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ORIGINAL RESEARCH ARTICLE

Feasibility and effects of GIS-based municipal solid waste vehicle routing for Bahrain

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ABSTRACT

In the realm of waste management, efficient route optimisation for municipal solid waste (MSW) collection is becoming increasingly crucial, particularly for developing nations with budgetary considerations. This study leverages the capabilities of the geographic information system (GIS) and integrates the Dijkstra algorithm to enhance route optimisation for MSW vehicles in Bahrain. Utilising comprehensive local vehicle routing data from Urbaser and applying GIS methodologies, three distinct areas in Bahrain were methodically analysed. The results revealed a notable 55% reduction in travel distance, a 17% decrease in time, and a yearly fuel cost saving of 6405 BHD (16,974 USD) in the optimal scenario. Given these findings, the potential applicability of this optimisation algorithm extends beyond Bahrain, suggesting significant benefits for regions with similar challenges. To further refine this approach, the integration of real-time traffic data into the routing algorithm is recommended. Other additions to the optimization process could include additional parameters such as safety.

Keywords: Bahrain; fuel cost; municipal solid waste; route optimization; travel distance; travel time

1. Introduction

Municipal solid waste (MSW) significantly impacts the environment and economy in the modern era. The upsurge in population and urbanisation in a developing world resulted in classifying MSW as an inevitable crisis due to the growth of waste streams. According to the World Bank's data in 2012, about 1.3 billion tons per year of MSW was generated globally, with approximately 2.2 billion tons per year expected by the year 2025[1]. Furthermore, in 2018, the global waste produced was 2.01 billion tons annually (54.62% increase since 2012), while the forecast for 2050 is projected to be 3.40 billion tons per year[2]. Such predictions require a global response to control the crisis and diminish the consequences.

Low-income countries deal with high MSW collection costs, which account for 80%–90% of the total MSW budget[3]. In addition, the middle-income countries' collection costs represent 50%–80% of the MSW

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budget[4]. On the other hand, high-income countries have significantly lower costs for MSW collection (10%) and most of the budget is allocated for disposal[5]. The review of the earlier-mentioned studies shows that the MSW collection and disposal budget is inversely proportional with respect to the total MSW management budget. As a result, experts worldwide are hastening to find MSW management solutions to tackle this phenomenon and assist in reducing MSW collection costs.

Vehicle route optimisation is one of the solutions applied in MSW management to find efficient and effective routes to handle the MSW collection operations and lessen the environmental consequences while addressing the economic effects[6]. Within the last couple of decades, efforts to find optimal routing solutions have been a challenge[7]. Route optimisations are algorithms based on mathematical models to reach sub-optimal/optimal routes[8]. These optimisations are of a complex nature due to the diversity of the optimisation criteria and constraints considered in them[9].

The literature review shows that this type of optimisation technique cannot be generalised. Hence, the feasibility of the optimisation technique must be established based on local conditions. This point was highly emphasised by Sulemana et al.[10] in their review article. It is worth noting that studies that deal with any Gulf Cooperation Council (GCC) member country are limited/scarce, while those for Bahrain are not found at all. Moreover, it was also found that few studies consider and compare the application of specific optimisation algorithms in a variety of areas. Lastly, many optimisation studies consider optimisation through road geometry while neglecting hauling time. These issues will be further highlighted in the literature presented in the next section.

The current study aims to fulfil the following objectives in light of the above points: Firstly, determining the feasibility of geographic information system (GIS) route optimisation for MSW vehicles in Bahrain. Secondly, to apply and compare the GIS route optimisation algorithm on three different study areas in Bahrain. Lastly, determine the impacts of GIS route optimisation on fuel and, consequently, monetary savings while considering the operational parameters of vehicle speed, road characteristics, and hauling time.

This proposition aims to contribute to and assist Bahrain in regard to MSW management as a preventive measure for future circumstances by positively influencing the economy and environment through optimised routes. The algorithm developed in this research can be applied to neighbouring countries, as they mainly operate with similar arrangements for MSW collection.

In a broader context, this research contributes to the academic discourse on MSW management and provides actionable insights for policymakers and stakeholders in the waste management sector. As the world grapples with the dual challenges of urbanisation and environmental conservation, studies like this pave the way for sustainable and efficient solutions.

The following sections of this paper are organised as follows: Section 2 consists of the literature reviewed on MSW vehicle route optimisation and optimisation applications. Section 3 provides the experiment setup and application process. Section 4 demonstrates the yielded results along with the discussion. Finally, section 5 presents the research conclusions and possible future work for this study.

2. Literature review

In many MSW collection routing cases worldwide, the collection route is selected based on driver experience, especially in developing countries. The common MSW collection systems consist of a depot, a landfill, and many collection points, such as bins. Moreover, some systems also include transfer stations[11]. The process begins with the vehicles departing from the depot to the assigned collection sites. The vehicles in this setup can be homogenous or heterogeneous, for instance, tricycles, forklifts, trucks, etc. At this stage, the routing mainly depends on the driver's experience. In addition, more developed countries utilise route optimisation tools[12]. The process proceeds in one of two scenarios. The first scenario consists of vehicles driving directly to the landfill for dumping, while the second scenario for the vehicles is to continue to the nearest transfer station. In the transfer stations, the waste is collected in large quantities to be delivered for dumping in the landfill by specially equipped vehicles. The collection system in both scenarios operates within time limits, referred to as shifts[13]. Depending on the size of the vehicle fleet and daily waste quantities, the process may require additional trips to fulfil the daily waste collection quota[14].

Recently, many route optimisation methods have been developed and applied. Multiple papers published in the past utilised the geographic information system (GIS)-based vehicle routing algorithm to investigate and produce optimal routing solutions for respective regions[15,16]. Louati et al.[13] proposed using an improved GIS Dijkstra algorithm to discover optimal solutions for routes in Sfax City (Tunisia) based on the total travelling distances and vehicle operational time. The summary of the reviewed route optimisation literature is listed in **Table 1**. Sanjeevi and Shahabudeen[17] tested the applications of ArcGIS to find the optimal routes that would introduce cost-reduction opportunities in parts of Chennai, India. A few researchers[18, 19] attempted to infuse GIS with other algorithms and models, such as evolutionary algorithms, equation-based models, and agent-based models, to find optimised routing solutions. However, limited research on the subject is available in which such systems' full potential is realised. This is mainly due to the complexity of the infusion process and the wide variety of algorithms and models available. Thus, recent studies have shown a greater inclination towards using GIS as a standalone or hybrid system[13].

Table 1. Reviewed literature on MSW vehicle route optimization.

Author	Country	Optimisation technique
Mai CV et al.[20]	Vietnam	GIS
Vishnuvardhan K and Elangovan K[21]	India	GIS
Blazquez C and Paredes-Belmar G[22]	Chile	Mixed-integer linear programming (MILP) and large neighbourhood search
Bányai T et al.[23]	Hungary	Binary bat algorithm
Louati A et al.[13]	Tunisia	GIS
Dao-Tuan A et al.[8]	Vietnam	1) Integer linear programming (ILP) 2) Mixed-integer linear programming (MILP)
Kamal MA and Youlla D[14]	Indonesia	Branch and bound integer programming
Nesmachnow S et al.[24]	Uruguay	Non-dominated Sorting Genetic Algorithm II (NSGA-II) and Strength Pareto Evolutionary Algorithm 2 (SPEA-2)
Akhtar M et al.[25]	Malaysia	Backtracking search algorithm (BSA)
Assaf R and Saleh Y[26]	Palestine	Genetic algorithm (GA)
Nguyen-Trong K et al.[27]	Vietnam	GIS, equation based model, and agent-based model
Son LH and Louati A[28]	Vietnam	GIS
Paul K et al.[29]	India	GIS
Xue W and Cao K[30]	Singapore	Ant colony optimisation (ACO) and GIS
Son LH[31]	Vietnam	Chaotic particle and GIS
Malakahmad A et al.[32]	Malaysia	GIS
O'Connor DL[33]	USA	GIS
Makan A et al.[34]	Morocco	Custom software "container collector" utilising Tabu search algorithm
Chalkias C and Lasaridi K[35]	Greece	GIS
Apaydin O and Gonullu MT[36]	Turkey	Route view Pro™ software and GIS
Karadimas NV et al.[37]	Greece	GIS
Agha SR[38]	Palestine	Mixed-integer programming model (MIP)

2.1. Findings from literature

Based on the previous literature review, several findings were realised. Almost 42% of the reviewed literature utilised GIS functions for MSW route optimisation. GIS seems to be a popular choice for researchers in route optimisation studies, and most applications yielded positive cost and time savings results. Furthermore, the majority of literature selected the total travelling distance as a criterion for route optimisation. The observed findings show that most available optimisation solutions are based on the local orientation of the solution.

Moreover, modifications are necessary when the same optimisation algorithm is used in different regions due to significant differences in the contributing factors. Furthermore, most of the literature does not conclusively point to the superiority of a specific method over others. Moreover, it also means that the optimisation process has to be started all over again whenever any condition changes or targets a different region. These gaps justify the need for the current research since no such effort is found in the context of GCC (Cooperation Council for the Arab States of the Gulf) countries.

2.2. Geographic information systems (GIS)

GIS is a tool capable of storing, retrieving, managing, and analysing extensive data. This platform is unique due to its ability to utilise both spatial (georeferenced) and non-spatial (attribute) data[39]. Moreover, GIS can produce a visualised output of the data. Additionally, it is available as open-source (e.g., QGIS) as well as commercial software (such as ArcGIS). However, using GIS as a standalone or with other algorithms depends on the optimisation criteria and data availability constraints. The core of the GIS optimisation algorithm is known as the Dijkstra algorithm, which was developed in 1959[40]. However, the current algorithm utilised by the GIS is a modified version of the Dijkstra algorithm to accommodate real-world transportation data. The optimisation process by GIS is based on the shortest/low-cost distance or time impedances[17].

Using the Dijkstra algorithm, the GIS's network analyzer separates each road in a network dataset into lines. These lines signify the network's traversable and non-traversable parts. Additionally, the algorithm generates points known as nodes or junctions at each intersection, as well as the line's start and end points. Initially, the algorithm scans and calculates the costs associated with each line until it reaches the targeted destination from the starting point. These costs are values that depend on the chosen criterion. Commonly, the GIS uses the travel distance (cumulative line length) or time (cumulative traverse time) criterion. Once the initial costs of the network have been calculated, the system re-evaluates and confirms the potential routes until it yields the optimal route (the path with the least costs) as per the selected criterion[17].

3. Study area

Bahrain, a member of the GCC, is an archipelago that consists of a minimum of 33 small islands in the Arabian Gulf. This high-income country is located in zone 39N (Northern Hemisphere) UTM. It features an area of approximately 780.03 km^2 with flat topography, with the highest elevation point of 135 m (Jabal ad Dukhan) above sea level[41]. The population of Bahrain in 2020 was approximately 1.7 million, according to United Nations (UN) data. The current MSW generation in the country is approximately 951,943 tonnes annually at a rate of 1.83 kg/capita/day[2]. The only landfill available in Bahrain is Asker, located approximately 25 km from Manama (the capital city). The daily capacity of the landfill is about 200,000 m^3/day[42]. The main MSW collection service providers are Urbaser (operating in north and south governorates) and Gulf City Cleaning Company (GCCC), which handles Muharraq and Manama governorates.

In Bahrain, the collection services have been delegated to private companies. Daily operations are practiced throughout the year. The collection process is engaged during early morning periods for some companies. There are approximately 200 vehicles in the operating fleet per governorate, with 63 vehicles concerned with collection activities. The waste is directly transported to the landfill, as there are no existing transfer stations. The waste disposal fees per load in Bahrain are relatively low compared to other neighbouring countries[43].

The operational management of one of the waste collection companies in Bahrain, Urbaser, was interviewed for more insight into the current MSW collection and management operations. This Spanish-based company has approximately 6800 MSW bins in its operating regions. The bins are equipped with a radio frequency identification (RFID) tag that stores the latest data recorded, such as location, weight, etc. Iveco primarily manufactures MSW collection trucks in capacities of 8 tonnes, 15 tonnes, 24 tonnes, and 26 The vehicles utilise GPS and RFID systems to produce monitoring data, which is stored in the company's database. The data is monitored and controlled by a custom-made system for Urbaser, known as Smart Tools. These data assist the company's operations in updating and optimising vehicle routes. Additionally, the system tracks the position of all vehicles in real-time while displaying the average fuel consumption and current quantity. The vehicles start their operation after midnight and continue until the afternoon, in a session of ten to twelve hours daily. They start and end at the depot located near the MSW landfill in Asker.

4. Route optimisation methodology

The local vehicle routing data was obtained from Urbaser during the interviews with the local operational management. The company was provided insight into the proposition of this research. As a result, they suggested three different regions with distinct characteristics for testing, which the authors accepted. A preview of the custom-made system (Urbaser Smart Tools) was demonstrated, enabling possible data identification for route optimisation and obtaining exportable data for research applications. Most of these datasets (**Table 2**) belong to the company. However, additional data can be obtained from the respective ministries or internet-based platforms, such as maps, population data, vehicle accident locations, traffic data, etc.

Table 2. Local Bahrain available data from Urbaser.

Data	Availability	Data	Availability
1) Digital map	YES	12) MSW bin smart sensors	YES
2) Bin locations	YES	13) Digital terrain model (DTM)	NO
3) Bin capacities	YES	14) MSW vehicle GPS tracker	YES
4) MSW collection vehicle capacity	YES	15) MSW vehicle smart sensors	YES
5) Facilities location	YES	16) MSW vehicle specification	YES
6) Map zoning (districts, wards, blocks, etc.)	YES	17) Traffic signals & stop signs location	NO
7) Spatial population data (number, density, distribution)	YES	18) Accident data (black spots)	NO
8) Road attributes (name, width, lane, etc.)	YES	19) Number of MSW collection vehicles	YES
9) Vehicle or road speed	YES	20) Traffic volumes	NO
10) Road level or elevation at the intersections	YES	21) Daily waste generated quantity	YES
11) One-way roads	YES	-	-

The three selected regions for testing purposes, illustrated in **Figure 1**, were considered individual cases. Most of these regions, referred to as cases (I), (II), and (III) henceforth, are located between the northern and central governments. Each case includes a region of operation that consists of partial areas of two towns (or cities). Case (I) is for a designated road network between the regions of Hawarat Aali (26.1597° N, 50.5182° E) and Salmabad (26.1856° N, 50.5267° E). The nature of the road network is more complicated regarding junctions and road sizes than in the other cases. The household MSW produced in the region is primarily from apartment buildings. The residing population is of mixed-income categories. The vehicle route optimisation for this case consists of 124 MSW bins, from which collection is to be made. According to the current route plan provided, the vehicle starts at the depot, collects the designated bins, and ends at the depot without passing by the landfill site. The average distance travelled by the MSW vehicle is approximately 58 km. In addition, the total travel time during the collection operation is around seven hours, which does not consider the additional break time.

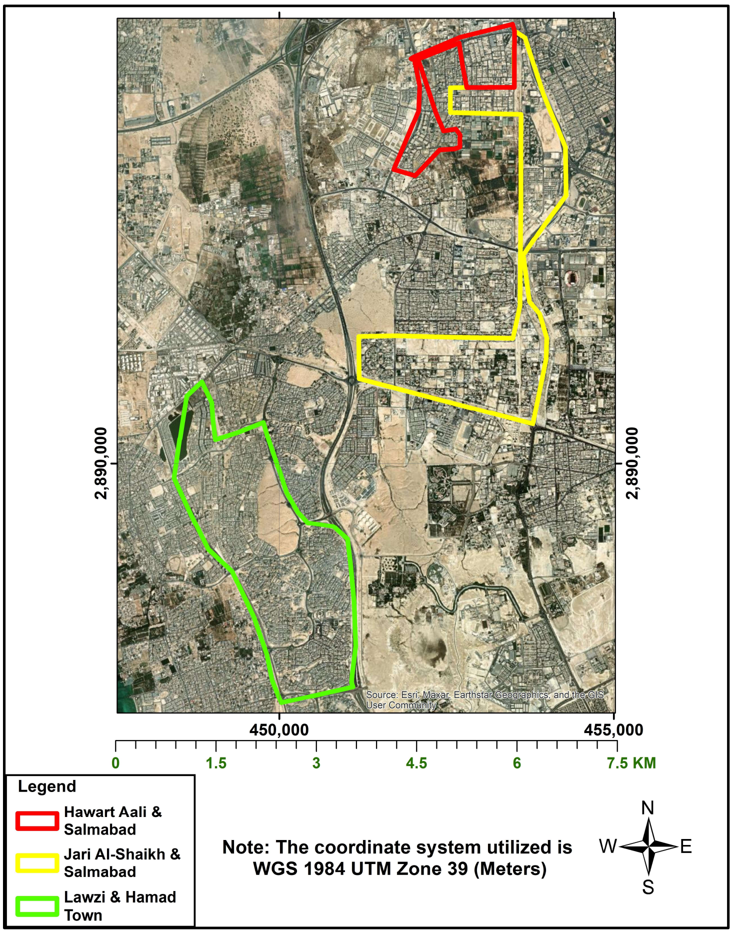

Figure 1. Location of Bahrain and the three selected regions.

Case (II) is an MSW collection route between Jari Al-Shaikh (26.1390° N, 50.5278° E) and Salmabad (26.1856° N, 50.5267° E). The road network is more straightforward than in case (I). This region is identified locally as a residential area for high-income members of the population. A high percentage of this residential area consists of individual housing units (villas). There are 157 MSW bins, which are partially distributed in different segments of Salmabad and mainly located closer to and in Jari Al-Shaikh. The current MSW collection route begins and ends at the depot. Once the vehicle reaches its waste capacity, it travels to the landfill site to empty the waste load. In this particular case, the vehicle often requires two trips to the landfill site per day of collection operation. The first trip usually starts with Salmabad MSW bin collection, while the second trip passes through Jari Al-Shaikh and ends when the vehicle collects the remaining waste quantities. The vehicle travels a total distance of 122.12 km, including the second landfill site trip, for approximately eleven hours, exclusive of the established break time.

Finally, case (III) consists of the MSW collection route situated between Al Lawzi (26.1239° N, 50.4851° E) and Hamad Town (26.1166° N, 50.5028° E). This region consists of a high-income population majority and individual housing units (villas). Similar to case (II), the road network is mostly uniform. In addition, the road network was built most recently compared to the previous cases (I) and (II). Most of the 166 MSW bins in this region are located in Al Lawzi, while a few are situated in Hamad Town. This case has the highest total travelling distance and time at 159.92 km and 12 h 11 min (excluding break time), respectively. The current MSW collection route often requires the MSW vehicle to perform two landfill trips, similar to case (II).

For the selected cases, the total travelling distance and time were selected as the most important criteria for route optimisation based on the interview with the MSW collection service provider. The data available in **Table 2** was utilised for MSW vehicle route optimisation. The GIS method was proposed to be used in this research for the following reasons: It can manage and modify road networks and create, store, manage, and edit a variety of transportation data. It also allows the use of geodatabases to store transportation data and set up the road network optimizer. It has a relatively simple route optimisation analyzer setup and processing. It has the capability to optimise vehicle routes based on distance and time impedances and also contains strong visual capabilities.

For the scope of this research, ArcGIS 10.5 and the embedded Network Analyst Tool were utilised for the route optimisation of MSW collection vehicles in Bahrain.

All collected data was configured in an acceptable GIS format to optimise the MSW collection vehicle route for the three cases in Bahrain. This research only considered static scheduling for the optimisation as the available resources were limited and not suited to perform an optimisation in a dynamically scheduled vehicle routing system. Dynamic scheduling would require continuous collection and monitoring of data from bins and collection vehicles, which the collection company did not do at the time of this study. Most of the necessary data collected for the research application was exportable, for instance, bin and facility locations. The data was obtained in December 2019. However, the data received from the company was registered in their database during the period of March to May 2019. On the other hand, the local map of Bahrain could not be obtained through their system as they use the online platform TomTom maps (TomTom International).

Bahrain's road map (GIS format) was initially found and obtained from an online source between December 2019 and January 2020 (https://download.geofabrik.de/asia/gcc-states.html). However, the map obtained for the GCC states requires extracting Bahrain's road map using ArcGIS software. Furthermore, the roads on the digital map were not complete. Using the software's editing tool, the necessary streets were drawn using polyline shapes, ensuring the joint connections were joined and accurate. This process is crucial to ensuring proper production of the road network dataset that the vehicle routing solver uses. The new roads were based on the World Imagery found in ArcGIS's database. Hence, they required configuring the alignment between the road data layer and the base map due to differences in the coordinate systems.

Additionally, unnecessary attributes were removed for organisation and computing optimisation purposes. Using ArcGIS's tools, a road network dataset for Bahrain was established. This dataset is the foundation of the route optimisation, as each road connection yielded a junction point and road edges were created based on each road segment. The road junctions were based on any connected vertex rather than endpoints due to the nature of the available road network and the newly added roads. This helps the vehicle route solver identify travel costs to reach each junction from the starting point, in addition to allowing the vehicle to traverse both ways. All roads were considered two-way.

The location data for the MSW bins was received in an Excel file format that dated back to March–May 2019. The file included information on the available MSW bins, such as coordinates (WGS 1984), manufacturer, activity status, region and block number, etc. The exported bin data was based on a national block system in which a town or city is clustered into several blocks. Each bin data file represents the bins in a designated block. Each optimisation case's relevant bin data files were grouped into a larger GIS-importable Excel file (comma-separated values, CSV). The larger GIS files were imported individually into ArcGIS and saved as a shapefile (SHP) based on the WGS 1984 coordinate system in decimal degrees. The coordinate system for the bin location shapefiles was projected to WGS 1984 UTM zone 39N, similar to the road network coordinate system.

The locations of the facilities (depot and landfill sites) were identified by utilising the current MSW collection vehicle route for each case. The current route was received as a screenshot image illustrating the roads traversed and important locations such as the depot. The coordinates of the depot and landfill were obtained from Google Earth software (WGS 1984 coordinate system) based on the identification of the current route. Similar to the bin locations, the facilities' location was configured to meet the eligible GIS format and chosen coordinate system (i.e., WGS 1984 UTM zone 39N). The locations were stored in three separate shapefiles.

The current MSW collection vehicle route images were used to filter the necessary bins from the main bin location files created earlier. This step is required because the existing vehicle routes for the selected cases do not cover the entire block but partial segments of multiple blocks. The company's system cannot export the exact locations of the bins collected by a specific vehicle or a particular collection route. For the bin filtering process and route comparison purposes, the current routes from the images were drawn in individual GIS layers, utilising ArcGIS's editing tool for each case. The filtering process produced three files with the correct bin configuration based on the three available cases.

For the scope of this research, several practical assumptions were considered for the route optimisation application. They are listed as follows:

The MSW vehicle has enough fuel for the full length of the trip without the need for refuelling. Each case utilises one 24-tonne-capacity MSW compactor. The capacity of the MSW collected is less than or equal to the capacity of the vehicle. The vehicle travels at a constant speed of 40 km/h on all roads. Each bin weighs an average of 110 kg based on the net weights of the waste hauled for March 2019 from the company's landfill reports. Each bin is only visited once per day during the collection operation. Traffic congestion, stops, and idle times are not considered. The hauling time of each MSW bin is set at an average of 3 min.

Based on the company's data, the selected speed of 40 km/h is the average speed for heavy vehicles on city roads. The hauling time per MSW bin was found by backtracking the total travelled time with respect to the current total distances travelled, constant speed (at 30 km/h, 40 km/h, 50 km/h, and 70 km/h), and number of bins per case, and validated with visual observations.

All the data files were organised into a geodatabase to begin the vehicle route optimisation. The Network Analyst Extension in ArcGIS was used to initiate a new route for the optimisations. The new optimised route was based on the shortest distance impedance. The analyzer was allowed to change the order of the MSW bins to suit the optimisation criteria. However, the start and endpoints were preserved. Additionally, U-turns were allowed at intersections and dead ends. The directions output feature was also enabled to verify the correct travel order and view the total travel distance and time. The files were loaded into the route analyzer in the following order: depot start location, MSW bins location, landfill site (if used by the current route), and depot end location.

This process was carried out three times (one for each case). The experiment was repeated multiple times to ensure the consistency of the results. The results produced for each case are presented in the next section, along with a discussion of the observations.

From the prepared geospatially corrected Bahrain road map, ArcGIS's Network Analyst Extension uses the Dijkstra algorithm to separate each road in the network dataset into lines that are defined by the start, intersection, and endpoints (nodes). Each line is given a proprietary identification (ID) by the analyzer, which the algorithm needs to compute the individual line cost/weight. The system-produced lines signify network traversability and direction as well. The Dijkstra algorithm embedded within the analyzer mainly computes two criteria: distance and time, which are experimented with in this paper[37]. The distance criterion is the summation of the individual line length (mainly in kilometres), specifically from node to node. On the other hand, the Time criterion is considered to be the total travelled time, which is the combination of collection vehicle runtime (cumulative) and average hauling time (cumulative). The collective vehicle runtime is calculated based on the cumulative traversed length of roads and the vehicle's average speed. Moreover, the cumulative hauling time is determined by the selected three minutes per bin and the number of bins in the selected simulation.

Using the uploaded item database, the path costs required for the route optimisation are initially computed by the analyzer. The analyzer identifies each road cost (in terms of distance or time, depending on the selected criterion) between each node in all road network datasets and yields initial results. The system automatically records the road costs/weightage and identifies the roads with the lowest costs between the required locations. As per the Dijkstra algorithm, the connection of lines (roads) with the least cumulative costs is the optimal solution[13]. This utilised method only allows for one criterion to be computed at a time, for which the authors repeated the experimentation for all proposed cases to cover both total travelled distances and time, respectively. The results from each analysis run (per case and criterion) are recorded and compared to the benchmark records received from the local MSW collection service provider.

5. MSW vehicle route optimization results

Three MSW vehicle routing cases were tested in this research. Most of Bahrain's data was obtained from Urbaser operational management and benchmark statistics for the actual routes. The first case (I) contains 124 MSW bins in the Hawarat Aali and Salmabad regions. The second case (II) of the Jari Al-Shaikh and Salmabad regions includes 157 MSW bins with multiple trips to the local landfill. Finally, the third case (III) has multiple landfill trips and 166 MSW bins for the Al-Lawzi and Hamad Town regions. Each case has a unique setup regarding the road network, population income class, bin distribution, MSW generation, travel distance, and time. All the previous cases utilised one collection vehicle per case. The network analyst tool in ArcGIS 10.5 was used for database preparations as well as the MSW vehicle route optimisation setup. The authors optimised a fourth-generation Intel I7 (4700MQ) Alienware 14 laptop with 16 GB of DDR3 RAM. Each case required approximately a few minutes for the solver to yield routing results. The contents of **Table 3** list the optimised results for all three tested cases.

Table 3. Results for MSW collection routes for all cases.

	Case (I): Hawart Aali & Salmabad		**Case (II): Jari Al-Shaikh & Salmabad**		**Case (III): Lawzi & Hamad Town**	
Total distance travelled	Current route	New proposed route	Current route	New proposed route	Current route	New proposed route
	57.97 km	45.7 km	122.12 km	70.9 km	159.92 km	73.3 km
Total travelling time	6 h 51 min	7 h 21 min	10 h 59 min	9 h 38 min	12 h 11 min	10 h 08 min

Using the GIS method for route optimisation, a 21.17% reduction was achieved in total distances travelled by the MSW vehicles in case (I). This reduction (approximately 12.3 km) resulted from using the local side roads instead of the highway path and minor path tweaks within the local neighbourhood road network. However, it was observed that the total time travelled has increased by 7.2%. The results remained constant after multiple attempts. An investigation was carried out to discover the reasons for the yielded results, for which multiple explanations were found. The most obvious explanation is that the number of MSW bins provided in this case is greater than the actual bins found in the vehicle path of case (I). This was due to the fact that, on the specific collection day path received, many bins were empty/near empty. Thus, the driver did not collect those bins, which would significantly affect the total travel time with respect to the bins collected. Considering an ideal scenario of three minutes for manual collection per bin (moving, loading, and unloading), it would take approximately six hours and twelve minutes. In addition, the remaining time for the vehicle to travel the 57.97 km would be 39 min. It would not be possible for the vehicle to cover the total distance at a constant speed of 40 km/h with no stops or traffic congestion. **Figure 2** illustrates the newly proposed optimised route for case (I) compared to the currently utilised routes.

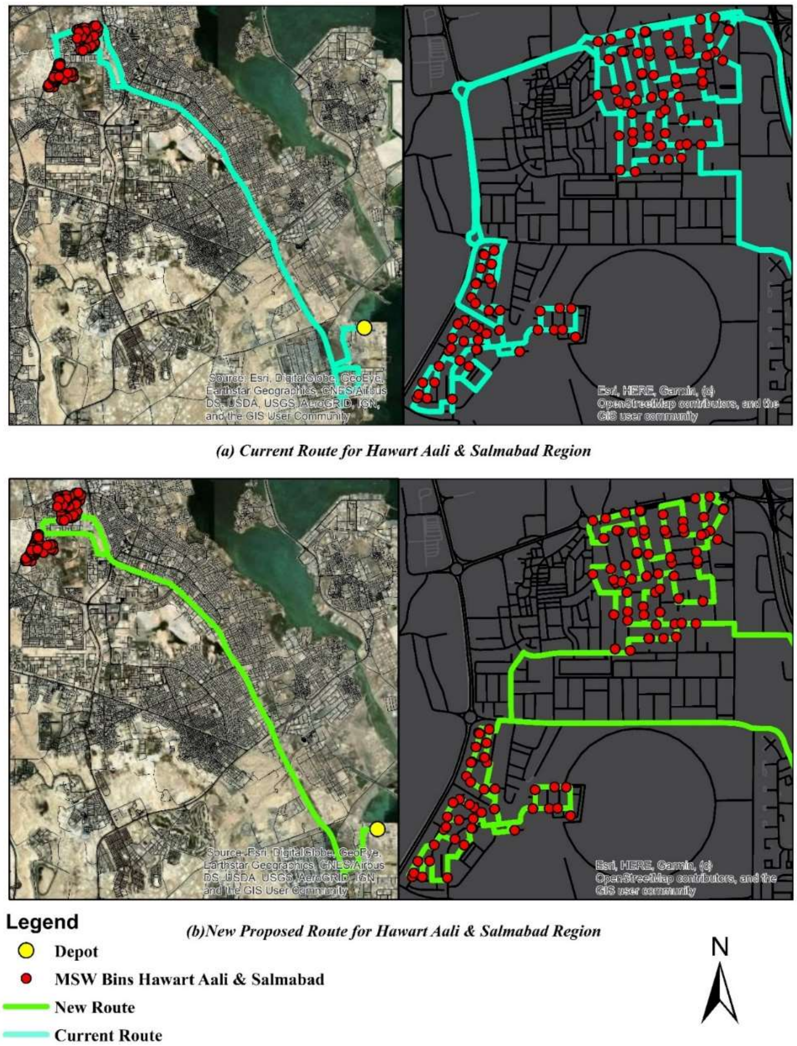

Figure 2. Hawart Aali & Salmabad optimised MSW vehicle route.

Jari Al-Shaikh and Salmabad region, case (II), yielded significant improvements in minimising the travelled distances, approximately 51.22 km. Furthermore, the total travel time on the new proposed route for case (II) is reduced by about one hour and 21 min. The optimisations in case (III) yielded the highest travelling distance and time reductions compared to the other cases. For case (III), the distance travelled by the MSW vehicles was minimised by approximately 87 km, while the total duration was decreased by two hours and three minutes. In addition, the new proposed routes for cases (II) and (III) are displayed in **Figures 3** and **4**, respectively.

By utilising the GIS method, significant gains have been recorded for all tested cases, especially regarding the distance criterion. One of the contributions to the high percentage reductions in cases (II) and (III) is the elimination of the second landfill site trip travelled by the MSW vehicles. Considering the number of MSW bins, the average weight per bin, and the vehicle capacity, no MSW vehicles have reached the full loading capacity in both cases. In cases (II) and (III), there are 17,270 kg and 18,260 kg of overall MSW, respectively, which is less than the 24,000 kg vehicle's capacity. This eliminates about 25 km in travelled distances for both cases. However, this optimisation only considered the MSW weight. At the same time, the volume of waste (cardboard, styrofoam, plastics, and glass products) would affect the vehicle's space capacity, possibly leading to a second landfill trip. In case (III), the vehicle was observed to travel additional roads within the current route with no MSW bins nearby. The optimisation eliminated those roads, further reducing total travel distances.

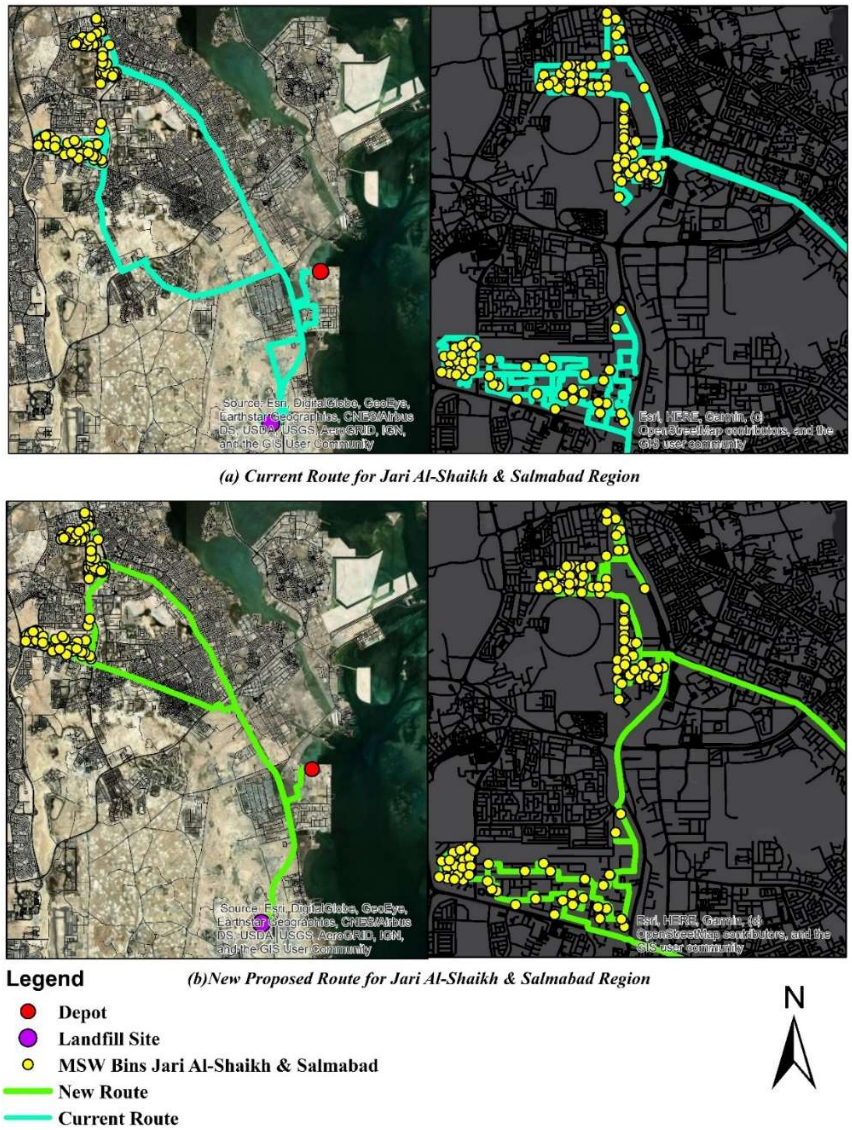

Figure 3. Jari Al-Shaikh & Salmabad optimised MSW vehicle route.

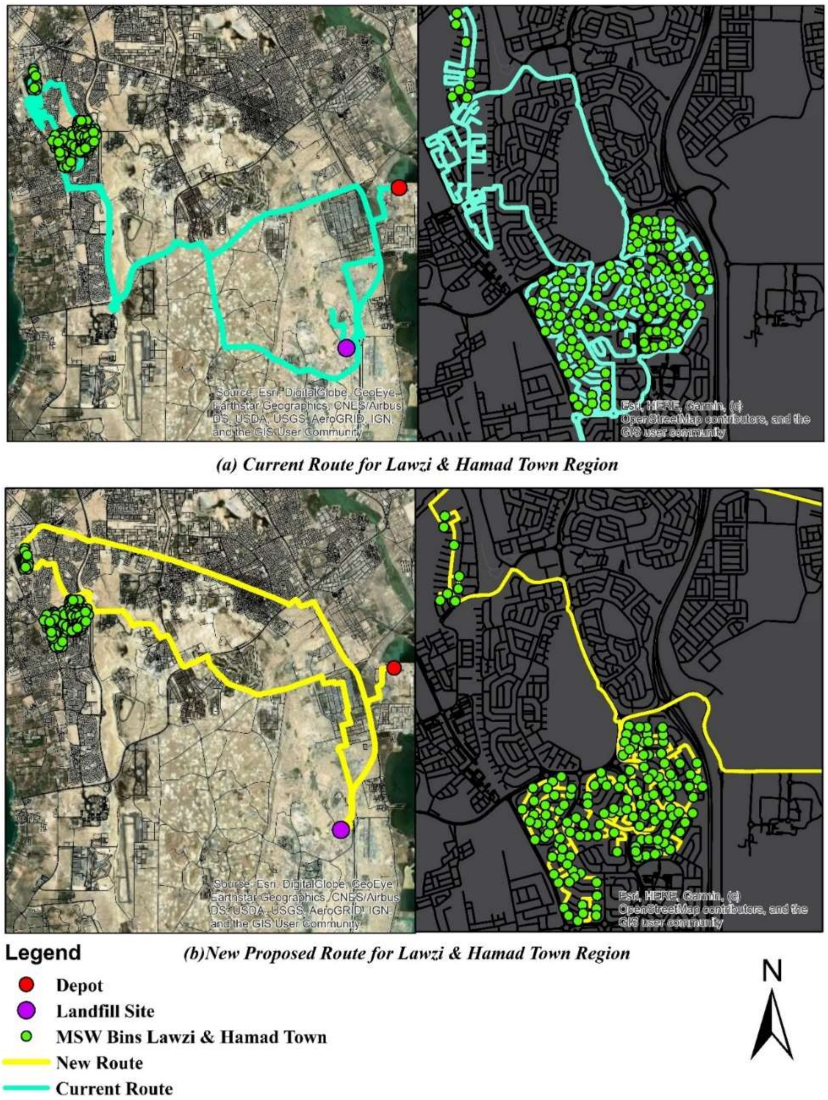

Figure 4. Lawzi & Hamad Town optimised MSW vehicle route.

Nevertheless, the company seems to have a near-optimal current route for case (I), as the difference in travel distance is only 12 km. Additionally, the proposed optimisation recommended a route that utilises local side roads to travel between the main area and the main/highway roads traversed by the collection vehicle. On a positive note, the overall results for distance reductions indicate a potential margin of improvement for further optimisation of the current routing practices. Furthermore, the achieved results offer significant cost savings for vehicle fuel consumption. Based on the data received from the MSW collection service provider, the average MSW vehicle consumes approximately 74 litres for every 100 km. When this research was composed (from September 2019 to April 2020), the diesel price in Bahrain was 0.16 BHD per litre (0.424 USD). For cases (I) to (III), the fuel cost savings introduced are 525 BHD (1391 USD), 2186 BHD (5792 USD), and 3695 BHD (9792 USD) per year, respectively, due to the route optimisation. There have not been any changes in these prices since the date these lines were written. In addition, these cost savings are only for three collection vehicles (one for each case) out of hundreds in the MSW collection vehicle fleet. This is calculated by calculating the difference between the distances travelled per case and the new proposed route cumulative distance with the fuel consumption rate and local prices of fuel.

The proposed GIS technique utilising the embedded Network Analyst Tool is far from perfect to be able to yield exact solutions. This research aims to test the feasibility of implementing a selected route optimisation method to unveil opportunities of interest such as potential gains (positive reductions) and savings applicable to Bahrain and similar case regions. It was observed that near-optimal solutions can be obtained, although the technique seems to be biassed towards distances and time impendence. Moreover, optimisations of static routing are built on assumptions and criteria that roads are obstacle-free and the bin locations are fixed. In real cases, roads have traffic congestion, accidents, traffic signs/signals, construction works, and pavement-related issues that may introduce detours, lower travel speeds, or waste travel time, ultimately affecting optimisation results. Furthermore, changes in bin locations (for instance, unloading the bin on the opposite side of the road) affect the traverse direction, paths used, number of stops, and hauling time by the vehicle to reach its target.

These limitations are caused by human errors and data, which can be rectified by dynamic data collection. This means the necessary and supplementary data are collected in real-time, which assists in running multiple route optimisation simulations to achieve near-exact solutions that are the most accurate and precise. As per the literature, exact solutions have proven difficult to find due to the wide variety of optimisation models available; thus, there is no perfect solution. For the available GIS model to incorporate the dynamic data streams, heavy coding modifications to the embedded analyst code are required, which are often quite complex and challenging. This is mainly due to the vast data types and extensions that should undergo a synchronisation and compatibility process within the optimisation modelling to be mathematically processed to produce favourable results.

6. Conclusion and recommendation

This research aimed to develop GIS-based route optimisation for MSW collection in Bahrain. Three different cases with unique characteristics were tested using the GIS optimisation technique. Most of the local data was obtained from one of the local MSW collection service providers, namely Urbaser. The decision to use the GIS technique was based on its popularity and effectiveness, which are evident in the reviewed literature. The technique was used to optimise the vehicle collection routes based on total travelled distances and time impedances. This recommended method achieved notable reductions in travel distances up to approximately 55%. In addition, the total travel time was minimised by 17% for the best-case scenario. Furthermore, the suggested method was able to produce a cumulative fuel cost savings of 6405 BHD (equivalent to 16,974 USD) per year for three MSW vehicles from the vast MSW collection fleet.

Based upon the results of this study, the feasibility of the GIS routing algorithm proved to be an efficient technique for the optimisation of MSW vehicle routes for road conditions and available data in Bahrain. The algorithm was equally effective in a variety of areas in Bahrain. Incorporating road conditions and realistic hauling times makes the results more appealing to the authorities and policymakers. Hence, it is recommended that GIS routing optimisation be incorporated into the MSW collection systems in Bahrain as well as other GCC countries. Moreover, this method can prove helpful in other fields, such as logistics businesses, the education sector (school bus routing), the health sector (ambulance routing), and mass transit systems (bus routing).

The proposed route optimisation process can be enhanced in multiple aspects, such as utilising GIS integrated with other optimisation, using prediction models, and adding more constraints to the GIS optimisation model. These constraints may include traffic congestion in regions, work schedule flexibility, waste segregation implementation, etc. However, this would require adequate programming technical expertise and more detailed data collection, especially from government departments, which could not be done for this research due to administrative issues.

While the current discussion highlights the practices of MSW collection routing in developed and developing nations, it's crucial to understand the latter's underlying challenges. Developing countries often grapple with limited resources, a lack of technological infrastructure, and rapidly growing urban populations. These challenges exacerbate the complexities of waste management. By integrating GIS-based route optimisation, these nations can leverage data-driven insights to streamline their waste collection processes, ensuring efficiency even with limited resources.

Another pivotal aspect to consider in the realm of MSW collection routing is the integration of real-time data. Traffic congestion, road closures, and other unforeseen circumstances can significantly impact the efficiency of waste collection routes. The recommended real-time traffic data can dynamically adjust routes by incorporating data into the GIS-based optimisation algorithm, ensuring minimal disruptions and delays. This adaptability enhances operational efficiency and translates to tangible cost savings.

The implications of efficient MSW collection routing extend beyond mere cost savings. Some of the broader benefits include environmental conservation, reduced carbon emissions from waste collection vehicles, and improved urban sanitation. As urban centres continue to grow, sustainable and efficient waste management practices become paramount. This research, thus, serves as a beacon, guiding policymakers and stakeholders towards a sustainable urban future.

Author contributions

Conceptualization, AMRO and UG; methodology, AMRO and UG; software, AMRO; validation, MRM and MA; formal analysis, AMRO; investigation AMRO and UG; data curation, AMRO; writing—original draft preparation, AMRO and UG; writing—review and editing, UG, MRM and MA; visualization, AMRO and MA; supervision, UG. All authors have read and agreed to the published version of the manuscript.

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Conflict of interest

The authors declare no conflict of interest.

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