Route Optimization for Multi-trip Urban Waste Collection using Vehicle Routing Algorithm: A Case Study in Thimphu City

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Abstract

Solid waste management (SWM) is a critical challenge for urban sustainability, influenced by factors such as economic development, technological advancement, and regulatory frameworks. These factors have pushed the management of municipal solid waste into crisis, especially in developing countries including Bhutan. Thimphu, the capital city of Bhutan, faces significant SWM issues due to rapid urbanization and population growth. This research aims to optimize the solid waste collection system in Thimphu City through the implementation of the Vehicle Routing Problem (VRP) algorithm and the development of a simple web-based visual interface. The study involves identifying optimal locations for Garbage Accumulation Points (GAPs) and developing an optimized routing strategy for waste collection vehicles. The study considers a truck scheduling problem to effectively distribute collection vehicles in Thimphu City. For this study, a geographic information systems (GIS) based approach consisting of the spatial data analysis, network analysis, and VRP algorithm is performed using Python 3.12. The algorithm considers constraints like vehicle capacity, service time, working hours, and break periods to ensure feasible and efficient routing. For multi-trip solid waste collection in Thimphu city, our algorithm resulted in the deployment of a total of six trucks with different capacities. The simple analysis from the study shows the total time taken for waste collection in North and South Thimphu, is 35.5 hrs and 39.5 hrs with total distances of 202.76 km and 216.93 km respectively. The results demonstrate that managing waste collection in subdivided areas (North and South Thimphu) is more efficient than integrating the entire city, highlighting the complexity of city-wide SWM. The optimized routes show significant reductions in travel time and distance, underscoring the potential of advanced algorithms in enhancing operational efficiency.

Keywords— Solid waste management, Vehicle routing problem, Optimization, Geographic Information Systems, Thimphu City

1 Introduction

Solid waste management (SWM) involves the collection, transportation, processing, recycling, and disposal of solid wastes [1]. The effectiveness of SWM varies globally, influenced by factors such as economic development, technological advancement, and regulatory frameworks [2]. While developed countries employ advanced SWM technologies and systems, developing countries often struggle with inadequate infrastructure, leading to inefficient waste management and significant environmental impacts [3]. Thimphu the capital city of Bhutan is grappling with SWM issues due to its growing population, urbanization, and changing consumption patterns [4]. Currently, Thimphu generates about 40.3 metric tons of waste daily, which is predicted to rise to 124 metric tons by the year 2027 with an estimated population of approximately 200,000 [4]. Off-all waste collection and transportation account for 60-80% of SWM costs, making system improvements crucial for reducing municipal expenses [5]. Additionally, urban waste collection and disposal are expensive tasks due to high operating costs (fuel, maintenance, recycling, manpower, etc.), and even small advances in this field can significantly reduce municipal expenditures. Efforts to enhance Thimphu's waste management include legislative reviews and private sector involvement, yet challenges persist. Additionally, the current practice of manual scheduling and siren-based waste collection systems is outdated, and collection timings are inconvenient for many residents [4], [6]. The limited number of garbage trucks and inconsistent collection routes and times exacerbate these issues. There is a possibility that a certain percentage of Thimphus population might miss the services as the garbage needs to be physically brought outside to the garbage trucks. However, integrating technology, such as GPS tracking on garbage vehicles, offers the potential for smarter waste management. Geographic Information systems (GIS) in combination with Artificial Intelligence (AI) provides a promising alternatives for optimizing waste collection processes [7], [8], [9]. Regression models and Artificial Neural Network(ANN) were used to optimize the waste collection routine, while GIS aids in detailed mapping and analysis of waste generation patterns and collection routes [10], [11]. These innovative approaches, validated through various experiments, underscore the pivotal role of AI in revolutionizing SWM practices [12]. This project aims in optimizing and improving waste management by increasing the disposal and minimizing the costs. A web-based Vehicle Routing Problem (VRP) solution is proposed. In this project optimal locations for garbage accumulation points (GAPs) and efficient routes are determined for the garbage trucks, considering capacity constraints and time windows for each GAP. This approach seeks to reduce overall costs and enhance the waste collection system's efficiency.

2 Study Area

Thimphu, the capital and largest city of Bhutan, lies within the longitude range of $89°36'18''E$ to $89°40'50''E$ and latitude range of $27°32'32''N$ to $27°25'14''N$. It is the main economic and commercial hub of the country, situated in a valley at about 2,334 meters (7,657 ft) above sea level, surrounded by mountains and forests. Covering an area of 26 sq. km, Thimphu stretches 15 km long and 3 km wide, from Dechencholing in the north to Babesa in the south. The city has seen rapid urbanization and population growth, with an estimated population of 144,197 in 2024 and an annual growth rate of 3.34% [13]. This growth has led to increased waste generation, necessitating the development of an efficient waste management system.

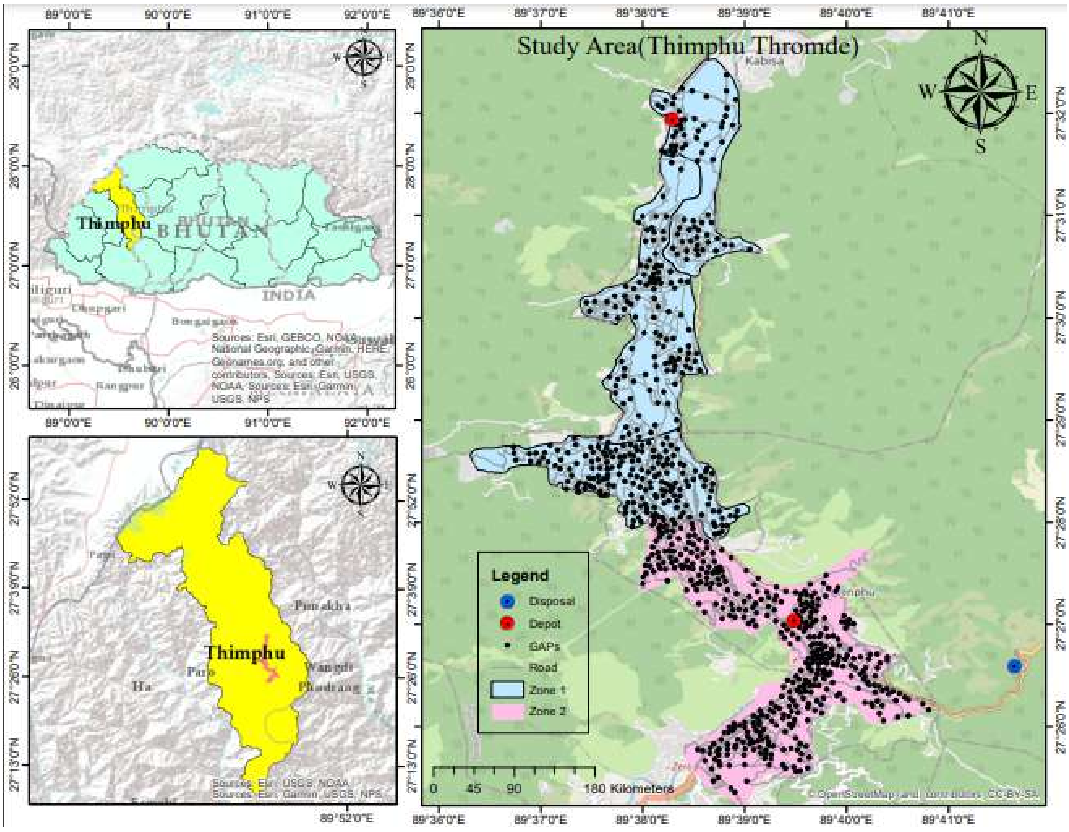

Figure 1: Study Area

3 Methodology

3.1 Data Collection

Data were collected from different agencies(table 1). For instance, road network, and settlement data was obtained from the Ministry of Infrastructure and Transport (MoIT). Administrative boundaries were collected from Thimphu thomdre. These spatial data provide crucial information on the identification of optimal waste collection points based on settlement patterns and the availability of roads.

Table 1: Data used and their sources

Type	**Data Source**
Road Network and Settlement	Ministry of Infrastructure and Transport (MoIT)
Thromde Shapefile	Thimphu Dzongkhag Administration

3.2 Method

Firstly, optimal Garbage Accumulation Points (GAPs) were identified, and located near the buildings based on settlement density and proximity. The components of network analysis; Service area and origin-destination (OD) matrix was used to validate the Gaps locations. Subsequently, optimal GAPs were integrated into a Python-based Vehicle Routing Problem (VRP) algorithm. This algorithm manages garbage trucks' routes from depots to collection points, and then to disposal sites after reaching capacity, optimizing both vehicle usage time and collection efficiency. Consideration of capacity constraints and time windows for each node ensures urban waste collection policies,

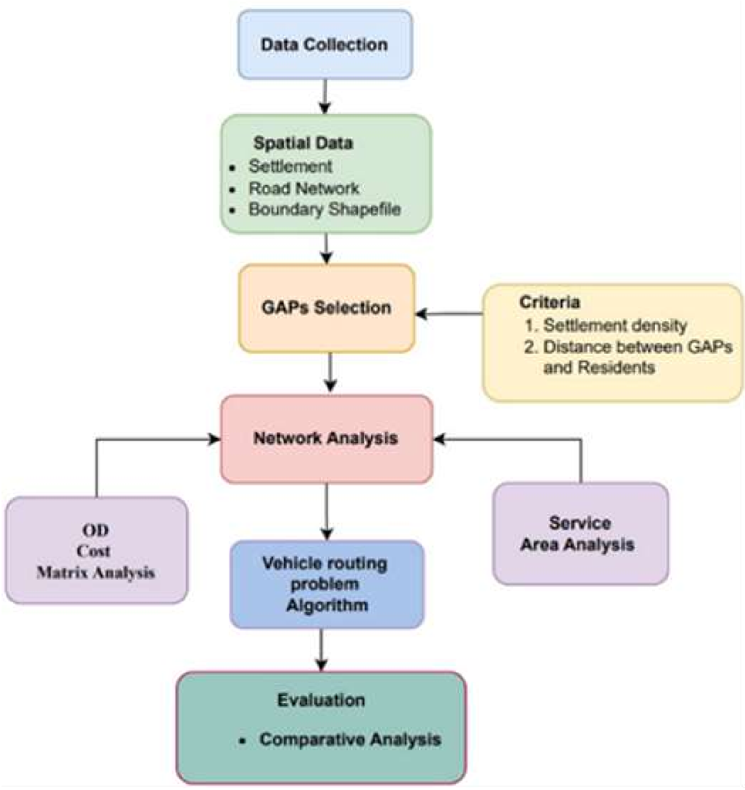

Figure 2: Methodology Flowchart

benefiting municipalities and residents alike in achieving a smarter waste management system. The general flow chart of our methodology is shown in Figure 2.

3.3 Establishment of GAPs

The process for the establishment of GAPs begins with collecting spatial and attribute data, including road networks and settlement patterns from various sources as shown in Table 1. This data is integrated and analyzed based on settlement density and the proximity of GAPs to buildings, ensuring a maximum distance of 300 m to optimize accessibility. Higher settlement densities, which correlate to increased waste generation, are prioritized for the placement of additional GAPs. Selected GAPs are mapped onto the road network for accurate representation, enabling detailed network analysis. Network analysis, including origin-destination (OD) cost matrix analysis and service area analysis, verifies the suitability of GAPs and assesses accessibility and coverage. The optimal GAP locations are then used to generate optimized waste collection routes, ensuring efficient waste management.

3.4 Vehicle Routing Algorithm

The vehicle routing algorithm developed for optimizing waste collection in Thimphu City minimizes total travel distance and time while adhering to various operational constraints. It begins with vehicles stationed at the depot and routes them to collect waste from designated GAPs. After filling, vehicles proceed to the disposal site to unload, and then potentially start new trips if time allows. The algorithm accounts for heterogeneous vehicle capacities, ensuring each demand node is serviced once under strict time windows and working hours. It utilizes a distance matrix for efficient route planning, considering factors like truck speed (40 km/hr.), service times (set at 5 minutes/GAP), and considerable break time (30 minutes). Utility functions calculate travel

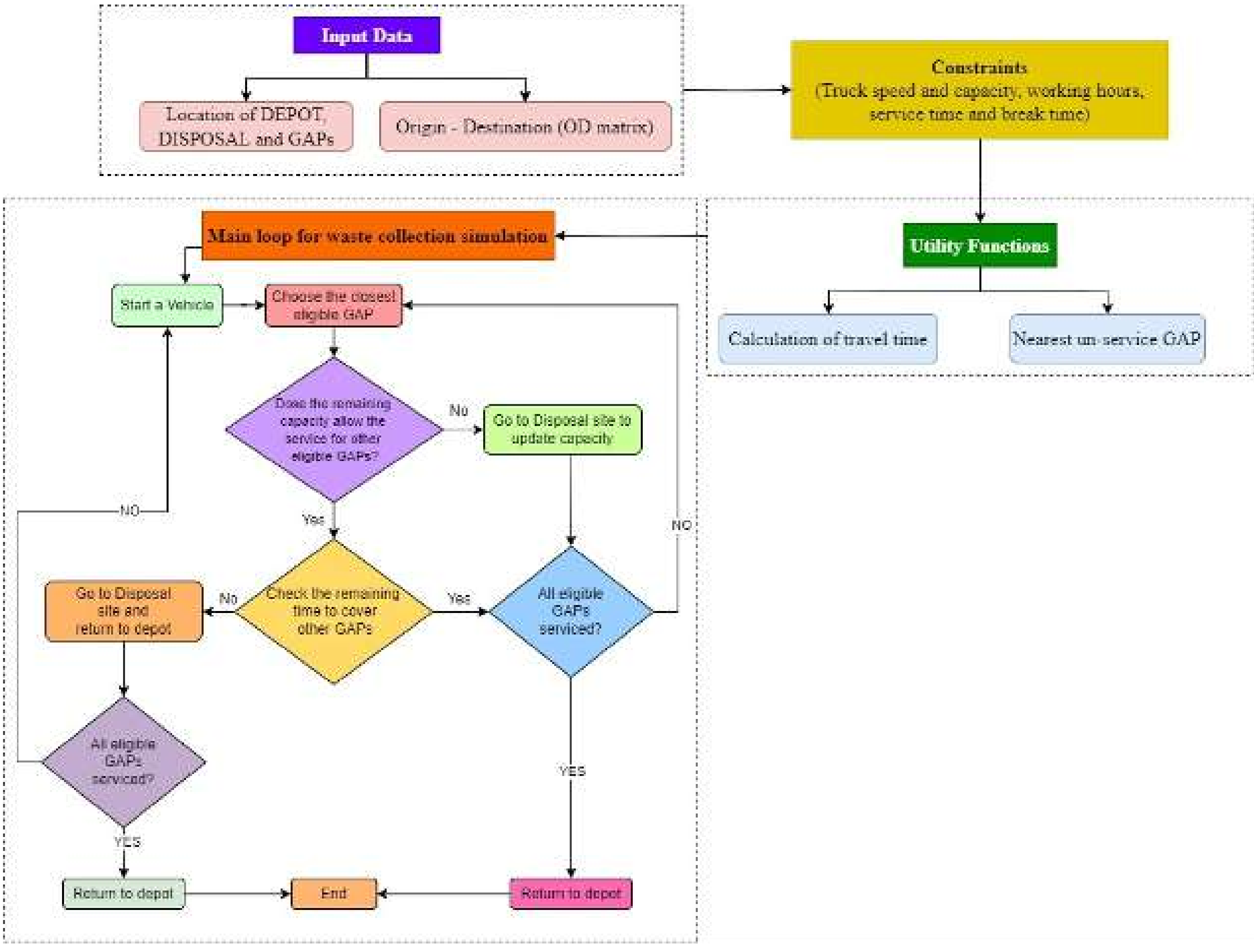

Figure 3: Flowchart for VRP

time and dynamically route vehicles to the nearest un-serviced GAP, optimizing efficiency. The algorithm's main loop simulates truck operations, managing resources and ensuring compliance with constraints, thereby enhancing waste collection logistics through strategic route planning and operational efficiency. Evaluation and comparison of VRP-generated routes across distinct zones (North-Thimphu and South-Thimphu) within Thimphu City and for the entire city reveal varying efficiencies in terms of total distance travelled, total time taken, and overall route optimization. This analysis underscores the algorithm's capability to enhance waste collection logistics by optimizing routing decisions tailored to specific urban contexts. The generation of VPR for the solid waste collection route in Thimphu City follows the methodology as shown in Figure 3.

3.5 Web Map Generation

The web-based application further enhances waste collection logistics by facilitating route optimization, resource allocation, and real-time operational monitoring, benefiting both municipal service providers and urban residents through improved efficiency and informed waste management. The interactive web-based application, developed using Folium and GeoPandas, visualizes optimized truck routes, depot and disposal sites, including arrival and departure times at each GAP.

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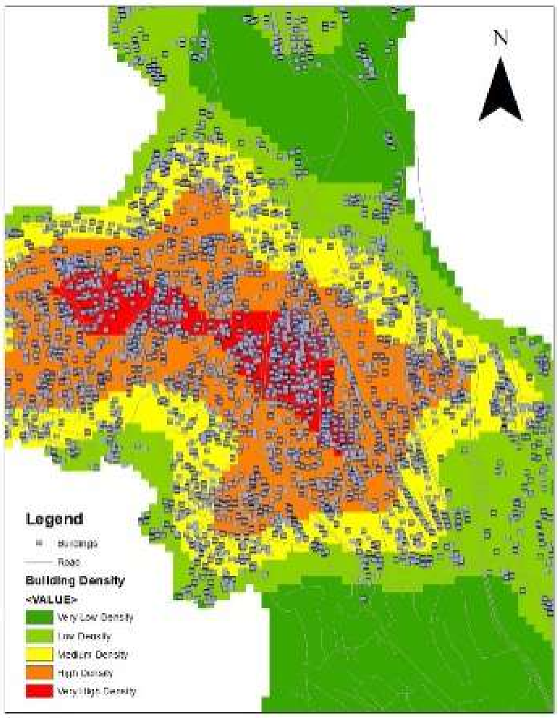
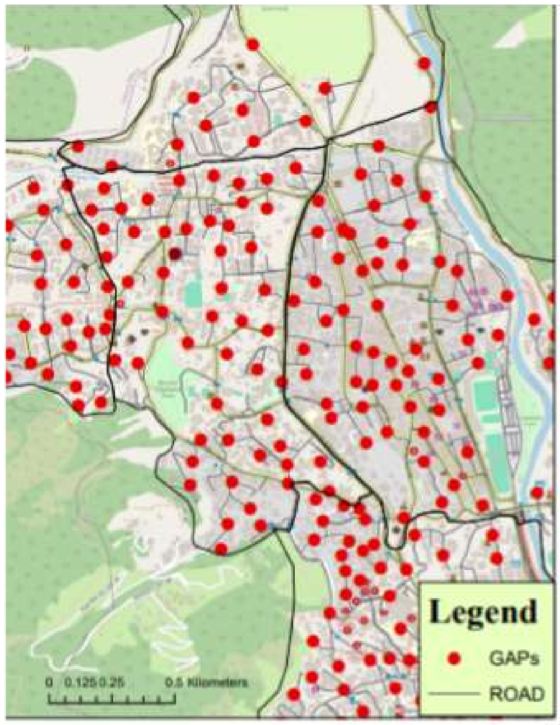
4 Result and Discussion

4.1 Establishment of GAPs

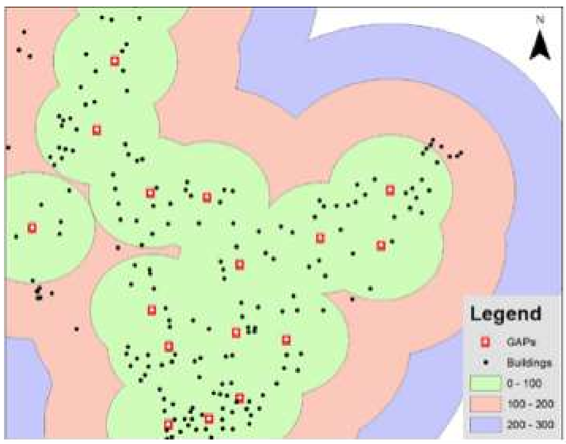
Settlement density analysis identified areas requiring more GAPs. Service area and OD matrix analyses confirmed the effectiveness of GAP placement concerning population distribution. Figure 4 (a) shows the settlement density for Thimphu city. It is classified into five categories where the darkest areas (red) represent very high density and the dark green areas represent very low density. Areas with higher settlement densities have more potential users requiring a greater number of GAPs as shown in Figure 4 (b). For this study, 796 GAPs were well distributed across the study area with 367 GAPs in North Thimphu and 429 GAPs in South Thimphu.



(a)



(b)



(c)

Figure 4: (a) Settlement density, (b) Distribution of GAPs, and (c) Number of buildings accessible within buffer zones

The Origin-Destination (OD) matrix analysis revealed the travel distances required for waste collection, ensuring that all buildings are well within the designated 300 m range. Service area analysis confirmed that most settlements fall within 100 m of a GAP, with all locations served within a 300 m radius. Buffer analysis further quantified building accessibility, highlighting that most buildings in both zones are within 100 m of a GAP (see Figure 5).

4.2 Route Optimization

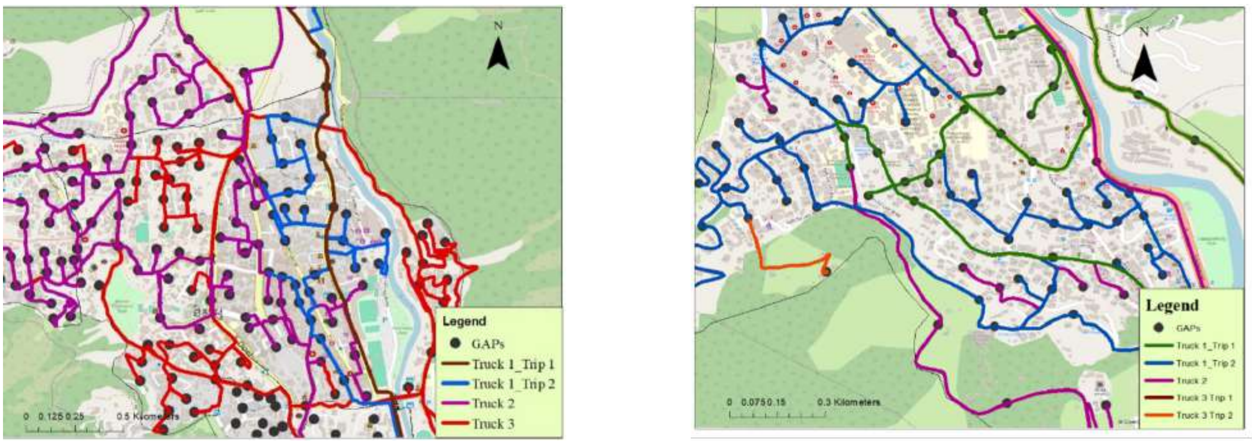
The optimization of waste collection routes is determined for North, South, and the entire Thimphu City.

4.2.1 North Thimphu

The optimized waste collection routes in north Thimphu involved deploying three trucks with different capacities. Truck 1, with a 4 mş capacity, completed two trips due to its smaller capacity, efficiently servicing the allocated GAPs within the working hours as shown in Figure 6. The first trip serviced 80 GAPs and covered a distance of 41.87 km, while the second trip serviced 63 GAPs covering over 40.64 km. While, truck 2, with 8 mş capacity, made a single trip covering 62.42 km servicing 147 GAPs. Also, truck 3 with a 4 mş capacity, serviced 76 GAPs covering 57.82 km in a single trip. This strategic deployment and routing resulted in an efficient waste collection process for North Thimphu, ensuring comprehensive coverage while minimizing travel distances and operational time.

4.2.2 South Thimphu

In South Thimphu, the optimization of waste collection routes involved deploying three trucks with different capacities to efficiently service the area as shown in Figure 7. Truck 1, with a 4 mş capacity, undertakes two trips, maximizing its collection efficiency within the extended working hours where the first trip serviced 80 GAPs and covered a distance of 23.62 km, while the second trip serviced 67 GAPs over 35.05 km. Truck 2, with an 8 mş capacity covered 62.37 km and serviced 145 GAPs in a single trip. Truck 3, also with a 4 mş capacity, similarly completed two trips; the first trip serviced 80 GAPs and covered 36.81 km, while the second trip serviced 56 GAPs over 59.09 km.



(a) (b)

Figure 5: (a) Optimized route for North Thimphu, and (b) Optimized route for South Thimphu

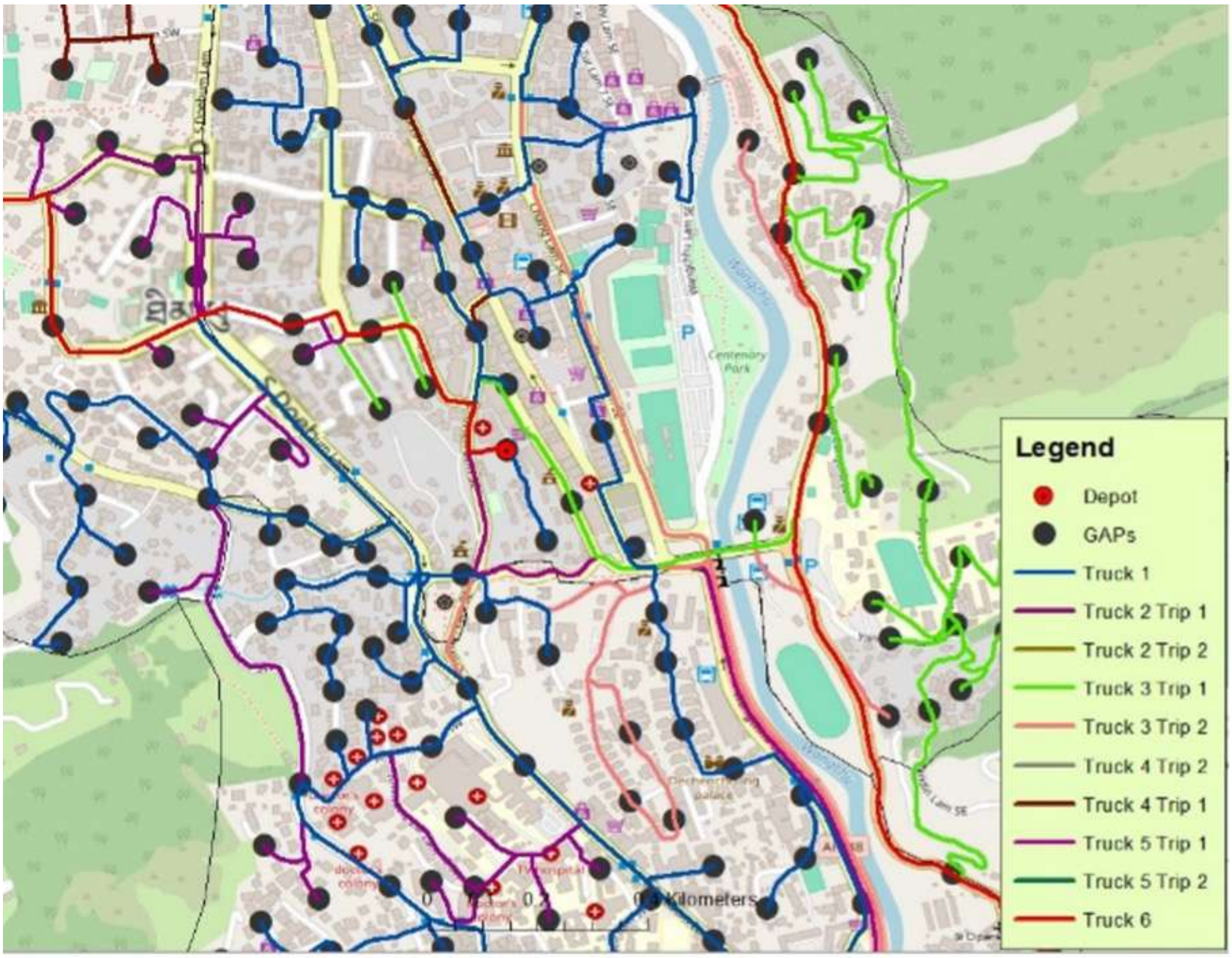


Figure 6: Optimized route for entire Thimphu

4.2.3 Entire Thimphu City

For the entire Thimphu city, encompassing 798 GAPs, six trucks with different capacities are deployed. Each truck follows an optimized route starting from the municipal office (depot) to the dumping site (disposal) at Memelakha as shown in Figure 8. Truck 1, with an 8 mş capacity, completes its route in one trip, covering 50.44 km and servicing 151 GAPs. Truck 2, a 4 mş vehicle, makes two trips, servicing 80 GAPs with a distance of 36.809 km on the first trip and 26.178 km on the second servicing 68 GAPs. Similarly, Truck 3, also with a 4mş capacity, covers 29.772 km and serviced 80 GAPs on the first trip and 55.468 km with 60 GAPs on the second. Truck 4 undertakes two trips as well, covering 44.246 km and 80 GAPs in the first and 53.058 km, and 62 GAPs in the second. Truck 5, with a 4mş capacity, travels 32.561 km servicing 80 GAPs in the first trip and 46.487 km and 62 GAPs in the second. Finally, Truck 6, another 4mş vehicle, completes its service in one trip, covering the longest single-trip distance of 73.626 km, while servicing 73 GAPs. This strategic deployment and routing ensure comprehensive and efficient waste collection across Thimphu, minimizing total distance travelled and operational time, thereby enhancing the city's waste management efficiency and sustainability.

4.2.4 Comparative Analysis

The results of the VRP algorithm for North Thimphu, South Thimphu, and the entire Thimphu City reveal critical insights into the efficiency of waste collection routes. The total distance covered and time taken for the three scenarios are discussed in Figure 9. Comparative analysis of the

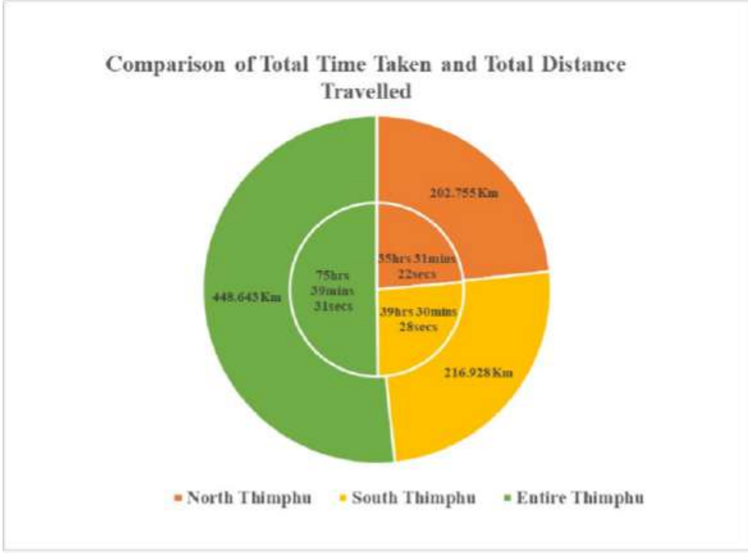


Figure 7: Comparative analysis

routes of North and South Thimphu to that of the entire city, the total travel time for North and South Thimphu was 75 hours, 1 minute, and 50 seconds, with a total distance of 419.68 km, which indicates that the travel time for the entire Thimphu City is higher by 37 minutes and 41 seconds. The analysis suggests the requirement of additional route. Additionally, the total distance traveled for the entire city exceeded the combined distance of North and South Thimphu by 28.96 km. suggesting the optimization of routes within North and South Thimphu than the route of entire city. The larger travel time and distance for the entire city underscore the need for advanced VRP solutions to manage the increased complexity and ensure efficient routing across a more extensive urban area. The results showed that managing waste collection in subdivided areas is more straightforward than integrating the entire city. The findings highlight the significance of dividing large urban area in a number of smaller zones to increase the efficiency of waste collection systems.

4.3 Web-based Waste Collection System

The web-based waste collection system was developed, so that the residents can be informed about the schedule of waste truck at each GAP. The user friendly web-based system provides flexibility to the residents of Thimphu city to dispose their waste and also reduce their waiting time for the truck by promoting transparency and efficiency in waste collection operations, the platform encourages community engagement and supports sustainable urban development initiatives. Its intuitive interface and real-time functionalities provides the potential of technology to improve municipal services in urban communities.

5 Conclusion

Efficient routing and vehicle allocation are crucial for reducing costs in urban waste collection. This study introduces a web-based VRP algorithm to optimize waste collection in Thimphu city, aiming to minimize the distance and time required to collect and transport municipal waste. The determination of optimal GAP locations and efficient routing garbage trucks, reduces overall time and distance, further reducing the overall costs and increasing the efficiency. The results indicate that waste collection in North and South Thimphu is more straightforward compared to managing

Figure 8: Interactive web map

the waste considering the entire city, which involves increased travel time and distance due to additional complexity. This demonstrates the algorithm's effectiveness in subdivided areas. Further, the optimized routes for North, South, and the entire Thimphu City, utilizing trucks with varying capacities and effective working hours highlighted the importance of advanced algorithms in improving operational efficiency. Its intuitive web-based interface and real-time functionalities provides the potential of technology to improve municipal services. The study provides the framework on improving waste management system in Thimphu, highlighting the scalability of this algorithm to other urban area with the waste management challenges.

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