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Optimization of municipal solid waste collection and transportation routes, through linear programming and geographic information system: a case study from Şanlıurfa, Turkey

Onur Rızvanoğlu · Serkan Kaya · Mustafa Ulukavak · Mehmet İrfan Yeşilnacar

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Abstract Solid waste is one of the important causes of the environmental crisis that negatively impacts human health throughout the world and is fast approaching a disaster level that will pose a direct threat to human life. As with all other environmental problems, the increase in solid waste production that goes hand in hand with growing population and rising consumption has become a focus of great concern. Along with these rising levels, the investment, management and maintenance of solid waste collection and transport vehicles is seeing a continual increase in financial outlay. It is clear from the budgets of local authority solid waste management systems, 65 to 80% of which are accounted for by domestic waste, that the collection and transport of solid waste is a high-cost process and that this expenditure can be significantly reduced by the reorganisation of solid waste collection routing schedules and the minimization of collection frequency. This study demonstrates a linear programming model in order to develop an optimal routing schedule for solid waste collection and transportation, thereby reducing costs to a minimum. The neighbourhood of Veysel Karani in the Haliliye District of Şanlıurfa Province, Turkey, was specifically selected for this case study, having the suitable socio-economic and demographic variables to be representative of a metropolitan urban area. Firstly, the data regarding the municipal solid waste collection and transport routes were obtained from the local authority. Analysis and verification of these data were then performed. With the field study, these data were verified on-site, and the missing data were completed. Linear programming and geographic information system (GIS) analysis were used to determine the best route. Consequently, it is concluded that it is possible to save the route by 28% with GIS analysis and 33% with linear programming analysis according to the existing municipal solid waste collection and transportation routes.

Keywords Municipal solid waste · Collection and transportation routes · Optimization · Linear programming model · Vehicle routing · GIS · Network analysis · Turkey

O. Rızvanoğlu · M. İ. Yeşilnacar (✉)
Engineering Faculty, Department of Environmental Engineering, Harran University, 63050 Şanlıurfa, Turkey
e-mail: mirfan@harran.edu.tr

e-mail: iyesilnacar@gmail.com

O. Rızvanoğlu
e-mail: orizvanoglu@hotmail.com

S. Kaya
Engineering Faculty, Department of Industrial Engineering, Harran University, 63050 Şanlıurfa, Turkey
e-mail: serkankaya@harran.edu.tr

M. Ulukavak
Engineering Faculty, Department of Geomatics Engineering, Harran University, 63050 Şanlıurfa, Turkey
e-mail: mulukavak@harran.edu.tr

Introduction

Today's solid waste problem does not merely compromise human health but has reached the level of being a real threat to human life. As with many environmental problems, this is only being exacerbated by growing populations and increased consumption such that it has become a major cause of global concern. One of the important issues facing the management of solid waste generally is the business of solid waste collection and transportation.

The municipal solid waste management system is one of the most important items in the budget and about 65 to 80% of the budget is spent on the collection and transportation of solid wastes. Therefore, the smallest savings on these items will result in significant financial revenues and, most importantly, dramatic reductions in exhaust emissions. In this context, two methods (geographic information system (GIS) and linear programming) are used separately and compared in this paper to analyse this saving. In the following, brief information about these methods will be given and evaluated together for the purpose of the study.

Geographic information system can be defined as 'a system of hardware, software and methods for the management, manipulation, analysis, modelling and visualisation of spatially referenced data, designed for the solution of complex planning and management problems' (Töreyen et al. 2010). Being a flexible numerical tool for the calculation of combinations of spatial variables and statistical interpretations, GIS can be considered an effective method for analysing spatial data in many areas of application, such as the identification of solid waste storage site locations, monitoring, evaluation and optimization operations (Salah Sadek et al. 2006). As well as speeding up the calculation of solutions for the modelling involved in these kinds of operations, which is a benefit of computer technology generally, this system is also of great assistance to decision-makers in carrying out analyses and evaluating different scenarios (Lunkapis et al. 2002; Nas and Berktay 2002; Sadek et al. 2001). As part of this study, the existing solid waste collection routing and scheduling for the Veysel Karani neighbourhood of Haliliye district in Şanlıurfa province was obtained and examined (Rızvanoğlu 2018). A linear programming model was then established for routing optimization with the goal of minimizing costs. The problem dealt with in the study was solved by both linear programming and also GIS and all results were compared. The basic data used was developed from the topography of the study area, main transport routes, settlement areas and contemporary land use information. The second section of this study surveys works dealing with this field of study in the literature. The third section deals with materials and methods. The fourth section covers research findings and discussion. The last section concludes with the obtained results and research recommendations.

Literature review

Published in 1736, Euler's *Seven Bridges of Konigsberg* problem is considered the beginning of Graphic Theory and modern route-finding solutions. Network analysis, route-finding and planning algorithms working on the graphic theory and basic vectors of geographic information system (GIS) are able to find solutions for known networks and grids. With the use of computers for GIS in the 1970s, it began to be used for location analysis, commonly in the form of simulations of space frames and grids. Criticism of this approach with its approximate results was first made by Goodchild (1977).

When the general literature of vehicle routing problems is examined, for the solution of a distribution problem of 48 cities, Dantzig et al. (1954) introduced a mathematical model for the first time. Dantzig and Ramser (1959) proposed an integer linear programming model to solve the problem of transporting gasoline to gas stations. Later Clarke and Wright (1964) presented a heuristic saving algorithm (Dincer and Diskaya 2018). The studies mentioned so far are given in chronological order. The literature studies given below are given in chronological order from the studies on capacity limited vehicle routing problem. For the solution of the capacity constrained vehicle routing problem, Osman (1993) simulated annealing algorithm, Toth and Vigo (2002) and Lysgaard et al. (2004) branch boundary algorithm, Ralphs et al. (2003) integer linear programming model, Chandran and Raghavan (2008) integer linear programming model, El Hassani et al. (2008) a hybrid algorithm from the combination of ant colonies and local search algorithms, Mazzeo and Loiseau (2004), Gajpal and Abad (2009), Reed et al. (2014) and Pala and Aksaraylı (2018) ant colonies algorithm, Wang and Lu (2009) genetic algorithm, Lal et al. (2009) genetic algorithm and column generation algorithm, Takes and Kosters (2010) Monte Carlo simulation and Clarke Wright algorithm, Szeto et al. (2011) artificial bee colonies algorithm, Venkatesan et al. (2011) particle flock optimization, Bozyer et al. (2014) and Kirci (2016) Tabu search algorithm, Aydemir et al. (2016) genetic algorithm, Mostafa and Eltawil (2017) mathematical model and fuzzy linear programming model and Akhand et al. (2018) presented particle swarm optimization and sweep algorithm. New methods used with developing technology add meaningful results to the solution of many problems in application areas.

Materials and method

For the purposes of this routing optimization study, Haliliye district, one of the three central districts of Şanlıurfa province, was chosen and the case study carried out in a neighbourhood known as Veysel Karani neighbourhood (37° 10′ N, 38° 48′ E–37° 09′ N, 38° 49′ E) (see Fig. 1).

According to data obtained in 2017, the population of Haliliye district was 375,112. Comprising a total of 169 neighbourhood, 32 of these are central neighbourhood with the remaining 137 being more rural. The urban neighbourhood or quarter known as Veysel Karani neighbourhood is 604,878 m^2 and has a population of 16,163. The average slope of the elevation profile of Veysel Karani neighbourhood is 1%. According to the geometric standards of highways (slope ≤ 4%), the neighbourhood's area is considered to be gently sloped (Yoldaş 2008). The Google Earth application's elevation profile for Veysel Karani neighbourhood is shown in Fig. 2.

While both geographic information system and linear programming models were used to calculate potential solutions, the current study presents a linear programming model solution to the routing optimization problem. Using vehicle routing mathematical coding for the linear programming model, the gathered data was processed with a General Algebraic Modelling System (GAMS) application and the results tabulated for comparison. The Arc Map module was used for the basic functions of GIS problem solving, namely Dijkstra algorithm and tabu search heuristic analysis to find the shortest route, with the network analyst tool of this module carrying out the actual analyses. System analyst tool can carry out a variety of different analyses including the production of network data sets in single or multiple modes, identification of optimal route using one network data set, developing a model for route analysis, transportation of a series of orders using a vehicle fleet, network analysis using traffic data and specification of most suitable sites. Esri ArcGIS 10.3 software was used for the GIS method employed in this study. The database of the network topology software for the neighbourhood of the optimization study was processed, and the road restrictions, like direction, speed limits and time taken, were identified. Once the network topology and road specifications had been completed, the coordinates of the solid waste collection vehicles were marked as points on the roads. Following this, the network analyst tool using its route function for optimal route identification was able to develop a rota for the vehicles. A combination of dijkstra and tabu search, as used by the ArcGIS 10.3 application of the GIS solution, was employed for the solution algorithms (Rızvanoğlu 2018). Dijkstra algorithm determines the shortest distance between two nodes on a network. For this algorithm, the simple selection of a starting point is required. From this point outwards, it can update the distances to reach all other nodes on the network, seemingly ad infinitum. Dijkstra algorithm assesses all the neighbouring points at each step from node to node and if it finds a shorter distance to travel it updates the distances and moves to the next nearest node. This algorithm travels over all the nodes of the whole network and finds the shortest path. The ArcGIS application uses dijkstra and tabu search heuristics to solve the vehicle routing problem. In the given example, the vehicle routing problem starts at every point between the actual stop nodes of the route for the fastest route between the stops to be ascertained by a tabu search algorithm which discovers the optimal order to visit the nodes in. Tabu search algorithm, specifies tabu moves and aims to find the best local solution in a process known as best fit strategy. Once the algorithm has identified the best local solution, this is pronounced tabu for the next step in the algorithm, thereby preventing immediate repetition of the same moves. The tabu list is also dynamic. With every new element entered into the list, the element which has been in the list longest is removed. In this way, the algorithm gains a memory.

Existing state of solid waste collection in the case study area

Haliliye Council possesses a fleet of rear-loading, 13 m^3 capacity, hydraulic compression, solid waste collection

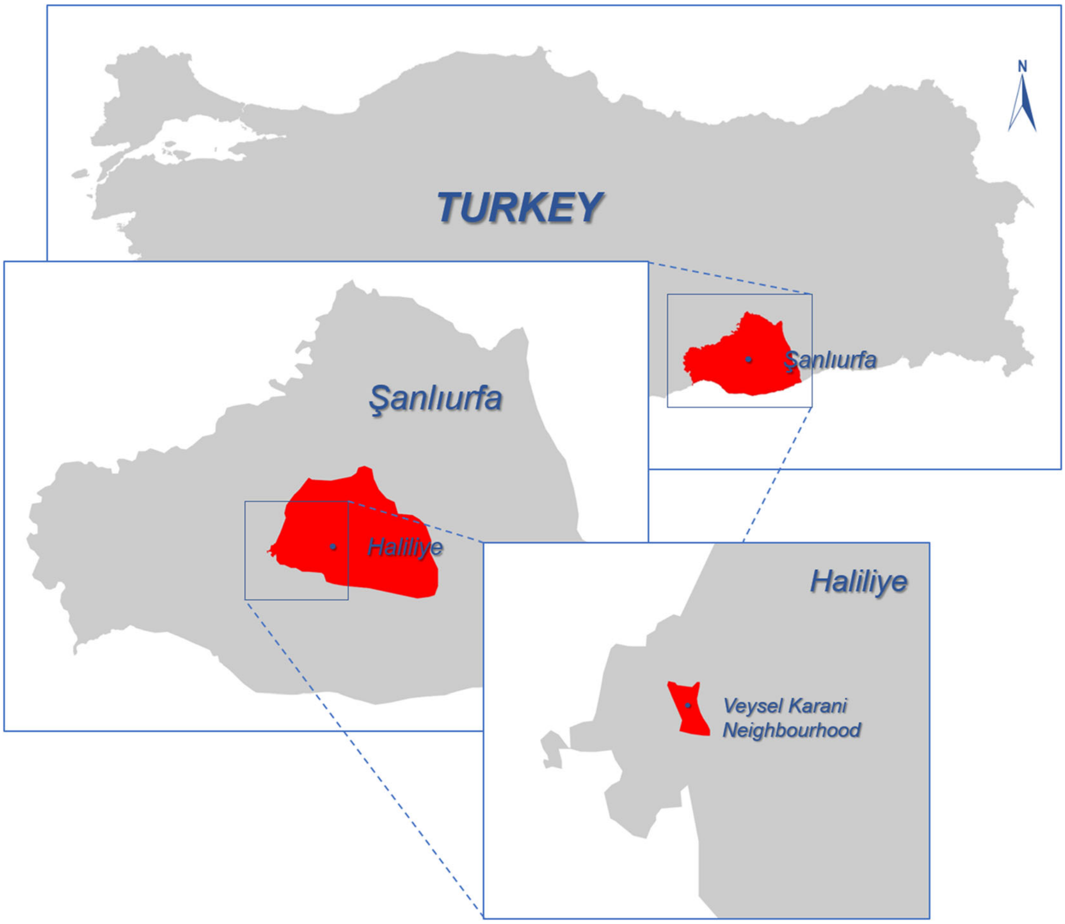

Fig. 1 Location map of the study area

vehicles which carry out a daily collection rota of two hundred and eighty 800-l capacity waste containers situated in front of the apartment blocks of Veysel Karani neighbourhood (Fig. 3). The total distance covered by the vehicles is 21.6 km. A complete plan of Veysel Karani neighbourhood with its road network and the locations of all waste containers is shown in Fig. 4.

Data collection

The GIS application supported by Esri ArcGIS 10.3 software converted the road map of Veysel Karani neighbourhood obtained from Haliliye Council Project and Planning Office into '.shp' format. The coordinates of the waste container points were established with the help of personnel from the Haliliye Council Cleaning Services Office during the course of the fieldwork and the coordinates of these location points were then transferred to the Esri ArcGIS 10.3 software. Speed View GPS Pro was used to check the waste container location points on the neighbourhood road map and also to help establish the routes taken by the waste collection vehicles. In this way, the routes travelled by the waste trucks and the current locations of all the waste containers were collected and saved as data.

Linear programming model

When it comes to NP-hard vehicle routing problems in the literature, the solution approach is primarily heuristic as reflected by the number of associated studies, whereas mathematical modelling and algorithms providing best solutions are not adequately covered. In recent years with developing computer software and hardware, there is no longer any need to be restricted to heuristic approaches, and mathematical modelling is now a realistic option. Heuristic models are devised for a specific problem and do not always give the best solution;

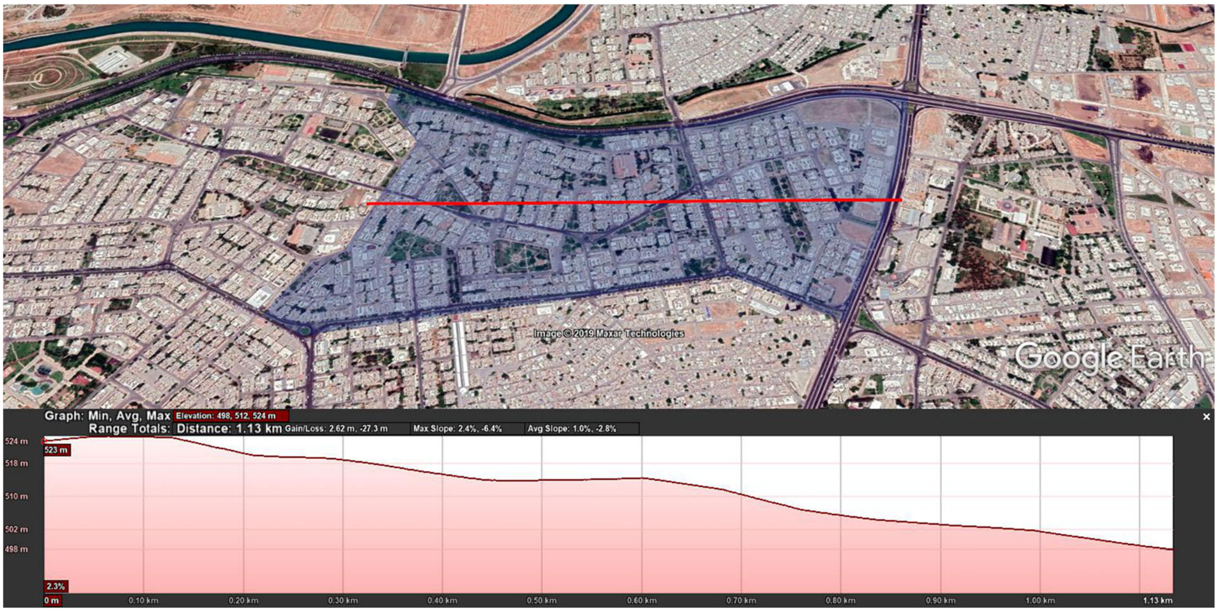

Fig. 2 Elevation profile for Veysel Karani neighbourhood (Google Earth)

sometimes, they merely provide a value close to the optimal solution, thereby presenting the decision maker with a guide. However, these specifically designed models do not provide the decision-maker with the required flexibility. In addition to always supplying the optimal solution, mathematical models also carry out analysis after the best solution and can perform sensitivity analysis too, all of which give the decision-maker the scope and flexibility for a properly considered decision (Yalçın 2014). The linear programming model used for the current problem is presented below.

Indices

i, j: nodes ($i, j = 1, 2, \ldots, N.$)

Fig. 3 Hydraulic compression waste collection vehicle

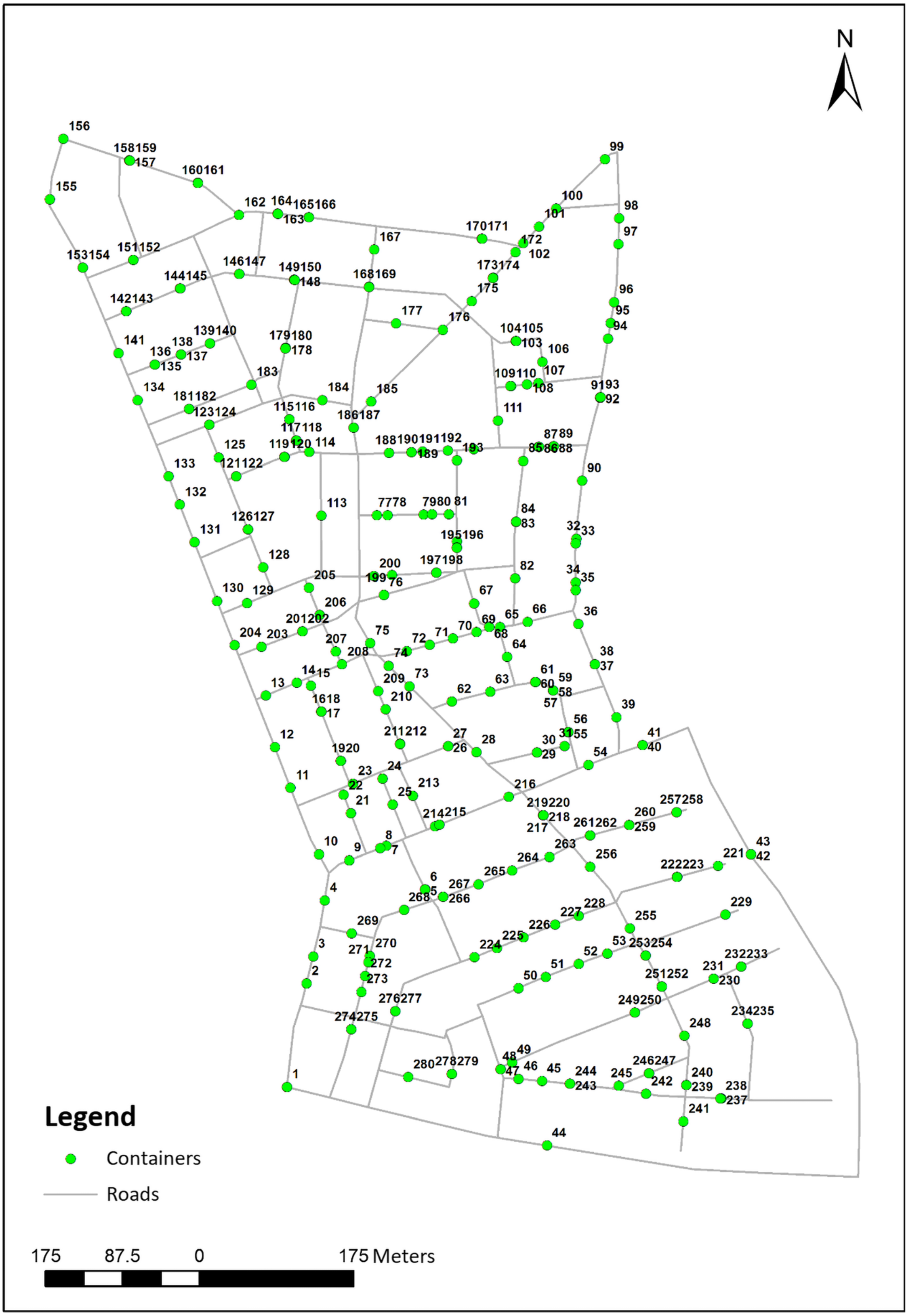

Fig. 4 Existing road network and waste container locations for Veysel Karani neighbourhood

Parameters

Distance between $d_{i,\,j}$: *i*. node and *j*. node ($\forall i, j \in N : i \neq j$)

Here, N represents the total number of nodes and u_i expresses variables which help to prevent inferior tours from occurring ($\forall i \in N$).

Decision variables

$$x_{i,j} = \begin{cases} 1 & \text{If vehicle goes from node i to node j} \\ 0 & \text{If otherwise} \end{cases}$$

($\forall i, j \in N : i \neq j$)

Objective function

$$Min\ Z = \sum_{i,j \in N} x_{ij} d_{ij} \tag{3.1}$$

Constraints

$$\sum_{i \in N} x_{ij} = 1, \qquad \forall j \in N \tag{3.2}$$

$$\sum_{j \in N} x_{ij} = 1, \qquad \forall i \in N \tag{3.3}$$

$$u_i - u_j + |N| x_{i,j} + |N-2| x_{ji} \leq |N| - 1, \forall (i,j) = 2, 3, \ldots, |N| : i \neq j \tag{3.4}$$

$$0 \leq u_i \leq |N|, \qquad \forall j \in N \tag{3.5}$$

$$x_{ij} \in \{0, 1\}, \qquad \forall (i,j) \in N \tag{3.6}$$

In this model, the objective function (3.1) aims to find the tour of shortest distance. The second constraint (3.2) is that each node can only be entered once; the third constraint (3.3) is that each node can only be left once. The fourth constraint (3.4) is directed at the prevention or elimination of inferior tours. The $|N-2| x_{ji}$ part of the model is a strengthened constraint: this can be removed from the model, but when it is included it speeds up the process of finding the optimal solution and has no effect on the feasibility of the model. The fifth constraint (3.5) shows the value range of the variables which help to prevent inferior route formation. The final constraint (3.6) is the signal constraint of the decision variables.

Results and discussion

The 'closest facility' feature of the network analyst tool was used to calculate the distances between each of the solid waste container points as mapped out by the Esri ArcGIS application. In this way, a starting point is determined from which distances to all other points are measured and then also the distances between each of those other points, and these measurements are transferred as tabulated data onto the excel platform using the excel converter tool from the ArcMap toolbox. Collected from separate excel files, the 78,400 data elements resulting from the calculations are saved in a 280 × 280 data matrix. In the route-finding process for Veysel Karani neighbourhood, three different solutions were found. The first was a GAMS solution using linear programming, the second was a CBS solution with Esri ArcGIS application, and the third solution was processed as a real-world route identification problem using the Speed View GPS Pro application.

The linear programming models used in this study only give an optimal solution for problems of a certain size, so as the dimensions of the problem grow the linear programming model can become inadequate. In order to know how many of the 280 points in the real-world problem would still provide an optimal solution, adjusting by a factor of 10, a total of 28 problem sets were established. Using the GAMS application, a 30-min processing duration produced the results in Table 1, and for the 280 points, the routes found are shown in order in Fig. 5a. Each result in the table represents the optimal route to take from a given starting point visiting the specified series of targeted points and returning to the start point again.

The second method used in this study, the Esri ArcGIS application using dijkstra and tabu algorithms, employed the ArcMap network analyst tool to solve the rota characteristics. The results of these solutions for the 28 problem sets are shown in Table 1, and the routes for the 280 points are ranked in Fig. 5b.

Speed View GPS Pro application was used to extract the data for the daily solid waste collection routes. The application was downloaded to the cell phones of the

Table 1 Route distances obtained by different methods

No.	Points	Linear programming model (meter)	ArcGIS model (meter)	Current state (meter)
1	1–10	791	791	1377
2	1–20	1236	1236	1701
3	1–30	1725	1725	2234
4	1–40	2388	2483	2643
5	1–50	3485	3485	3429
6	1–60	3554	3675	4012
7	1–70	3902	4282	4595
8	1–80	4434	4824	4884
9	1–90	4697	5241	5605
10	1–100	5370	5928	8437
11	1–110	5933	6035	10,431
12	1–120	7550	6422	11,156
13	1–130	8229	6939	11,697
14	1–140	8178	7479	12,571
15	1–150	8294	7844	12,683
16	1–160	9138	8545	13,094
17	1–170	8199	9014	13,644
18	1–180	9571	9069	14,583
19	1–190	10,296	9940	15,735
20	1–200	10,540	9410	16,106
21	1–210	10,544	9877	16,445
22	1–220	10,346	10,478	17,089
23	1–230	11,285	11,215	17,512
24	1–240	14,058	11,391	18,108
25	1–250	12,075	11,921	18,846
26	1–260	14,664	12,543	19,302
27	1–270	15,316	12,818	20,361
28	1–280	14,342	13,170	21,603

waste collection vehicle drivers so that the data of the movements within the study area could be collected. At the end of the day, this data could then be analysed, and a waste collection route established for the Veysel Karani neighbourhood. The data obtained appears in Table 1 and a route was found for the 280 points. The found route solutions for the current daily situation are ranked in Fig. 5c.

The results of the mathematical model and Esri ArcGIS application used in the study are given in Table 1 and the routes in Fig. 5. Route lengths are given in meters. To explain in detail, linear programming and ArcGIS results of the first 10-point problem are obtained as 791 m, while in real case, the vehicle has travelled 1377 m to reach 10 points.

In this way, the current state data can easily be compared with the other data as they all appear in one table. As a result of this comparison, the various optimal solutions contained in the table could be assessed in terms of improvement on the current state and this improvement expressed as a percentage (see Table 2). For this calculation, all the different models were treated in the same way (3.7).

$$\%improvement = \frac{Current\ State\ Data - Model\ Result}{Current\ State\ Data} \times 100 \quad (3.7)$$

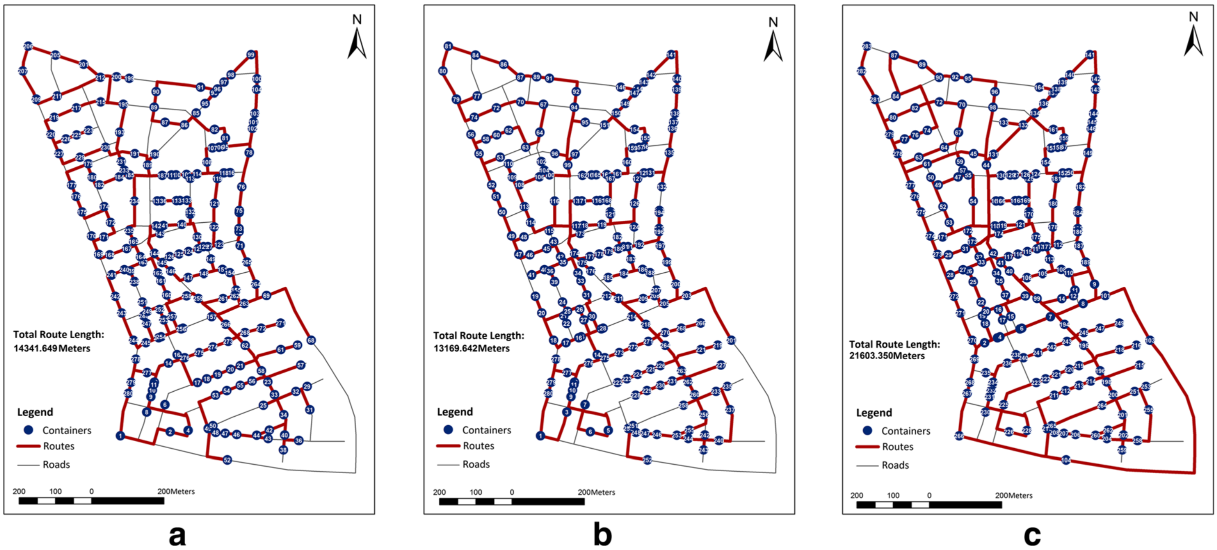

Fig. 5 Completed route maps obtained with linear programming, GIS and current state models

The calculated improvement values are given in Table 2. Where the better solution in terms of improvement is found with the GIS platform, a light green colour is used; where the better solution is obtained using linear programming, a light blue colour is used. If, after analysis, it turns out that there is no variation in improvement (i.e., the improvement value is the same for both approaches), then a grey colour is used.

Examination of these results reveals that of the 28 problem sets, a better solution was calculated by GAMS for 8 problem sets, but ArcGIS performed better for 15 of the problem sets. For small-scale problems, linear programming model proved to be more effective than the other two methods, but as the dimensions of the problem increased, the heuristic approach of ArcGIS became the more successful method.

As part of the fieldwork information entered to the data platform, various constraints were identified which the waste collection vehicles were subject to including waste capacity, time constraint, road direction constraint and degree of congestion. A network map was produced of the neighbourhood roads and this was checked against data from a satellite map. The coordinates of the waste containers in front of apartment blocks and along the roads were also entered onto the data platform and the waste capacity defined. Once all these types of data had been entered into the system, the process of calculating the shortest route could be carried out using the network analyst tool. It was felt that a solution result for 280 points would require the operation of two waste collection vehicles, so the linear programming model was revised for two vehicles. This revised version of the linear programming model and the GIS solution finally calculated the shortest routes as having distances of 14,498 m and 15,606 m, respectively. The separate distances involved in these route lengths are presented in Table 3. These data were compared with the current state data and their relative efficiency obtained through an equalising calculation method (3.7).

The current state situation for the first problem set of 200 points presented a distance 16,106 m, whereas the linear programming model produced a route of 10,017 and the GIS solution resulted in 11,048 m. The second problem set of 80 points involved a current state route distance of 5497 m which was reduced to 4481 m by the linear programming model and 4558 m by the GIS model. For both of the problems, the linear programming model provided a better result than both the ArcGIS application and the current state calculations. As a result of the studies, it is seen that the linear programming model improves vehicle routing problem by 33% and ArcGIS application results by 28% in total. In both problems, linear programming method gave better results than the others.

Table 2 A comparison of linear programming and GIS methods with current state data

No.	Points	Improvement ArcGIS (%)	Improvement GAMS (%)
1	1–10	43	43
2	1–20	27	27
3	1–30	23	23
4	1–40	6	10
5	1–50	− 2	− 2
6	1–60	8	11
7	1–70	7	15
8	1–80	1	9
9	1–90	7	16
10	1–100	30	36
11	1–110	42	43
12	1–120	42	32
13	1–130	41	30
14	1–140	41	35
15	1–150	38	35
16	1–160	35	30
17	1–170	34	40
18	1–180	38	34
19	1–190	37	35
20	1–200	42	35
21	1–210	40	36
22	1–220	39	39
23	1–230	36	36
24	1–240	37	22
25	1–250	37	36
26	1–260	35	24
27	1–270	37	25
28	1–280	39	34

The difference between the results computed by the linear programming model and GIS for the purposes of this study are presented in Table 4.

Table 3 Comparison of route optimization results with current state data

No.	Points	ArcGIS results (meter)	L. P. results (meter)	Real world data (meter)	ArcGIS (%)	GAMS (%)
1	1–200	11,048	10,017	16,106	31	38
2	201–280	4558	4481	5497	17	18
	Total	15,606	14,498	21,603	28	33

Conclusions

This study carried out a route optimization for solid waste collection employing both linear programming and geographic information system. Within the study, the results obtained from the linear programming model and the GIS application were analysed and compared with the current state data. The solid waste collection and transport problem can be solved with route optimization using the vehicle routing problem algorithm of the GAMS model application and the network analyst tool in the ArcMap module of the Esri ArcGIS platform. The Esri ArcGIS platform was chosen as this study involves a large-scale problem and these problems are more successfully solved by GIS applications. In the end, the route optimization process was a matter for the district council and their solid waste collection and transportation operations; it was found that using a heuristic approach significant environmental and economic gains could be made. Improvement over the

Table 4 Comparison of linear programming and GIS operations

GIS application	Linear programming application
• Quick and easy operation	• Quick and easy operation
• Easy to operate with small-scale data and provides near optimal solution	• Easy to operate with small-scale data and provides optimal solution
• Large-scale data are easy to update	• Large-scale data are difficult to update, and this takes time
• Offers large-scale data storage	• Offers large-scale data storage
• Large-scale data processing duration shorter than linear processing method	• Large-scale data processing takes a long time
• Easy filtration and evaluation of results	• Difficult and time-consuming filtration and evaluation of results
• Easy to reach data in acceptable amount of time with inquiry feature	• Easy to reach data in acceptable amount of time with inquiry feature
• Enables processing of data with the help of programming languages	• Enables processing of data with the help of programming languages
• Visualization of manipulated data is rendered easy and enjoyable	• Difficult and time-consuming to make visualisations of data being worked on
• Considerable time savings	• As problem scale increases, visualisations become increasingly difficult and result in time loss

current state data was by a rate of 33% for linear programming model, and 28% for GIS. These improvements would have a particularly large impact on vehicle costs, including fuel expenditure, vehicle price depreciation, and labour costs.

In the next work plan, the problem will be solved to cover the whole district and the whole province. While these problems are solved, other real-life constraints such as vehicle failure and traffic congestion will be added, and solutions will be produced for optimization purposes. It is planned to use heuristic and meta-heuristic algorithms to solve such problems. It is suggested that researchers develop meta-heuristic methods with hybrid solution algorithms for such problems.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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