap operator that exchanges the positions of two TPS either within the same route or between routes. In each iteration, the swap process generated a set of neighbor solutions that were re-evaluated by computing the total travel distance using the Haversine distance matrix formed in the previous stage. The total distance of each neighbor solution was compared with the current solution, so that only solutions providing a travel-distance reduction while still satisfying all operational constraints — such as maximum vehicle capacity and the established route structure — could be accepted as the best solution. Conversely, if a swapped solution did not improve or increased the total distance, it was rejected and the swap step was stored in the Tabu List to prevent the algorithm from re-evaluating the same combination in subsequent iterations. This mechanism enables the search to move toward different regions of the solution space, reducing the likelihood of becoming trapped in a local optimum and increasing the chance of finding a better solution. Using optimization parameters consistent with the existing TPS scenario also maintains methodological uniformity, so that the differences in results more clearly reflect the effect of the change in the number and distribution of TPS rather than differences in algorithm parameters. The evaluation using Tabu Search thus functions not only as a refinement of the initial solution but also as a validation of the quality of the routes produced by the Clarke and Wright Saving Matrix method in the new relocated-TPS planning scenario.

I. Comparison of Saving Matrix and Tabu Search Results

The comparison shows that the reduction in total distance after applying Tabu Search was relatively small, and most routes did not change at all. This finding is consistent with that of the existing TPS scenario and indicates that the initial Clarke and Wright Saving Matrix solution in this scenario was also of good quality and close to optimal, leaving limited room for improvement by Tabu Search. Because the change in route arrangement after optimization was relatively minor and did not alter the overall route grouping pattern, the Tabu Search route visualization is not presented separately for this scenario; the total-distance comparison table is considered sufficient to represent the effect of the Tabu Search algorithm on the initial solution.

Table 8. Comparison of Actual and Optimized Distances (New TPS Scenario)

No.	Vehicle	Actual distance (km)	Optimized distance (km)	Efficiency (%)
1	Dump truck 1	186.782	186.8	0
2	Dump truck 2	179.354	179.4	0
3	Dump truck 3	137.998	138.0	0
…	…	…	…	…
47	Dump truck 47	2.068	2.068	0

The complete tables are available at the following drive folder: https://drive.google.com/drive/folders/1IUl_aQVLCdar_gRYnC8uyXG-O97AR5Po

4. Conclusion

Based on the research conducted, the existing waste transportation system in Balikpapan City still holds considerable potential for improvement through the application of route optimization methods. The actual routes serving the 399 existing concrete TPS with 47 dump trucks had a total travel distance of 2,297 km, and these routes were still based on field-derived operational patterns without systematically considering travel-distance optimization or vehicle capacity utilization. Applying the Clarke and Wright Saving Matrix method produced an initial solution of 51 transportation routes for the existing TPS scenario and 76 transportation routes for the 430 newly relocated TPS scenario, with a total travel distance of 2,250.34 km. Under the existing TPS condition, the method reduced the total transportation distance from 2,297 km to 1,083 km, achieving an efficiency of 52.84% relative to the initial operational condition. The initial solution was then refined using the Tabu Search algorithm with a swap operator over 100 iterations, which produced only a 0.007 km reduction in total distance, indicating that the initial Clarke and Wright Saving Matrix solution was already very close to optimal. This shows that the combination of the two methods can produce efficient transportation routes while still satisfying the imposed operational constraints, such as vehicle capacity and route formation structure. The proposed approach therefore has the potential to serve as an alternative for supporting more effective and efficient waste transportation planning in Balikpapan City.

For future research, the optimization model is recommended to be extended by incorporating the actual road network, traffic congestion levels, travel time, and road-direction restrictions, so that the results better represent operational conditions in the field. Furthermore, future studies could integrate a heterogeneous fleet, such as dump trucks and arm roll trucks, into a single optimization model, and test various Tabu Search parameters — such as variations in tabu tenure, the number of iterations, and the use of alternative search operators such as 2-opt, Or-opt, or relocate — so that the opportunity to obtain more optimal and more applicable solutions can be further enhanced.

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