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Collection of recyclable wastes within the scope of the Zero Waste project: heterogeneous multi-vehicle routing case in Kirikkale

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Abstract There is an increase in the amount of resource use due to the rise in population, urbanization, and industrialization. Also, the amount of waste increases due to an increase in consumption and resource use. Countries are developing new policies depending on both decreasing resources and environmental problems caused by waste. The "Zero Waste" project was launched to recycle waste and to reduce environmental pollution in Turkey. The project aims to separate recyclable waste at its source and recycle them. One of the problems encountered in the implementation of the project is collecting the waste from temporary storage areas. In this study, the problem of transportation of wastes from temporary warehouses to the main warehouse was discussed in Kırıkkale/Turkey. A three-step solution approach has been proposed to the solution of the problem. In the first stage, the amounts of waste generated at the addresses to collect were estimated. In the second stage, the addresses to be visited are classified with an approach based on Pareto analysis according to the calculated waste amounts. According to this classification, it is planned which addresses will be visited on which day of the week. At the last stage, the problem is modeled as a heterogeneous multi-vehicle routing problem, which also takes into account the daily working hours and vehicle capacity constraints. According to the result of the mathematical model, the number of vehicles needed for waste collection, the types of vehicles, and the routes of the vehicles were found. Considering the implementation stages of the Zero Waste project, three different case studies are handled for Kırıkkale. These case studies have been solved by considering different waste rates. According to the results, the waste collection plan was made economically by visiting fewer spots in a week.

Keywords Waste management · Recycling · Zero waste · Vehicle routing · Heterogeneous vehicles

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Introductıon

Waste is called any kind of substance that is harmful to the environment and is intended to be disposed of by the consumer because of being useless (Uzunoğlu 2014). Waste management, which is a form of control to get rid of waste, contains the operations such as reduction of waste at source, separation, collection, temporary storage, intermediate storage, recovery, transportation, disposal, and control after disposal processes. The priority of waste management is to prevent waste generation, and if it is not possible, to minimize the amount of waste. Then, reuse, recycling, energy recovery, and eliminating are intended (Yalçın Çelik and Demirarslan 2013).

Interest in zero waste, an approach to waste management, has been increasing in recent years. Zero waste is first used in the name of a company as a term in the USA in the mid-1970s. It is a new waste management strategy that demands a carbon-neutral life cycle in production and consumption. Zero waste management means the reduction of waste to zero and so ensuring its sustainability. Saving large quantities is done by minimizing waste, even during production with Zero Waste Management. If waste is generated, it is also within the objectives to recover the waste correctly (Er 2012).

There are some problems encountered in waste management. One of them is the process of collecting the waste to the recycling centers or temporary storage areas with minimum cost. Studies show that transportation costs represent 95% of recycling costs (Reed et al. 2014). Therefore, the planning of transportation activities is of great importance. The collection of wastes from waste management is an exemplary work area of the vehicle routing problem (VRP). VRP consists of routing of a vehicle set starting from the main depot and visiting customers in a particular order and returning to the main depot (Düzakın and Demircioğlu 2009). Various studies are carried out in Turkey on waste management. The Zero Waste project, initiated in 2017, is one of them. In this project, it is aimed to prevent wastage and to use resources more efficiently. It is intended to implement in all public institutions/organizations, educational institutions, hospitals, shopping centers, and large workplaces. Then it is aimed to put into practice in all of Turkey until 2023 and to recycle 35% of waste (sifiratik.gov.tr).

In this study, the collection of recyclable wastes and transportation to the main warehouse were discussed within the scope of the Zero Waste project in Kırıkkale. The amounts of the recyclable waste in the addresses were estimated and the addresses were classified based on recyclable waste amounts with Pareto analysis method. The weekly visit plan was made according to the classification obtained with the Pareto analysis results. The collection of recyclable wastes problem was considered heterogeneous vehicle routing problem (HVRP). The time taken for the waste collection was taken into consideration and the waste collection was ensured during daily working hours in the solution to this problem. For each weekday, the types of vehicles to be used, the number of vehicles, and their routes were found.

The remainder of this paper is organized as follows. In the literature review is given related to zero waste, waste collection, and VRP. Waste management, the zero waste concepts, vehicle routing problems, and case studies are mentioned in the "Materials and methods" section. Numerical results and discussion are given and the results and suggestions conclude this paper.

Literature review

The studies in the literature have been searched by taking into consideration two topics. Firstly, a research has been carried out on zero waste, which is discussed in the study. The studies in the literature are evaluated according to the types of waste studied. Secondly, studies that include both waste collection and vehicle routing problems are examined. These studies are evaluated according to the solution methods, waste types, and whether the vehicles in the fleet are homogeneous or heterogeneous. The studies on zero waste are given in Table 1.

Rajanikam and Poyyamoli (2014), Song et al. (2015), Laštůvka et al. (2016), and Ayeleru et al. (2018) studied on solid wastes. These studies are generally based on analysis and evaluations that have been made regarding the solid waste characterization in the studied area. Rajanikam and Poyyamoli (2014) have aimed to design a sustainable waste management system on a university campus. On the other hand, Song et al. (2015) analyzed the challenges and opportunities of converting traditional waste management into zero waste vision. Also, they analyzed the challenges arising from solid wastes, zero waste practices, and discussed the zero waste strategy. In another study, Laštůvka et al. (2016) aimed to evaluate the use of non-recyclable waste parts. Ayeleru et al. (2018) have made waste characterization depending on the production of municipal solid wastes to be used in solid waste management.

In addition to the studies on solid wastes, studies on recyclable wastes such as paper, glass, plastic, metal, wood, electronic wastes, and domestic wastes are included in the literature. Matete and Trois (2008) and Cole et al. (2014) considered a case study on the development of a zero waste strategy for a domestic waste management system. Sharma et al. (2019) examined the effects of paper and plastic waste properties on quality and recycling rates and studied on the technical feasibility of zero waste. Yang et al. (2017) worked on

Table 1 Studies related to the zero-waste

	Solid Waste	Metal	Plastic	Glass	Paper	Agricultural Waste	Industrial Waste	Domestic Waste	Waste Battery	Electronic Waste	Phosphorus, Protein, Chitin	Liquid Waste	Research
Mason et al. (2003)													X
Dileep (2007)		X	X	X	X								
Matete and Trois (2008)								X					
Yaman and Olhan (2010)													X
Zaman and Lehmann (2011)													X
Zaman and Lehmann (2013)													X
Usapein and Chavalparit (2014)							X						
Cole et al. (2014)								X					
Rajanikam and Poyyamoli (2014)	X												
Song et al. (2015)	X												
Yoo and Yi (2015)													X
Marinos and Mishra (2015)									X				
Lin and Chiu (2015)									X				
Jaiswal et al. (2015)										X			
Zaman (2016)													X
Laštůvka et al. (2016)	X												
Ebrahimi and North (2017)													X
Phuong et al. (2017)											X		
Yang et al. (2017)		X											
Sun et al. (2017)										X			
Ayeleru et al. (2018)	X												
Sommerfeld et al. (2018)		X											
Alakaş et al. (2018)		X	X	X	X								
Bhattacharyya (2019)		X											
Zhao et al. (2019)		X											
Mishra et al. (2019)												X	
Rocha-Meneses et al. (2019)												X	

Table 1 (continued)

	Solid Waste	Metal	Plastic	Glass	Paper	Agricultural Waste	Industrial Waste	Domestic Waste	Waste Battery	Electronic Waste	Phosphorus, Protein, Chitin	Liquid Waste	Research
Sharma et al. (2019)			X		X								
Duc et al. (2019)						X							
Marín et al. (2019)						X							
Smol (2019)											X		
Amato et al. (2019)										X			
Yektiningsih et al. (2019)						X							
Atia et al. (2019)									X				
Romano et al. (2019)													X
Ma et al. (2019)												X	
Önal et al. (2019)													X
Copani et al. (2019)										X			

the process of producing steel again by preventing the waste of fly ash from electric arc furnaces. Sommerfeld et al. (2018) examined the use of slag containing manganese content and obtaining precious metal within the scope of zero waste in their studies. Bhattacharyya (2019) investigated the availability of a new technology called RECYRON in the reuse of waste metals. Zhao et al. (2019) developed a zero waste recycling method for obtaining nickel from nickel-containing components by direct reduction and magnetic separation methods in their study. Alakaş et al. (2018) estimated demand for the collection of recyclable waste such as paper, glass, plastic, and metal and then tried to find the most cost-effective waste collection routes. Jaiswal et al. (2015), Sun et al. (2017), Amato et al. (2019), and Copani et al. (2019) conducted studies on electronic waste. In these studies, Amato et al. (2019) studied on recycling of expired LCD screens, and Sun et al. (2017) and Copani et al. (2019) have tried to develop different methods on the recycling of critical metals from electronic waste. Marinos and Mishra (2015), Lin and Chiu (2015), and Atia et al. (2019) studied on waste batteries. They have introduced new methods for the recycling of waste batteries in the context of zero waste and made analyses. There are also studies on agricultural waste in the context of zero waste by Marin et al. (2019), Duc et al. (2019), and Yektiningsih et al. (2019).

Apart from the studies on solid wastes, there are also some studies on liquid wastes by Mishra et al. (2019), Rocha-Meneses et al. (2019), and Ma et al. (2019). In addition to these studies, Phuong et al. (2017) studied obtaining protein and chitin and Smol (2019) studied phosphorus production. Apart from such studies on zero waste, there are also studies focused on examination/evaluation (Mason et al. 2003; Yaman and Olhan 2010; Zaman and Lehmann 2011; Zaman and Lehmann 2013; Yoo and Yi 2015; Zaman 2016; Ebrahimi and North 2017; Romano et al. 2019; Önal et al. 2019).

Waste collection is an example of VRP. Most of the waste collection problems using VRP have been related to solid wastes and their types. The studies that take into account both waste collection and vehicle routing problems together are given in Table 2.

Most of the researchers studied solid wastes and types of solid waste, and the problems are addressed as a multi-vehicle VRP in many studies. However, Bogh et al. (2014) and Baran (2017) studies are marked with (-) because they are not multi-vehicle. Also, Cattaruzza et al. (2016) and Tu et al. (2017) have not provided any information on the waste type. According to literature research, researchers prefer heuristic methods (H.M.) more than mathematical methods (M.M.) in problem-solving. In addition, the routing problems are solved mainly by homogeneous vehicle fleet. There are also many studies solved by both heuristic and mathematical solution methods. Considering the studies solved by heuristic methods, the number of studies used homogeneous vehicle fleet and heterogeneous vehicle fleet are approximately equal. However, homogeneous VRP is preferred in about 70% of the studies in the problems solved by mathematical methods. In Ramos et al. (2014a), Pareto-optimal method aims to support the tactical and operational planning decisions of reverse logistics systems by considering economic, environmental, and social objectives.

In this study, the estimates of waste quantities are calculated by taking into account the number of people present at the addresses, the daily duration of the people at the addresses, and the recyclable waste percentages within the total waste amount. Addresses are classified using calculated waste estimates and a weekly visit plan is made based on this classification. To the best of the authors' knowledge, this is the first study to classify the addresses where the waste will be collected with Pareto analysis. According to the weekly plan, the number of vehicles needed and the vehicle types were found with a mathematical model for each weekday. Consequently, the most significant contribution of the study is to propose a holistic approach to the processes from the demand estimation of the waste amount to transportation of the waste to the warehouse, within the scope of zero waste.

Materials and methods

Waste management and zero waste

Waste management is the application that deals with the process from the collection stage to the disposal stage with certain methods without harming the society and the environment (Palabıyık 1998). The primary purpose of waste management is to minimize the generation of new waste and to reduce the harm of wastes to environmental and human health. In accordance with this purpose, the waste management hierarchy in Fig. 1 that is determined by EU legislation is followed and the waste problem is tackled. According to the waste management hierarchy, first of all, preventions should be taken to avoid waste. Two other proposed options are reducing waste generation at its source and reusing it in the production of another product. Recycling and recovery are two other preferred methods to re-evaluate the products used. Incineration is not highly recommended as it causes waste to be disposed of in waste management. Finally, waste disposal is the last method to be preferred for waste management.

The zero waste approach, a new approach in waste management that has emerged in recent years, is increasingly being adopted. The zero waste approach aims at zero waste production throughout the life cycle of the products and 100% efficient use of energy, raw materials, and human resources. The essence of this approach is the production cycle and the recycling cycle in nature. In this cycle, all waste is the source of another production; therefore, no waste is generated (Yaman and Olhan 2010). If the materials occurred by the use of people are not separated at their source and are not evaluated under the zero waste approach, many valuable wastes can make each other worthless as a result of mixed contact with each other (Er 2012).

Vehicle routing problem

The VRP was proposed by Dantzig and Ramser in 1959. VRP is the determination of the vehicle routes that serve customers whose demands are already known, are starting from a depot and ending in the same depot, and are ensuring minimum cost or distance. Examples of vehicle routing problems can be given as distribution of products or services from one or more depots to various customer locations, transportation of raw materials, semi-finished and finished products, delivery of beverages to markets, fuel, milk, products etc. in internet shopping, postal services, or waste collection 2009).

The most basic form of VRP is called classical VRP or general VRP, and the problem varies according to the adding constraints. The VRP classification given in Fig. 2 is developed based on the Koç (2012) study. The figure is designed according to the criteria of road condition, routing condition, environmental conditions, constraints, number of depots, and vehicles.

In this study, a periodic heterogeneous multi-vehicle vehicle routing problem (PHMVRP) is discussed. PHMVRP is a variant of heterogeneous multi-vehicle VRP, which is repeated periodically, and customers can be visited more than once. The number of services to be

Table 2 Studies related to the waste collection and the VRP

	Solution Method		Vehicle Fleet		Type of waste
	H.M.	M.M.	Homogeneous	Heterogeneous	
Shih and Lin (1999)		X	X		Medical waste
Tung and Pinnoi (2000)	X		X		Domestic waste
Shih and Chang (2001)		X	X		Medical waste
Demir et al. (2001)		X		X	Domestic waste
Apaydın (2005)		X	X		Solid waste
Kim et al. (2006)	X		X		Commercial waste
Bianchessi and Righini (2007)	X		X		Solid waste
Kaçtıoğlu and Şengül (2010)		X	X		Paper, plastic, glass, metal, non-recyclable waste
Mar-Ortiz et al. (2011)	X			X	Electronic waste
Faccio et al. (2011)	X		X	X	Domestic waste
Demirel et al. (2011)	X	X	X		Solid waste
Geetha et al. (2012)	X			X	Solid waste
Güvez et al. (2012)		X	X		Medical waste
Wy et al. (2013)	X			X	Solid waste
Mar-Ortiz et al. (2013)	X			X	Electronic waste
Ramos et al. (2013)		X	X		Waste oil
Benjamin and Beasley (2013)	X		X		Commercial waste
Wy and Kim (2013)	X		X		Solid waste
Hemmelmayr et al. (2013)	X	X	X		Glass, plastic, paper, metal
Alaykıran and Güner (2013)		X		X	Solid waste
Bing et al. (2014)	X			X	Plastic
Ramos et al. (2014a)		X	X		Glass, plastic, metal
Ramos et al. (2014b)		X		X	Glass, plastic, metal
Reed et al. (2014)	X			X	Glass, plastic, metal
Hemmelmayr et al. (2014)	X	X	X		Solid waste
Son (2014)	X			X	Solid waste
Bogh et al. (2014)	X		–	–	Paper, glass
McLeod et al. (2014)	X			X	Clothing waste
Doğan and Kırda (2014)	X			X	Medical waste
Huang and Lin (2015)	X	X	X		Solid waste
Henke et al. (2015)	X		X		Glass
Miranda et al. (2015)		X	X		Solid waste
Anagnostopoulos et al. (2015)	X		X		Hazardous waste
Köse et al. (2015)		X		X	Paper, plastic, metal, aluminum, glass
Lu et al. (2015)	X			X	Solid waste
Delgado-Antequera et al. (2016)	X		X		Solid waste
Iwańkowicz and Sekulski (2016)	X		X		Solid waste
Markov et al. (2016)	X	X		X	Solid waste
Chari et al. (2016)	X	X		X	Glass, plastic, paper, metal
Cattaruzza et al. (2016)			X		–
Laureri et al. (2016)	X		X		Liquid waste
Nowakowski et al. (2017)	X			X	Electronic waste
Gilardino et al. (2017)		X	X		Solid waste

Table 2 (continued)

	Solution Method		Vehicle Fleet		Type of waste
	H.M.	M.M.	Homogeneous	Heterogeneous	
Sackmann et al. (2017)	X		X		Solid waste
Arias and Jiménez (2017)	X			X	Waste oil
Akhtar et al. (2017)	X		X		Solid waste
Nowakowski (2017)	X			X	Electronic waste
Gruler et al. (2017)	X		X		Solid waste
Baran (2017)		X	–	–	Medical waste
Tu et al. (2017)	X		X		–
Rabbani et al. (2018)		X		X	Hazardous waste
Nowakowski et al. (2018)	X			X	Electronic waste
Vu et al. (2018)		X	X		Solid waste
Armington and Chen (2018)		X	X		Domestic waste
Hannan et al. (2018)	X		X		Solid waste
Li et al. (2018)	X		X		Solid waste
Shah et al. (2018)		X		X	Plastic
López-Sánchez et al. (2018)	X		X		Solid waste
Cingöz et al. (2018)		X	X		Solid waste
Azadeh and Farrokhi-Asl (2019)	X			X	Solid waste
Molina et al. (2019)	X			X	Solid waste
Louati et al. (2019)	X			X	Solid waste
Wei et al. (2019)	X		X		Solid waste
Kızıltaş (2019)		X		X	Paper, glass, plastics, metal
Rızvanoğlu et al. (2020)	X	X	X		Solid waste
Total	44	27	37	27	

provided to customers varies according to the demand amount and stock area of the customers. The aim is to minimize the total travel distances of all vehicles over a period of time. Especially short shelf life food distribution problems and waste collection problems are included in this problem class. In PHMVRP, vehicles can visit the same spot more than once in each period. Each route should have only one type of vehicle, and each customer should be visited by only one type of vehicle. Each vehicle route must start in a warehouse and end in a warehouse. The amount of cargo collected in each route should not exceed the vehicle capacity.

Case study: collection of recyclable wastes in Kırıkkale

The Republic of Turkey Ministry of Environment and Urbanization has started a zero waste project. In this project, recyclable wastes, which are paper, plastic, glass, metal, wood, composite, organic waste, battery, and electronic waste, are collected and evaluated. It is aimed to increase productivity, reduce costs by preventing waste, and reduce environmental risks with the zero waste approach (Republic of Turkey Ministry of Environment and Urbanization 2017).

In this study, a vehicle routing problem is addressed within the scope of the Zero Waste project. In this problem, it is aimed to collect the recycling of recyclable wastes such as paper, metal, glass, and plastic from all public institutions, schools, and shopping centers in Kırıkkale and its eight districts with minimum cost. The problem is a heterogeneous multi-vehicle structure solved in weekly periods, and it is solved under the capacity constraints and working hours. The flow chart of the problem is given in Fig. 3.

Two hundred seventy-two addresses are received from the provincial directorate of the environment to collect recyclable wastes. The locations of 272 addresses where the recyclable wastes will be collected

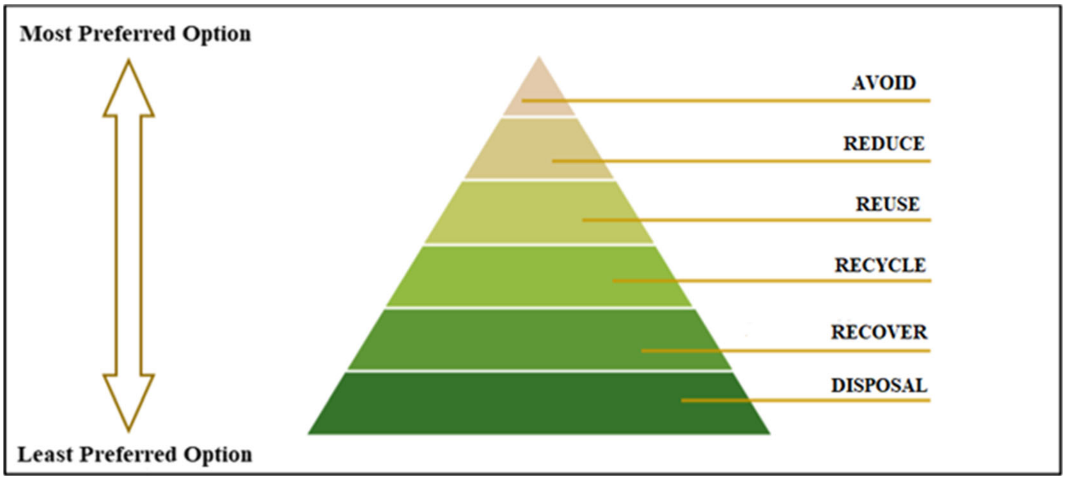

Fig. 1 Waste management hierarchy (Sayar 2012)

are determined on the map. They are grouped according to the distance between them and reduced to 104 spots to reduce the problem size. While grouping according to the distances between themselves, the addresses within 200-m distance are grouped in the city center. Also, the addresses within 1000-m distance are grouped in the suburbs of the city. One hundred four spots to be routed are marked on the map as in Fig. 4, and the distances between them are determined.

The Zero Waste project is planned to be implemented in the official institutions at the first stage. In the next stages of the project, it will be implemented in other places such as schools and shopping malls. Therefore, the problem addressed in this study is divided into three separate cases. These are as follows:

Case 1: It deals with waste collection from all public institutions such as the governorship, district governorships, municipalities, and police offices in Kırıkkale and its eight districts. Accordingly, 97 institution buildings are handled, and these addresses are combined according to their proximity to each other and reduced to 56 spots. Waste collection routes of 56 spots are determined with PHMVRP.

Case 2: It is created by adding schools in Kırıkkale to the addresses in case 1. There are 268 addresses in case 2 and these addresses are combined according to their proximity to each other and reduced to 104 spots. Waste collection routes of 104 spots are determined with PHMVRP.

Case 3: It deals with waste collection from the addresses in case 2 and four large shopping centers in Kırıkkale. There are 272 institution buildings in case 3 and these addresses are combined according to their proximity to each other and reduced to 104 spots. In this case, because the shopping centers have added to the spots at close range, number of spots is equal that of case 2. In case 3, waste collection routes of 104 spots are determined with PHMVRP.

Since the Zero Waste project is a new project, the recyclable waste amounts data in the past years is unknown. Therefore, the daily waste amount at these spots is calculated by the daily waste amount per person (1.17 kg) given by the Turkish Statistical Institute (TUIK) and the amount of daily recyclable waste is calculated using 19%, 25%, 30%, and 35%. The annual recyclable waste amount specified in the 2016 Turkish Association of Evaluable Waste Materials Industrialists (TUDAM) Incentive Report is approximately 6 million tons of waste. According to the 2016 TUIK data, the annual amount of waste collected in municipalities is about 31.6 million tons. According to these two rates, the amount of recyclable waste rate in 2016 is found to be 19%. Apart from this rate, the amount of waste at the spots is estimated by taking 25% and 30% recyclable waste rates in 5% annual increments and the recycling rate target determined by the ministry (35%). People in the spots spend half of their days at these spots. Therefore, the amount of waste they generate at these spots is 50% of the amount of waste they generate daily.

Waste collection cost has an important place among all costs in waste management. Waste collection spots can be classified to reduce waste collection cost. According to this classification, high waste generated spots can be visited more frequently, and low waste generated spots can be visited less frequently. For this purpose, waste collection spots can be classified with Pareto

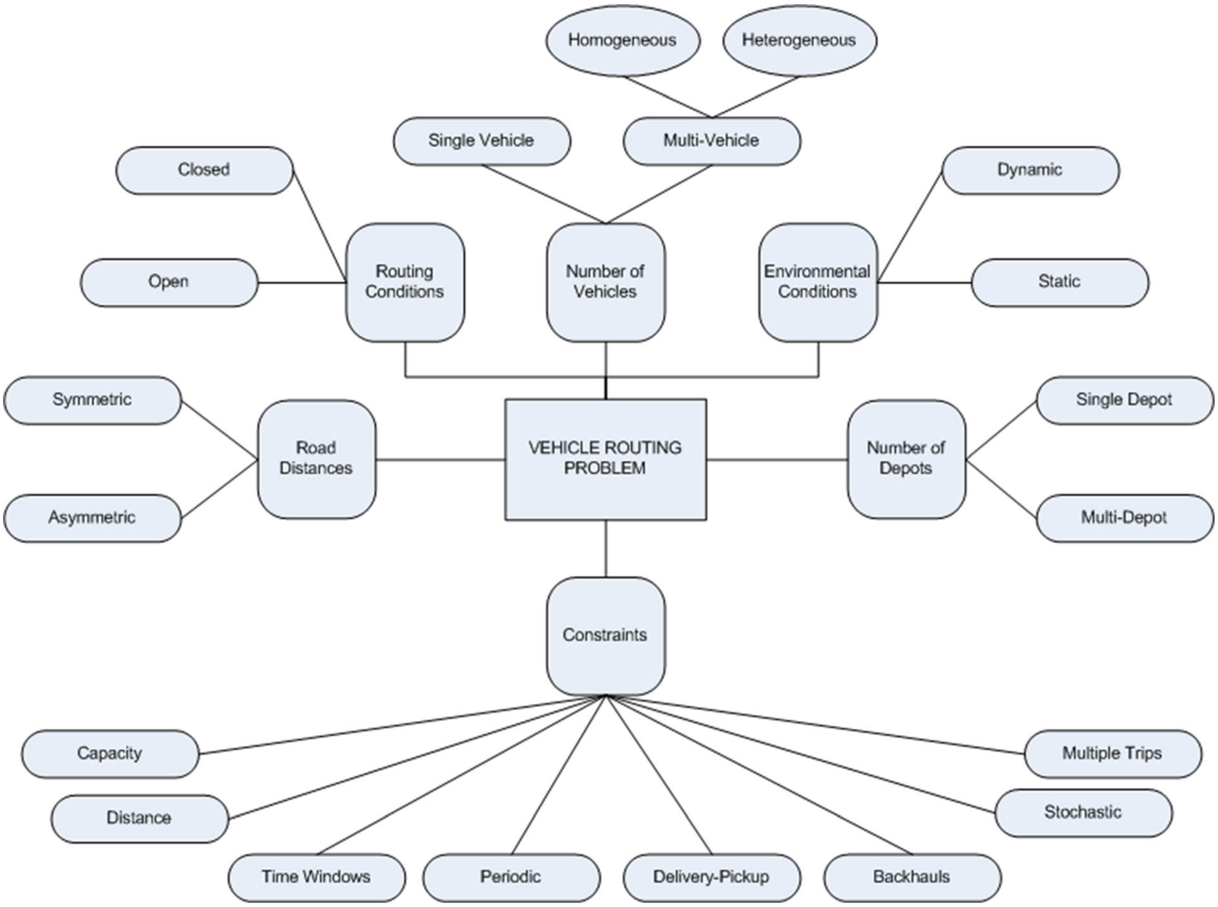

Fig. 2 Vehicle routing problem types

analysis. Pareto analysis is used in many areas from economy to stock control. It is used to classify the data related to a problem, as well as to see the ones that have the most impact on the reasons affecting a problem. In this problem, waste collection spots are classified according to estimated waste amounts. As a result of the Pareto analysis, the spots are grouped into A, B, and C groups. More waste is generated at spots in group A and less waste is generated at spots in group C. Therefore, it is planned to visit every weekday to the spots in the A group, the spots in the B group are visited twice a week, and the spots in C group are visited once a week. Based on this plan, the weekly itinerary is prepared as in Table 3 and the routes of the vehicles are determined according to this planning.

In the case studies, the amount of waste to be collected from the addresses is certain, known, and indivisible. The distances between the depot and the addresses where waste were to be collected are fixed, known, and equal in round trip distances. Waste collection is made from a single depot. There are three different types of vehicle that are used to collect waste. The vehicle capacities are known and these are 2500 kg (type 1), 5500 kg (type 2), and 10,000 kg (type 3). The vehicles' fixed cost are 391.86, 426.7, and 705.43 Turkish liras (TL) and their variable costs are 0.5, 1.0, and 1.3 TL per kilometer, respectively. The vehicles are loaded with 20 kg of waste per minute, and the vehicles travel at a speed of 60 km/h. Waste can be collected in 480 min working time per day; because of this limit, total vehicle loading time and travel time of vehicles should not exceed 480 min. There has to be only one vehicle type on each route, and each customer has to be visited by only one vehicle. Each vehicle route must start and end in the same depot. The amount of load collected in each route must not exceed the vehicle capacity. The sum of the travel time and waste collection time must not exceed the working hours.

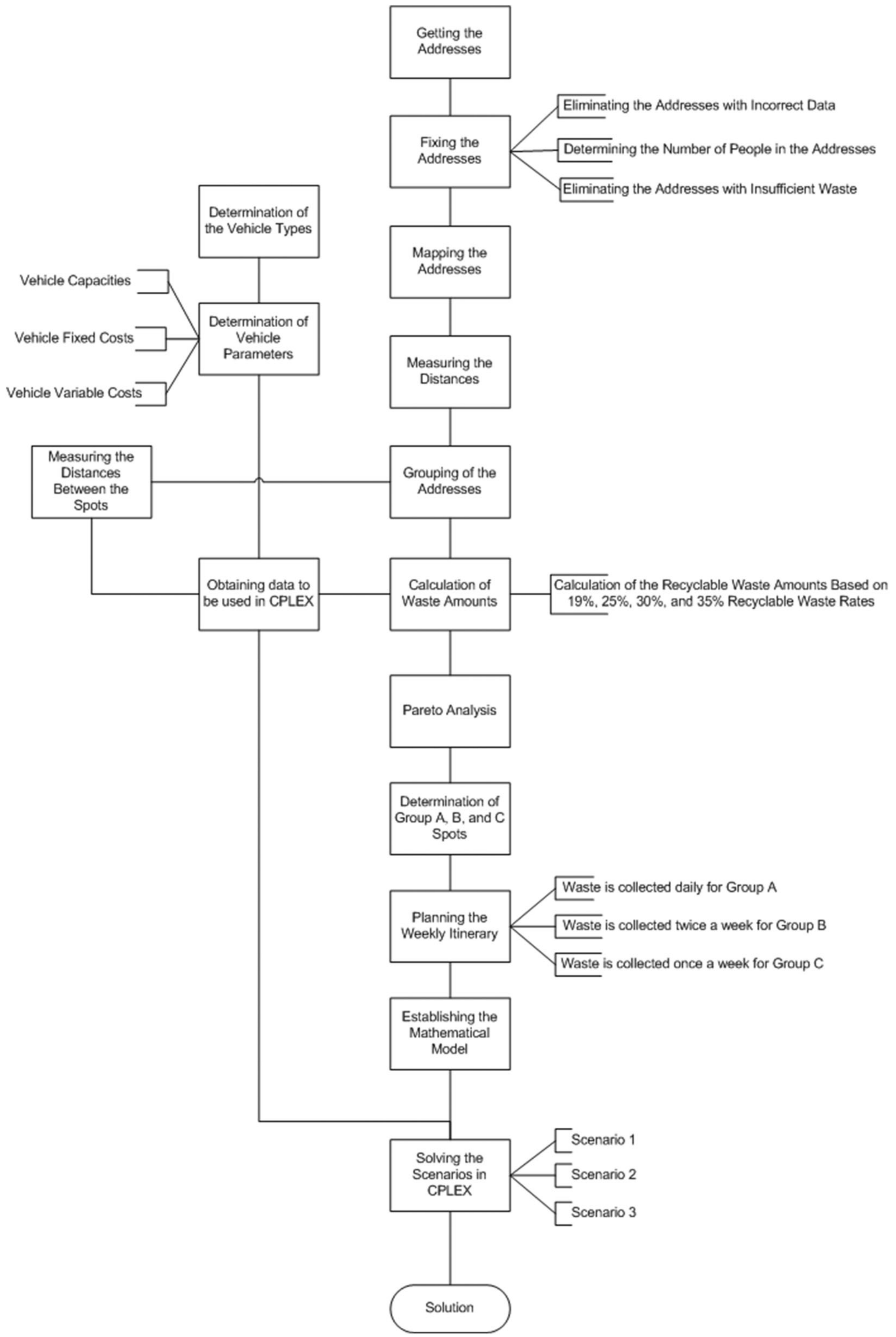

Fig. 3 The flow chart of the solution approach

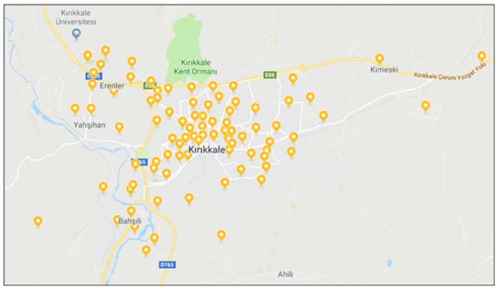

Fig. 4 The location of 104 spots on the map

The mathematical model of the PHMVRP

The PHMVRP model in this study is adapted from Keçeci et al.'s (2015) study.

Parameters:

- J Set of waste collection spots
- V Vehicle-type set
- C_{ij} The distance between node i and node j ($i, j \in J$)
- p_i Amount of waste to be collected from node i ($i \in J$)
- f_v Fixed cost of v-type vehicle ($v \in V$)
- T_v Number of vehicles available from v-type vehicle ($v \in V$)
- Q_v v-type vehicle capacity ($v \in V$)
- R_v Variable cost of v-type vehicle (per meter) ($v \in V$)

Decision variables:

$$x_{ijv} = \begin{cases} 1, & \text{if vehicle } v \text{ travels from node } i \text{ to node } j \\ 0, & \text{otherwise} \end{cases}, (\text{i, j} \in \text{J, v} \in \text{V})$$

- y_v = the number of vehicles to be selected in v type vehicle in the fleet, (v ∈ V)
- m The number of rounds;
- t_{ij} = the amount of load the vehicles collect until they reaches j, ($i, j \in J$)
- πj Variable preventing sub-round (j ∈ J)

Mathematical Model:

$$\text{Min} \sum_{i \in J} \sum_{j \in J} \sum_{v \in V} R_v C_{ij} x_{ijv} + \sum_{v \in V} f_v y_v \tag{1}$$

$$\sum_{j \in J, j \neq 0} \sum_{v \in V} x_{0jv} \leq m \tag{2}$$

$$\sum_{i \in J, i \neq 0} \sum_{v \in V} x_{i0v} \leq m \tag{3}$$

$$\sum_{i \in J, i \neq j} \sum_{v \in V} x_{ijv} = 1, \qquad (j \in J, j \neq 0) \tag{4}$$

$$\sum_{j \in J, i \neq j} x_{ijv} = \sum_{j \in J, i \neq j} x_{jiv}, \qquad (i \in J, i \neq 0, v \in V) \tag{5}$$

$$t_{ij} \leq \sum_{v \in V} Q_v x_{ijv}, \qquad (i, j \in J, i \neq j) \tag{6}$$

$$\sum_{j \in J, i \neq j} t_{ij} - \sum_{j \in J, i \neq j} t_{ji} = p_i, \qquad (i \in J, i \neq 0) \tag{7}$$

$$\sum_{v \in V} p_i x_{ijv} \leq t_{ij} \leq \sum_{v \in V} \left(Q_v - p_j \right) x_{ijv}, \qquad (i, j \in J, i \neq j) \tag{8}$$

$$t_{0j} = 0, \qquad (j \in J, j \neq 0) \tag{9}$$

$$\sum_{v \in V} y_v \leq m \tag{10}$$

$$y_v \leq T_v, \qquad (v \in V) \tag{11}$$

$$\sum_{j \in J, j \neq 0} x_{0jv} = y_v, \qquad (v \in V) \tag{12}$$

$$\sum_{i, j \in J, i \neq j, j \neq 0} 0,05 p_i x_{ijv} + \sum_{i, j \in J, i \neq j} 0,001 C_{ij} x_{ijv} \leq 480, \qquad (v \in V) \tag{13}$$

$$\pi_j \geq \pi_i + 1 - J \left(1 - \sum_{v \in V} x_{ijv} \right) \qquad (i, j \in J, j \neq i, i, j \neq 0) \tag{14}$$

$$\pi_j \geq 0 \qquad (j \in J) \tag{15}$$

$$x_{ijv} \in \{0, 1\} \qquad (i \neq j, i, j \in J, v \in V) \tag{16}$$

Table 3 Weekly itinerary

	Group A	Group B	Group C
Monday	X		
Tuesday	X	X	
Wednesday	X		
Thursday	X	X	
Friday	X		X

Table 4 Case 1 Pareto analysis results

Groups	Spots
A	16-21-22-38-39-40-41-42-43-44-54
B	3-5-8-11-14-20-24-28-29-30-32-33-35-36-45-46-55-56
C	1-2-4-6-7-9-10-12-13-15-17-18-19-23-25-26-27-31-34-37-47-48-49-50-51-52-53

$$y_v \geq 0 \; ve \text{ integer}, \quad (v \in V) \tag{17}$$

$$t_{ij} \geq 0, \qquad (i, j \in J) \tag{18}$$

$$m \geq 0 \tag{19}$$

In this model, Eq. 1 represents the objective function and provides the total minimization of the fixed costs arising from the selection of vehicles and the variable costs that vary according to the distance they take. Equations 2 and 3 allow that no more than m vehicles are separated from the depot and returned to the depot. Equation 4 allows any node to come from only one node, and Eq. 5 ensures that the vehicles that are subject to and disconnect from any node are of the same type. Equation 6 ensures that vehicle capacity is not exceeded. Equation 7 provides an increase in the load the vehicle collects as the vehicle travels, while Eq. 8 determines the upper and lower bounds for the load the vehicle collects. Equation 9 equals the load collected by the vehicle to zero at the turn of the cycle. Equation 10 allows the selection of up to m vehicles in the problem solution, while Eq. 11 enables the selection of the maximum number of vehicles available. Equation 12 ensures that the number of v-type vehicles coming out of the depot is equal to the number of v-type vehicles to be selected from the set of vehicles. Equation 13 ensures that the daily working hours for each vehicle are not exceeded. Equation 14 is a sub-round elimination constraint. Equations 15, 16, 17, 18, and 19 are used to declare the decision variable definitions.

Results and discussion

The three different case studies discussed were solved with the proposed mathematical model according to different waste recycling rates. According to the model results, the number of vehicles and routes of vehicles that the waste collection company will need at each stage of the project are determined. In order to determine vehicle routes, it should be known how much waste will be generated at each address. Since the project has just begun to be implemented, four different waste recycling rates have been determined by taking into account the statistics of waste per capita and forecasting that these rates will increase in the later stages of the project. Analyses were made with the estimated waste amounts based on these waste recycling rates and the number of people at the addresses.

The weekly itinerary plan, that which addresses to visit on which day, is determined according to the results of Pareto classification analysis. Instead of visiting every address on every day, waste was collected more economically by visiting certain addresses on certain days. Addresses with excess waste (A) are visited every day; addresses with less waste (B) twice a week and addresses with very little waste (C) are visited once a week. According to the weekly itinerary given in Table 3, the results obtained for each case study and waste rate are discussed in detail below.

Case 1 results: Fifty-six spots to collect waste in case 1 were analyzed with Pareto analysis method and the spots were classified as A, B, and C (Table 4). The results obtained for the problems in the first stage of the project are given in Table 5. According to these results, only type 1 vehicle is needed from three different vehicle types. In the results obtained according to different waste rates, one vehicle was generally needed. Only in the sample problem where waste is collected from type A and B spots and the waste rate is 35%, two vehicles are needed. Although waste rates and waste collection spots change in problems, single vehicle type was sufficient because the amount of waste to be collected is low.

Case 2 results: One hundred four spots to collect waste in case 2 were analyzed with the Pareto analysis method and the spots were classified as A, B, and C (Table 6). Vehicle routes were determined according to different waste rates and weekly plan for the spots

Table 5 Case 1 solution results

Groups	Waste rate (%)	Vehicle type	Cost	Routes
A	19	1	465,147	0-38-22-21-43-39-16-44-42-40-41-54-0
	25	1	465,147	0-38-22-21-43-39-16-44-42-40-41-54-0
	30	1	465,147	0-38-22-21-43-39-16-44-42-40-41-54-0
	35	1	465,147	0-38-22-21-43-39-16-44-42-40-41-54-0
A+B	19	1	540,245	0-38-35-24-32-46-33-22-36-21-28-43-45-30-29-8-5-11-16-20-14-44-42-40-3-39-41-56-55-54-0
	25	1	540,245	0-38-35-24-32-46-33-22-36-21-28-43-45-30-29-8-5-11-16-20-14-44-42-40-3-39-41-56-55-54-0
	30	1	540,245	0-38-35-24-32-46-33-22-36-21-28-43-45-30-29-8-5-11-16-20-14-44-42-40-3-39-41-56-55-54-0
	35	1	955,689	0-54-0
	35	1		0-55-56-41-39-3-40-42-44-14-20-16-11-5-8-29-30-45-43-28-21-36-22-33-46-32-24-35-38-0
A+C	19	1	586,87	0-54-53-51-52-38-25-41-39-40-42-16-15-18-17-19-9-13-44-2-1-31-43-21-23-22-37-27-34-50-26-4-7-6-12-10-48-47-49-0
	25	1	586,87	0-54-53-51-52-38-25-41-39-40-42-16-15-18-17-19-9-13-44-2-1-31-43-21-23-22-37-27-34-50-26-4-7-6-12-10-48-47-49-0
	30	1	586,87	0-54-53-51-52-38-25-41-39-40-42-16-15-18-17-19-9-13-44-2-1-31-43-21-23-22-37-27-34-50-26-4-7-6-12-10-48-47-49-0
	35	1	586,87	0-54-53-51-52-38-25-41-39-40-42-16-15-18-17-19-9-13-44-2-1-31-43-21-23-22-37-27-34-50-26-4-7-6-12-10-48-47-49-0

Table 6 Case 2 Pareto analysis results

Groups	Spots
A	9-11-12-13-14-18-19-20-23-28-30-35-36-42-45-48-50-52-53-54-55-56-58-59-60-62-75-85-86-87-88-101
B	1-10-15-21-26-31-32-33-34-37-38-44-51-57-61-63-65-66-67-69-70-74-78-79-80-81-83-84-89-91-92-94-96-98
C	2-3-4-5-6-7-8-16-17-22-24-25-27-29-39-40-41-43-46-47-49-64-68-71-72-73-76-77-82-90-93-95-97-99-100-102-103-104

Table 7 Case 2 solution results

Groups	Waste rate (%)	Vehicle type	Cost	Routes
A	19	2	1011,2	0-42-0
		2		0-23-9-11-12-36-101-54-48-20-13-14-60-28-35-62-75-45-86-30-58-87-59-19-52-18-53-88-56-55-85-50-0
	25	1	1221,72	0-18-53-50-62-54-101-36-11-12-9-85-55-56-88-52-0
		3		0-23-20-35-48-13-75-45-28-14-60-87-19-58-86-59-30-42-0
	30	2	1325,9	0-19-60-14-48-35-23-20-54-101-12-11-9-36-50-18-52-88-56-55-59-86-87-13-0
		3		0-42-30-58-45-62-53-85-28-75-0
	35	1	1670,72	0-101-36-11-9-12-53-50-54-0
		2		0-87-58-19-56-88-55-85-52-18-62-35-13-14-59-60-20-23-0
		3		0-48-28-45-75-86-30-42-0
A+B	19	1	1399,36	0-94-38-98-85-55-88-56-65-79-50-36-96-10-11-9-12-83-1-101-0
		3		0-58-67-45-75-28-20-54-14-15-86-87-60-26-70-69-63-59-66-61-19-78-80-52-35-30-51-31-33-23-13-48-57-91-44-92-89-21-18-81-53-62-37-74-84-32-34-42-0
	25	1	2186,69	0-74-84-32-34-9-12-10-96-11-83-36-1-31-33-101-0
		1		0-94-98-38-19-56-21-80-66-52-50-37-23-51-20-54-0
		2		0-44-92-89-42-0
		3		0-67-58-30-48-13-62-79-18-65-81-53-78-85-88-55-61-69-70-63-87-60-26-59-45-28-35-14-86-15-75-57-91-0
	30	1	2244,55	0-85-81-36-83-96-10-11-9-12-98-38-94-44-0
		2		0-54-20-13-48-51-23-31-33-101-1-84-32-34-74-37-50-0
		2		0-63-69-19-61-66-78-80-52-55-88-56-53-65-79-18-21-62-35-26-60-14-28-15-75-0
		3		0-42-92-30-67-58-86-70-59-87-45-57-89-91-0
	35	1	2591,27	0-96-11-10-12-9-55-61-67-94-98-38-0
		2		0-30-21-85-63-66-69-44-32-34-83-36-101-91-31-74-81-79-18-88-56-53-65-37-50-0
		3		0-57-58-19-86-59-70-89-92-42-0
		3		0-84-1-33-23-51-20-48-13-28-14-15-45-75-87-78-26-60-80-52-62-54-35-0
A+C	19	1	2090,89	0-6-5-103-36-7-71-100-99-4-77-48-0
		2		0-95-43-11-8-102-9-12-72-42-45-75-16-90-0
		3		0-41-40-50-17-49-76-97-24-60-25-30-46-27-47-54-35-68-20-13-28-14-29-86-59-58-19-87-104-62-22-82-39-52-64-53-88-56-85-55-18-73-93-3-101-2-23-0
	25	1	2009,05	0-100-99-4-6-9-8-5-103-7-11-12-102-64-77-53-50-18-0
		2		0-42-72-36-2-3-0
		3		0-17-14-104-60-24-59-58-47-46-27-30-90-95-76-49-22-71-73-85-55-88-56-82-40-93-43-41-39-19-45-28-20-35-101-54-62-97-25-52-87-86-29-75-16-48-68-13-23-0
	30	1	2897,62	0-43-90-8-102-12-72-95-93-0
		1		0-73-71-6-100-99-4-77-85-59-18-53-62-30-0
		2		0-17-50-52-82-22-64-60-56-55-88-28-45-75-16-46-27-104-87-86-29-14-35-20-13-68-23-0
		2		0-41-0
		3		0-24-97-25-19-47-58-39-54-36-7-103-5-9-11-101-49-2-3-76-48-40-42-0

Table 7 (continued)

Groups	Waste rate (%)	Vehicle type	Cost	Routes
	35	1	2765,84	0-7-103-5-6-4-77-73-71-99-47-95-0
		2		0-101-36-11-102-8-9-12-72-100-56-55-88-97-62-85-53-64-18-50-17-76-0
		3		0-41-43-93-40-42-0
		3		0-54-28-45-75-46-16-48-13-20-35-68-14-23-49-2-3-19-59-25-82-52-22-39-24-60-29-104-87-86-58-27-30-90-0

discussed in the second stage and the results are given in Table 7. When only the types and numbers of vehicles required for collecting waste from class A spots are evaluated, two vehicles are needed, albeit from different vehicle types. The number of vehicles of different types is needed for the spots in A+B and A+C classes depending on the increase in the number of spots to be visited. When vehicle fleets are evaluated separately according to the waste rates, they are approximately similar for both spot combinations. Since A+B spots will be collected two days a week, it will be more appropriate to choose the vehicle combinations determined for these spots. Vehicle routes can be re-determined for other days by limiting vehicle types and numbers in the mathematical model, taking into consideration the determined vehicle fleets.

Case 3 results: One hundred four spots to collect waste in case 2 were analyzed with the Pareto analysis method and the spots were classified as A, B, and C (Table 8). Vehicle routes were determined according to different waste rates and weekly plan for the spots discussed in the third stage of project and the results are given in Table 9. Then only the types and numbers of vehicles required for collecting waste from class A spots are evaluated; two vehicles are needed, albeit from different vehicle types like case 2. Because the number of spots to collect waste did not change, vehicle combinations were obtained similarly to the results in case 2. However, when the number of vehicles is calculated considering the spots in A+B and A+C classes, it is seen that more vehicles are needed than case 2. When vehicle fleets are evaluated separately according to waste rates, more vehicles are needed to collect waste from A+B spots than A+C spots. Because A + B spots will be collected two days a week, it will be more appropriate to choose the vehicle combinations determined for these spots. Similar to our suggestion in case 2, after the vehicle combinations are determined, the vehicle numbers can be limited and the vehicle routes can be redetermined for the other days with the mathematical model.

According to the results for all three case studies, the results obtained for A+B spots are the dominant solution. Types and numbers of vehicles to be used in collecting wastes can be found by calculating for these spots with proposed mathematical model, and vehicle routes for other days can be found with the mathematical model according to this vehicle fleet, too.

In the studies in the literature, it is seen that the routes are determined with the assumption that every spot is visited daily in weekly plans (Sackmann et al. 2017; Gilardino et al. 2017; Hannan et al. 2018). In this study, weekly plan was determined according to Pareto analysis results in all three case studies and certain spots were visited less. If the weekly plan was not made according to the Pareto analysis results, every spot would be

Table 8 Case 3 Pareto analysis results

Groups	Spots
A	9-11-13-14-17-18-19-20-23-28-30-35-36-42-45-48-50-52-53-54-56-58-59-60-62-75-85-86-87-88-101
B	1-10-12-15-21-26-29-31-32-33-34-37-38-44-51-55-57-61-63-65-66-67-69-70-74-78-79-80-81-83-89-91-92-94-98
C	2-3-4-5-6-7-8-16-22-24-25-27-39-40-41-43-46-47-49-64-68-71-72-73-76-77-82-84-90-93-95-96-97-99-100-102-103-104

Table 9 Case 3 solution results

Groups	Waste rate (%)	Vehicle type	Cost	Routes
A	19	3	897,564	0-17-86-58-19-59-85-88-56-52-18-53-62-50-35-54-48-13-20-23-9-11-36-101-28-60-14-45-75-87-30-42-0
	25	1	1218,828	0-101-36-11-9-85-56-88-52-53-18-50-62-35-23-0
		3		0-17-75-45-28-48-13-54-20-60-14-87-19-59-86-58-30-42-0
	30	2	1308,795	0-23-20-13-54-87-59-60-35-101-9-11-36-88-56-85-62-53-50-18-52-19-58-17-0
		3		0-42-30-45-14-28-86-75-48-0
	35	1	1712,256	0-85-9-11-54-101-35-50-62-52-88-56-0
		2		0-30-19-28-14-36-20-23-13-48-0
		3		0-17-75-45-86-58-87-53-18-60-59-42-0
A + B	19	1	1962,601	0-1-101-34-80-32-52-33-31-29-55-65-78-74-87-54-53-83-20-37-0
		2		0-81-60-59-92-98-36-88-30-67-70-86-57-51-79-45-35-62-75-17-69-94-9-38-89-0
		3		0-91-28-61-66-63-50-14-85-18-42-15-26-58-44-13-19-10-11-12-21-48-23-56-0
	25	1	2282,15	0-36-9-12-10-11-74-98-38-62-52-1-33-51-23-0
		1		0-42-94-0
		2		0-83-32-34-101-31-80-78-29-67-19-30-0
		3		0-91-57-75-87-86-14-60-20-35-37-50-79-18-53-81-21-85-55-56-88-65-54-26-63-66-61-69-58-70-59-45-28-15-13-48-92-44-89-17-0
	30	1	2556,465	0-11-9-12-10-83-36-34-94-98-38-91-0
		2		0-65-79-50-66-61-58-56-88-55-85-78-52-62-21-53-81-37-74-32-1-101-0
		3		0-18-31-23-51-20-13-35-80-63-69-19-70-54-15-48-28-45-87-29-14-60-26-59-86-75-57-17-33-0
		3		0-44-92-30-67-89-42-0
	35	1	3058,335	0-80-94-38-98-37-66-85-55-88-53-0
		1		0-91-62-50-52-17-36-83-9-31-0
		2		0-34-65-81-79-18-32-48-51-69-23-12-11-10-74-67-30-92-0
		3		0-44-89-86-70-59-78-63-19-60-20-33-42-0
		3		0-45-75-15-13-54-35-26-61-56-21-1-29-87-28-58-14-57-101-0
A + C	19	1	1997,296	0-90-49-36-5-103-7-84-54-100-99-6-71-22-52-23-39-19-87-16-17-41-95-0
		2		0-72-8-102-9-96-11-77-73-4-88-60-45-2-3-0
		3		0-101-76-27-30-46-47-58-59-24-64-85-56-53-82-18-50-62-97-25-14-86-104-13-48-75-68-35-28-20-42-43-40-93-0
	25	1	1942,772	0-11-103-5-7-36-72-84-100-99-4-6-71-77-88-18-97-13-90-95-0
		2		

Table 9 (continued)

Groups	Waste rate (%)	Vehicle type	Cost	Routes
				0-16-58-86-87-104-60-25-35-20-54-23-68-48-59-62-50-64-73-85-56-82-52-102-8-9-96-53-22-47-19-24-39-76-49-2-3-101-0
		3		0-75-45-28-14-41-43-42-93-40-30-27-46-17-0
	30	1	2485,048	0-40-101-3-72-23-20-25-60-24-64-18-53-22-52-104-75-0
		1		0-56-50-71-77-99-100-73-47-14-19-58-90-93-0
		2		0-43-49-2-36-7-5-103-11-96-8-102-9-46-28-30-16-45-84-76-27-41-0
		3		0-95-6-4-88-82-85-62-97-39-59-87-86-68-17-54-35-13-48-42-0
	35	1	2704,045	0-85-77-73-71-6-4-99-100-19-56-88-62-49-76-54-0
		2		0-84-101-3-36-2-18-53-22-52-82-64-50-97-72-8-102-96-9-11-103-5-7-0
		3		0-86-87-104-60-75-28-14-35-20-68-48-13-47-27-30-16-45-59-58-24-39-25-23-0
		3		0-90-93-17-46-40-41-43-95-42-0

visited daily and 280 spots would be visited in case 1. However, the number of weekly visits decreased to 118 in the planning made with Pareto analysis. Similarly, the number of visits for case 2 has been reduced from 520 to 266 and for case 3 from 520 to 263. Consequently, a more economical waste collection plan was prepared by reducing the number of vehicles and reducing the number of spots visited.

According to the literature research, studies using homogeneous tools in waste collection problems are more common. In these studies, the number of vehicles and routes is generally minimized (Gilardino et al. 2017; Akhtar et al. 2017; Gruler et al. 2017; Sackmann et al. 2017; Alessandro et al. 2017; Hannan et al. 2018 Rızvanoğlu et al. 2020). However, there are also studies that use vehicles with different features in waste collection problems (Shah et al. 2018; Molina et al. 2019; Louati et al. 2019). In these studies, problems are solved with the assumption that the types and numbers of vehicles to be used are fixed and each vehicle should be used for waste collection. In this application, how many vehicles are needed from different vehicle types was calculated with the mathematical model. Thus, an investment plan for the vehicles that will be needed at each stage of the project has been developed to collect waste in the most economical way.

Conclusion

Today, the population and needs in the world are increasing rapidly. The demand for new products is increasing continuously. This increase causes more raw material usage, thus more waste. The negative impact of the environment and human health is increasing due to the wastes. Therefore, waste management studies are becoming more and more critical in the world.

This study focuses on the collection and transportation of wastes within the scope of the Zero Waste project. In the study, the problem of collecting recyclable waste, such as paper, glass, plastic, and metal, is discussed. It is solved with a heterogeneous vehicle fleet, and the wastes are collected from the governorship, prefectures, civil registry, safety, and such directorates, schools, and shopping centers in Kırıkkale. The amounts of recyclable waste generated by using different recyclable waste rates in the addresses are calculated. The addresses are sorted out by Pareto analysis according to the amount of generated recyclable waste, and address sets are created for routing. Then, a mathematical model has been created with a purpose function that minimizes the sum of fixed costs of trucks and employees used and fuel costs per kilometer of vehicles. Furthermore, it is ensured that the waste collection is completed within daily working hours. The vehicle routes are determined for each weekday.

The recyclable waste collection problem in Kırıkkale was solved in three stages based on the "Zero Waste" project implementation stages. These stages are only government agencies, government agencies and schools, and government agencies, schools, and shopping centers. According to the results of the case studies, first of all, the number of vehicles and vehicle types should be determined for the addresses in A+B class because these results constitute the dominant solution for the waste collection problem. The vehicle routes for other classified addresses, according to the determined vehicle fleet, can be found with the mathematical model. As a result, a more economical waste collection plan was made by visiting the addresses less, and the number of vehicles needed for a different amount of waste was found at each stage of the project.

This study can be expanded by adding sites and other settlements with high population density. It can be integrated for the collection of other waste as well as recyclable waste. Waste collection plans can be made by following the procedure recommended in other provinces. In addition, people should be informed about the zero waste approach because public participation is critical in increasing the amount of recycled waste.

Data Availability The data that support the findings of this study are available from the corresponding author upon reasonable request.

Compliance with ethical standards

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

Ethical approval This article does not contain any studies with human participants or animals.

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