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Developing an Optimization Model for Minimizing Solid Waste Collection Costs

Semih CENGİZ [1], Mehmet ŞEN*[2], Muciz ÖZCAN[2]

Abstract

With the increase in population in cities, the number of solid waste to be collected has also increased. Because the garbage collection route must be traveled repeatedly, even minor improvements in these routes can result in a significant increase in fuel usage. Shortening the journey would provide a significant contribution to lowering fuel expenses in all towns, especially given the rising cost of fossil fuels. Furthermore, lowering fuel usage is critical for Turkey to meet its national objectives under the Paris Agreement. The Simulated Annealing (SA) algorithm, one of the heuristic optimization techniques used to identify the best solutions to complicated problems, is employed to solve the routing problem of solid waste collection vehicles in this study. This method, which was inspired by the metal annealing process, stands out for its ability to avoid regional minima while looking for the optimal solution. The applicant region was selected as the Kosova Neighborhood of Konya's Selçuklu District. The container distances needed for the method to execute were acquired by extracting the coordinates of the containers. Kosova Neighborhood was separated into 7 distinct regions due to the restricted capacity of rubbish collection vans. All regions were analyzed independently, and the best feasible routes were estimated using the SA algorithm approach, and the results were compared to the greedy algorithm findings. The SA algorithm outperformed the greedy algorithm by 26.49%.

Keywords: Smart cities, waste collection, fuel consumpiton, simulated annealing, greedy algorithm

1. INTRODUCTION

The concept of smart city has been high on the agenda of both academic studies and countries since its introduction. Smart city projects aim to explain the problems that may be encountered for the sustainability of life in cities and to produce effective solutions to these problems. With the technological leap in the field of information technologies in the world, the smart city concept is seen as a strategic roadmap for cities to achieve their welfare goals [1-2].

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In order to minimize the problems arising from the dense population in cities, studies are carried out in many different fields such as smart energy systems, smart transportation systems, smart stadiums, smart hospitals, smart airports. All of these studies are part of the goal of establishing a smart city structure.

The aim of people to lead a more comfortable, efficient, relaxed and safer life combined with the use of technological structures has led to faster, error-free and automated processes, and these processes have formed the basis of smart cities [3].

One of the problems observed in cities with crowded populations is the increasing amount of waste every day. It is important that waste collection is carried out in an organized manner so that waste does not harm the environment and human health. Therefore, waste collection systems play an important role for the infrastructure of smart cities. Efficient waste collection is important due to the increase in urbanization and limited natural resources. There are different solid waste collection methods such as direct collection of waste from homes, factories or collection from waste containers in certain areas [4].

When collecting solid waste, reasons such as not using a specific route and not checking the occupancy of the containers in advance cause both time losses during the implementation and unnecessary fuel consumption. The increase in fuel consumption creates a negative situation for the national energy policy of our country [5]. In this context, a number of studies have been carried out worldwide to save energy.

In a study conducted in Austin, Texas in 2019, they created 48 different scenarios such as collection frequency, waste composition, collection type, and truck type in a small waste collection area and investigated the impact of these parameters on garbage collection. [6]. In 2017, a study was conducted by drawing attention to the negative effects of uncontrolled population growth in cities, emphasizing that the use of natural resources should be reduced and resources should be recovered from waste for the sustainability of development. According to the results of their study in Vellore, one of the smart cities in India, solid waste collection routes and travel distance were reduced by 59.12% in areas with routine collection [7].

In a study conducted in Japan in 2018, urban sensing technology was shown as one of the indispensable foundations for the research, development and implementation of smart cities. With sensors and communication systems placed on solid waste collection vehicles in Fujisawa, Japan, they conducted a study in that region by addressing the urban sensing system, an important technology in smart city applications. [8]. The effect of the mechanical structure of solid waste collection vehicles on waste collection performance was investigated in Russia in 2015, and in this context, the process model of a structure that enables waste loading from the side of the solid waste collection truck body by redesigning the garbage vehicle's chassis was realized. [9].

The region where the optimization algorithm proposed in this study will be applied to the problem is Kosova Neighborhood of Selçuklu District, Konya Province. According to the location of the waste collection containers in Kosova Neighborhood and their empty and full status, the route of the garbage collection vehicle will be optimized at the start of each collection process and will increase the efficiency of the waste collection system by calculating the shortest route between the containers that need to be collected.

2. TECHNICAL BACKGROUND

2.1. Simulated Annealing Algorithm

Algorithms used for local search and optimization have recently started to be inspired by nature [10-11]. One of the nature-inspired algorithms is the SA algorithm proposed by Kirkpatrick, Gelatt, and Vecchi (1983) [12]. As the name suggests, the SA algorithm is a probabilistic heuristic optimization algorithm inspired by the annealing process of metals [13-14]. SA algorithm is a type of algorithm used to obtain effective results in local search problems [14].

Annealing is the process of slowly cooling a solid object after heating it to its highest temperature. The unbalanced structure of the atoms of the solid, which is heated to its highest temperature [14-15], minimizes the potential energy when the object is cooled slowly, allowing the atoms of the object to move freely and align perfectly. In order to achieve this perfect structure, the cooling process must be very slow [16]. Rapid cooling leads to irregularities, causing the desired crystal structure to be distorted.

One of the most important features of the SA algorithm is that it can consider more costly solutions than the current solution as a possibility for the new solution and does not get stuck at the local minimum point. Boltzmann distribution is utilized to construct this system. In Eq. (1), P is compared to a random decimal number in the interval [0,1) so that more costly solutions can be considered.

$$P(E) = e^{(-E/(kT)}\tag{1}$$

The main parameters of the SA algorithm are as follows; T represents the temperature value, alpha (α) represents the cooling rate, (ε) represents the freezing value [17]. The SA algorithm usually starts with the generation of a random solution set. After this solution set is generated, a new solution is generated in the problem space that is close to the random solution generated and the change in the cost of these two solutions is compared. $C_i i$ in Eq. (2) refers to the newly obtained solution at the i th iteration, while C_{i-1} refers to the solution at the $i-1$th iteration, i.e. the best solution before the new solution is obtained [18].

$$\Delta C = C_i - C_{i-1}\tag{2}$$

If the new solution is more cost-effective than the previous solution, the best available solution is replaced by the new solution. The new solution is now the best solution. If the new solution is not cost-effective, the old solution is kept as the best solution according to Eq. (3). The cost difference between the new solution and the current best solution is denoted by ΔC.

$$\exp(-\Delta C / T) > R\tag{3}$$

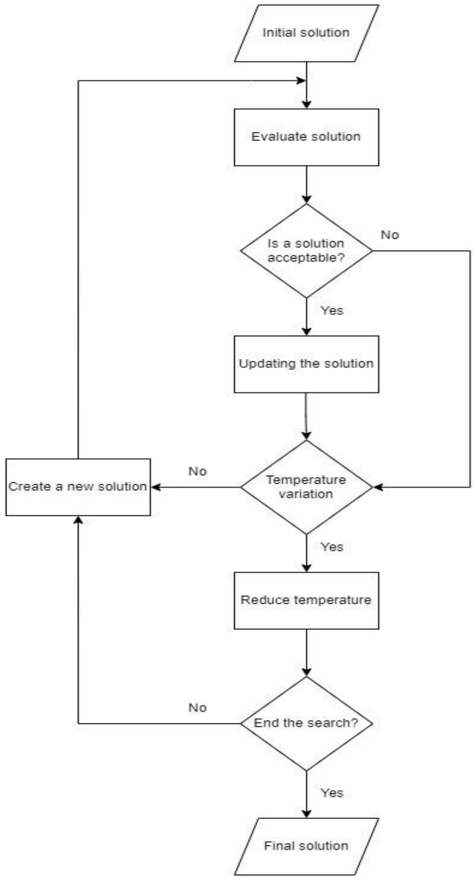

Figure 1 SA algorithm flow diagram

R, a random number between 0 and 1, is generated to be uniformly distributed. If the temperature, T, is initially high, the new solutions found have a higher chance of being suitable. As the process progresses, the temperature T is lowered. As the temperature is lowered, solutions with lower costs are obtained, i.e. the selectivity of the solutions gradually increases. If no further changes are observed in the near solutions, the Annealing process is completed. A flowchart showing the steps of the SA algorithm is given in Fig. 1. How the cooling process will work, i.e. how much the temperature will be reduced in each iteration, is determined in advance. The number of iterations and the criteria for stopping the algorithm are also predetermined.

2.2. Greedy Algorithm

The greedy algorithm is one of the most widely used algorithms among the classical heuristic algorithms. They are analyzed separately from classical heuristic algorithms because they perform more limited, localized searches than metaheuristic algorithms [19-20]. The working principle of the greedy algorithm is to cover the maximum points that it can cover while trying to reach the selected node and to complete this job with minimum cost. This procedure is continued until all nodes are included in the system [21-22]. The main goal of this algorithm is to always optimize the utility. The greedy algorithm is very widely used. It is widely used because it is easy to use, easy to adapt to most problems and has a low computational cost. In addition, the greedy algorithm is preferred because it can be used in hybrid form with many other algorithms. Fig. 2 shows the flow diagram of a general greedy algorithm [23].

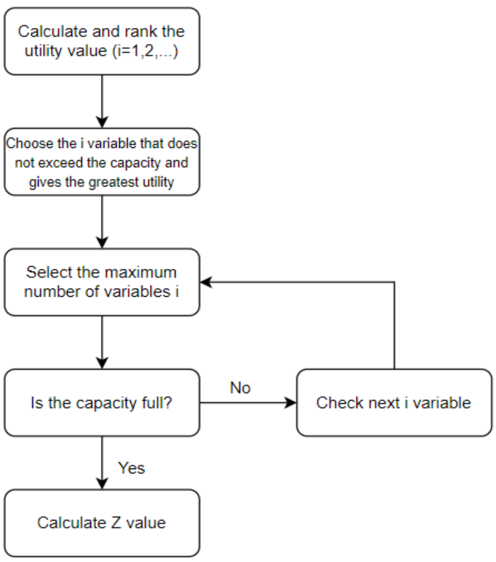

Figure 2 Greedy algorithm flow diagram

3. MATERIAL AND METHOD

The problem considered in this paper is the garbage truck routing problem. Although it is very similar to the traveling salesman problem [24], it differs in some aspects such as the fact that there is no need to return to the starting point [25]. The solid waste collection containers in Konya Province are buried in the ground, Fig. 3 shows a photograph of one of the solid waste collection containers. The capacity of each waste container is approximately 500 kg [26-27].

Figure 3 Kosova neighborhood ground buried garbage container

There is no occupancy measurement device on these containers. In this study, the system was designed considering the necessity of using sensors or sensors in order to determine the occupancy of the containers. In this way, containers below the predetermined occupancy level will be removed from the route to be calculated, thus increasing the efficiency of the system. During collection, the containers are removed with the help of a crane on the garbage vehicle and emptied into the waste collection hopper of the vehicle. This process is shown in Fig. 4 [27]. Waste collection vehicles can have different capacities such as 6-8-11-13m^3. The vehicle in this study was evaluated as 13m^3 capacity.

In the waste collection system, the solid waste collection vehicle will start collecting garbage according to the recalculated route before each collection, starting from the first region, and when its capacity is full, it will discharge the solid waste to the Aslım dumping area. After the emptying is completed, it will start collecting again according to the recalculated route. Whether the vehicle will continue from where it left off will be determined according to the system of the recalculated route. Since the sensors in the waste containers will exclude the emptied containers from the calculation, no matter where the collection process is interrupted, when it starts again, the most suitable route at that moment will be redetermined.

Figure 4 Emptying waste containers into the garbage truck

"Google Maps" application was used to find the location coordinates of the waste containers. Within the scope of this study, 137 potential points were identified and there are approximately 250 solid waste containers at these points. While the distance between two containers on two-way roads is considered the same, the distance between containers on one-way roads is different when the collection order is changed.

3.1. Simulated Annealing Algorithm and Application of Greedy to The Problem

The greedy algorithm is used to generate the initial solution, which is the first step of the SA algorithm. The SA algorithm starts from a random point, i.e. a random waste container, to generate the best solution. The first selected point is deleted from the idle and navigable points and the nearest neighbors are searched. According to the effect of the temperature value, the closest point found is advanced to and the advanced point is removed from the idle points. This step is repeated over and over again until there are no idle points left. In case there are no empty points, a new candidate solution is generated. This candidate solution is compared with the previous best solution.

If a better solution is found than the previous solution, it is set as the new best solution, if no better solution is found, the old best solution is kept. If the temperature has not dropped to the point where the algorithm stops running or the number of iterations has not been reached to stop the algorithm, cooling takes place and the search for a new candidate solution continues. If the predefined iteration limit or predefined minimum temperature is reached, the loop is terminated and the last best solution found is printed on the screen as the global best solution.

3.2. Applications Used and Software Development Environment

Python (version 3.6) programming language was used to transfer the SA algorithm into code to turn it into a working application. Pycharm (version 2020.1.5), one of the free integrated development environments (IDE), was used to prepare and run the software in Python programming language quickly and smoothly. Technical specifications of the computer on which the algorithm was run:

- Operating system: 64 Bit Windows 10 Home
- Processor: Intel(R) Core(TM) i7-7700HQ CPU @2.80GHz 2.81 GHz
- Ram: 16GB 2666Mhz

Google Maps application was used to determine the location coordinates of solid waste containers. The neighborhood map used to show the locations of the containers and the generated routes was taken from the neighborhood boundaries system of Selçuklu Municipality [27]. The map data required for measuring and calculating the distance between the garbage containers and creating the appropriate route for the vehicle were obtained by sending the starting point and destination point information to a free-to-use server that generates distance data.

3.3. Obtaining and Using Map Data

In this study, the distance data to be optimized by the algorithm was obtained by using an application that calculates distances. Measuring only the distances as the crow flies is not suitable for one-way roads as the distance from any point A to any point B may be different from the distance from point B to point A. Since it is not known which of all garbage containers will be collected at each routing requirement, the distance between each container must be calculated before routing. Each query for the distance between two containers requires an internet connection and also adds a new cost to the querying application. Since the locations of the solid waste containers are fixed and known in advance, all queries for all container distances are made and saved as a database. In this way, the algorithm does not require the internet every time it is run.

In addition, since the number of iterations will require as many queries as the number of iterations, an additional cost is avoided in repeated queries for the same distance. The area between Yeni İstanbul Street, Veysel Karani Street and Coşandere Street was defined as Region 1. There are 21 solid waste containers in Region 1. Container nomenclature is random and given in this way in order to observe which steps will be followed in the application. Tab.1 shows the container nomenclature and coordinate information in the region selected as Region 1. There are 21 solid waste containers in District 1. The container nomenclature in Table 1 is random and is given in this way in order to observe which steps will be followed in the implementation.

In order to find the distance between containers using coordinate data about garbage locations in Python code, an application (API) that provides distance matrix data is used. The route calculation is always done assuming that the route goes from the first given parameter to the second given parameter. When the distance function is run, in addition to the distance to be traveled between the two points, an estimated time is also generated according to the traffic density, but in this application, the time data is not included in the route calculation process.

Table 1 Region 1 container coordinates respectively

Containers No	Container Coordinates	
1	38.00134817340276	32.52119983957413
2	38.001339026537586	32.52225846648771
3	38.00070727346458	32.52315201148032
4	37.99996183285936	32.52123673096998
5	37.99760946535191	32.520595717032194
6	37.99953772006359	32.52258701716178
7	37.99981397163974	32.52321551258152
8	38.00014573277816	32.5252519534322161
9	38.0002971252376	32.52630472968777
10	37.999542466349716	32.52529725916028
11	37.999372569329175	32.52391724497001
12	37.99800452560539	32.5263029559933964
13	37.9979824673397	32.52521602263854
14	37.99734471488008	32.524177918945206
15	37.99628429964277	32.524444399657035
16	37.9959151860695	32.525716969212816
17	37.9959151860695	32.52638703670926
18	37.99544694503087	32.5217627841824
19	37.995679519759925	32.5236461739465
20	37.9951047161878	32.5224971039237
21	37.99444383421898	32.52225410076425

In the application, a text document with the extension ".txt" was created in order to enter the container coordinates into the distance finding function. This text document contains the garbage container coordinates taken from the Google Maps application. In the Python application, the "open" function was used to read the data in the ".txt" document. After the container coordinates were sent to the application that generates distance data, the resulting data was taken into a new matrix variable and saved in a different text document. Table 2 shows the document containing the distances between containers in Region 1. The first row and the first column contain the names of the containers. In other parts, the distances between the containers are given in meters for precision.

Divided into 7 different regions, coordinate lists and distance matrices were created separately for each region of Kosovo Neighborhood. When the SA algorithm is run, the distance matrices are processed and solutions are generated according to this information. For Region 1, the solid waste containers selected are shown on the map in Fig. 5.

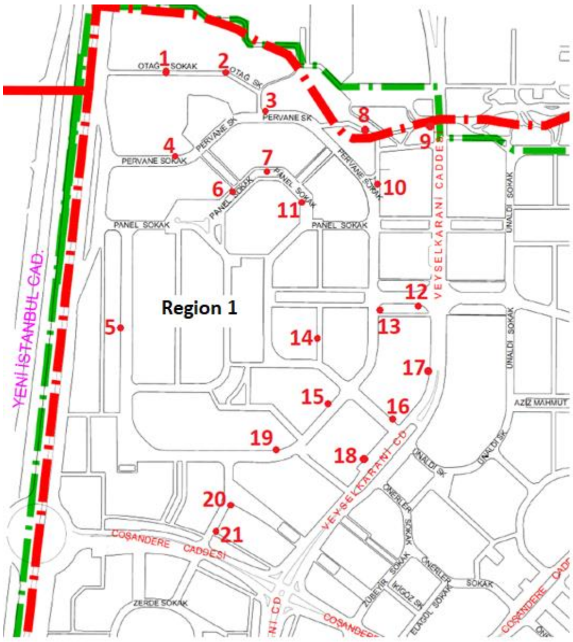

Figure 5 Map showing the location of containers in Kosova Neighborhood 1st region

Table 2 Region 1 distances between containers (m)

Con. No	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
1	0	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	1164
2	93	0																			1072
3	216	.	0																		948
4	396	.		0																	911
5	618	.			0																489
6	377	.				0															874
7	422	.					0														901
8	416	.						0													861
9	515	.							0												964
10	483	.								0											721
11	482	.									0										815
12	715	.										0									644
13	617	.											0								545
14	816	.												0							486
15	832	.													0						332
16	1540	.														0					446
17	1686	.															0				593
18	1467	.																0			374
19	1391	.																	0		233
20	1234	.																		0	78
21	1158	.																			0

4. RESULT AND DISCUSSION

After investigating the effects of the initial parameters of the SA algorithm on the result, T= 4.69, α=0.995, number of iterations=2000 were used as the final choice. The program output obtained for Region 1 is given in Table 3.

The greedy algorithm solution generated as an initial solution started at container 2 and completed the route at container 4. The total distance to be moved was calculated as 4838 meters. Then the SA algorithm started to calculate possible solutions. After the algorithm produced 10 results, the best solution was found, starting from waste container 1 and ending at waste container 18. The distance to be followed in the route found by the SA algorithm was calculated as 3210 meters. For Region 1, the SA algorithm suggested a 33.65% shorter distance than the greedy algorithm. In other words, the route to be followed was shortened by approximately 1.6 km. Furthermore, Fig. 6 shows the progress steps of the greedy algorithm and Fig. 7 shows the progress steps of the SA algorithm. As can be seen in the maps, in the greedy algorithm, the situation of re-passing the same points was observed more than once, but in the SA algorithm, this situation was observed only once.

Table 3 Output when the SA algorithm is run

Containers No	Container Coordinates
Greedy algorithm route	[2,1,3,6,7,11,8,10,9,12,13,14,15,19,20,21,16,18,17,5,4]
Greedy algorithm solution	4838
Best fitness (meter)	3210
Algorithm recovery rate	33.65%
Best route	[1,2,3,8,9,10,11,7,6,4,5,20,21,19,15,14,13,12,17,16,18]
Operation time	42.1810999999997 ms
Total working time	424.8852 ms

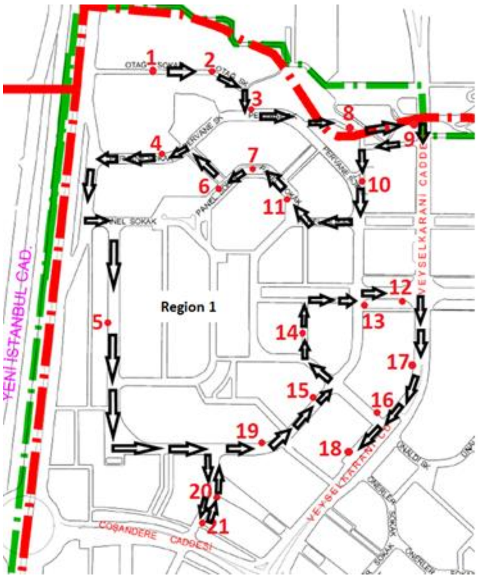

Figure 6 The route taken by the greedy algorithm

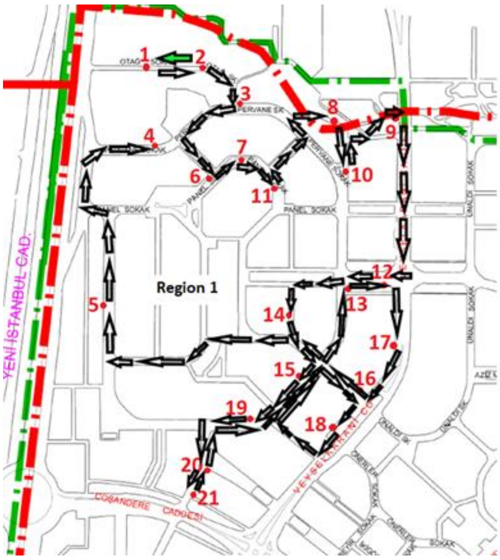

Figure 7 The route taken by the SA algorithm

In all regions, the SA algorithm produced a more efficient route than the greedy algorithm results, which are given in Table 4. Approximately 8 km can be saved in the total route. In this way, the amount of fuel to be used by the waste collection vehicle will decrease, the CO2 emission to the environment will decrease, and the total route time will be shortened. As can be seen from the results, the routes of solid waste collection vehicles should not be left to the driver's initiative [27] and should not be random.

Table 4 Result obtained by regions

Regions	Distance Traveled with Greedy Algorithm (m)	SA Algorithm Results (m)	Distance Shortened for Route (m)	Improvement Rate (%)
Region 1	4838	3210	1628	33,65
Region 2	3411	3202	209	6,13
Region 3	3685	2643	1042	28,28
Region 4	5547	4202	1345	24,25
Region 5	5165	3483	1682	32,57
Region 6	2763	2292	471	17,05
Region 7	4561	2998	1563	34,27
Total	29970	22030	7940	26,49

Various brands of vehicles can be used for solid waste collection. One of them is the Ford 1833 model truck shown in Fig. 4. Since this type of vehicle can carry 13-15m^3 of garbage and can reach up to 18 tons of capacity, there is no official fuel consumption value on the company page, as there can be significant fuel consumption differences between empty and full vehicles. Vehicle operators using similar brands and models were asked about the fuel consumption of their vehicles and different answers were obtained. Depending on whether the vehicle is empty or full, fuel consumption can vary between 25 liters and 40 liters per 100 kilometers. This value will vary depending on the brand of the vehicle, its use and weather conditions. There will also be changes from the first container to the last container. For this reason, in this study, the fuel consumption of the vehicle will be accepted as 30 liters /100km on average.

In the scenario where all containers are considered full, it is expected to save approximately 2.4 liters of fuel for the route given in Table 4, which will be shortened by approximately 8 km in 1 round trip in Kosovo Neighborhood. On 08.09.2023, 1 liter of diesel fuel costs approximately 37.91 Turkish Liras in Konya. For Kosovo Neighborhood only, the solid waste collection vehicle will provide approximately 181 Turkish Liras of benefit in a single tour.

5. CONCLUSIONS

In this study, a solution method is presented using SA algorithm and greedy algorithm for optimal route calculation in the solid waste management system of Konya Province. Kosova Neighborhood of Selçuklu District is selected as the application region. It is assumed that there is only one solid waste collection vehicle in the neighborhood. For this reason, when all the containers in Kosova Neighborhood are full, the capacity of one vehicle is not enough to collect the waste in all containers, hence the need to group the containers. Kosova Neighborhood was divided into 7 different regions according to the locations of the containers that could be identified. While dividing the neighborhood into regions, street crossings that make the distance between two containers too long were taken into consideration.

Python language was used to code the SA algorithm and Pycharm application was preferred as an integrated development environment. First of all, the factors affecting the solid waste system are presented, and then, when the SA algorithm is used in this system, how the results are affected by which parameters are analyzed separately. The results obtained using the SA algorithm are compared with the results of the greedy algorithm.

Considering the results in all regions, it is clear that the paths to be followed should not be random. The route that any solid waste collection vehicle should follow should not be determined randomly, but the shortest route should be calculated and made available to the operator of the vehicle. In this way, even if the amount of fuel saved for each region is small, when these regions are added together, a significant fuel saving will be achieved for the whole city.

For Kosovo Neighborhood only, the total route calculated with the SA algorithm is approximately 8 km more advantageous than the greedy algorithm results. In this way, approximately 2.4 liters of fuel savings will be achieved during the completion of one round of the total route only for Kosova Neighborhood. The number of neighborhoods in the central districts of Konya is 221. It is estimated that if the result obtained in Kosova Neighborhood is achieved in other neighborhoods, a gain of around 500 liters can be achieved in a single tour. The shortening of the solid waste collection route is thought to make significant contributions to the reduction of fuel cost, reduction of CO_2 emissions, and reduction of operator costs due to the shortening of the time to be spent.

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Authors' Contribution
The authors contributed equally to the study.

The Declaration of Conflict of Interest/ Common Interest
No conflict of interest or common interest has been declared by the authors.

The Declaration of Ethics Committee Approval
This study does not require ethics committee permission or any special permission.

The Declaration of Research and Publication Ethics
The authors of the paper declare that they comply with the scientific, ethical and quotation rules of SAUJS in all processes of the paper and that they do not make any falsification on the data collected. In addition, they declare that Sakarya University Journal of Science and its editorial board have no responsibility for any ethical violations that may be encountered, and that this study has not been evaluated in any academic publication environment other than Sakarya University Journal of Science.

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