VEHICLE ROUTING PROBLEM IN WASTE COLLECTION: A CASE STUDY IN SON TRA, DANANG

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Abstract - This study investigates the application of network analysis to optimize solid waste collection routes in Son Tra District, Da Nang City. Twelve collection routes, encompassing 30 collection points, were tracked using GPS equipment and digitized in QGIS. Key parameters such as length, velocity, and time were analyzed. By employing the Dijkstra algorithm, route optimization resulted in a significant reduction in average route length, from 12.94 ± 3.5 km to 9.42 ± 2.67 km, representing a 9-42% improvement. A paired sample t-test confirmed the statistical significance of this reduction ($p<0.001$). These findings demonstrate the potential of network analysis to optimize waste collection routes and reduce operational costs. However, the model's limitations, such as its focus on static, point-based collection routes and the exclusion of dynamic factors like traffic conditions and residential habits, should be considered for future research.

Key words - Municipal solid waste; Waste collection and transportation; Vehicle routing problem; QGIS; Optimization

1. Introduction

Urbanization, driven by population growth and economic development, worsens the challenge of managing municipal solid waste (MSW). Increased consumption of goods and products, especially those with short lifespans and excessive packaging, contributes to a growing volume and diversity of waste, particularly MSW [1]. Vietnam's MSW generation has increased significantly, reaching 23.6 million tons annually. Urban areas contribute 35,000 tons daily, while rural areas generate 28,000 tons daily. This represents a substantial 46% increase compared to 2010. Major cities like Ho Chi Minh City (3.4 milions ton/year), Hanoi (2.4 milion ton/year), and others account for about a quarter of this total [2]. While 83-85% of urban MSW is collected for treatment, the remaining 15-17% is disposed of unsustainably, leading to severe environmental pollution from open dumping and burning. The increasing generation of MSW exacerbates the burden on waste management authorities.

The national master plan aims to achieve a 95% collection and treatment rate for municipal solid waste in urban areas by 2030, ensuring compliance with all relevant standards and regulations [3]. The socialization of waste collection and transportation has been a key factor in improving urban waste management. Thanks to this approach, the MSW collection rate has risen from 78% in 2008 to 92% in 2019. Large and medium-sized cities have achieved particularly high collection rates, with some cities collecting 100% of their MSW. The collection services have also been extended to smaller urban areas, covering household, community, and public places [2].

While residents contribute through tipping fees (regular environmental sanitation fees), these fees only account for a small portion (20-25%) of the total costs of collecting and transporting MSW. To ensure the sustainability of waste management services, local governments, particularly the People's Committees of provinces and cities, must allocate a substantial portion of their budgets (48-55% of urban public service costs) to cover the remaining expenses [4]. However, the inconsistency in tipping fees across different localities remains a problem, leading to a lack of standardization and uniformity. Lower service rates for mechanized collection compared to manual methods have discouraged businesses from investing in modern technology to improve efficiency and reduce labor [5]. In low-income areas, the collection and transportation of MSW is often the most expensive part of urban solid waste management, typically accounting for 70-90% of the total costs [6]. Given the need to improve productivity and cut costs, optimizing collection routes is imperative for waste collection and transportation services [7].

Vehicel routing problems, or route optimization has become a standard practice in the transportation sector, but its application in urban solid waste collection remains limited. Current collection routes in the city are manually designed, heavily reliant on the experience of workers who must possess a thorough understanding of local geography and traffic conditions. The informal nature of these routes, shaped by individual habits and gradual adjustments, is time-consuming and lacks a systematic approach. The overarching objective of route planning is to minimize the number of trips and total distance traveled, thereby reducing operational costs and increasing efficiency [8]. Numerous studies have demonstrated the significant benefits of route optimization, including improved labor productivity, reduced operational costs, and enhanced competitiveness among waste collection companies. Common optimization techniques involve the use of Geographic Information Systems (GIS) [9] - [14] or weighted graph models [15] - [18]. This study aims to optimize waste collection routes in Son Tra district, Da Nang City by implementing a vehicle routing problem (VRP) model using network analysis functions within QGIS.

2. Methodology

2.1. Research area

This study was conducted in Son Tra District, Da Nang, Vietnam (Figure 1), focusing on residential areas served by URENCO Son Tra. The district generates approximately 185 tons of MSW daily, collected through communal bins and door-to-door services. Wards with high population densities and commercial activities, such as Nai Hien Dong, An Hai Bac, An Hai Dong, and Man Thai, produce over 24 tons of waste per day, while wards with lower population densities, such as Tho Quang, An Hai Tay, and Phuoc My, generate less than 20 tons. At the time of the study (March 2023), 30 meeting points were operational.

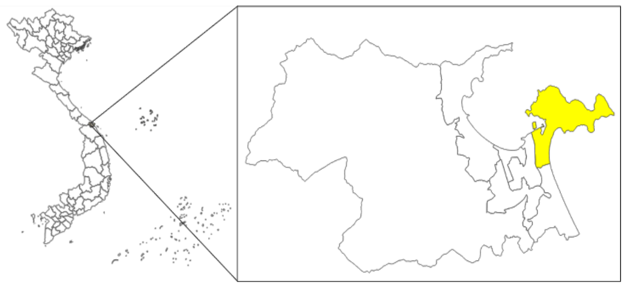

Figure 1. *Research area*

2.2. Data collection and analysis method

Data was collected through on-site surveys in the study area. Based on the production plan of Son Tra Environmental Enterprise, the research team identified the collection routes, including: time, collection point names, the order of collection at each collection point in each route, and the type of vehicle. Additionally, investigators directly followed the garbage trucks and used GPS applications on smartphones to determine the coordinates of the collection points. The location of the transfer station and collection points is shown in Figure 3. Each waste collection route consisted of three stages:

Moving forward: starting from the "*transfer station*" to the "*first collection point*".

Collection: starting from the "*first collection point*" to the "*last collection point*".

Moving backward: starting from the "*last collection point*" to the "*transfer station*".

The study period was from December 2022 to March 2023.

2.3. Developing a spatial map

Each record includes survey route information, including starting point, start of collection, end of collection, and ending point, along with GPS coordinates. VN-2000 grid coordinate (central meridian: 107º45', zone: 3 degrees, ellipsiod: WGS84) were used for this study, corresponding to the Da Nang City area. Data was processed using QGIS to analyze distances, times, and speeds for each segment based on field data. Using the collected route data on the QGIS map, the research team constructed a weighted matrix of points and distances between them to serve the optimization process. Figure 3 shows the results of the data processing on the QGIS platform.

2.4. Data analysis

The mean and standard deviation were used to present the analytical results. A paired sample t-test was conducted to compare the travel distance before and after route optimization. Data analysis was performed using R.

2.5. Assessment of the service coverage

This study employed the Time Travel Plugin in QGIS to assess the coverage range of various features, including collection points, service areas, and delivery routes. Figure 2 shows service coverage of collection point 23rd. The following steps were undertaken:

① *Feature Selection:* The point layer representing collection points, service areas, or delivery routes was selected.

② *Parameter Setting:* The starting time, ending time, and travel speed (set at 7.7 km/h) were specified.

③ *Analysis Execution:* The Time Travel analysis was initiated.

④ *Coverage Visualization:* A new layer representing the coverage area for each feature within the specified time frame was created.

⑤ *Coverage Evaluation:* The extent and overlap of the coverage areas were analyzed to assess the efficiency of collection points, service areas, or delivery routes.

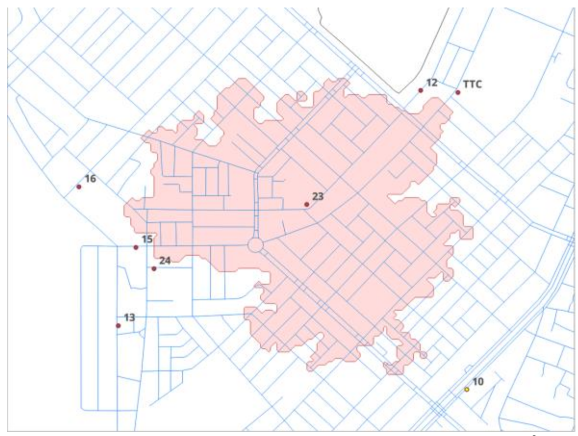

Figure 2. *Service coverage of collection point 23rd*

2.6. Waste collection route optimization

To identify the most efficient waste collection routes, a network analysis was performed using QGIS Network Analyst extension. By leveraging network analysis functions within QGIS, efficient and cost-effective collection routes that minimize travel distances, reduce fuel consumption, and improve overall operational efficiency was conducted.

The road network was modeled as a network dataset with nodes representing intersections and links representing road segments. A shortest path analysis was conducted to determine the optimal routes for each vehicle, considering factors such as road distance, traffic congestion, and vehicle capacity. The outline of optimization processes as follow:

① *Data Collection and Preparation:* Relevant data on the road network, waste collection points, and vehicle characteristics was gathered. This data was subsequently used to construct a network dataset in QGIS, with intersections defined as nodes and road segments as links. Attributes such as length, travel time, and road type were assigned to these links.

② *Define the Optimization Problem*: The primary objective of this study is to minimize total travel distance, working hours, and workload among vehicles. This optimization is subject to constraints such as vehicle capacity, driver hours of service, time windows for waste collection, and road restrictions.

③ *Create Network Analysis Layers*: Point layers were established for waste collection points, demand points, and transfer stations. A line layer was also created to represent the road network.

④ *Configure Network Analysis Settings*: The network dataset attributes were defined as length (km) and travel time (minutes). The Dijkstra algorithm was selected as the solver based on the optimization objectives and constraints.

⑤ *Run Network Analysis*: Using QGIS's network analysis tools, shortest paths between waste collection points and transfer stations were generated, incorporating factors such as time windows, vehicle capacity, and traffic congestion.

6. *Analyze and Interpret Results*: The generated routes were evaluated to ensure their alignment with optimization objectives and constraints. QGIS was used to visualize the optimized routes on a map. Potential areas for further optimization were identified through a thorough assessment of the results.

3. Result and discussion

3.1. Current status of collection routes

The manual collection of MSW in Son Tra district is a labor-intensive process, with an average of 389 daily trips to 30 collection points, amounting to 58.9 tons of waste. Compactor trucks are then used to transport this waste to the Son Tra transfer station. The locations of these collection points and the transfer station are depicted in Figure 3.

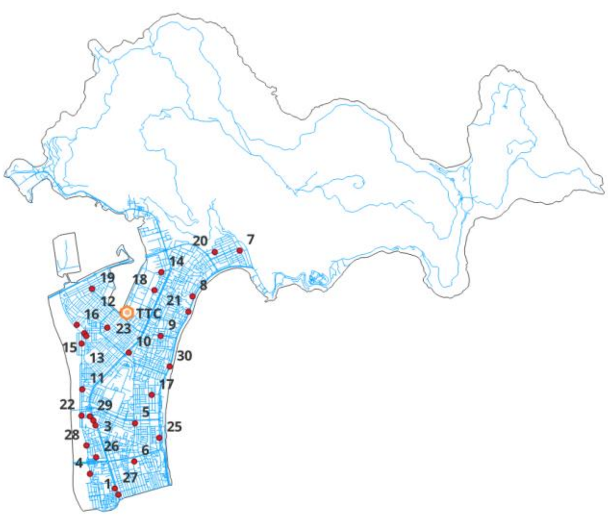

Figure 3. *Collection points and transfer station*

The daily routine of primary waste collectors involved starting their shift at 6:30 AM and ending at 3:00 PM, completing an average of 9 collection trips. Each manual collection required traversing a distance of approximately 2.4 ± 0.3 km, taking around 18.4 ± 4.3 minutes at an average speed of 7.7 ± 1.6 km/h. The round trip component of each collection, which accounted for approximately 1.0 ± 0.2 km, was typically completed in 4.0 ± 1.2 minutes [19].

URENCO Son Tra employs a fleet of 2 compactor trucks, each with a 5-ton capacity, to facilitate secondary waste collection. These trucks can accommodate approximately 34 dustbins (660L) per trip, transporting MSW from collection points to the Son Tra transfer station. The average round trip distance for these collections is 12.94 ± 3.5 km, completed in an average of 29 ± 3 minutes. As outlined in Table 1, a total of 12 trips are necessary to collect and transport the equivalent of 389 dustbins (660L) from the 30 designated collection points, covering a cumulative distance of 155.3 km and requiring a total of 348 minutes.

Table 1. *Curent status of collection route*

Route	Dustbin	Distance (km)	Time (min)
1	33	12.9	29
2	33	13.2	31
3	34	7.8	25
4	29	16.8	31
5	31	12.1	28
6	33	13.8	27
7	34	7.8	25
8	33	18.9	37
9	31	11.0	28
10	30	13.6	27
11	34	10.0	26
12	34	17.3	34
Ave	32.42 ± 1.73	12.94 ± 3.5	29 ± 3
Total	389	155.3	348

3.2. Assessment of the service coverage

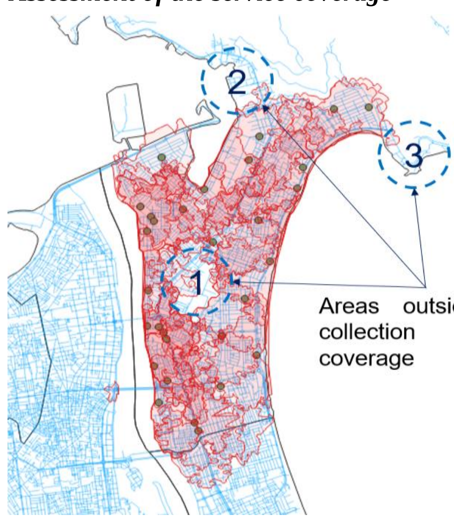

Figure 4. *Collection point's coverage*

Figure 4 illustrates the simulated service areas of the planned collection points. The analysis reveals three uncovered areas: ① An Don Industrial Zone, ② Tien Sa Port, and ③ Son Tra Marina F&B service area. Since these areas are non-residential, the current distribution of collection points in Son Tra adequately serves the residential population.

Figure 5 highlights instances where the proximity of collection points results in overlapping service areas, compromising the efficiency of waste collection operations in those areas. To address this issue and improve both operational efficiency and urban aesthetics, a realignment of collection points within the Son Tra area is recommended.

Figure 5. *Overlapping service areas*

3.3. Waste collection route optimization

As summarized in Table 2, route optimization resulted in a total distance reduction from 155.3 km to 113 km, representing a 27.2% savings. Additionally, the optimization process reduced working time from 348 minutes to 262 minutes, resulting in a 24.7% time savings.

Table 2. *Optimization of collection route*

Route	Dustbin	Distance (km)	Time (min)
1	33	9.3	19
2	33	10.0	20
3	34	5.7	17
4	29	11.6	24
5	31	9.1	25
6	33	12.4	25
7	34	5.7	17
8	33	11.6	25
9	27	6.4	17
10	34	12.4	27
11	34	6.6	20
12	34	12.0	26
Ave	32.42 ± 1.73	9.42 ± 2.67	22 ± 4
Total	389	113	262

As illustrated in Figure 6 and Figure 7, route optimization led to a significant reduction of 9% to 42% compared to current practices, with variation across different routes. A paired sample t-test confirmed the statistical significance of this difference ($p<0.001$). These findings align with previous studies by Navarro et al. (Bolivia, 7%) and Rim Sallem et al. (Tunisia, 4.19-14.68%) [8, 16]. In line with Kinobe et al.'s findings in Kampala, route optimization in this study demonstrated a potential reduction in travel distance of 2-40% [7]. The optimized routes No 5 are visualized in Figure 8.

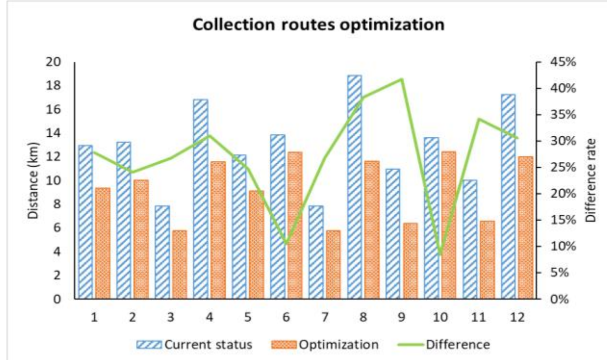

Figure 6. *Evaluation by distance*

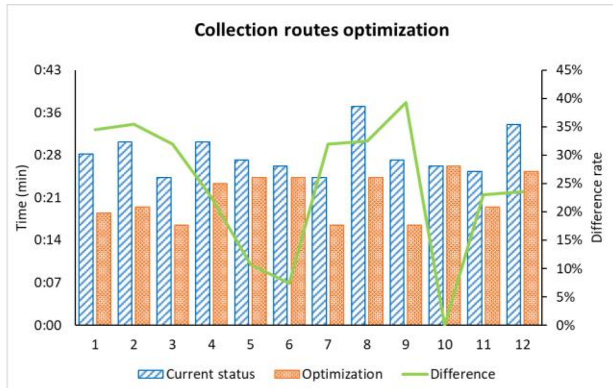

Figure 7. *Evaluation by working time*

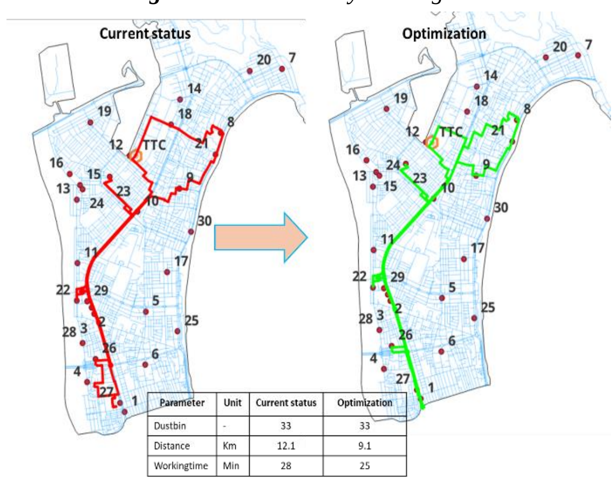

Figure 8. *Optimization for route No 5.*

4. Conclusion

This study explored the application of network analysis to optimize solid waste collection routes in Son Tra District. The results demonstrate the effectiveness of this approach in reducing travel distance and potentially lowering operational costs. However, it is crucial to note that the model's limitations include a focus on point collection routes and the exclusion of dynamic factors like traffic conditions and residential habits.

Our findings suggest that by optimizing routes, a substantial reduction in travel distance, ranging from 9% to 42%, can be achieved. This improvement is statistically significant and has the potential to enhance the overall efficiency of waste collection operations.

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