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Safe distance-based vehicle routing problem: Medical waste collection case study in COVID-19 pandemic

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ABSTRACT

In addition to the increasing population and rapid urbanization, the amount and variety of medical waste are rapidly increasing due to the coronavirus disease (COVID-19) pandemic affecting the whole world. COVID-19 does not only increase the amount of medical waste produced, medical wastes generated in the care of COVID-19 carries a high risk of transmission as well. In this regard, the safe and effective management of medical wastes has become a serious health and safety issue. This research aims to determine the safest and shortest transportation routes for medical waste vehicles. The safety scores used in this study were obtained in our previous study. The resulting safety scores were used in a multi-objective traveling salesman problem for deriving two objective functions, which are based on safety scores and total transportation distance. A conciliating solution was obtained by solving this linear programming model. The proposed model faced by health institutions in Istanbul has been applied for a specific district. According to the obtained results, suggestions for the direction of medical waste vehicles have been proposed.

1. Introduction

All types of wastes generated in healthcare institutions, research centers, and medical laboratories are referred to as healthcare wastes. 75–90% of wastes generated by healthcare service providers can be defined as domestic wastes, which are often regarded as "non-hazardous" or "general healthcare" wastes. In other words, wastes that do not pose any physical, chemical, biological or radioactive hazards. Such wastes are generated by the administrative, catering, cleaning, etc. services of healthcare institutions. The remaining portion of 10–25% is termed as "hazardous" healthcare wastes. World Health Organization (WHO) categorizes this type of hazardous healthcare waste into seven main groups depending on their characteristics and risk levels, which are: pathological waste, infectious waste, sharps waste, radioactive waste, chemical waste, cytotoxic waste and pharmaceutical waste (Win et al., 2019). According to standard procedures in the medical field, the characteristics of healthcare wastes are similar in almost all countries. However, legal regulations regarding the safe management of medical waste may differ from one country to another. For example, according to USA regulations, used and unused implements, cultures and stocks of infectious agents, human blood and blood products, human pathological waste, and contaminated animal waste are referred to as medical waste (Mato & Kaseva, 1999). Another example, in China, medical waste is classified as chemical waste, medicine waste, injury waste, pathologic waste, and infectious waste (He, Li, & Fang, 2016). In Turkey, published in January 2017 by the Medical Waste Control Regulation, sharps waste, pathological waste and infectious waste are classified as medical waste. In this study, transport of medical waste in Turkey is discussed.

As a popular subject, Medical Waste Management (MWM) has been addressed with a variety of methods. Survey studies have been performed on detection, MWM generated by hospitals in various countries and cities. The amount of medical wastes generated has been reported to be 0.59 kg/(bed.day) for the European side, and 0,6199 kg/(bed.day) for the Asian side of Istanbul by Alagoz and Kocasoy (2008a); 0.63 kg/(bed.day) by Birpinar, Bilgili, and Erdogan (2009); 0.68 kg/(bed.day) by Yong, Gang, Guanxing, Tao, and Dawei (2009); and 0.89 kg/(bed.day) by Rolewicz-Kalińska (2016), and reportedly the amount of medical wastes increases each passing year. In these studies conducted before COVID-19 pandemic, it has been observed that the amount of medical waste generated in the light of factors such as urbanization, industrialization and population growth is increasing day by day. With today's COVID-19 outbreak, the number of patients in hospitals is increasing

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rapidly compared to before the pandemic. In Wuhan, China, where COVID-19 cases were first seen, an average of 45 t/d of medical waste was produced before the COVID-19 pandemic (Yu, Sun, Solvang, & Zhao, 2020). With the increase in COVID-19 cases, the amount of medical waste generated rose 110–150 t/d in mid-February and increased nearly six-fold by 15 March when the pandemic peaked, reaching an average of 247 t/d (Singh, Tang, & Ogunseitan, 2020; Singh, Tang, Zhang, & Zheng, 2020). On the other hand, with the increase of COVID-19 cases, materials such as masks, gloves, linens, glasses, plates and towels used by COVID-19 patients have also increased significantly. Therefore, today an unusual increase is observed in the amount of medical waste generated. Ma et al. (2020) reported that in China, the national medical waste disposal level was 1164.0 t/d until 20 January 2020 and reached 6066.8 t/d on 21 March 2020. With the COVID-19 pandemic, the extraordinary increase in medical waste production has created an important environmental and health problem not only in China but also in many countries (Sangkham, 2020)

Medical wastes consist of a large number of pathogenic bacteria, and considering the infectious agents and viruses within its content, such wastes pose serious health-related and environmental risks (Birpinar et al., 2009; Patwary, O'Hare, & Sarker, 2011; Qi et al., 2018). The unsafe management of medical waste not only pollutes the environment, but also causes the spread of infectious diseases such as HIV / AIDS, hepatitis, typhoid, cholera and respiratory complications, especially coronavirus. Kampf, Todt, Pfaender, and Steinmann (2020) observed that human coronaviruses can remain infectious for up to 9 days on various inanimate surfaces. Considering the COVİD-19 pandemic today, the rapidly increasing amount of medical waste must be safely handled to ensure that it does not pose a greater risk of infection. The main purpose of medical waste logistics is the collection, transportation, temporary storage, and disposal of medical wastes by reducing their volume and quantity without harming the environment and human health. This study aims to propose not only the shortest but also the safest route for medical waste transportation through implementing İstanbul, the most crowded city of Turkey.

According to the WHO, an epidemic is defined as the occurrence of cases of disease that exceed the normal expectation caused by an infectious disease, usually through human-to-human transmission or animal-to-animal transmission (Yu et al., 2020). MWM is an essential part of controlling an infectious epidemic (Kargar, Pourmehdi, & Paydar, 2020). Patwary et al. (2011), approached the subject from an administrative point of view and mentioned the inadequacy of personal protective equipment and storage facilities for collected medical wastes. He et al. (2016), proposed that the most costly and risky process of MWM is the collection of the wastes and inadequacies in this process is likely to incur numerous accidents and financial loss. Singh, Tang, Zhang, and Zheng (2020) stated in their study that in many developing countries, medical waste is dumped in open landfills easily accessible to garbage collectors or animals and collected with municipal solid waste. Sarkodie and Owusu (2020) stated that before the COVID-19 outbreak, more than two billion people worldwide faced difficulties in waste management as they did not have access to waste collection and more than three billion people did not have access to waste disposal. Sangkham (2020) emphasized that some Asian countries still do not follow appropriate waste management strategies and the spread of infectious waste can increase the spread of the coronavirus. These studies reveal the deficiencies and disruptions in the MWM process even in the period before COVID-19 pandemic. Improper management of emerging medical wastes has irreversible effects on human health and the environment. The environmental and vital risks caused by the pandemic process, the extraordinary conditions we are in, have led to the obligation to manage medical waste with correct and safe management.

Determining safety levels in MWM is a very important issue. In the study of Eren and Tuzkaya (2019), MWM stages were determined, and a hierarchical structure was formed. At the top of the hierarchy is the objective of process improvement of MWM. In the lower sections, the criteria for MWM to the disposal facility and the sub-criteria affecting these criteria. With the Analytical Hierarchy Process (AHP) method, the criteria within the hierarchical structure and the sub-criteria affecting these criteria were weighted in order to form a priority scale by paired comparisons. At the same time, the extent to which these criteria were met in hospitals was evaluated by the medical waste managers of hospitals by giving a score of 1–10. Then, in order to obtain the safety scores of the hospitals in the region examined, the safety scores for each hospital were obtained by correlating the weights obtained with the AHP method and the suitability ratings of the hospitals between 1 and 10.

The subject has also been addressed from the financial point of view as the management of medical wastes is costlier than the management of other waste types. Dursun, Karsak, and Karadayi (2011) used fuzzy multi-criteria decision-making methods, and Hong, Zhan, Yu, Hong, and Qi (2018), used LCC (Life cycle cost) and LCA (Life cycle assessment) methods to determine the most effective way for medical wastes' disposal. In both studies, the most suitable and expensive method for disposal was determined as steam sterilization. Ho (2011) used the fuzzy analytical hierarchy process (FAHP) methods, and Hsu, Wu, and Li (2008) used the AHP to choose among the most effective operating medical waste disposal company in Taiwan. By use of AHP and FAHP based methods, they proposed two different models by which they could determine the most suitable medical waste disposal companies in a more systematic and objective way than subjective evaluation methods. A similar work that uses AHP was carried out by Ishtiaq, Khan, and Haq (2018) to choose among the MWM service suppliers in Karachi, the largest city of Pakistan. The results showed that the two most important criteria are waste management costs (by 45.5%), and supplier selection (by 31.5%). The three most important sub-criteria for supplier selection was reported to be the competence of suppliers (10.9%), waste handling costs (14.7%), and storage costs (15.7%).

There are many studies in the literature on the risks of transporting hazardous materials and multi-objective vehicle routing problems. Jozefowiez, Semet, and Talbi (2008) in their study, they examined over thirty existing researches related to multi-objective optimization in routing problems such as vehicle routing problem and traveling salesman problem. They examined the objectives and solutions of the proposed multiobjective algorithms for routing problems. The main objectives in these studies can be listed as objectives related to node/arc activity, objectives related to the tour, objectives related to resources. Multiobjective optimization algorithms are classified as scalar techniques, Pareto methods, non-Pareto, and non-scalar algorithms. As a result, they stated that although multi-objective routing problems have attracted considerable attention in recent years, the number of available publications is small, and this area is still young.

Paredes-Belmar, Bronfman, Marianov, and Latorre-Núñez (2017), using the integer programming method, proposed a new approach to solve the problem of hazardous waste collection in a transport network. In their studies, they aimed to minimize the risk of exposure and transportation costs of the total population affected by the route in case of an accident. The model is sensitive to loading multiple products on the same truck, optimizing both the cost and the population exposed to the risk of hazardous materials. The implementation of the model is based on the transport network of dangerous goods in Santiago, Chile. They have designed a model that can be used appropriately for multiple product loading, including the formulation of an integer programming model that tracks risks along the route followed by trucks and predicts optimal paths across all nodes for risk changes that occur when new waste is added.

In Murray and Chu (2015), a type of problem aimed at minimizing the transport time of trucks and drones was examined. Similar to this study, Ha, Deville, Pham, and Hà (2018), addressed a new variant of Travelling Salesman Problem (TSP) called Travelling Salesman Problem with Drone (TSP-D), which tries to minimize operating costs, including shipping costs, and collection costs that occur when one vehicle has to wait for another. Ha et al. (2018); first formulated the problem mathematically. Then, two algorithms is proposed. The first algorithm (TSP-LS), Murray and Chu (2015) adapted into a TSP-D solution applicable to the TSP solution. The second algorithm, the Greedy Random Adapted Search Procedure (GRASP), is based on a new division procedure that optimally separates any TSP round into the TSP-D solution. Once a TSP-D solution is produced, it is developed through local search operators. Numerical results obtained in different cases and different dimensions and properties of both objective functions are presented. The results showed that the GRASP performed better than TSP-LS.

In the literature, there are very few studies dealing with vehicle routing problems and Medical Waste Collection (MWC). Shih and Chang (2001) developed a computer system to solve the optimization problem that emerged in the MWC problem based on a two-step approach proposed in a different study. In the first stage, a standard vehicle orientation problem is solved to determine the route the collection vehicles will follow. In the second step, a mixed integer programming method is used to assign routes to certain days of the week. The effectiveness of the developed system is presented with an illustrative example for the collection of medical waste of 348 hospitals in Tainan City.

Turkey was also found in three studies that dealt with the routing of Medical Waste Collection Vehicles (MWCV).

The first of these studies, Alumur and Kara (2007) proposed a new model for multi-objective location routing in their research. The proposed model involves some limitations which were observed in the literature but not included in the previous models. The model also provided information on the possible locations of new medical centers, the technologies to be used, the locations of new disposal facilities, and how to treat hazardous waste types with suitable disposal technologies and route them to suitable waste disposal facilities. The model also aimed to minimize the total operating costs and transportation risks. Central Anatolian Region of Turkey was chosen as the research area, and a large scale application of the model was introduced.

Other, Alagoz and Kocasoy (2008b), carried out a work to develop a MWC and transportation system for İstanbul province. Within the scope of the research, cost analysis for existing and estimated optimum transportation routes for collection of healthcare service wastes, temporary storage facilities of healthcare institutions, and transportation of wastes to final disposal areas were investigated, and the most cost-effective route was determined accordingly. Specific software named MapInfo and Roadnet were used for programming and route optimization. The geographical locations of hospitals, the amount of medical wastes generated, waste load-unload processing times, and the capacity of waste collection vehicles were considered for use in the software.

Another, Mete and Serin (2019) studies, Turkey's TRB1 area of Bingöl, Elazığ, Malatya and Tunceli the disposal center to determine the most appropriate location, geographic information systems have proposed a model using a solution approach. The proposed approach is applied in TRB1 between regions in Turkey, 167 MWC center and 5 disposal center. Thus, they determined the shortest distance location for the waste disposal center among 5 different alternative locations. For the most suitable routes between the collection and disposal center of these alternatives; If the disposal center is located in the province of Bingöl, the total journey takes 8.308.406 m, whereas if it is located in the province of Malatya, the total journey takes 5.082.553 m. While the distances for other provinces are in this range, the most suitable location for the disposal center has been determined as the province of Malatya. It has been suggested that minimizing the total distance can also minimize the total risk of medical waste during transportation.

The performed literature survey has shown that there is a limited number of studies addressed the use of vehicle routing models for MWC. In the same research, it was determined that these wastes increased rapidly with the COVID-19 pandemic. There is no study in which medical waste transportation vehicles are integrated with both safety and distance-oriented mathematical modeling. The fact that a similar study specific to Istanbul, which has been chosen as the city of application, has not been done before provides a separate benefit. Based on these literature gaps, a solution approach to the MWCV routing problem was developed and a compromise model focused on minimum distance and maximum safety was tried to be obtained. For medical waste logistics, an application has been made for a sub-region of Istanbul. In the following parts of the study, firstly, solution techniques were given and then the application phase started. In this context, the city of Istanbul was evaluated in terms of subject and the results obtained after the solution of the vehicle routing problem were analyzed.

2. Methodology

2.1. Travelling salesman problem (TSP)

TSP aims to determine the shortest route among $n!$ routes where n represents the number of points with specified distances to each other (Cambazard & Catusse, 2018). In the problem, distance value can be substituted by another factor such as cost, time, etc. for varying problem types, and it is obligatory to visit all points but only once (Kóczy, Földesi, & Tüű-Szabó, 2018).

TSP was formulated by Karl Menger in 1930 (Kóczy et al., 2018). Today, researchers around the world still use this problem to prove the superiority of their optimization method over others (Kóczy et al., 2018; Sun, Karwan, & Diaby, 2018).

TSP can be defined as follows:

$$X_{ij} \begin{cases} 1; & \text{the route from city i to city j} \\ 0; & else \end{cases} \tag{1}$$

where (equation (1)), $X_{ij} = 1$ if the route is from city i to city j, and otherwise $X_{ij} = 0$

TSP can be expressed as follows where c_{ij} is the distance between city i and city j (Cárdenas-Montes, 2018).

$$\min \sum_{i}^{N} \sum_{j}^{N} c_{ij}.x_{ij} \tag{2}$$

Limitations:

$$\sum_{i=1}^{N} x_{ij} = 1 \qquad \forall_j \tag{3}$$

$$\sum_{j=1}^{N} x_{ij} = 1 \qquad \forall_i \tag{4}$$

$$\sum_{j\in S} . \sum_{i\in S} x_{ij} \quad \leq |S| - 1 \quad \forall S\subset N, \quad |S| \geq 2 \tag{5}$$

$$x_{ij} \in \{0,1\} \qquad \forall_{i,j} \tag{6}$$

where; equation (2) is the objective function that aims to minimize the distance for completion of the tour using the shortest possible route. Equation (3) and equation (4) define the limitations that prompt single entry and exit to/from each point. Equation (5) and equation (6) are to avoid possible sub-tours.

In the present work, multi-objective TSP was used for achieving a conciliating solution by simultaneously addressing the shortest tour and the safest tour.

2.2. Membership function

Membership functions provide the basis for both classical and fuzzy sets. In classical set theory, the degree of membership is 0 if the object is not a member of the set, and 1 if it is a full member. In classical sets, the expression that indicates whether a given value × is a member of set A is shown with the following equation (7).

$$X_A : X \rightarrow \{0,1\} \tag{7}$$

The membership of any value × to a classical subset A in a universe X can be mathematically expressed with the following equation (8);

$$X_A(x) = \begin{cases} 0; & x \notin A \\ 1; & x \in A \end{cases} \quad (8)$$

In other words, a number is either a member of a set or not.

Fuzzy set theory, introduced by Zadeh in 1965, is also defined as a set consisting of an infinite number of randomly chosen elements between 0 and 1 (Muhuri & Shukla, 2017; Zadeh, 1965). Zadeh expanded this expression, which has only two degrees of membership, to another expression that can incorporate an infinite number of membership degrees between 0 and 1. Membership function defines the grade of membership of any element to a specified set. Thus, uncertain concepts that are difficult to define are assigned a grade of membership and acquire a level of certainty. This derived membership function $\mu(x)$ is expressed with the following equation (9) (Tepe & Kaya, 2019; Zadeh, 1965).

$$\mu(x) : X \rightarrow [0, 1] \quad (9)$$

The numeric values that the membership function takes are termed as the grade of membership. The types of membership functions can be listed as triangular membership function, trapezoidal membership function, bell-shaped membership function, and gaussian membership function depending on the type of problem (Muhuri & Shukla, 2017). One of the important factors that should be considered during the solution of a problem with fuzzy optimization method is the selection of the type of fuzzy membership function since the suitability of the type of the chosen membership function for the structure of the specified problem has direct effect on the accuracy of the solution (Komal, 2018).

In this paper, the trapezoidal membership function was used for the linear programming problem for which the upper and lower limit values of the objective functions are known.

In the below equation (10) and equation (11) $\lambda = \mu_A(x)$; defines the grade of membership. As $\mu_A(x)$ converges to 1, the grade of membership for element × increases. The value of λ in equation (10) and equation (11) is calculated using the upper and lower limits of the objective function (Ak, 2019).

$$\mu_A(X) = \begin{cases} 0\,; & x \leq a \\ \frac{x-a}{b-a}\,; & a < x < b \\ 1\,; & x \geq b \end{cases} \quad (10)$$

$$\mu_A(X) = \begin{cases} 0\,; & x \geq d \\ \frac{d-x}{d-c}; & c < x < d \\ 1\,; & x \leq c \end{cases} \quad (11)$$

The fuzzy decision or decisions with the highest grade of membership yields the optimum result.

3. Application

3.1. Medical waste management in Istanbul

The first regulation on the management of medical wastes in Turkey is the "Regulation on the Control of Medical Wastes" which was issued in the Official Gazette dated 20.5.1993 and numbered 21586, and the same regulation was amended with the issue dated 22.07.2005, numbered 25,883 in line with the European Union's Environmental Impact Assessment Directives as per European Union membership requirements (Birpinar et al., 2009; Uysal & Tinmaz, 2004). The last amendment and update on the regulation were reissued in the Official Gazette dated 25.01.2017 and numbered 29959. As required by this regulation, metropolitan municipalities in large cities, and municipalities in other cities are liable to establish a waste management plan. In this regard, medical wastes in Istanbul are collected by ISTAC, a subsidiary of the Istanbul Metropolitan Municipality, and these wastes are then transported to Odayeri medical waste incineration and sterilization facility by the same company. The medical wastes generated by hospitals with more than 20 beds and those generated by hospitals with less than 20 beds are collected with different vehicles.

In this work, hospitals with more than 20 beds, are investigated. In the period before COVID-19 pandemic, approximately 30–35 tons of medical wastes are collected daily from 252 hospitals in İstanbul which have more than 20 beds. Considering the COVID-19 pandemic, these data have increased significantly. Ozkaya et al. (2020) stated that in the first half of 2020, 320 to 620 tons of medical waste was collected per week in Istanbul. 161 of these 252 hospitals with more than 20 beds are located in Europe, and 91 are located in Asia. ISTAC provides MWC service in the 11 sub-regions of the European side of Istanbul with 27 licensed vehicles. These 27 vehicles with capacities varying between 10 m^3 and 28 m^3. MWM processes from the collection of medical waste to the disposal are shown in the summarized diagram of MWM shown in Fig. 1.

In the study, we obtained the safety scores, since this step is the same for different hospitals, the disposal phase of the process is excluded from evaluation. The safety scores shown in Fig. 1 were obtained via evaluation of the collection and temporary storage processes and their transportation from the healthcare institution to the disposal facility (Eren & Tuzkaya, 2019).

In the present work, the problem of collection of medical wastes of 15 hospitals by the licensed vehicle of the municipality's subsidiary on a daily basis (7 days of the week) is dealt. A GPS simultaneously followed the routes of the vehicles. However, the vehicle did not have an exact route. The distances between 15 hospitals and Odayeri medical waste incineration and sterilization facility (***H₀***) in kilometers are shown in Table 1.

3.2. Application of safety scores in the travelling salesman problem

In this section, the first objective function optimizing the minimum distance for medical waste transportation and the second objective function for conducting transportation with the highest possible safety are optimized together.

The mathematical model for TSP accomplishing the tour with minimum distance is as follows.

$$Z_{1min} = \sum_{i}^{N}\sum_{j}^{N} d_{ij}.y_{ij} \quad (12)$$

Limitations:

$$\sum_{i=1}^{N} y_{ij} = 1 \qquad \forall_j \quad (13)$$

$$\sum_{j=1}^{N} y_{ij} = 1 \qquad \forall_i \quad (14)$$

$$\sum_{j\in S}.\sum_{i\in S} y_{ij} \quad \leq |S|-1 \quad \forall S\subset N, \quad |S| \geq 2 \quad (15)$$

$$y_{ij} \in \{0,1\} \qquad \forall_{i,j} \quad (16)$$

where; equation (12) is the objective function that enables the collection of medical wastes with the shortest route via minimization of the tour distance. Equation (13) and equation (14) are the limitations prompting that each hospital is to be visited and left once, whereas equation (15) and equation (16) are the limitations written to prevent the possible sub-routes.

The coding and solution of the objective function were performed by Gams 23.5.1 software package. The tour was completed in 188,05 km by

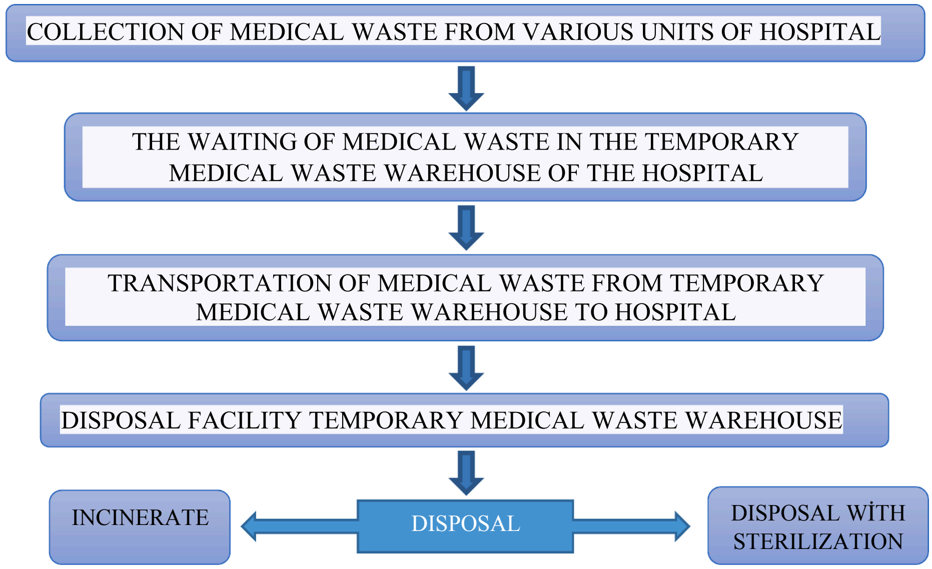

Fig. 1. Summarized diagram of MWM.

Table 1
Hospital distances.

H (km)	H_0	H_1	H_2	H_3	H_4	H_5	H_6	H_7	H_8	H_9	H_{10}	H_{11}	H_{12}	H_{13}	H_{14}	H_{15}
H_0	0	38,7	41,2	42,5	42,8	42,1	44,6	46,5	46,5	49,8	53,5	68,6	72,3	78	80,6	91
H_1	38,7	0	1,8	5,2	5,3	8,8	4,8	6,6	7	10,1	29,9	32,1	37	42,8	45,4	60,4
H_2	41,2	1,8	0	5,2	5,4	9,2	4,4	6,3	6,2	9,8	31	32,6	46,1	43,2	45,8	60,8
H_3	42,5	5,2	5,2	0	0,75	5,2	3,6	6,2	6,2	9,5	26,7	28,3	33,2	39	41,6	64,5
H_4	42,8	5,3	5,4	0,75	0	5,8	2,7	4,4	5,6	9,8	27	28,6	42,1	39,3	41,9	57,4
H_5	42,1	8,8	9,2	5,2	5,8	0	9,6	10,7	10,7	14,8	32	33,6	47,1	44,3	46,9	56
H_6	44,6	4,8	4,4	3,6	2,7	9,6	0	3	3,4	6,7	23,8	25,5	30,4	36,2	38,8	47,9
H_7	46,5	6,6	6,3	6,2	4,4	10,7	3	0	1,6	4,9	24	25,7	39,2	36,3	39	48,1
H_8	46,5	7	6,2	6,2	5,6	10,7	3,4	1,6	0	3,8	24,3	25,9	40,4	36,6	39,2	48,3
H_9	49,8	10,1	9,8	9,5	9,8	14,8	6,7	4,9	3,8	0	18,5	20,2	33,7	30,8	33,5	42,6
H_{10}	53,5	29,9	31	26,7	27	32	23,8	24	24,3	18,5	0	14,2	26,5	23,6	27,4	35,3
H_{11}	68,6	32,1	32,6	28,3	28,6	33,6	25,5	25,7	25,9	20,2	14,2	0	2,3	2,3	2	11,2
H_{12}	72,3	37	46,1	33,2	42,1	47,1	30,4	39,2	40,4	33,7	26,5	2,3	0	3,7	2,5	9
H_{13}	78	42,8	43,2	39	39,3	44,3	36,2	36,3	36,6	30,8	23,6	2,3	3,7	0	1,7	13,6
H_{14}	80,6	45,4	45,8	41,6	41,9	46,9	38,8	39	39,2	33,5	27,4	2	2,5	1,7	0	11
H_{15}	91	60,4	60,8	64,5	57,4	56	47,9	48,1	48,3	42,6	35,3	11,2	9	13,6	11	0

* H_1: Hospital **1,** H_2: Hospital **2,** H_3: Hospital **3,** H_4: Hospital **4,** H_5: Hospital **5,** H_6: Hospital **6,** H_7: Hospital **7,** H_8: Hospital **8,** H_9: Hospital **9,** H_{10}: Hospital **10,** H_{11}: Hospital **11,** H_{12}: Hospital **12,** H_{13}: Hospital **13,** H_{14}: Hospital **14,** H_{15}: Hospital **15.**

following the route $H_0 \rightarrow H_1 \rightarrow H_2 \rightarrow H_5 \rightarrow H_3 \rightarrow H_4 \rightarrow H_6 \rightarrow H_7 \rightarrow H_8 \rightarrow H_9 \rightarrow H_{11} \rightarrow H_{12} \rightarrow H_{15} \rightarrow H_{14} \rightarrow H_{13} \rightarrow H_{10} \rightarrow H_0$ specified for transportation of the wastes from 15 hospitals with the shortest possible distance, as shown in Fig. 2.

MWM safety scores in hospitals obtained from our previous study, Eren and Tuzkaya (2019), are used as input in this article. These values are shown in Table 2.

While determining the hospital safety scores, collection, temporary storage and transportation criteria were established by examining the risk of contamination of viruses in the process of transporting medical waste from the formation to the disposal facility. Under the collection criteria, four sub-criteria have been established: the measures taken against possible effects on hospital staff, patients and third persons (Patient visitors, etc.) while collecting medical wastes, and the collection of medical wastes separately at the source in accordance with the regulation. Under the temporary medical waste storage criteria of the hospitals, three sub-criteria have been established: the volume of the temporary medical waste storage, the convenience of vehicle entry and exit to the warehouse, and the suitability of the warehouse's lighting, impermeable and cooling system. Under the transportation criterion, four sub-criteria have been established as the measures taken on the environmental impact of medical wastes while transporting them to the disposal facility, the population density of the route where the medical wastes are transported, the possible effects on logistics personnel, and the suitability of the measures taken against weather conditions such as snow, rain, etc.

A hierarchical structure has been established with the criteria and sub-criteria created. Then, by applying to the medical waste officers of 15 hospitals in the region we examined in Istanbul province, comparison matrices were created and weighted for each criterion and sub-criteria in a hierarchical structure with the AHP method. At the same time, the medical waste officers of 15 hospitals were asked about the

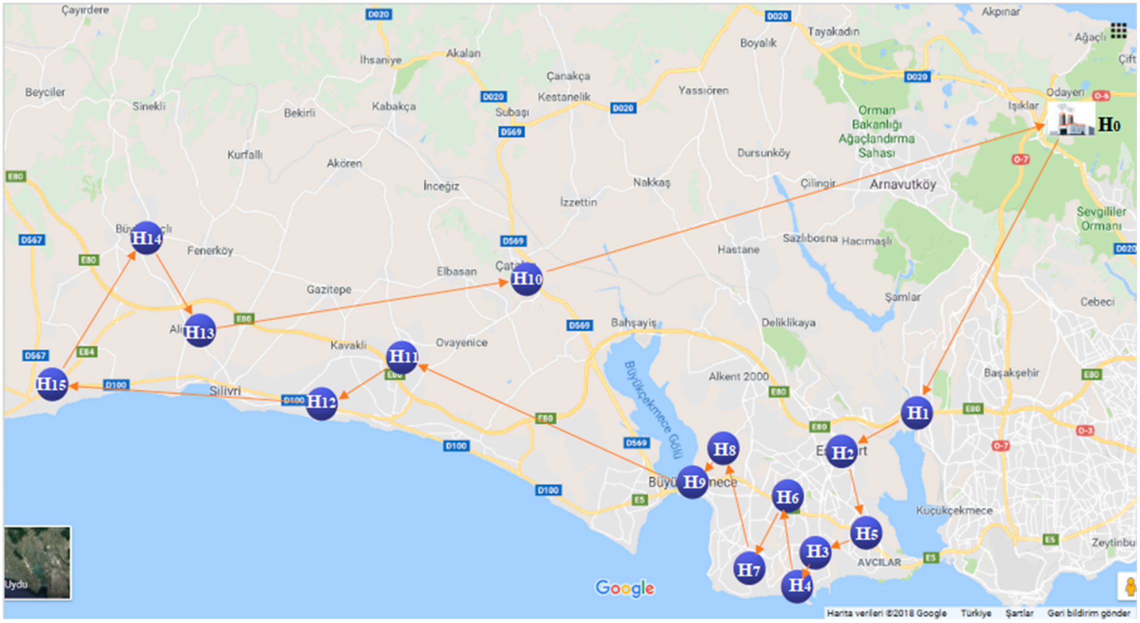

Fig. 2. The route followed by the MWC vehicle for completing the tour with minimum distance.

Table 2
Hospital safety scores (Eren & Tuzkaya, 2019).

Hospital (H)	H_1	H_2	H_3	H_4	H_5	H_6	H_7	H_8	H_9	H_{10}	H_{11}	H_{12}	H_{13}	H_{14}	H_{15}
Hospital safety scores (S)	**5,02**	**7,72**	**6,67**	**7,68**	**5,42**	**8,75**	**6,28**	**5,66**	**8,01**	**6**	**6,99**	**7,13**	**9,01**	**6,03**	**7,17**

compliance of the sub-criteria within the hierarchical structure in terms of the safety of medical waste logistics in their hospitals and scored between 1 and 10. Safety scores were obtained for each hospital by establishing a relationship between the general weights of the sub criteria obtained by the AHP method and the scored hospitals.

The obtained security scores are used in the traveling salesman problem, which has been made multi-purpose, and an objective function based on the safety of medical waste logistics has been established.

The safety scores the objective function for traveling salesman completing the tour with maximum safety is as follows;

$$Z_{2max} = \sum_{i}^{N}\sum_{j}^{N} S_{ij}.x_{ij} \tag{17}$$

Limitations:

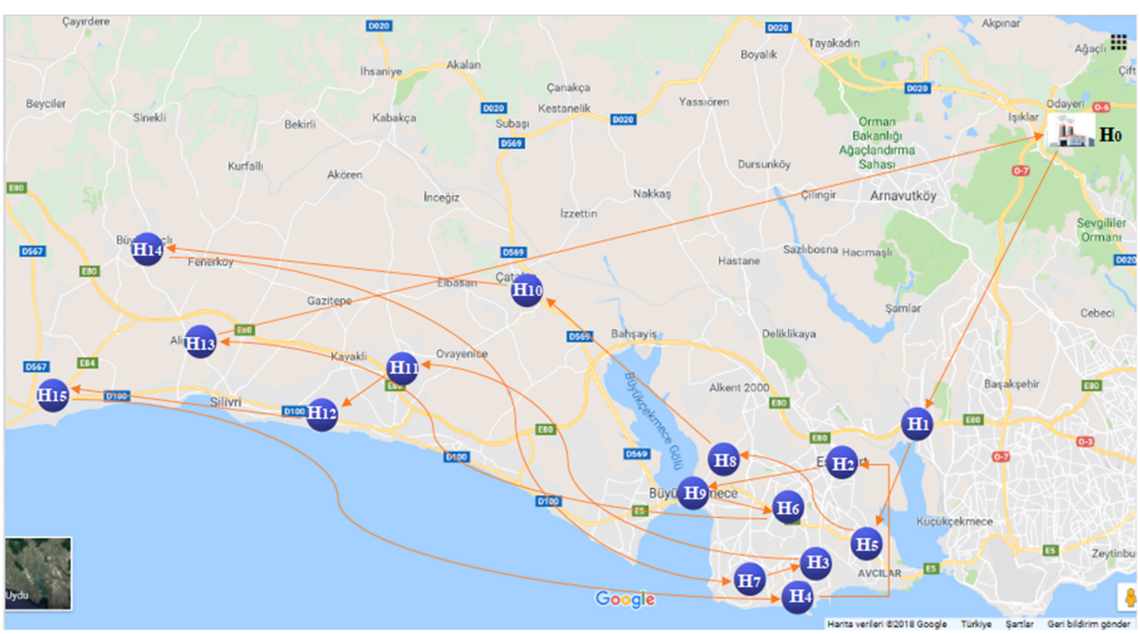

Fig. 3. The route followed by the MWC vehicle to achieve maximum safety score.

$$\sum_{i=1}^{N} x_{ij} = 1 \qquad \forall_j \tag{18}$$

$$\sum_{j=1}^{N} x_{ij} = 1 \qquad \forall_i \tag{19}$$

$$\sum_{j\in S}\cdot\sum_{i\in S} x_{ij} \quad \le |S| - 1 \quad \forall S\subset N, \quad |S| \ge 2 \tag{20}$$

$$x_{ij} \in \{0,1\} \qquad \forall_{i,j} \tag{21}$$

where; equation (17) is the objective function for ensuring transportation of medical wastes with maximum safety through maximizing the safety scores. Equation (18) and equation (19) impose the limitations that each hospital is to be visited and left for once, whereas equation (20) and equation (21) are for preventing the possible sub-tours.

The route for transportation of medical wastes from 15 hospitals with maximum safety is $H_0 \rightarrow H_1 \rightarrow H_5 \rightarrow H_8 \rightarrow H_{10} \rightarrow H_{14} \rightarrow H_7 \rightarrow H_3 \rightarrow H_{11} \rightarrow H_{12} \rightarrow H_{15} \rightarrow H_4 \rightarrow H_2 \rightarrow H_9 \rightarrow H_6 \rightarrow H_{13} \rightarrow H_0$, where hospitals with low safety scores were prioritized. Thus the tour was completed with a safety score of 104.54. The route is shown in Fig. 3.

3.3. Optimization with membership functions

The calculation of the optimum values for the objective functions was followed by the solution stage in which a linear programming model approach was used. Deriving the membership functions for each objective requires determination of the lower and upper limit values that the objective functions can take on. Accordingly, the routing values obtained for the solution of each objective function were plugged in the other objective function, which yielded the values in Table 3.

The best $W_{1m}{}^{min} = 188{,}05$ and the worst $W_{1m}{}^{max} = 388{,}2$ membership functions of the 1st objective functions that are to ensure transportation of medical wastes with minimum distance, were determined as follows (equation (22)).

$$\mu_{1m}(W_{1m}) = \begin{cases} 0 & ; W_{1m} \ge W_{1m}{}^{max} \\ \dfrac{W_{1m}{}^{max} - W_{1m}}{W_{1m}{}^{max} - W_{1m}{}^{min}} & ; W_{1m}{}^{min} < W_{1m} < W_{1m}{}^{max} \\ 1 & ; W_{1m} \le W_{1m}{}^{min} \end{cases} \tag{22}$$

The best $W_{1g}{}^{max} = 104{,}54$ and the worst $W_{1g}{}^{min} = 32{,}32$ membership functions of the 2nd objective functions that are to ensure transportation of medical wastes with minimum distance, were determined as follows (equation (23)).

$$\mu_{1g}(W_{1g}) = \begin{cases} 0 & ; W_{1g} \le W_{1g}{}^{min} \\ \dfrac{W_{1g} - W_{1g}{}^{min}}{W_{1g}{}^{max} - W_{1g}{}^{min}} & ; W_{1g}{}^{min} < W_{1g} < W_{1g}{}^{max} \\ 1 & ; W_{1g} \ge W_{1g}{}^{max} \end{cases} \tag{23}$$

After adding the constraints of membership functions belong to each objective function should be lower than or equal to the λ value, the model has solved again for the remaining constraints set. The resulting λ values (equation (24)) yields the best compromise solution. The resulting λ values (equation (24)) yields the best conciliating solution via fuzzy optimum decision logic.

$$\max \lambda \tag{24}$$

Limitations:

$$W_{1m} = \sum_{i}^{N}\sum_{j}^{N} d_{ij}.y_{ij} \tag{25}$$

$$W_{1g} = \sum_{i}^{N}\sum_{j}^{N} S_{ij}.x_{ij} \tag{26}$$

$$\frac{W_{1m}{}^{max} - W_{1m}}{W_{1m}{}^{max} - W_{1m}{}^{min}} \le \lambda \tag{27}$$

$$\frac{W_{1g} - W_{1g}{}^{min}}{W_{1g}{}^{max} - W_{1g}{}^{min}} \le \lambda \tag{28}$$

$$\sum_{i=1}^{N} x_{ij} = 1 \qquad \forall_j \tag{29}$$

$$\sum_{j=1}^{N} x_{ij} = 1 \qquad \forall_i \tag{30}$$

$$\sum_{j\in S}\cdot\sum_{i\in S} x_{ij} \quad \le |S| - 1 \quad \forall S\subset N, \quad |S| \ge 2 \tag{31}$$

$$y_{ij} \in \{0,1\} \qquad \forall_{i,j} \tag{32}$$

The general satisfaction level (λ) for the obtained solution was found as 0.644. The values of the objective functions and corresponding satisfaction levels are shown in Table 3.

Thus, the two objective functions compromised with each other resulting in the route $H_0 \rightarrow H_1 \rightarrow H_5 \rightarrow H_8 \rightarrow H_{10} \rightarrow H_{11} \rightarrow H_{12} \rightarrow H_{15} \rightarrow H_{13} \rightarrow H_{14} \rightarrow H_7 \rightarrow H_3 \rightarrow H_4 \rightarrow H_2 \rightarrow H_9 \rightarrow H_6 \rightarrow H_0$shown in Fig. 4 with 235,75 km distance and a safety score of 78.83.

4. Results

As shown in Fig. 2, with the sole consideration of minimum distance, the MWCV completes its route with 188.05 km following the route: $H_0 \rightarrow H_1 \rightarrow H_2 \rightarrow H_5 \rightarrow H_3 \rightarrow H_4 \rightarrow H_6 \rightarrow H_7 \rightarrow H_8 \rightarrow H_9 \rightarrow H_{11} \rightarrow H_{12} \rightarrow H_{15} \rightarrow H_{14} \rightarrow H_{13} \rightarrow H_{10} \rightarrow H_0$.However, this route ends up with a significantly low safety score (32.32).

As shown in Fig. 3, ın the case of sole consideration of safety, the same vehicle follows the route: $H_0 \rightarrow H_1 \rightarrow H_5 \rightarrow H_8 \rightarrow H_{10} \rightarrow H_{14} \rightarrow H_7 \rightarrow H_3 \rightarrow H_{11} \rightarrow H_{12} \rightarrow H_{15} \rightarrow H_4 \rightarrow H_2 \rightarrow H_9 \rightarrow H_6 \rightarrow H_{13} \rightarrow H_0$which yields a safety score of 104.56. In this case, however, the distance covered by the MWCV reaches 388,2 km. This distance poses a high risk for the environment and human health, in addition to its significantly high cost.

As shown in Fig. 4, the conciliating solution that we obtained in this work resulted in a distance of 235.75 km with a safety score of 78.83 through following the route: $H_0 \rightarrow H_1 \rightarrow H_5 \rightarrow H_8 \rightarrow H_{10} \rightarrow H_{11} \rightarrow H_{12} \rightarrow H_{15} \rightarrow H_{13} \rightarrow H_{14} \rightarrow H_7 \rightarrow H_3 \rightarrow H_4 \rightarrow H_2 \rightarrow H_9 \rightarrow H_6 \rightarrow H_0$. With this route, we compromised on distance by a 47.7 km increase as per the 1st objective function aiming minimum distance in exchange for an increase in the safety score by 46.51. This is quite a significant increase in terms of the safety of MWM.

Table 3
Values of the objective functions and optimum result.

	Min. distance (km) Max. safety (S)	Result depending on the other objective	Optimum Result	The general satisfaction level (λ)
1. **Objective function (Z_{1min})**	188,05	388,2	235,75	0,644
2. **Objective function (Z_{2max})**	104,54	32,32	78,83	

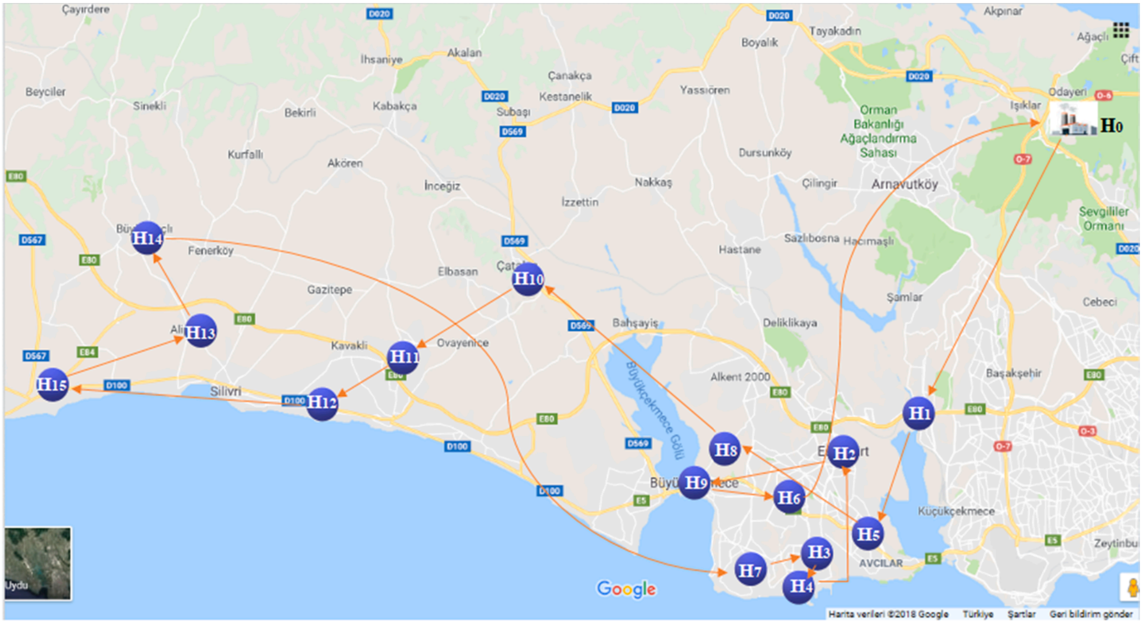

Fig. 4. The Optimum tour of MWC vehicle.

After leaving the disposal facility represented with H_0, the MWCV firstly visited hospital H_1 with the lowest safety score (5.02) in consideration of the distance and completed its route by respectively visiting the hospitals with safety scores 5,02→5,42→5,66→6→6,99→7,13→7,17→9, 01also taking into account the distances between the hospitals, thus completing its departure course. Likewise, during the return course, after leaving hospital H_{13}, the vehicle proceeded with H_{14} with the lowest safety score (6.03) among the remaining hospitals, and respectively visited the hospitals with safety scores 6, 03→6, 28→6, 67→7, 68→7, 72→8, 01→8, 75to complete its tour by returning point H_0. This way, in both departure and return tours, both distance and safety were considered by prioritizing the hospitals with low safety scores in additional consideration of distance, thus enabling the collection of medical wastes with the shortest distance and highest safety.

In Fig. 5, membership function of the 1st obj function, different values from 1 to 0 are given from large to small, the results of the goal functions and the max λ value are analyzed.

For example, membership function of the 1st obj function, when the value of 0.95 is given, the MWCV completed the tour with a distance of 193.35 km and a safety score of 39.48. In addition, this vehicle has followed the route: $H_0 \rightarrow H_{10} \rightarrow H_{11} \rightarrow H_{12} \rightarrow H_{15} \rightarrow H_{14} \rightarrow H_{13} \rightarrow H_9 \rightarrow H_8 \rightarrow H_7 \rightarrow H_6 \rightarrow H_3 \rightarrow H_4 \rightarrow H_2 \rightarrow H_1 \rightarrow H_5 \rightarrow H_0$. When we compare this route with the route we obtained in the compromised solution given in Table 3, the route taken by the MWCV decreased by 42.4 km and decreased the safety score by 39.35. In this way, MWCV, more distance-oriented collect medical waste.

In Fig. 6, membership function of the 2nd obj function, different values from 1 to 0 are given from large to small, the results of the goal functions and the max λ value are analyzed.

For example, membership function of the 2nd obj function, when the value 0.8 is given, the MWCV completed the tour with a distance of 312.9 km and a safety score of 93.52. In addition, this vehicle followed the route: $H_0 \rightarrow H_1 \rightarrow H_5 \rightarrow H_8 \rightarrow H_{10} \rightarrow H_{11} \rightarrow H_{12} \rightarrow H_{15} \rightarrow H_4 \rightarrow H_2 \rightarrow H_9 \rightarrow H_6 \rightarrow H_{13} \rightarrow H_{14} \rightarrow H_7 \rightarrow H_3 \rightarrow H_0$. When we compare this route with the

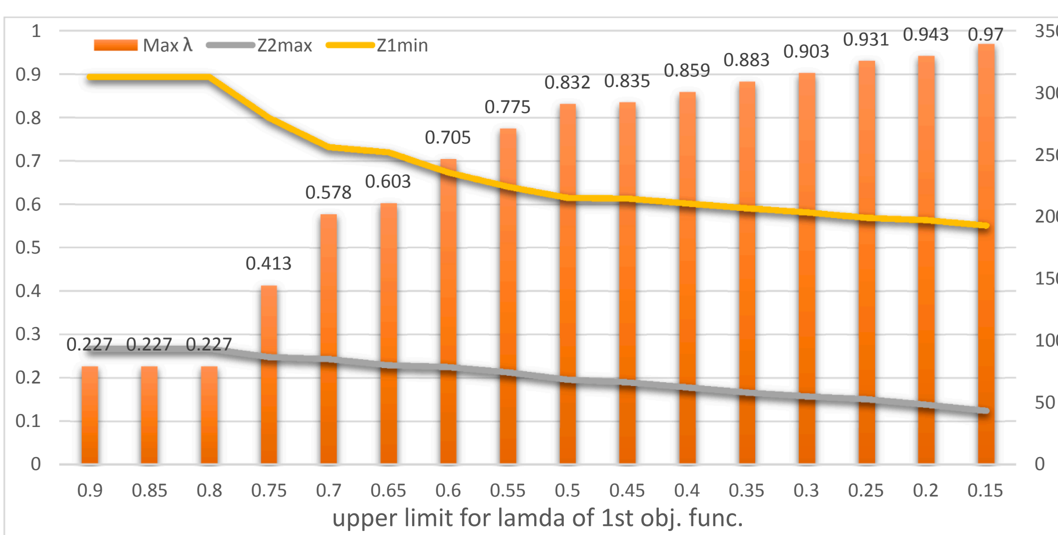

Fig. 5. Membership function analysis of 1st obj function.

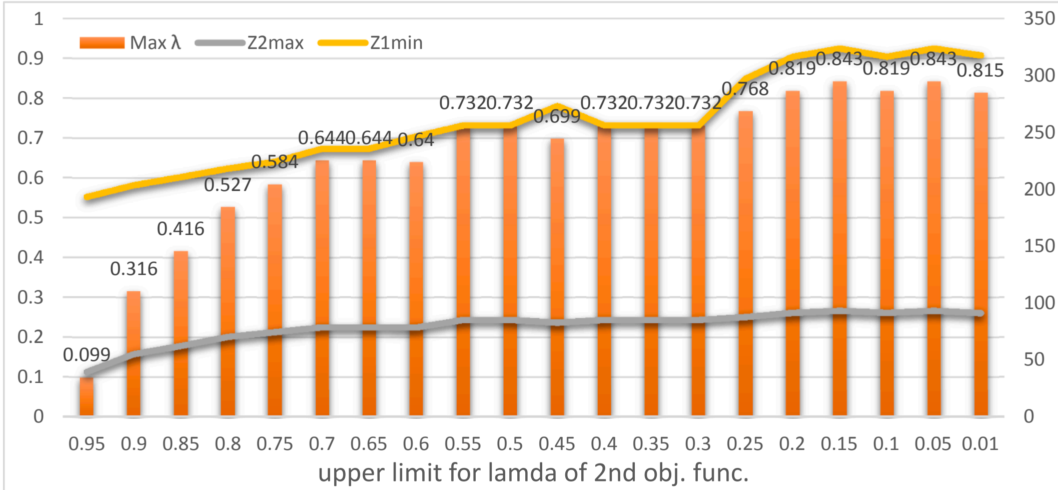

Fig. 6. Membership function analysis of 2nd obj function.

route we obtained in the compromised solution given in Table 3, the route followed by the MWCV increased by 77.15 km and increased the safety score by 14.69. In this way, MWCV, more safety-oriented collect medical waste.

5. Conclusions

Due to Covid-19 also currently produces more medical waste. In addition, if the number of COVID-19 cases continues to increase in this way, we may face even greater dangers from medical waste in the coming days. In this work, a model is proposed for the transportation of medical wastes with the safest and shortest possible route within the city of Istanbul, which is the most crowded province of Turkey.

MWM safety scores used in this study were obtained in the Eren and Tuzkaya (2019) study in the literature. The obtained safety scores were used in the multi-objective TSP to derive two objective functions, which are based on MWM safety and total transportation distance. The membership function approach was used for these objective functions to build a compromising model. A conciliating solution for both distance and safety scores was obtained by solving the model. In this way, medical waste was transported in the shortest safe way.

As a result, the model we proposed also offered the opportunity to use distance priority or safety score priority. In this way, safety is the priority when we want medical waste to be transported more safely, and on the contrary, when we want it to be transported at a shorter distance, it provides the opportunity to be transported with priority. Membership function of the 1st obj function, when the value of 0.95 is given, when compared with our distance solution obtained in Table 3, it is 49.9%, while the safety score has decreased, the distance has only decreased by 17.9%. Given 0.8 membership function of the 2nd obj function, compared to our distance solution obtained in Table 3, the distance increased by 32.7%, while the safety score increased only by 18.6%. These results show that the values we obtained in our compromised solution are more optimal than other solutions.

This model proposed for transportation of medical wastes with maximum safety and minimum distance within the city of Istanbul has a very flexible structure, which enables its implementation on diverse regions and sectors.

In this study, the problem of medical waste transportation is considered as one vehicle, one collection area and 15 hospitals. However, this problem can be considered as a multi-vehicle, single collection area and much more hospitals in future studies.

CRediT authorship contribution statement

Emre Eren: Software, Investigation, Resources, Data curation, Writing - original draft, Writing - review & editing, Visualization. **Umut Rıfat Tuzkaya:** Conceptualization, Methodology, Validation, Formal analysis, Supervision.

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