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A new model for the hazardous waste location-routing problem

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Abstract

Hazardous waste management involves the collection, transportation, treatment and disposal of hazardous wastes. In this paper a new multiobjective location-routing model is proposed. Our model also includes some constraints, which were observed in the literature but were not incorporated into previous models. The aim of the proposed model is to answer the following questions: where to open treatment centers and with which technologies, where to open disposal centers, how to route different types of hazardous waste to which of the compatible treatment technologies, and how to route waste residues to disposal centers. The model has the objective of minimizing the total cost and the transportation risk. A large-scale implementation of the model in the Central Anatolian region of Turkey is presented.

Keywords: Hazardous waste; Facility location; Routing; Multiobjective model

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1. Introduction

A waste can be characterized as hazardous if it possesses any one of the following four characteristics: ignitability, corrosiveness, reactivity or toxicity. Hazardous wastes, which are usually the waste by-products of our industrial processes, present immediate or long-term risks to humans, animals, plants, or the environment. Many types of businesses generate hazardous waste. Some of these businesses are small-scale ones located in communities, such as dry cleaners, auto repair shops, hospitals, exterminators, and photo processing centers, and some hazardous waste generators are larger businesses like chemical manufacturers, electroplating companies, and petroleum refineries. In addition to these industries, there

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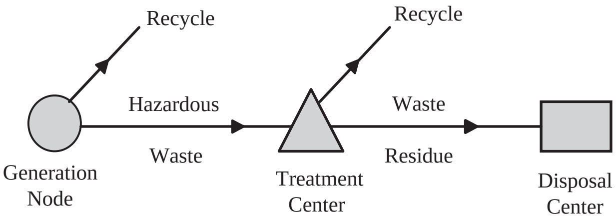

Fig. 1. Hazardous waste management problem.

are also hazardous household waste such as batteries, gasoline, antifreeze, oil-based paints and thinners, household cleaning products and pesticides.

The industrial and technological advances of the last two centuries have created a significant hazardous waste management problem in the developed world. Even though the trend in the world is to produce no hazardous waste by waste minimization or by using replaceable non-hazardous materials, large amounts of hazardous waste, which have to be managed, are still being produced. The objective of the hazardous waste management problem stated by Nema and Gupta [1] is “to ensure safe, efficient and cost effective collection, transportation, treatment and disposal of wastes”. But the question still remains: how are we going to manage the hazardous waste?

The solution to the hazardous waste management problem comes from different perspectives. There are various objectives to managing the problem in a safe and cost-effective manner. For example, for a carrier firm, the best solution would be the one with the least cost, while for the government, the best solution would be the one with the least risk. One should select a compromise solution considering these different objectives.

Another aspect of the hazardous waste management problem is that there are various kinds of hazardous waste, which may or may not be managed together. There are also various treatment technologies that are specific to the kind of the hazardous waste, such as chemical treatment technologies, or that serve more than one type of hazardous waste, such as incinerators. Also, compatibility issues are important. There are wastes that are incompatible with certain kinds of treatment technologies. For example, a highly reactive chemical waste cannot be incinerated. Therefore, any proposed mathematical model should also include these real-life aspects of the hazardous waste management problem.

Hazardous waste treatment facilities are not usually the ultimate disposal centers. After the treatment process the produced waste residues, which are no longer hazardous, should be disposed of. The amount of waste residue is almost always dependent on the treatment technology employed. For example, the volume or mass reduction after incineration is significantly higher than the volume or mass reduction after chemical disinfection. As the transportation cost of these waste residues is another issue, the location of the disposal facilities and the routes of the waste residues should also be determined when locating the treatment facilities.

Another important concern is recycling. Recycling should be encouraged for both the hazardous wastes and the waste residues produced, if possible, which is usually dependent on the hazardous waste type and the treatment technology employed.

The frame of the hazardous waste management problem (Fig. 1) starts with the generation of hazardous wastes; then the non-recycled amounts of hazardous wastes are routed to the compatible treatment technology in the treatment facility, which is to be located. After the treatment process, the non-recycled amount of waste residues is routed to the ultimate disposal facility, which is to be located.

In this paper, we present a review of the existing literature and a new model for the hazardous waste location-routing problem. The aim of our hazardous waste location-routing model is to decide the following:

- where to open treatment centers and with which technologies;
- where to open disposal centers;
- how to route different types of hazardous waste to which of the compatible treatment technologies; and
- how to route waste residue to disposal centers.

The remainder of this paper is outlined as follows: in Section 2, we review the existing literature with emphasis on the similarities, differences and deficiencies of the models presented. Section 3 is devoted to the mathematical model that we propose, and Section 4 presents a large-scale implementation of our model in Turkey. Lastly, in Section 5, some concluding remarks and suggestions for future research are provided.

2. Literature review

The hazardous waste management problem is first handled in the location literature in locating treatment or disposal facilities. The treatment facilities, such as incinerators, and the disposal facilities, such as landfills, are usually termed as “undesirable facilities” in this literature. There is a significant amount of literature on undesirable facility location. For an extensive discussion on undesirable facility location one can refer to Erkut and Neuman [2], which is the most recent review published in this area. In the location of undesirable facilities the aim is to minimize the nuisance and the adverse effects on the existing facilities or the population centers. Although the service cost of an undesirable facility increases when the facility is located far from the population centers, the undesirability of the facility usually seems to be more important.

There are also studies in the literature that are only concerned with the routing aspect of the hazardous waste management problem. These studies attempt to find optimal routes for hazardous materials (hazmats) that minimize the risk between given origin–destination pairs. Various attitudes and risk measures are used in hazmat papers. Two of the risk measures commonly used are the societal risk and the population exposure. Societal risk is the product of the probability of a hazardous waste accident occurrence multiplied by the consequences of that accident; the population exposure is the number of people exposed to hazardous wastes [3].

We see that an approach to solving the hazardous waste management problem could have two steps. The first step would determine the optimum locations for the facilities, and the second step would determine the optimal routing strategies. The locations of the facilities directly affect both the transportation risk and the transportation cost. Thus, if the location and routing problems are considered simultaneously, the resulting solutions will be more efficient than the step-wise approach in terms of both cost and risk.

The focus in this section is on the combined location-routing models for hazardous wastes. The hazardous waste location-routing models in the literature are usually multiobjective mixed-integer programming models that can be solved by commercial software packages. In these hazardous waste location-routing models the aim is to model the problem effectively. Therefore, the studies in this area vary, mainly due to the models presented rather than the solution procedures.

The first effort to model the location-routing problem simultaneously was by Zografos and Samara [4]. They propose a goal-programming model for one type of hazardous waste, which minimizes travel time, transportation risk, and disposal risk. The disadvantages of their model are that each population center is affected only by its nearest treatment facility, and that every source node can send its hazardous waste to only one treatment facility. For measuring risk, they assume that the weight of each link of the network representing the risk factor is known. Later Revelle et al. [5] presented a model that minimized a convex combination of cost and risk. The cost measure is taken as the distance traveled, and the risk measure is taken as the population exposure. Their model aims to find the location of disposal sites, the assignment of sources to disposal sites, and the routes between sources and destinations. If only one objective is considered, their formulation is the same as the p-median problem.

Stowers and Palekar [6] consider only risk in their location-routing model. They use population exposure as a surrogate for risk in minimizing risk due to both location and transportation. However, the location of the treatment facility is not restricted to some known set of potential sites in their model. This approach is unrealistic, as most of the locations may not be suitable from an environmental perspective. For example, as to the location of landfills, the site should be far away from rivers, lakes and groundwater supplies to prevent any probable contamination from leakages.

Jacobs and Warmerdam [7] model the hazardous waste location-routing problem as a continuous network flow problem. Their model locates the storage and disposal facilities and determines the routing strategies while minimizing the linear combination of cost and risk in time. They define risk as the total probability of a release-causing accident during transportation, storage or disposal. Later, Current and Ratick [8] presented a model with the addition of equity considerations. In addition to minimizing cost and risk, they maximize equity by analyzing the transportation and facility location components of risk and equity separately. Risk is measured with population exposure. An important drawback of their formulation is that it assumes that wastes cannot be transported through a generation or a facility node. Wyman and Kuby [9] consider the same objectives, and their formulation is similar to Current and Ratick's [8]. An additional consideration in Wyman and Kuby [9] is the selection of different technologies for treatment facilities. A new technology, solar-driven waste detoxification, is compared with incineration, considering cost, risk and equity. Giannikos [10] considers four objectives and uses the goal-programming technique. These objectives are the minimization of cost, the minimization of total perceived risk, the equitable distribution of risk among population centers, and the equitable distribution of disutility caused by the operation of the treatment facilities. His perceived risk definition is similar to population exposure.

The first location-routing model to consider multiple hazardous waste types is by List and Mirchandani [11]. The model has three objectives: minimization of risk, minimization of cost, and maximization of equity. In addition to locating treatment facilities, the model also locates storage and disposal facilities. The authors propose a new risk impact function that is inversely proportional to the square of the distance. However, they could not use this complex risk function, and they assumed a single type of hazardous waste, while applying the model to the capital district of Albany, NY. The most recent location-routing model to consider different hazardous waste types is by Nema and Gupta [1]. They use a composite objective function consisting of total cost and total risk, including treatment, disposal and transportation costs and risks. They propose two new constraints: waste–waste and waste–technology compatibility constraints. The waste–waste compatibility constraint ensures that a waste is transported or treated only with a compatible waste, and the waste–technology compatibility constraint ensures that a waste is treated only with a compatible technology. However, the researchers were not able to implement these constraints in their proposed mathematical model.

Alidi [12,13] presents two models, both of which consider only the cost of managing different hazardous waste types. As the models consider only the cost, the hazardous wastes are routed through the shortest paths. These models are valuable, as different aspects of hazardous waste management are considered, such as recycling, waste minimization, and energy production as a result of incineration. In [12], the model locates incinerators for treatment, landfills for disposal, and markets for recycling. In [13], Alidi focuses only on the wastes generated by petrochemical industries. This model identifies the optimum configuration of the amount of waste to be recycled in recycling facilities and to be processed in incineration facilities, waste minimization facilities, and landfills.

Based on the current literature, we may say that the minimization of cost and the minimization of risk are the most commonly employed objectives. Some authors also use equity as an objective, which may result in locating more treatment or disposal facilities so that the population is equally exposed to risk. Most of the papers only consider one type of hazardous waste, which is a significant simplification, as hazardous waste management includes various types of hazardous wastes. Different risk measures are used in the papers. The most popular of these are population exposure and societal risk.

A deficiency of the hazardous waste location-routing literature is that the models usually do not reflect real-life situations. The single waste-type assumption presented in most of the papers is such an example. In addition, only one model considers different treatment technologies and the waste types that are compatible with these technologies. Neither do recycling issues appear in most of the hazardous waste location-routing papers. Another shortcoming of the literature is that it lacks large-scale application. Most of the papers present applications with small instances, such as 10- or 15-node networks and 3 or 4 candidate sites. The largest application presented in the literature is by List and Mirchandani [11], which is on an 86-node network with only 15 generation nodes and 4 candidate sites.

The papers in the relevant literature also tend to ignore the waste residue problem, which includes locating disposal centers and routing waste residues. However, the transportation costs of waste residues should be included in the calculation of hazardous waste management costs, and thus, if the cost is to be minimized, one should also account for the costs related to waste residue management.

Consequently, it can be concluded that the hazardous waste location-routing literature lacks a mathematical model that includes significant real-life aspects of the hazardous waste management problem.

3. Mathematical model

The treatment of generated hazardous waste and the disposal of waste residue at certain sites require a transportation network. The nodes of this transportation network may be a generation node, a transshipment node (a node junction), a potential treatment facility, a potential disposal facility, or a combination of any of the above. We propose a mathematical model with an aim to treat all of the generated hazardous waste and to dispose all of the generated waste residues in a safe and cost-effective manner. There is cost in transportation, treatment and disposal operations, and there is risk posed to the environment in transporting hazardous wastes. It is assumed in the model that the potential sites for treatment and disposal facilities have already been identified.

The hazardous waste location-routing problem can be stated as follows: given a transportation network and the set of potential nodes for treatment and disposal facilities, find the location of treatment and disposal centers and the amount of shipped hazardous waste and waste residue, so as to minimize the total cost and the transportation risk. The hazardous waste location-routing problem can be proven to be NP-hard by reducing it to the uncapacitated facility location problem (UFLP).

For each link in the transportation network, the costs of transporting one unit of hazardous waste and one unit of waste residue are known and are assumed to be directly proportional to the network distance used. It is assumed that all hazardous wastes are transported with the same type of trucks at the same unit costs. Thus, the transportation cost only depends on the distance of transport and the amount of hazardous waste transported. The transportation costs of hazardous waste and waste residue may differ, as special trucks or containers may be needed to transport hazardous waste, while waste residue can be transported casually as domestic waste, since it is no longer hazardous. There is also a fixed cost in locating treatment and disposal facilities. This cost can depend on the treatment technology employed, the size of the facility to be located, or other factors.

The transportation of hazardous wastes poses some risk to the environment. Different measures of risk can be used to estimate this transportation risk. For example, one may use societal risk (the product of the probability of a hazardous waste accident times the consequences of that accident) or population exposure (the number of people exposed to hazardous waste) as a risk measure. For our proposed model the only assumption about the risk measure is its linearity. The model presented uses population exposure as a surrogate for risk measure.

Our model can manage different types of hazardous waste and different treatment technologies. The important parameter in such management is compatibility.

Our model also allows that recycling can either be done at a generation node or at a treatment center. The model does not consider the location of recycling centers or the transportation of recyclable material. The recycling percent of a hazardous waste type from a generation node is assumed to be known for each type of hazardous waste at each generation node. The recycling percent of waste residues is also assumed to be known and to be dependent on the treatment technology employed.

The proposed model is formulated as a multiobjective mixed integer programming model with two objectives: (1) minimizing total cost and (2) minimizing transportation risk. The model is subject to the conservation of flow constraints for both hazardous waste and waste residue. An important constraint is the mass balance constraint, which is usually absent in transportation problems. Through mass balance, the treated and non-recycled hazardous waste is transformed into waste residues, which are to be disposed of. Apart from the above constraints, there is also a minimum amount requirement constraint, which ensures that a treatment technology is opened only if the minimum amount of waste required for that technology is available. The other constraints are the capacity and the compatibility constraints.

The following indices, parameters and decision variables are used in the mathematical model:

Given;

$N=(V, A)$ transportation network
$G=\{1, \ldots, g\}$ generation nodes
$T=\{1, \ldots, t\}$ potential treatment nodes
$D=\{1, \ldots, d\}$ potential disposal nodes
$Tr=\{1, \ldots, tr\}$ transshipment nodes

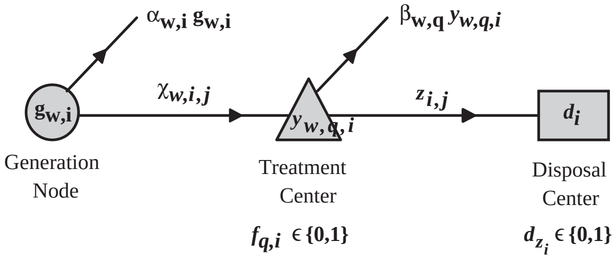

Fig. 2. Decision variables of the mathematical model.

$W = \{1, \ldots, w\}$ hazardous waste types
$Q = \{1, \ldots, q\}$ treatment technologies

Parameters:
$c_{i,j}$ cost of transporting one unit of hazardous waste on link $(i, j) \in A$
$cz_{i,j}$ cost of transporting one unit of waste residue on link $(i, j) \in A$
$fc_{q,i}$ fixed annual cost of opening a treatment technology $q \in Q$ at treatment node $i \in T$
fd_i fixed annual cost of opening a disposal facility at disposal node $i \in D$
POP_{wij} number of people in the bandwidth for hazardous waste type $w \in W$ along link $(i, j) \in A$
$g_{w,i}$ amount of hazardous waste type $w \in W$ generated at generation node $i \in G$
$\alpha_{w,i}$ recycle percent of hazardous waste type $w \in W$ generated at generation node $i \in G$
$\beta_{w,q}$ recycle percent of hazardous waste type $w \in W$ treated with technology $q \in Q$
$r_{w,q}$ percent mass reduction of hazardous waste type $w \in W$ treated with technology $q \in Q$
$t_{q,i}$ capacity of treatment technology $q \in Q$ at treatment node $i \in T$
$t^{\mathrm{m}}_{q,i}$ minimum amount of hazardous waste required for treatment technology $q \in Q$ at treatment center $i \in T$
dc_i disposal capacity of disposal site $i \in D$
$com_{w,q}$ 1 if waste type $w \in W$ is compatible with technology $q \in Q$; 0 otherwise

Decision variables:
$x_{w,i,j}$ amount of hazardous waste type w transported through link (i, j)
$z_{i,j}$ amount of waste residue transported through link (i, j)
$y_{w,q,i}$ amount of hazardous waste type w to be treated at treatment node i with technology q
d_i amount of waste residue to be disposed of at disposal node i
$f_{q,i}$ 1 if treatment technology q is established at treatment node i; 0 otherwise
dz_i 1 if disposal site is established at disposal node i; 0 otherwise

The decision variables and some parameters of the proposed model are schematically shown in Fig. 2. In the model, the non-recycled amount of generated hazardous wastes $((1 - \alpha_{w,i})g_{w,i})$ are to be routed $(x_{w,i,j})$ to the compatible treatment technology in the treatment facility $(y_{w,q,i})$ to be located $(f_{q,i})$. After the treatment process, the non-recycled amount of waste residues are to be routed $(z_{i,j})$ to the ultimate disposal facility, which is also to be located (d_i).

$$\text{Minimize} \quad \sum_{(i,j)\in A}\sum_{w} c_{i,j}x_{w,i,j} + \sum_{(i,j)\in A} cz_{i,j}z_{i,j} + \sum_{i}\sum_{q} fc_{q,i}f_{q,i} + \sum_{i} fd_i dz_i$$

$$\text{AND}$$

$$\text{Minimize} \quad \sum_{(i,j)\in A}\sum_{w} POP_{w,i,j}x_{w,i,j}$$

$$\text{subject to}$$

$$(1-\alpha_{w,i})g_{w,i} = \sum_{j:(i,j)\in A} x_{w,i,j} - \sum_{j:(j,i)\in A} x_{w,j,i} + \sum_{q} y_{w,q,i}, \quad w\in W, \quad i\in V, \tag{1}$$

$$\sum_{q}\sum_{w} y_{w,q,i}(1-r_{w,q})(1-\beta_{w,q}) - d_i = \sum_{j:(i,j)\in A} Z_{i,j} - \sum_{j:(j,i)\in A} Z_{j,i}, \quad i\in V, \tag{2}$$

$$\sum_{w} y_{w,q,i} \leqslant t_{q,i}f_{q,i}, \quad q\in Q, \quad i\in T, \tag{3}$$

$$d_i \leqslant dc_i dz_i, \quad i\in D, \tag{4}$$

$$\sum_{w} y_{w,q,i} \geqslant t^{\mathrm{m}}_{q,i}f_{q,i}, \quad q\in Q, \quad i\in T, \tag{5}$$

$$y_{w,q,i} \leqslant t_{q,i}com_{w,q}, \quad w\in W, \quad q\in Q, \quad i\in T, \tag{6}$$

$$\sum_{q}\sum_{w} y_{w,q,i} = 0, \quad i\in(V-T), \tag{7}$$

$$d_i = 0, \quad i\in(V-D), \tag{8}$$

$$x_{w,i,j}, z_{i,j} \geqslant 0, \quad w\in W, \quad (i,j)\in A,$$

$$y_{w,q,i} \geqslant 0, \quad w\in W, \quad q\in Q, \quad i\in T,$$

$$d_i \geqslant 0, \quad i\in D,$$

$$f_{q,i}\in\{0,1\}, \quad q\in Q, \quad i\in T,$$

$$dz_i\in\{0,1\}, \quad i\in D.$$

The cost objective minimizes the total cost of transporting hazardous wastes and waste residues and the fixed annual cost of opening a treatment technology and a disposal facility. The risk objective minimizes the transportation risk, which is measured with population exposure. The amount of shipped hazardous wastes on a given link times the amount of people living along a given bandwidth on that link is to be minimized. As the given bandwidth may differ for each hazardous waste type, the equation is summed for all hazardous waste types. One can determine the bandwidth by considering the *initial isolation distances* listed in the Emergency Response Guidebook [14] for each type of hazardous waste.

The first constraint is the flow balance constraint for hazardous wastes. This constraint ensures that all generated non-recycled hazardous waste is transported to and treated at a treatment facility. The model allows opening a treatment facility at a generation node if that generation node is a potential site. Therefore, part of the generated and non-recycled hazardous waste is either treated at that generation node, if a treatment facility is located at that node, or transported to a node on which a treatment facility is located.

The second constraint is the mass and flow balance constraint for waste residue. The treated and non-recycled hazardous waste is transformed into waste residue by this constraint, which also ensures that the entire generated and non-recycled waste residue is transported to a disposal site and disposed of. The model allows opening a treatment and a disposal facility at the same node, which may be a generation node. So, if a treatment and a disposal facility are located at the same node, some part of the generated waste residues can be disposed of at the same node where they are generated. Otherwise, the generated waste residues are to be transported to a node where a disposal facility is located.

The third and fourth constraints are capacity constraints. That is, the amount of hazardous wastes treated at a treatment technology should not exceed the given capacity of that treatment technology, and the amount of waste residue disposed of in a disposal facility should not exceed the capacity of that disposal facility. The fifth constraint is the minimum amount of requirement constraint. A treatment technology is not established if the minimum amount of waste required for that technology is not exceeded. Lastly, the sixth constraint is the compatibility constraint, which ensures that a hazardous waste type is treated only with a compatible treatment technology.

The first and second constraints are written for all nodes, which necessitates the seventh and eighth constraints. We should restrict the model so that no waste is treated and no waste residue is disposed of at nodes that are not among the candidate nodes for treatment and disposal centers.

If n is the number of nodes in the network, m is the number of links, w is the number of hazardous waste types, q is the number of treatment technologies, t is the number of potential treatment nodes, and d is the number of potential disposal nodes, then the model has $(qt + d)$ $0-1$ decision variables and $(wm + m + wqt + d)$ real variables. The number of constraints of the model is $(wn + n + 2qt + d + wqt + (n-t) + (n-d))$. If the candidate sets of the treatment and disposal facilities are composed of the nodes of the network, then the model has $(n(q+1))$ $0-1$ decision variables, $(m(w+1) + n(wq+1))$ real variables, and $(n(w + 2q + wq + 2))$ constraints.

4. Application in Turkey

The model is applied in the Central Anatolian region of Turkey. There are 184 administrative districts in this region, and the population of the districts ranges from 3700 to 77,000 people. It is assumed that the districts with a population of more than 25,000 produce hazardous waste, which makes a total of 92 administrative districts. The 92 administrative districts and the highway network in the region can be seen in Fig. 3.

The total length of the highway network in the Central Anatolian region is about 16,870 km. The density of our network is similar to the density of the highway network of the provinces of Quebec and Ontario in Canada, where the total length of the highway networks within both of these provinces is 16,972 km. When we compared our network to three of the US states; we found that our network is denser than the Connecticut road network, which has a total length of about 7900 km. Our network is also denser than the West Virginia road network, which has a total length of about 14,980 km, but is less dense than the Wisconsin road network, which has a total length of about 37,900 km [15].

The data on the amount of hazardous waste produced by each district in Turkey are not available presently. We assumed that the amount of hazardous waste generated by each district is proportional to the population times the industrial activity level of the district.

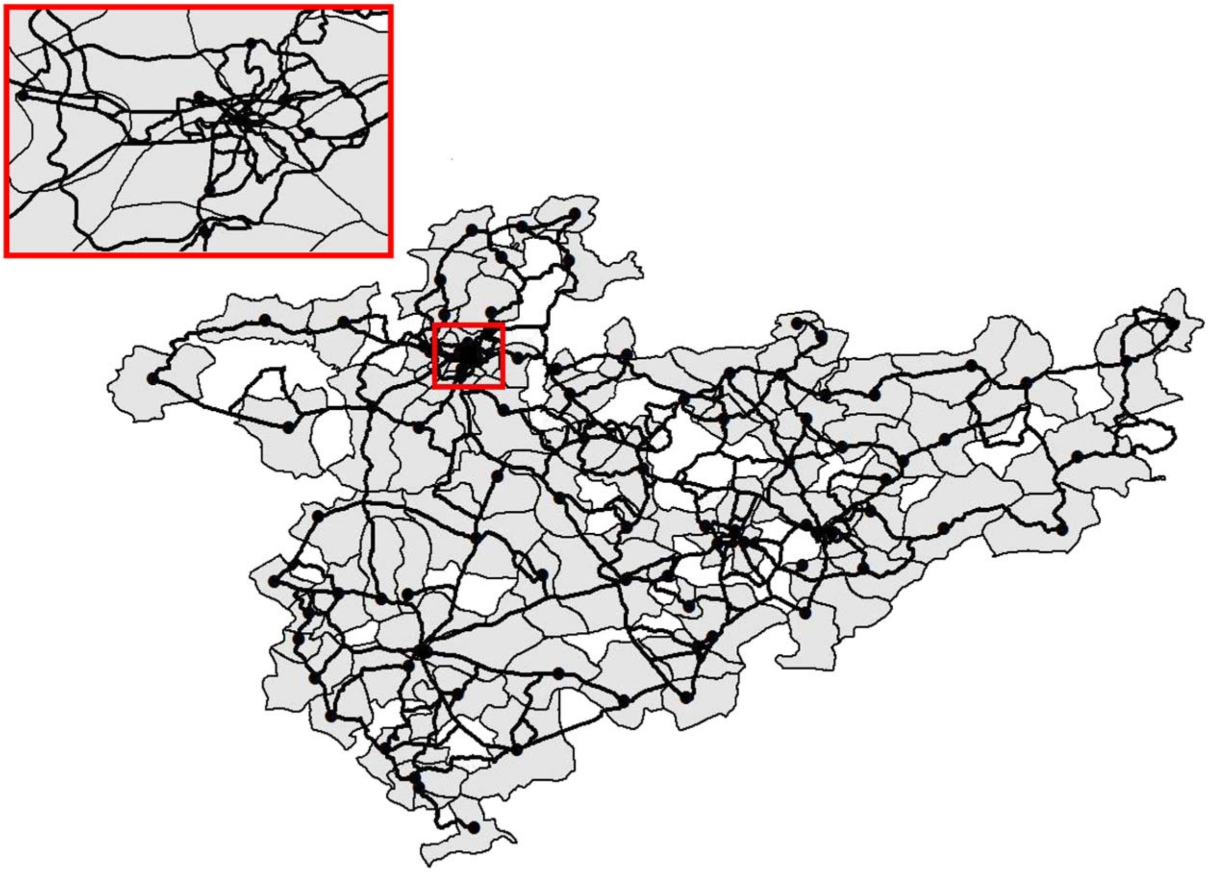

Fig. 3. Ninety-two administrative districts and the highway network in the region. The inset displays an enlarged view of the network around Ankara.

Two candidate sets are generated. First, 15 candidate nodes are selected for the location of both treatment and disposal centers. These 15 candidate nodes are among the generation nodes, and both treatment and disposal facilities are allowed to be located at the same node. Then, a set with 20 candidate nodes is obtained by adding 5 new nodes to the previous 15-node candidate set.

An important issue is to determine the candidate sites. In real life, candidate sites are determined by the related authorities, which are the Ministry of Environment and the municipalities in Turkey. For our application, we determined the candidate set: there are 13 provinces in the Central Anatolian region. We selected one candidate location in each of the provinces. We added two more candidate locations in the provinces with higher hazardous waste production, which are Ankara and Kayseri. Selecting the candidate administrative district among the provinces is done by subjective judgment. In determining the 20-node candidate set, we added one district to the candidate set from the provinces with higher hazardous waste production.

Three types of hazardous waste are generated. The first type can be incinerated, the second type is not suitable for incineration but suitable only for chemical treatment, and the third type is suitable for both incineration and chemical treatment. For example, organic hazardous waste is suitable for both incineration and chemical treatment, but flammable hazardous waste is suitable only for chemical treatment.

We suggested opening two treatment technologies: incineration and chemical treatment. The first type of hazardous waste, which is composed of wastes that can be incinerated, is compatible with incineration but not with chemical treatment. Conversely, the second type of hazardous waste is compatible with chemical treatment but not with incineration. Lastly, the third type of hazardous waste is compatible with both incineration and chemical treatment technologies.

Distances are used as a measure of cost. The cost of transporting waste residues is considered to be 30% less than that of hazardous waste, since hazardous waste is transported with special care and needs special trucks and equipment.

We need two fixed cost parameters for every candidate site in our model: the fixed cost of opening a treatment technology and the fixed cost of opening a disposal facility. In our preliminary results, we figured out that these cost figures played an important role in determining the optimal number of treatment and disposal centers and their locations. However, we were not able to find the correct cost figures for these values in Turkey. On the other hand, distances are taken from actual highway maps and are thus reliable. In our computational analysis, we wanted the distance to be the leading term in the cost objective. For this reason, we used the same fixed cost parameter for each technology and candidate site pair. However, the magnitude of the fixed cost parameter still determines the number of treatment technologies and disposal centers to be opened. (If the fixed cost value is too small, the model locates them at every candidate site; if it is too big, the model locates only one treatment and one disposal center.) In order to control this, we decided to exogenously affect the number of treatment technologies and disposal centers to be opened in the model. For treatment technologies, we used the minimum amount of requirement parameter. It needs to be reiterated here that a treatment technology is not established if the minimum amount of waste required for that technology is not exceeded. To determine the number of disposal centers to be opened, we defined a parameter p, which is the number of disposal centers to be opened and input this parameter into the model.

We take the population exposure bandwidth as 800 m [14] for all types of hazardous waste. Since Revelle et al. [5] state that their solutions were insensitive to different bandwidths, we used the same bandwidth for each type of hazardous waste. The population exposure data are calculated via GIS. A script is written in the GIS software ArcView 3.1, which calculates the number of people in the bandwidth of 800 m from one node to another. It is assumed that the population is uniformly distributed within the administrative districts.

While solving the model to minimize risk, the disposal centers can be located too far from the treatment centers, as waste residues pose no risk. In order to avoid this problem, we implemented a scaled “risk” value in the model for the waste residues. This value is proportional to the distance traveled. That is, we assumed that there is some risk in transporting waste residues, and that risk is taken as 10% of the cost of transporting waste residues.

As to the recycling, recycling after generation is not adopted, because hazardous waste may not always be suitable for recycling. However, 30% of recycling is assumed to take place after chemical treatment, which means that 30% of waste residues produced after chemical treatment have not been sent to disposal centers but recycled. The waste residues after incineration, however, are only composed of ashes, which are not suitable for recycling.

Chemical treatment is a process that aims to reduce the hazard characteristics of the wastes, not the volume or mass. On the other hand, incineration is a process with high mass and volume reduction. Thus, the mass reduction by incineration is taken as 80%, whereas the mass reduction after chemical treatment is taken as 20%.

With this given network and parameters, the problem is solved using CPLEX version 8.1, on a 1133 MHz Pentium III computer with 256 MB RAM.

We varied the minimum amount of waste to be processed at two of the given treatment technologies and the number of disposal centers to be opened. By varying the minimum amount of waste to be processed at the treatment technologies, the model decides on the number of treatment centers to be opened. We considered five cases. Case 1 is when the minimum amount requirements for technologies are such that the model opens one treatment technology of each type and one disposal facility. To obtain this, the minimum amount required for incineration is taken as 7000 units and is 4000 units for chemical treatment. Case 2 is when the minimum amount requirements for technologies are such that the model opens two treatment technologies of each type and one disposal facility. The other cases are defined in a similar way. The parameters of these five cases and the corresponding expected number of technologies to be opened are summarized in Table 1 below.

As the proposed model is multiobjective, a multiobjective solution technique should be adopted. Even though many multiobjective solution techniques exist, we employ a linear composite objective function for ease of application. We use a convex combination of cost and risk to define the impedance for each link. Since cost and risk have different units, we need to scalarize them. One may use different scalarization approaches, such as dividing each term by the maximum, minimum or total sum of that term. In our application we divided the terms by their maximums. Normally, this type of scalarization may be influenced by the data (by a single expensive or high-risk link); however, in our application the range of cost and risk data are not wide. In the multiobjective model, the impedance of each link is calculated by the following formulation:

$$(\lambda \times \text{ Cost of link/Max link Cost}) + (1-\lambda) \times (\text{Risk of link/Max link Risk}).$$

The problem is solved with the given parameters (cases 1, 2, 3, 4 and 5) by using the above linear composite scalarized objective function and by varying the weights given to λ.

The results for the 15-candidate solution are summarized in Table 2 for both minimum cost and minimum risk solutions in all of the five cases. The columns, which are named “Incinerator”, “Chemical Treatment” and “Disposal Center”, show the locations of these facilities by the corresponding node numbers. The node numbers corresponding to 92 administrative districts in the region can be seen in the appendix (Fig. 5).

Table 1
Parameters of the five cases in the application

	Minimum amount for incinerator (tons)	Expected number of incinerators	Minimum amount for chemical treatment (tons)	Expected number of chemical treatments	Number of disposal centers to be opened
Case 1	7000	1	4000	1	1
Case 2	3500	2	2000	2	1
Case 3	3500	2	2000	2	2
Case 4	2000	3	1500	3	2
Case 5	2000	3	1500	3	3

Table 2
Minimum cost and minimum risk solutions for the 15-candidate solution

Problem	Cost (ton km)/10^8	Risk (ton people)/10^{10}	Locations of		
			Incinerator	Chemical treatment	Disposal center
Case 1	26.99	28.93	41	32	32
	20.77	82.43	18	32	32
Case 2	28.03	26.50	37, 58	1, 41	41
	15.85	51.43	18, 58	18, 41	32
Case 3	26.78	26.50	37, 58	1, 41	1, 41
	13.63	52.84	18, 58	18, 58	18, 58
Case 4	20.39	22.89	18, 37, 58	1, 37, 64	37, 64
	12.17	45.69	18, 58, 84	18, 58	18, 58
Case 5	19.07	22.89	18, 37, 58	1, 37, 64	1, 37, 64
	11.59	91.63	18, 58, 84	18, 58	18, 58, 84

Table 3
Optimum locations of treatment and disposal centers with 15 candidate sites

Problem		Case 1	Case 2	Case 3	Case 4	Case 5
$\lambda = 0$	Incinerator plant	41	37, 58	37, 58	18, 37, 58	18, 37, 58
	Chemical treatment	32	1, 41	1, 41	1, 37, 64	1, 37, 64
	Disposal center	32	41	1, 41	37, 64	1, 37, 64
$\lambda = 0.25$	Incinerator plant	41	32, 58	32, 58	18, 58, 84	18, 58, 84
	Chemical treatment	41	14, 41	14, 41	32, 37, 58	32, 37, 58
	Disposal center	41	41	14, 41	18, 58	32, 37, 58
$\lambda = 0.50$	Incinerator plant	41	18, 58	18, 58	18, 58, 84	18, 58, 84
	Chemical treatment	41	32, 84	32, 84	14, 41, 58	14, 41, 58
	Disposal center	41	32	32, 84	14, 58	14, 41, 58
$\lambda = 0.75$	Incinerator plant	41	18, 58	18, 58	18, 58, 84	18, 58, 84
	Chemical treatment	41	14, 58	14, 58	14, 41, 58	14, 41, 58
	Disposal center	41	58	14, 58	14, 58	14, 41, 58
$\lambda = 1$	Incinerator plant	18	18, 58	18, 58	18, 58, 84	18, 58, 84
	Chemical treatment	32	18, 41	18, 58	18, 58	18, 58
	Disposal center	32	32	18, 58	18, 58	18, 58, 84

Table 3 summarizes the optimum locations of treatment technologies and disposal centers for the 15-candidate solution in all of the five cases. (The optimal routes are not shown due to space limitation.) Almost all of the selected districts in the solutions are located around provinces that have a high level of industrial activity compared to the other provinces in the Central Anatolian region. Although the location of the treatment centers and disposal centers are the same in some of the solutions, the routing strategies are different.

Table 4 summarizes the results obtained with the weights given to λ with 15 candidate sites. It also presents the deviations from the minimum for both cost and risk values. Percent deviation from the

Table 4
Cost and risk values for given linear combinations and deviations from the minimum with 15 candidate sites

Problem	$\lambda = 0$		$\lambda = 0.25$		$\lambda = 0.50$		$\lambda = 0.75$		$\lambda = 1$	
	Cost	Risk	Cost	Risk	Cost	Risk	Cost	Risk	Cost	Risk
Case 1	26.99	28.93	23.07	29.86	22.60	30.99	21.53	35.54	20.77	82.43
	29.95%	0%	11.07%	3.21%	8.81%	7.12%	3.66%	22.85%	0%	184.93%
Case 2	28.03	26.50	20.24	29.28	18.02	37.80	16.56	44.84	15.85	51.43
	76.85%	0%	27.70%	10.49%	13.69%	42.64%	4.48%	69.21%	0%	94.08%
Case 3	26.78	26.50	19.37	29.28	16.26	37.80	14.07	44.84	13.63	52.84
	96.49%	0%	42.11%	10.49%	19.30%	42.64%	3.23%	69.21%	0%	99.40%
Case 4	20.39	22.89	16.07	24.39	14.10	26.82	13.05	31.91	12.17	45.69
	67.54%	0%	32.05%	6.55%	15.86%	17.17%	7.23%	39.41%	0%	99.61%
Case 5	19.07	22.89	15.19	24.43	13.29	26.82	12.38	31.91	11.59	91.63
	64.54%	0%	31.06%	6.73%	12.79%	17.17%	6.82%	39.41%	0%	300.31%

Table 5
Average CPU times (in hours) obtained with 15 and 20 candidate sites

Problem	15 Candidate sites	20 Candidate sites
Case 1	0.33	0.71
Case 2	1.89	7.98
Case 3	1.24	6.57
Case 4	2.28	17.11
Case 5	2.26	16.33

minimum is calculated as follows:

$$\text{Percent deviation} = (\text{Value} - \text{Minimum value}) \times 100/\text{Minimum value}.$$

In general, solutions with $\lambda = 0.25$ and 0.50 seem to be reasonable as the percentages of deviations from the minimum for both cost and risk are less than 43% in all of the five cases. The minimum risk ($\lambda = 0$) and minimum cost ($\lambda = 1$) solutions may not be suitable for implementation, because if the minimum cost solution is adopted, the corresponding risk value is too high, and if the minimum risk solution is adopted, the corresponding cost value is again high. One should keep in mind that the best solution may differ for every decision-maker. In real life, the decision-maker would probably be the government; in Turkey, it is the Ministry of Environment.

The minimum cost solutions obtained with 20 candidate sites were the same as the ones obtained with 15 candidate sites. However, the minimum risk solutions are different. In general, the addition of 5 new candidate sites to the 15-node candidate set did not affect the optimal solutions substantially. The percentages of deviations from the minimums are similar to the results obtained with 15 candidate sites.

The problem is solved in reasonable CPU times, where the fastest result with 15 candidates is obtained in about 20 min, and the longest result took about 3 h (Table 5). When we compare the CPU times obtained

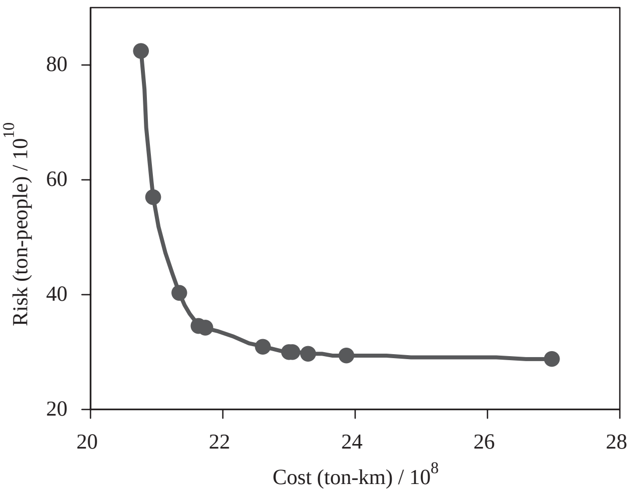

Fig. 4. Trade-off curve with 0.1 increments of λ.

in 15 candidate solutions with 20 candidate solutions, we observed that the CPU times for Case 1 do not differ much. However, in the rest of the cases there is a substantial increase in CPU times. We observed that enlarging the candidate set increases the CPU times drastically. Another approach to solve these tougher instances of the problem could be to use a heuristic method, which is beyond the scope of this study.

Lastly, a trade-off curve is drawn for Case 1 with 15 candidates (Fig. 4). We varied λ between 0 and 1 in increments of 0.1. Each point in the curve represents a different solution. As we move from the minimum risk value (28.93) to the minimum cost value (20.77), the risk increases in order to reduce the cost of transportation. The size of the trade-off changes as one moves along the curve. We observe that there is a steep increase in cost when λ approaches 0, and there is a steep increase in risk when λ approaches 1. This result means that relatively small increases in risk yield relatively large decreases in cost and vice versa. If a decision-maker were concerned about both cost and risk, we would expect the selection of a solution that is generated with a λ value between 0.7 and 0.2.

5. Conclusion and future research directions

We proposed a new mixed integer programming model in which we combined the applicable aspects from different models in the literature. Our model includes some constraints that were observed in the literature but were not incorporated into previous models, such as the compatibility constraint and additional constraints that we proposed. Our aim is to answer the following questions: where to open treatment centers and with which technologies, where to open disposal centers, how to route different types of hazardous wastes to which of the treatment technologies, and how to route the generated waste residues to disposal centers.

We considered many real-life aspects of the hazardous waste management problem and realistically implemented these aspects in the model. Some examples are recycling, the compatibility constraint, and the minimum amount requirement constraint. We considered different waste types and different treatment technologies to avoid simplifying the reality of the hazardous waste management problem. We formulated the model in a manner different from other models presented in the literature, as we also included mass balance.

We considered two objectives of the hazardous waste management problem, which are total cost and transportation risk. Our model is flexible, as it is applicable to various cost and risk measures. One may easily adopt different objectives in the model. One may also include the existing treatment centers or disposal facilities in the model by setting the relevant 0-1 decision variables to 1, before solving it, to find the location of future facilities in a region.

We demonstrated that our model is manageable for a realistic problem in the Central Anatolian region of Turkey. Given that the hazardous waste management problem is a strategic one that will be solved infrequently, we believe that the computational effort is reasonable for problems with up to 20 candidate sites. Our application is a few orders of magnitude better than other applications in the literature. Most of the papers present applications for small problems such as with 10 or 15 generation nodes and with 3 or 4 candidate sites, whereas we applied our model with 92 generation nodes and with 15 and 20 candidate sites.

To solve larger problems, one may have to resort to a heuristic. Although we were able to solve our problem optimally with CPLEX, with heuristics it may be possible to solve even larger problems in a shorter time. No attempt has been made to develop an efficient heuristic approach for the hazardous waste management problem, and it may be a future research direction.

As another research direction, various objectives of the hazardous waste management problem may be implemented in our model. For example, one can maximize the energy production after the incineration process, which will yield profit, as the energy can be sold. Or one can minimize the risk due to the location of the treatment facility. With more objectives, the model can be managed with different multiobjective solution techniques. We propose a relatively simple multiobjective solution technique for ease of application.

Apart from the different objectives, one can expand the mathematical model so that the locations of the recycling facilities and the corresponding routing strategies are also determined. Lastly, a multi-period version of the model can be used to schedule the processing of different types of waste. In this case, the compatibility constraint will gain more importance. That is, any new model should not allow wastes that are not compatible with each other to be transported or incinerated at the same time.

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Appendix

Ninety-two administrative districts, their node numbers and corresponding locations are shown in Fig. 5.

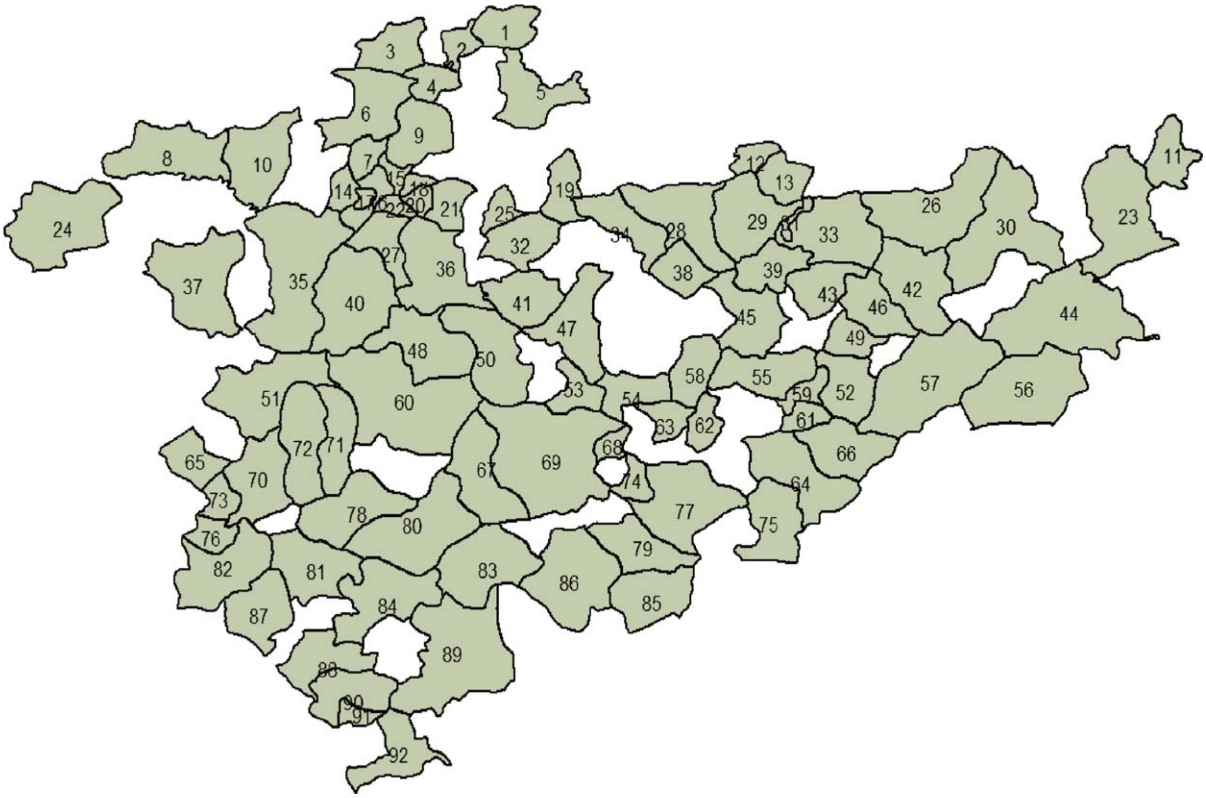

Fig. 5. Ninety-two administrative districts, their node numbers and corresponding locations.

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