European Journal of Operational Research 226 (2013) 332–340

Contents lists available at SciVerse ScienceDirect

European Journal of Operational Research

journal homepage: www.elsevier.com/locate/ejor

Innovative Applications of O.R.

A multi-objective mathematical model for the industrial hazardous waste location-routing problem

Funda Samanlioglu *

Department of Industrial Engineering, Kadir Has University, Kadir Has Campus, Cibali 34083, Istanbul, Turkey

ARTICLE INFO

Article history:
Received 9 February 2012
Accepted 12 November 2012
Available online 24 November 2012

Keywords:
Routing
Multiple objective programming
Location-routing problem
Pareto optimization
Industrial hazardous waste management
Multi-objective model

ABSTRACT

Industrial hazardous waste management involves the collection, transportation, treatment, recycling and disposal of industrial hazardous materials that pose risk to their surroundings. In this paper, a new multi-objective location-routing model is developed, and implemented in the Marmara region of Turkey. The aim of the model is to help decision makers decide on locations of treatment centers utilizing different technologies, routing different types of industrial hazardous wastes to compatible treatment centers, locations of recycling centers and routing hazardous waste and waste residues to those centers, and locations of disposal centers and routing waste residues there. In the mathematical model, three criteria are considered: minimizing total cost, which includes total transportation cost of hazardous materials and waste residues and fixed cost of establishing treatment, disposal and recycling centers; minimizing total transportation risk related to the population exposure along transportation routes of hazardous materials and waste residues; and minimizing total risk for the population around treatment and disposal centers, also called site risk. A lexicographic weighted Tchebycheff formulation is developed and computed with CPLEX software to find representative efficient solutions to the problem. Data related to the Marmara region is obtained by utilizing Arcview 9.3 GIS software and Marmara region geographical database.

1. Introduction

Industrial hazardous materials (hazmat) are produced as a result of the production and manufacturing industry and they are dangerous goods such as flammable, poisonous, toxic, and corrosive substances that pose risks to their surroundings. Examples of production and manufacturing processes that create hazmat are: wood preservation, inorganic pigment manufacturing, organic/inorganic chemicals manufacturing, pesticides manufacturing, explosives manufacturing, petroleum refining, iron and steel production, aluminum production, lead processing, veterinary pharmaceuticals manufacturing, ink formulation, coking, electroplating and other metal finishing operations, dioxin bearing, and production of certain chlorinated aliphatic hydrocarbons. Hazardous wastes exhibit one of the four characteristics: ignitability, reactivity, corrosivity, or toxicity. Ignitable wastes (e.g. waste oils and used solvents) might be spontaneously combustible, and they can create fires under certain conditions. Reactive wastes (e.g., lithium-sulfur batteries and explosives) are stable under normal conditions; however, when heated, compressed, or mixed with water, they can cause explosions, generate toxic fumes, or gases. Corrosive wastes (e.g., battery acid) are acids or bases that are capable of corroding metal containers. Toxic wastes (e.g., containing mercury and lead) are harmful or fatal when ingested or absorbed. They might pollute ground water if they are land disposed.

Hazmat management includes the collection, transportation, treatment, recycling and disposal of hazmat in an organized manner. As countries become more industrialized, hazmat management problems become more significant. Based on the Turkish Statistical Institute's 2004 data (TSI, 2004), hazmat generated as a result of the production and manufacturing industry in Turkey totals about 1.2 million tons per year. Of these 1.2 million tons of hazmat, 5.94% is recycled and reused, 20.74% is sold or donated, and 73.33% is treated. Increasing developments in technology and industry have led to a significant hazardous waste management problem, demanding a more structured and scientific manner of managing hazmat.

The frame of the proposed hazmat management problem is illustrated in Fig. 1. The frame starts with the generation of industrial hazardous wastes, and then non-recyclable amounts of hazardous wastes are routed to treatment centers with compatible technologies, whereas recyclable materials are routed to recycling centers. At the treatment centers, after the treatment process, recyclable waste residues are routed to recycling centers and non-recyclable waste residues are sent to disposal facilities. At recycling centers, after the recycling process, waste residues are also sent to disposal facilities. At present, there does not appear

---

* Tel.: +90 212 533 6532; fax: +90 212 534 0741.
E-mail address: fsamanlioglu@khas.edu.tr

http://dx.doi.org/10.1016/j.ejor.2012.11.019

Nomenclature

$N = (V, A)$	transportation network of nodes V and arcs A
$G = \{1,\ldots,g\}$	hazmat generation nodes, $G \in V$
$T = \{1,\ldots,t\}$	potential treatment nodes, $T \in V$
T'	existing treatment nodes, $T' \subset T$
$D = \{1,\ldots,d\}$	potential disposal nodes, $D \in V$
D'	existing disposal nodes, $D' \subset D$
$H = \{1,\ldots,h\}$	potential recycling nodes, $H \in V$
H'	existing recycling nodes, $H' \subset H$
$W = \{1,\ldots,w\}$	hazardous waste types
$Q = \{1,\ldots,q\}$	treatment technologies
Q'	existing treatment technologies, $Q' \subset Q$

Parameters

$c_{i,j}$	cost of transporting one unit of hazardous waste on link $(i, j) \in A$, $i \in G$, $j \in T$
$cz_{i,j}$	cost of transporting one unit of waste residue on link $(i, j) \in A$, $i \in T$, $j \in D$
$cv_{i,j}$	cost of transporting one unit of waste residue on link $(i, j) \in A$, $i \in H$, $j \in D$
cr_{ij}	cost of transporting one unit of recyclable waste on link $(i, j) \in A$, $i \in G$, $j \in H$
crr_{ij}	cost of transporting one unit of recyclable waste residue on link $(i, j) \in A$, $i \in T$, $j \in H$
$fc_{q,i}$	fixed cost of opening a treatment technology $q \in Q$ at node $i \in T$
fd_i	fixed cost of opening a disposal center at node $i \in D$
fh_i	fixed cost of opening a recycling center at node $i \in H$
$POPgt_{i,j}$	number of people within a given distance of the link $(i, j) \in A$, $i \in G$, $j \in T$
$POPtd_{i,j}$	number of people within a given distance of the link $(i, j) \in A$, $i \in T$, $j \in D$
$POPA_{q,i}$	number of people around node $i \in T$ with technology $q \in Q$
$POPB_i$	number of people around node $i \in D$
$gen_{w,i}$	amount of hazardous waste type $w \in W$ generated at generation node $i \in G$
$\alpha_{w,i}$	proportion of recycling of hazardous waste type $w \in W$ generated at generation node $i \in G$
$\beta_{w,q}$	proportion of recycling of hazardous waste type $w \in W$ treated with technology $q \in Q$
$r_{w,q}$	proportion of mass reduction of hazardous waste type $w \in W$ treated with technology $q \in Q$
γ_i	proportion of total hazardous waste recycled at node $i \in H$
$tc_{q,i}$	capacity of treatment technology $q \in Q$ at node $i \in T$
$tc^m_{q,i}$	minimum amount of hazardous waste required to establish treatment technology $q \in Q$ at node $i \in T$
dc_i	disposal capacity of disposal center $i \in D$
dc^m_i	minimum amount of waste residue required to establish a disposal center at node $i \in D$
rc_i	recycling capacity of node $i \in H$
rc^m_i	minimum amount of waste required to establish a recycling center at node $i \in H$
$com_{w,q}$	1 if waste type $w \in W$ is compatible with (can be treated with) technology $q \in Q$; 0 otherwise

Decision variables:

$x_{w,i,j}$	amount of hazardous waste type $w \in W$ transported through link $(i, j) \in A$, $i \in G$, $j \in T$
$z_{i,j}$	amount of waste residue transported through link $(i, j) \in A$, $i \in T$, $j \in D$
l_{ij}	amount of recyclable waste transported through link $(i, j) \in A$, $i \in G$, $j \in H$
k_{ij}	amount of recyclable waste residue transported through link $(i, j) \in A$, $i \in T$, $j \in H$
$v_{i,j}$	amount of waste residue transported through link $(i, j) \in A$, $i \in H$, $j \in D$
$y_{w,q,i}$, $y_{w,q,j}$	amount of hazardous waste type $w \in W$ treated at node $i, j \in T$ with technology $q \in Q$
dis_i, dis_j	amount of waste residue disposed at node $i, j \in D$
hr_i, hr_j	amount of waste recycled at node $i, j \in H$
$f_{q,i}$	1 if treatment technology $q \in Q$ is established at node $i \in T$; 0 otherwise
dz_i	1 if disposal center is established at node $i \in D$; 0 otherwise
b_i	1 if recycling center is established at node $i \in H$; 0 otherwise

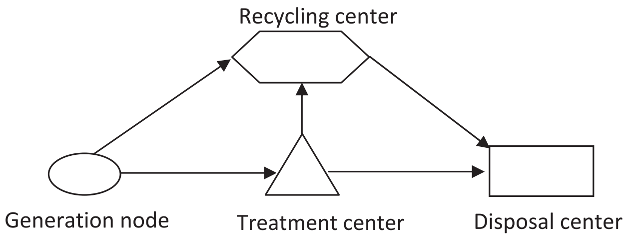

Fig. 1. Frame of the hazmat management problem.

to be a comprehensive mathematical model in the literature that focuses on decisions related to the locations of generation, treatment, disposal, and recycling centers, and routing of hazardous waste and waste residues to these centers as Fig. 1 illustrates. The general trend in hazmat management-related research is to concentrate on the location and routing decisions of treatment, as well as disposal facilities, but recycling centers are often neglected. The importance of recycling is continuously increasing around the world. Field and Sroufe (2007) and Baumgarten et al. (2004) mention the importance of efficient recycling and the use of recycled materials in production, manufacturing, and logistics networks. Hicks et al. (2004) state that effective waste management can reduce the costs and form new supply chains that reuse and recycle materials. In this paper, a new multi-objective location-routing mathematical model for the hazmat management problem is developed. The frame of the problem is presented in Fig. 1.

An extensive survey of location-routing models along with exact and heuristic solution methods is given in Nagy and Salhi (2007). In the literature, there are many perspectives on the mathematical modeling of hazmat location and routing. Some mathematical models focus on minimizing the risks involved in hazmat transportation. Erkut and Verter (1998) provided an overview of such mathematical models and suggested that researchers must be careful about modeling risks, since the optimal path for one model may not perform well for another model. In fact, risk has been modeled in numerous ways throughout hazmat literature. Revelle et al. (1991) used population exposure to model the public's perceived risk, since selecting those routes that minimize the size of the population exposed also minimizes public opposition. Zhang et al. (2000) studied the risks imposed on populations by airborne contaminants modeling dispersion using a Gaussian Plume model and GIS. Verter and Kara (2001) used three popular risk assessment models: societal/traditional risk (e.g., Erkut and

Verter (1995)), population exposure (e.g., Revelle et al. (1991)), and incident probability (e.g., Abkowitz et al. (1992)), and evaluated the risk associated with routes that minimize transport distances, population exposure, the expected number of people to be evacuated in case of an incident, and the probability of an incident during transportation.

Some mathematical models seek to minimize the total cost of hazmat management. Emek and Kara (2007) studied an incineration plant problem and minimized the sum of transportation costs of different types of wastes from factories, recycling centers, and hospitals to incinerators and from factories to recycling centers, while satisfying air pollution standards imposed by government regulations, and also taking into consideration the effects of wind. Cappanera et al. (2004) developed a discrete location routing model that minimizes the transportation cost of obnoxious materials derived from such areas as dump sites, chemical industrial plants, electric power supplier networks, and nuclear reactors, and the opening cost of obnoxious facilities. Berman et al. (2008) studied the problem of selecting obnoxious routes such as routes for transporting hazardous materials and nuclear waste, and developed a model to minimize the cost for compensating the affected population, the total weighted transportation cost and expropriation cost. Another study related to nuclear waste management was done by Delhaye et al. (1991) using an outranking method called ORESTE and taking into consideration several criteria.

In fact, hazmat management-related research usually requires simultaneous consideration of multiple objectives in mathematical models. Nema and Gupta (2003) developed a multi-objective goal programming model to select treatment and disposal facilities, and to allocate hazardous wastes and waste residues from generators to these facilities along transportation routes. Their model addresses compatibility issues of wastes and waste treatment technologies, and includes total capital, maintenance and operation costs related to treatment, transportation and disposal, and total risks including transportation risk, and treatment and disposal site risks. Risk is quantified by several factors, such as the probability of occurrence of an accident or release, estimated consequences of the event, waste quantity, hazard potential of the waste, and the population impacted in an accident. Zhang et al. (2005) developed a location/routing model in order to locate treatment centers and route hazmat from generation points to treatment centers, taking into consideration population centers that are on the route. Their model had three criteria: total cost, which is the sum of transportation costs, the fixed cost of opening facilities, and vehicle security costs; potential risk measured by population exposure; and, risk equity to make sure that each population center is fairly treated in terms of the population center's perceived location risk. Ahluwalia and Nema (2006) developed a bi-criteria integer programming model to select computer waste management facilities and to allocate waste to these facilities in India. The first criterion is total cost associated with waste segregation, storage, transportation, processing, and disposal, along with capital costs for processing and disposal facilities, and cost recovered from the sale of recyclable and reusable waste. The second criterion is total risk related to transportation risk and site risk, which is calculated as a function of waste quantity at the site, hazard potential of the waste, probability of accident and affected population. Caballero et al. (2007) worked on a multi-objective location routing problem in order to locate incineration plants for the disposal of animal waste, and to determine routes for slaughterhouses. They studied three economic objectives, which are related to start-up, maintenance, and transportation costs, along with several social rejection objectives. These social objectives are social rejection by towns along truck routes, risk equity which is calculated by minimizing the maximum social rejection corresponding to the town most affected by transportation of waste, and the social rejection by towns near incineration plants. Dadkar et al. (2008) worked on finding a collection of routes with approximately the same performance to offer alternative routes in order to be fair about population exposure and also as a potential security measure. They used two stochastic measures: "measure of consequence" which is a combined measure of population exposure and accident rates, and travel time. Huang et al. (2004) worked on the hazmat routing problem and identified five criteria: population exposure; socioeconomic impact including direct and indirect costs incurred in a hazmat accident or terrorist attack; risks of hijack related to the population density of surrounding areas; traffic conditions such as speed and flow of travel, road safety, and congestion; and capabilities of an emergency response in terms of locations of emergency response teams and hospitals. To be able to implement this approach in an area in Singapore, they integrated Geographic Information Systems (GISs) with a Genetic Algorithm and used a scoring system to determine weights for the five main criteria and their corresponding factors. Afterwards, Huang et al. (2008) extended this research and the solution technique, and proposed a novel approach to find an unbiased approximation of the Pareto front both supported and non-supported solutions by implementing a Tchebycheff-based function and tuning the search direction in the objective space to the largest unexplored region until a set of well-spread solutions are obtained. They determined eight objectives associated with operating costs, expected travel time, probability of accidental release, expected population exposure along the route, expected population with special needs at risk, expected risk of sensitive environment, expected industrial, commercial, and transportation facilities at risk and their burden on economy, emergency response capabilities, and transportation security concerns such as risks of hijacking and intentional hazmat release by terrorists.

The complexity of hazmat management decisions lies mostly in the existence of at least partially conflicting various objectives and goals concerning total cost, potential risk, risk equity, social rejection, security, and so on. Thus, during the decision making process, many conflicting objectives need to be resolved while decision makers' preferences and perspectives are brought into some form of consensus to attain compromising solutions. In hazmat management, multi-criteria decision making methods can be used to ensure transparency in decision-making processes and to support decision makers in determining operational, efficient, and preferred waste collection, transportation, treatment, disposal, and recycling solutions.

The most common multi-objective optimization method implemented in hazmat management problems (e.g., Ahluwalia and Nema (2006), Alamur and Kara (2007), Dadkar et al. (2008), Zhang et al. (2005)) is the weighted sums method. This method transforms multiple objectives into an aggregated objective function by multiplying each objective function by a weighting factor and summing up all weighted objective functions. A disadvantage of this method is the inability to find all efficient (Pareto optimal) solutions in discrete problems with non-convex feasible objective spaces. With the weighted sums method, only supported efficient solutions which lie in the convex hull of the Pareto front can be found; however, non-supported efficient solutions which lie in the non-convex portions of the Pareto front cannot be found (Steuer, 1986)). Recently, to find supported and non-supported efficient solutions for a mathematical model related to hazardous waste management, Huang et al. (2008) developed a weighted Tchebycheff-based method. However, the solution of this method is weakly efficient (weakly Pareto optimal, weakly non-dominated), and to determine efficient (Pareto optimal, non-dominated) solutions, more effort is needed. To obtain supported and non-supported efficient solutions directly, another method such as the lexicographic weighted Tchebycheff method, the modified weighted Tchebycheff method or the augmented weighted Tchebycheff method might be used. In this paper, the lexicographic weighted Tchebycheff method is used as the multi-objective optimization method to determine representative efficient solutions from the Pareto frontier, since, regardless of the shape of the feasible region, all criterion vectors turned by the lexicographic weighted Tchebycheff program are non-dominated and all non-dominated criterion vectors are uniquely computable. This method can be used in linear, nonlinear, finite discrete, infinite discrete and polyhedral cases (Steuer, 1986)).

In the literature, the closest mathematical models to this research were developed by Alamur and Kara (2007), Zhao and Zhao (2010), and Shuai and Zhao (2011). Alamur and Kara (2007) presented a multi-objective location-routing problem, and implemented it in the Central Anatolian region of Turkey. Their model determined technologies and locations of treatment centers, locations of disposal centers, routing of different types of waste to treatment centers with compatible technologies, and routing of waste residues to disposal centers. In contrast to their model, the mathematical model developed in this paper additionally determines the locations of recycling centers as well as the routing of hazmat to and from recycling centers. They studied two criteria in their model: minimizing the total cost which includes transporting hazardous wastes and residues and the fixed annual cost of opening a treatment technology and disposal facility; and, the total risk of transportation in terms of population exposure, which is associated with the amount of hazardous wastes shipped and the amount of people living within a certain distance of the route. In addition to the two criteria they determined, the mathematical model developed in this paper also includes another criterion: the total risk for the population living near these centers, also called site risk. Unlike their research, in which a weighted sums method is used as the multi-objective optimization technique, this study utilizes a lexicographic weighted Tchebycheff method to find efficient solutions. Note that the feasible region of this problem is not convex; therefore a method such as a lexicographic weighted Tchebycheff method is required to find supported and non-supported efficient solutions. Whereas, with weighted sums method only supported efficient solutions can be found (Steuer, 1986)). Zhao and Zhao (2010) presented a bi-objective mixed integer model to determine the locations of treatment and disposal centers, and the routing of different types of hazardous waste and waste residue from generation nodes to treatment or disposal centers and from treatment centers to disposal centers, taking into consideration different waste types, treatment technologies, waste-technology compatibility and the capacity of these centers. They studied two criteria: minimizing the total cost and total risk and presented a goal programming based algorithm to solve the problem. The mathematical model developed in this paper additionally determines locations of recycling centers, and routing of waste residues to disposal centers after the recycling process. Shuai and Zhao (2011) presented a bi-objective mathematical model to decide on the locations of treatment, disposal, and recycling centers, and the vehicle routes. Their model included two minimization criteria: total transportation and site costs and total transportation and site risks with constraints related to waste types, treatment technologies, waste-technology compatibility and center capacities. They designed a TOPSIS (technique for order preference by similarity to an ideal solution) algorithm to solve this problem and presented a representative example taken from the literature. The mathematical model presented in this research additionally determines routing of recyclable materials to recycling centers after generation and before the treatment process, and routing of waste residues to disposal centers after the recycling process. Also, in the presented research, transportation and site risks are modeled as two separate criteria and a three-criterion problem is solved in order to take into consideration the possibility of total cost objective, total site risk objective, and total transportation risk objective to be competing/conflicting objectives.

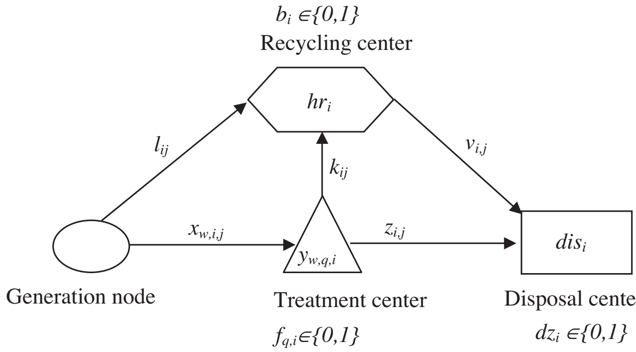

Fig. 2. Decision variables of the mathematical model.

In summary, in this paper, a three-objective location-routing mathematical model for industrial hazmat management decisions is formulated, a lexicographic weighted Tchebycheff formulation of the problem is developed in order to obtain representative efficient solutions from the Pareto frontier, and the formulation is implemented in the Marmara region of Turkey. In Section 2, details of the mathematical model are presented, along with the lexicographic weighted Tchebycheff implementation in Section 3. Details of the implementation of the mathematical model in the Marmara region of Turkey are presented in Section 4, along with conclusions and suggestions for future research directions in Section 5.

2. The mathematical model

The aim of the mathematical model is to answer questions related to: the locations of treatment centers with different technologies; routing different types of hazardous wastes to compatible treatment centers; the locations of recycling centers and routing hazardous wastes and waste residues to these centers; and, the locations of disposal centers and routing waste residues to these centers. The mathematical model of the proposed hazardous waste management problem is a three-objective, mixed integer, location routing model. Note that, even single objective location routing problem is an NP-hard problem since it combines two NP-hard problems: facility location and vehicle routing (Nagy and Salhi (2007)). Multi-objective location routing problem is more complicated, therefore it is also NP-hard. The notation, parameters, and decision variables of the model are presented below, along with a graphical display of the decision variables in Fig. 2.

The mathematical model is as follows:

$$\begin{aligned} \text{Minimize} \quad f_1(x) = {} & \sum_{i\in G}\sum_{j\in T}\sum_{w\in W} c_{i,j}x_{w,i,j} + \sum_{i\in T}\sum_{j\in D} cz_{i,j}z_{i,j} \\ & + \sum_{i\in H}\sum_{j\in D} cv_{i,j}v_{i,j} + \sum_{i\in G}\sum_{j\in H} cr_{i,j}l_{i,j} \\ & + \sum_{i\in T}\sum_{j\in H} crr_{i,j}k_{i,j} + \sum_{i\in T}\sum_{q\in Q} fc_{q,i}f_{q,i} + \sum_{i\in D} fd_i dz_i \\ & + \sum_{i\in H} fh_i b_i \end{aligned} \tag{1}$$

$$\text{Minimize} \quad f_2(x) = \sum_{i\in G}\sum_{j\in T}\sum_{w\in W} POPgt_{i,j}x_{w,i,j} + \sum_{i\in T}\sum_{j\in D} POPtd_{i,j}z_{i,j} \tag{2}$$

$$\text{Minimize} \quad f_3(x) = \sum_{w\in W}\sum_{q\in Q}\sum_{i\in T} POPA_{q,i}y_{w,q,i} + \sum_{i\in D} POPB_i dis_i \tag{3}$$

$$s.t. \quad gen_{w,i} = \alpha_{w,i} gen_{w,i} + \sum_{j \in T} x_{w,i,j} \qquad \forall i \in G, \quad \forall w \in W \tag{4}$$

$$\sum_{w \in W} \alpha_{w,i} gen_{w,i} = \sum_{j \in H} l_{i,j} \qquad \forall i \in G \tag{5}$$

$$\sum_{i \in G} x_{w,i,j} = \sum_{q \in Q} y_{w,q,j} \qquad \forall w \in W, \quad \forall j \in T \tag{6}$$

$$\sum_{w \in W} \sum_{q \in Q} y_{w,q,i} (1 - r_{w,q})(1 - \beta_{w,q}) = \sum_{j \in D} z_{i,j} \qquad \forall i \in T \tag{7}$$

$$\sum_{w \in W} \sum_{q \in Q} y_{w,q,i} (1 - r_{w,q}) \beta_{w,q} = \sum_{j \in H} k_{i,j} \qquad \forall i \in T \tag{8}$$

$$f_{q,i} = 1 \quad \forall q \in Q', \quad \forall i \in T' \tag{9}$$

$$\sum_{i \in T} k_{i,j} + \sum_{i \in G} l_{i,j} = hr_j \qquad \forall j \in H \tag{10}$$

$$hr_i (1 - \gamma_i) = \sum_{j \in D} v_{i,j} \qquad \forall i \in H \tag{11}$$

$$b_i = 1 \qquad \forall i \in H' \tag{12}$$

$$\sum_{i \in H} v_{i,j} + \sum_{i \in T} z_{i,j} = dis_j \qquad \forall j \in D \tag{13}$$

$$dz_i = 1 \qquad \forall i \in D' \tag{14}$$

$$\sum_{w \in W} y_{w,q,i} \leqslant tc_{q,i} f_{q,i} \qquad \forall q \in Q, \quad \forall i \in T \tag{15}$$

$$\sum_{w \in W} y_{w,q,i} \geqslant tc^m_{q,i} f_{q,i} \qquad \forall q \in Q, \quad \forall i \in T \tag{16}$$

$$y_{w,q,i} \leqslant tc_{q,i} com_{w,q} \qquad \forall w \in W, \quad \forall q \in Q, \quad \forall i \in T \tag{17}$$

$$dis_i \leqslant dc_i dz_i \qquad \forall i \in D \tag{18}$$

$$dis_i \geqslant dc^m_i dz_i \qquad \forall i \in D \tag{19}$$

$$hr_i \leqslant rc_i b_i \qquad \forall i \in H \tag{20}$$

$$hr_i \geqslant rc^m_i b_i \qquad \forall i \in H \tag{21}$$

$$\begin{aligned} & x_{w,i,j} \geqslant 0 \forall w \in W, \quad \forall i \in G, \quad \forall j \in T, \\ & y_{w,q,i} \geqslant 0 \forall w \in W, \quad \forall q \in Q, \quad \forall i \in T, \\ & z_{i,j} \geqslant 0 \forall i \in T, \quad \forall j \in D, \\ & k_{i,j} \geqslant 0 \forall i \in T, \quad \forall j \in H, \\ & l_{i,j} \geqslant 0 \forall i \in G, \quad \forall j \in H, \\ & v_{i,j} \geqslant 0 \forall i \in H, \quad \forall j \in D, \\ & dis_i \geqslant 0 \forall i \in D, \\ & hr_i \geqslant 0 \forall i \in H, \end{aligned} \tag{22}$$

$$\begin{aligned} & f_{q,i} \in \{0,1\} \forall q \in Q, \quad \forall i \in T, \\ & dz_i \in \{0,1\} \forall i \in D, \\ & b_i \in \{0,1\} \forall i \in H. \end{aligned} \tag{23}$$

There are three objective functions in the mathematical model. The first one (1) minimizes the total cost, which includes the transportation cost of hazardous materials and waste residues and the fixed cost of opening treatment, disposal and recycling centers. The second objective function (2) minimizes the total transportation risk related to population exposure along the transportation routes of hazardous materials and waste residues. Risk is assumed to be quantified as a function of the amounts of hazardous wastes and waste residues transported on a given route and the number of people living within a given distance of the route. The third objective function (3) minimizes the total risk for the population around treatment and disposal centers, which is also called site risk. Site risk is assumed to be quantified as a function of the amounts of hazardous wastes and waste residues available at those centers and the number of people living within a given radius of these centers. Constraints (4)–(6) are flow balance constraints of the flow from generation nodes to recycling centers, and treatment centers. Constraints (7) and (8) provide the flow from treatment centers to the disposal centers and recycling centers, taking into consideration the loss of mass due to different treatment technologies at treatment centers. Constraint (9) lists existing treatment centers with existing treatment technologies. Constraint (10) determines the flow from generation nodes and treatment centers to recycling centers. Constraint (11) is for the flow from recycling centers to the disposal centers. Constraint (12) lists existing recycling centers. Constraint (13) determines the flow from recycling centers and treatment centers to the disposal centers. Constraint (14) lists existing disposal centers. Constraints 15, 18, and 20 are the capacity limitation constraints for treatment, disposal and recycling centers, respectively. Constraint 16, 19, and 21 indicate the minimum amount of hazardous wastes or waste residues required to establish these treatment, disposal and recycling centers, respectively. Constraint (17) ensures that generated hazardous wastes are only sent to treatment centers with compatible treatment technologies. Constraints (22) are non-negativity constraints and constraints (23) state the binary variables.

If w is the number of hazardous waste types, q is the number of treatment technologies, g is the number of generation nodes, t is the number of potential treatment nodes, d is the number of potential disposal nodes, and h is the number of potential recycling nodes then the model has $(qt + d + h)0 - 1$ decision variables and $(wgt + td + gh + th + hd + wtq + d + h)$ real decision variables. The number of constraints of the model without the non-negativity (22) and binary (23) constraints and without the constraints listing the existing treatment (9), recycling (12), and disposal centers (14) is $(gw + g + wt + 2t + 4h + 3d + 2qt + wqt)$. If the candidate sets of treatment, disposal, and recycling centers are composed of all the generation nodes as the application presented in Section 4, then the model has $(qg + 2g)0 - 1$ decision variables, $(wg^2 + 4g^2 + wgq + 2g)$ real decision variables, and $(2gw + 10g + 2qg + wqg)$ constraints, excluding constraints 9, 12, 14, 22, and 23.

3. The lexicographic weighted Tchebycheff implementation

In this paper, a three-objective mathematical model is formulated in order to simultaneously consider three objectives and a methodology is developed to obtain representative efficient solutions from the Pareto frontier. If there is no conflict between objectives, then a solution can be found where each objective function is at its optimum; however, in reality, typically there is conflict, so only compromise solutions are attainable. Thus, during the decision-making process, potentially conflicting objectives need to be resolved while decision makers' preferences and perspectives are brought into some form of consensus to attain efficient, compromising solutions. Here, as the multi-objective optimization method, the lexicographic weighted Tchebycheff is used. Below, useful definitions related to multi-objective programs (MOPs) are given.

A MOP, $\min f(x) = \{f_1(x), f_2(x), \ldots, f_k(x)\}$ *s.t.* $x \in X$ is assumed to have $k (k \geqslant 2)$ competing objective functions $(f_i : \Re^n \to \Re)$ that are to be minimized simultaneously.

Definition 1. A decision vector $x' \in X$ is *efficient* (*Pareto optimal*) for MOP if there does not exist a $x \in X$, $x \neq x'$ such that $f_i(x) \leqslant f_i(x')$ for $i = 1, \ldots, k$ with strict inequality holding for at least one index i. ($x' \in X$ is efficient, $f(x')$ is non-dominated.)

Definition 2. A decision vector $x' \in X$ is *weakly efficient* (*weakly Pareto optimal*) for MOP if there does not exist a $x \in X$, $x \neq x'$ such that$f_i(x) < f_i(x')$ for $i = 1, \ldots, k$. ($x' \in X$ is weakly efficient, $f(x')$ is weakly non-dominated.)

Definition 3. A Pareto optimal solution is called *supported* if there exists positive weights $\lambda_1, \lambda_2, \ldots, \lambda_k$ such that the solution is optimal with respect to the linear combination (weighted sums problem): $\min \left\{ \sum_{i=1}^{i=k} \lambda_i f_i(x) \right\} s.t. x \in X$ with coefficients $\lambda_1, \lambda_2, \ldots, \lambda_k$. Otherwise the solution is called *non-supported.*

The lexicographic weighted Tchebycheff formulation of this problem is given in (24) as:

$$\begin{aligned} lex\quad & \min\{\alpha,\ e^T(f(x)-f^*(x))\} && (24)\\ s.t\quad & \alpha \geqslant \lambda_1\big(f_1(x)-f_1^*(x)\big) \\ & \alpha \geqslant \lambda_2\big(f_2(x)-f_2^*(x)\big) \\ & \alpha \geqslant \lambda_3\big(f_3(x)-f_3^*(x)\big) \\ & and\ (1)\text{–}(23) \end{aligned}$$

where $\lambda_i > 0$ are the weights $\left(\sum_i \lambda_i = 1\right)$, $f_i^*(x)$ $(i = 1, 2, 3)$ is the utopia point defined as $f_i^*(x) = \min_{\mathbf{x}\in X} f_i(x) - \delta_i$ for $i = 1, 2, 3$ $(\delta_i > 0)$ and e^T is the sum vector of ones $(e^T = [1 \quad 1 \quad 1])$. Here, a two-stage minimization process is used: the first stage is a weighted Tchebycheff program and the second stage is an L_1 metric. If the first stage does not yield a unique criterion vector (in case of alternative optima), then the second stage is used to break ties (Steuer, 1986)). In this paper, problem (24) with different weights ($\lambda_i > 0$ and $\sum_i \lambda_i = 1$) is solved each time to obtain several representative efficient solutions of the hazmat management problem.

4. Application in Turkey

This study applies this model to the Marmara region of Turkey. The data related to the Marmara region, the highway network, administrative districts, and population information was obtained by utilizing Arcview 9.3 and ArcGIS Spatial Analyst 9.3 Lab Kits, and the Marmara region geographical database. There are 131 administrative districts in this region, of which 70 have a population higher than 20,000. Based on the social-economic improvement index of the provinces (T.R. Prime Ministry State Planning Organization, 2003), and existing treatment, disposal, and recycling centers, 41 of these 70 districts have been selected for the application. It is assumed that the number of candidate administrative districts to consider in a province is proportional to the social-economic improvement index of the province. The number of candidate districts to consider in Istanbul province is higher than all other provinces in Marmara region since the social-economic improvement index of Istanbul (5.1373) is the highest. In Istanbul, existing treatment, disposal, and recycling centers are in eight different districts. It is assumed that existing centers remain open, so these eight districts are directly determined as candidate sites. Based on the number of available factories and related industry, populations of the remaining districts, and suggestions of local authorities, five more districts are selected in Istanbul as candidate sites with a total of 13 districts. The rest of the provinces are then compared with Istanbul, and the numbers of candidate administrative districts to consider in these provinces are determined proportionally. As an example, social-economic improvement index of Bursa is 2.6985 and based on the calculation $2.6985 * 13/5.1373 = 6.83$, approximately seven districts are selected as candidate sites in total. Here, three districts are selected directly since there are existing centers, and 4 are selected based on the number of available factories and related industry, populations of these districts, and suggestions of local authorities. In this manner, 20 districts are selected in Marmara region along with 21 districts with existing centers. The selected 41 districts are assumed to generate hazmat and also they are assumed to be candidate sites for treatment, disposal, and recycling centers, simultaneously. For convenience, these 41 districts are listed and numbered from 1 to 41 respectively as follows: Silivri (1), Kucuk Cekmece (2), Buyuk Cekmece (3), Gungoren (4), Bagcilar (5), Bayrampasa (6), Kagithane (7), Sisli (8), Sariyer (9), Umraniye (10), Kartal (11), Pendik (12), Tuzla (13), Gebze (14), Korfez (15), İzmit (16), Golcuk (17), Karamursel (18), Nilufer (19), Gursu (20), Kestel (21), Karacabey (22), Orhangazi (23), Osmangazi (24), Inegol (25), Corlu (26), Cerkezkoy (27), Malkara (28), Tekirdag (29), Bilecik (30), Bozuyuk (31), Yalova (32), Kirklareli (33), Luleburgaz (34), Hendek (35), Sakarya (36), Susurluk (37), Balikesir (38), Canakkale (39), Biga (40), and Kesan (41).

The data about the amount of hazmat produced by each district in the region is not available presently. Therefore, the amount of hazmat generated in these districts is assumed to be the same for all kinds of waste, and they are assumed to be proportional to the population of these districts times the social-economic improvement index (T.R. Prime Ministry State Planning Organization, 2003) of their corresponding provinces. Here, a social-economic improvement index is used as an indication of the industrial activity level of each province. It is assumed that there are two kinds of treatment centers with different treatment technologies: incineration and chemical treatment. Also, three types of wastes are considered; wastes that can be treated with incineration technology, with chemical treatment technology, or both.

The total costs of transporting hazardous wastes and waste residues are calculated based on the amounts that are transported, the transportation distances, and the average cost of fuel. It is assumed that, on average, fuel costs 2.117201$/liter in Turkey and a truck uses on average 0.0003liter/meter. Similar to Alamur and Kara's research (2007), the unit costs of transporting waste residues ($cz_{i,j}$, $cv_{i,j}$, crr_{ij}) are considered to be 70% of those of hazardous wastes, since hazardous wastes need special care, trucks and equipment. Based on the information obtained from existing centers, the fixed cost of establishing a treatment, disposal, and recycling center are assumed to be $50million, $20million, and $20million, respectively. Also, the capacities of treatment, disposal, and recycling centers are taken as 1500 ton, 1500 ton, and 750 ton, with minimum amount requirements of 500 ton, 500 ton, and 250 ton, respectively.

Similar to Alamur and Kara (2007) and Revelle et al. (1991) research, the population exposure bandwidth is determined to be 800 meter for all types of hazardous wastes and waste residues. It is assumed that the total risk of population exposure is proportional to the number of people nearby times the amounts of hazardous wastes or waste residues transported along a given route or are available in these centers. To determine the total transportation risk related to the population exposure along the transportation routes of hazardous materials and waste residues, the number of people in the bandwidth of 800 meter from one node to another (along the route) is calculated with Arcview GIS software. It is assumed that hazmat transported from the generation nodes to treatment centers, and waste residues transported from the treatment centers to the disposal centers, might be harmful to people if any exposure occurs. In a similar manner, to determine the total exposure risk of the population living near treatment and disposal centers (site risk), the population in the 800 meter radius of these centers is calculated with Arcview GIS software. During these calculations, the population is assumed to be uniformly distributed in each district.

Since hazmat is not usually suitable for recycling immediately after generation, only a small percentage is assumed to be sent to recycling centers after generation. Based on the information obtained from existing centers, this amount is taken as 10%, 0%, and 5% for wastes compatible with chemical, incineration or both treatment technologies, respectively. However, similar to Alamur and Kara's research (2007), 30% of the waste residues at a chemical treatment center are assumed to be sent to recycling after chemical treatment and none is sent to recycling after incineration since these are only composed of ashes. As Alamur and Kara (2007), mass reduction by incineration is taken as 80%, whereas the mass reduction after chemical treatment is taken as 20%. Also, based on the information obtained from existing centers, after the recycling process, 5% is assumed to be sent to disposal centers.

Table 1
Solutions obtained when each objective function is individually minimized.

	min $f_1(x)$	min $f_2(x)$	min $f_3(x)$
$f_1(x)$	151	1371	856
$f_2(x)$	2508	181	9567
$f_3(x)$	258	658	77

With this network and data, the problem was solved using CPLEX version 11.2, on an Intel Core 2 Duo 1.80 gigahertz computer with 1.99 gigabyte RAM. First, each objective function was individually minimized to obtain Table 1 and utopia and nadir points. These results are given in millions after rounding to the nearest million.

The utopia point of the problem is found as: $z_i^* = f_i^*(x) = \min_{\mathbf{x}\in X} f_i(x) - \delta_i \; i = 1\ldots3 = (151, 181, 77)$ where $\delta_i = 0.1$ $i = 1,\ldots,3$. The nadir point (z_i^{nad}) is defined as the upper bound of the Pareto optimal set, and it is found from Table 1 as: $z_i^{nad} = (1371, 9567, 658)$. Based on these results, the objective functions are scaled (normalized). In order to scale (normalize) objective functions, each objective function i is multiplied with corresponding $R_i = 1/(z_i^{nad} - z_i^*)$.

To determine representative efficient solutions of the problem from the Pareto frontier, a group of 16 dispersed weight vectors are generated in Table 2, where $\lambda_i > 0$ are the weights $(\sum_i \lambda_i = 1)$. Readers can find methods for generating dispersed weight vectors in Steuer (1986). These weight vectors are then used in a lexicographic weighted Tchebycheff formulation (24) to obtain sample efficient solutions of the Pareto front. The problem (24) is solved 16 times, each with a different weight vector to obtain 16 representative efficient solutions of the problem from the Pareto frontier. In Table 3, these solutions are presented along with CPU times in seconds. Note that normalized objective functions are used in the lexicographic weighted Tchebycheff calculations (24), but restored objective function values in the original scales are presented to the reader in Table 3 in order to prevent confusion. The objective function values are given in millions after rounding to the nearest million. In Table 4, locations of existing centers in the Marmara region of Turkey, and in Table 5, locations of new centers that need to be established based on each of these 16 representative efficient solutions are presented. Note that in reality one would select the most preferred solution to implement based on the preferences of decision makers.

In Fig. 3, a sample efficient solution (solution number 13 in Tables 3 and 4), obtained when equal weights ($\lambda_i = 1/3$, $i = 1, 2, 3$) are used in problem (24), is presented. In this figure, one can observe the locations of 41 generation sites and their corresponding node numbers, the highway network in the region, 10 chemical treatment centers, 14 incineration centers, seven disposal centers, and six recycling centers. Note that, some of these sites are determined as treatment, disposal, and recycling centers, simultaneously. For example, based on solution number 13, at node number 2, there should be a chemical treatment and a recycling center, at node number 14, a disposal and a recycling center, at node number 9, a chemical and an incineration treatment, and a disposal center, and at node number 16, a disposal, and a recycling center.

Table 3
16 Representative efficient solutions from the Pareto frontier.

Solution number	1	2	3	4
Solution of (24)	0.047	0.052	0.045	0.045
$f_1(x)$	251	401	371	231
$f_2(x)$	1933	1154	1873	1605
$f_3(x)$	185	197	129	341
CPU	852	54	85	1341
	5	6	7	8
Solution of (24)	0.048	0.028	0.022	0.034
$f_1(x)$	731	252	181	561
$f_2(x)$	924	2854	2222	575
$f_3(x)$	169	105	203	272
CPU	3869	3622	2972	267
	9	10	11	12
Solution of (24)	0.026	0.054	0.051	0.043
$f_1(x)$	471	301	451	281
$f_2(x)$	2643	1448	1369	2180
$f_3(x)$	96	234	150	139
CPU	4461	1614	3053	1673
	13	14	15	16
Solution of (24)	0.051	0.036	0.028	0.040
$f_1(x)$	331	201	322	631
$f_2(x)$	1616	1863	2803	713
$f_3(x)$	166	285	100	192
CPU	8241	504	4641	172

5. Conclusions and discussions

In this study, a new multi-objective mixed integer model for the location-routing decisions of industrial hazmat management was proposed. The model includes some aspects that can be seen in the literature; however, none of the existing models in the hazmat management literature simultaneously include the presented frame of generation nodes, treatment centers with compatible technologies, disposal centers and recycling centers within the same model. The aim in this study was to answer questions related to the locations of these sites, as well as the routing of hazardous waste and waste residues to and from these sites, taking into consideration the technological compatibility issues of wastes and treatment centers, and minimum and maximum capacity requirements of these centers. In the model, three different waste types and two compatible technologies were considered.

The hazmat management problem is a multi-criteria decision-making problem by nature since there are several potentially conflicting criteria to consider while making decisions related to the location and routing of hazmat. In this paper, three potentially conflicting significant criteria which need to be minimized simultaneously to attain compromising, efficient solutions are presented. These are: total cost, which includes the transportation cost of hazardous materials and waste residues and the fixed cost of establishing treatment, disposal and recycling centers; the total transportation risk of hazmat related to population exposure; and site risk. In contrast to existing mathematical models in the literature, to attain efficient solutions, as the multi-objective optimization method, the lexicographic weighted Tchebycheff method was implemented. 16 different representative Pareto optimal

Table 2
16 Dispersed weight vectors.

Solution	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
λ 1	0.5	0.25	0.25	0.6	0.1	0.3	0.8	0.1	0.1	0.4	0.2	0.4	1/3	0.7	0.2	0.1
λ 2	0.25	0.5	0.25	0.3	0.6	0.1	0.1	0.8	0.1	0.4	0.4	0.2	1/3	0.2	0.1	0.7
λ 3	0.25	0.25	0.5	0.1	0.3	0.6	0.1	0.1	0.8	0.2	0.4	0.4	1/3	0.1	0.7	0.2

Table 4
Locations of existing centers in the Marmara region of Turkey.

Locations of existing			
Treatment centers (chemical)	Treatment centers (incineration)	Disposal centers	Recycling centers
2, 3, 7, 11, 13, 16, 19, 26, 39	5, 12, 16, 23, 27, 29, 32, 33, 36, 38	8, 14, 24	2, 13, 14, 16, 19, 38

Table 5
Locations of new centers based on 16 representative efficient solutions from the Pareto frontier.

Solution number	Locations of new			
	Treatment centers (chemical)	Treatment centers (incineration)	Disposal centers	Recycling centers
1	9	9, 10	3, 9, 12, 16, 26	–
2	9	2, 3, 8, 9, 10	2, 3, 9, 16, 26	–
3	9, 10	3, 9, 10	1, 9, 10, 16, 23, 26	–
4	8	8, 9	3, 7, 16, 26	–
5	1, 9, 10, 12	2, 3, 8, 9, 10, 14, 17	1, 3, 9, 10, 12, 16, 23, 26, 39	–
6	9	1, 9	1, 9, 26, 36, 39	–
7	–	9, 10	3, 12, 16, 26	–
8	8, 10, 12	2, 3, 8, 9, 10	2, 3, 9, 10, 12, 16, 26	3
9	1, 14, 15	1, 9, 14, 15	1, 9, 15, 16, 23, 26	–
10	9	8, 9, 10	3, 9, 12, 16, 26	–
11	9, 10	2, 3, 9, 10, 14	3, 9, 10, 16, 26	–
12	9	3, 9, 10	3, 9, 16, 26	–
13	9	3, 8, 9, 10	3, 9, 16, 26	–
14	–	8, 9	2, 3, 11, 16, 26	–
15	9	1, 9, 14	1, 9, 23, 26, 35, 39	–
16	2, 3, 7, 9, 10, 11, 12, 13, 16, 19, 26, 39	2, 3, 8, 9, 10, 14	2, 3, 9, 10, 12, 16, 26, 36, 39	–

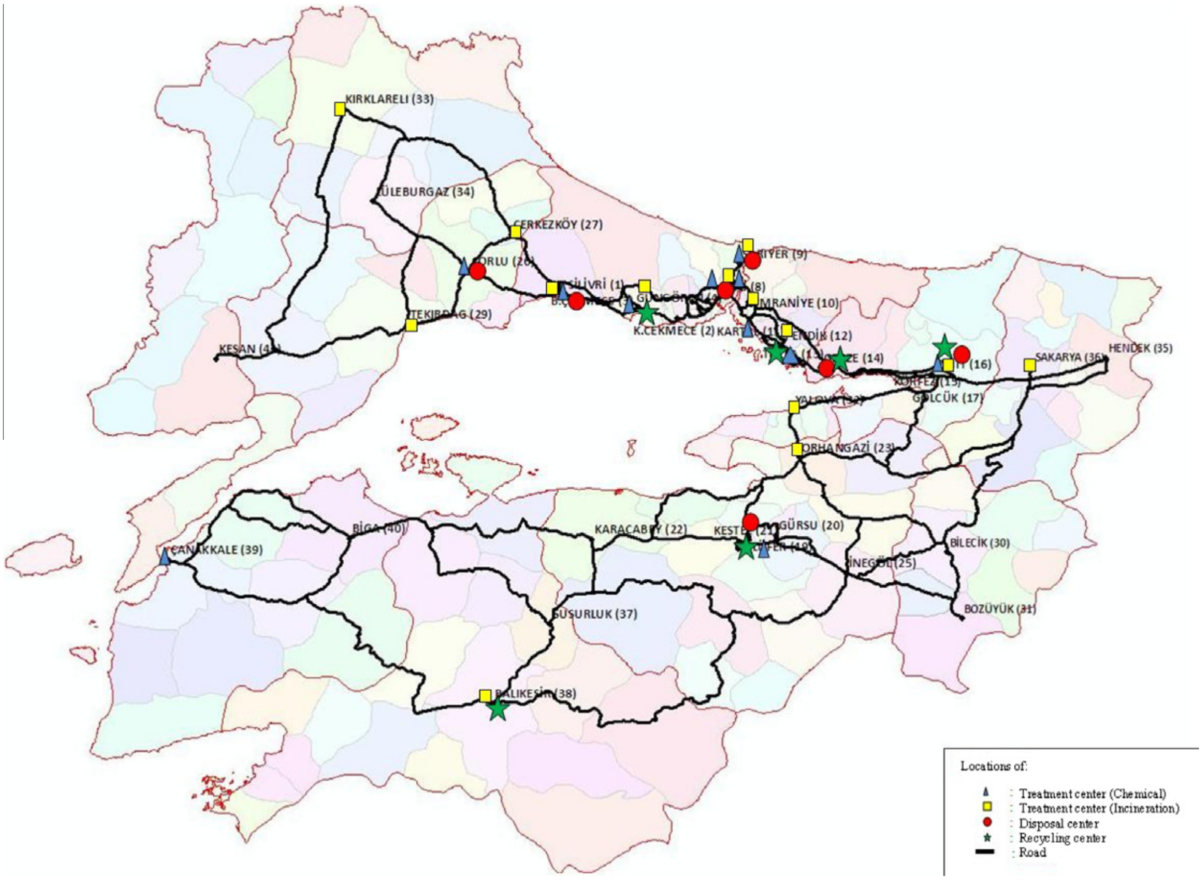

Fig. 3. Efficient solution obtained with equal weights (solution #13).

solutions for the problem were computed, taking into consideration the fact that decision-makers might have different preferences with respect to the importance they attach to each objective function, by generating 16 dispersed weight vectors.

The model was implemented in the Marmara region of Turkey. While some assumptions were made due to a lack of some information, in the implementation, many real-life aspects of the industrial hazmat management problem were considered and realistically implemented in the model. Based on the social-economic improvement index of the provinces in Marmara region, and existing treatment, disposal, and recycling centers, 41 districts were included in the implementation. These 41 districts were assumed to generate industrial hazmat and they were also assumed to be candidate sites for treatment, disposal and recycling centers. In terms of the number of candidate sites considered, the presented application is larger in size than other applications in the literature. So far, in the literature there are applications of up to 20 candidate sites. Also, none of the applications in the literature considered the fact that these candidate sites might be generation, treatment, disposal, and especially recycling center sites at the same time. In this study, the problem was solved with CPLEX with 41 candidate sites, assuming that these candidate sites might simultaneously be generation, treatment, disposal and recycling centers.

As mentioned in Alamur and Kara (2007), the computational effort is reasonable given the fact that this problem is a multi-criteria strategic decision making problem and it will be solved infrequently. To solve larger problems in a shorter time, one may have to develop an efficient heuristic; however, so far none has been developed for the hazmat management problem as presented here and this may well be a direction for future research. Another future research direction concerning decision-making in hazmat management could be to also include several other criteria such as the effects of wind and weather conditions on population exposure during an accident, the probability of an accident due to weather and road conditions, the effects of traffic, and the effects of terrorism.

References

Abkowitz, M., Lepofsky, M., Cheng, P., 1992. Selecting criteria for designating hazardous materials highway routes. Transportation Research Record 1333, 30–35.

Ahluwalia, P.K., Nema, A.K., 2006. Multi-objective reverse logistics model for integrated computer waste management. Waste Management & Research 24, 514–527.

Alamur, S., Kara, B.Y., 2007. A new model for the hazardous waste location-routing problem. Computers & Operations Research 34, 1406–1423.

Baumgarten, H., Klinkner, R., Sommer-Dittrich, T., 2004. Reconfigurable logistics systems in production and disassembly networks. International Journal of Production Research 42 (17), 3647–3655.

Berman, O., Drezner, Z., Wang, Q., Wesolowsky, G.O., 2008. The route expropriation problem. IIE Transactions 40, 468–477.

Caballero, R., Gonzalez, M., Guerrero, F.M., Molina, J., Paralera, C., 2007. Solving a multiobjective location routing problem with a metaheuristic based on tabu search. Application to a real case in Andalusia. European Journal of Operational Research 177, 1751–1763.

Cappanera, P., Gallo, G., Maffioli, F., 2004. Discrete facility location and routing of obnoxious activities. Discrete Applied Mathematics 133, 3–28.

Dadkar, Y., Jones, D., Nozick, L., 2008. Identifying geographically diverse routes for the transportation of hazardous materials. Transportation Research Part E 44, 333–349.

Delhaye, C., Teghem, J., Kunsch, P., 1991. Application of the ORESTE method to a nuclear waste management problem. International Journal of Production Economics 24 (1-2), 29–39.

Emek, E., Kara, B.Y., 2007. Hazardous waste management problem: the case for incineration. Computers & Operations Research 34, 1424–1441.

Erkut, E., Verter, V., 1995. A framework for hazardous materials transport risk assessment. Risk Analysis 15, 589–601.

Erkut, E., Verter, V., 1998. Modeling of transport risk for hazardous materials. Operations Research 46 (5), 625–642.

Field, J.M., Sroufe, R.P., 2007. The use of recycled materials in manufacturing: implications for supply chain management and operations strategy. International Journal of Production Research 45 (18–19), 4439–4463.

Hicks, C., Heidrich, O., McGovern, T., Donnelly, T., 2004. A functional model of supply chains and waste. International Journal of Production Economics 89, 165–174.

Huang, B., Cheu, R.L., Liew, Y.S., 2004. GIS and genetic algorithms for HAZMAT route planning with security considerations. International Journal of Geographical Information Science 18 (8), 769–787.

Huang, B., Fery, P., Xue, L., Wang, Y., 2008. Seeking the Pareto front for multiobjective spatial optimization problems. International Journal of Geographical Information Science 22 (5), 507–526.

Nagy, G., Salhi, S., 2007. Location-routing: issues, models and methods. European Journal of Operational Research 177 (2), 649–672.

Nema, A.K., Gupta, S.K., 2003. Multiobjective risk analysis and optimization of regional hazardous waste management system. Practice Periodical of Hazardous, Toxic, and Radioactive Waste Management ©ASCE 7 (2), 69–77.

Revelle, C., Cohon, J., Shobrys, D., 1991. Simultaneous siting and routing in the disposal of hazardous wastes. Transportation Science 25 (2), 138–145.

Shuai, B., Zhao, J., 2011. Multi-objective 0–1 linear programming model for combined location – routing problem in hazardous waste logistics system. Journal of Southwest Jiaotong University 46 (2), 326–332.

Steuer, R.E., 1986. Multiple criteria optimization: theory, computation and application. John Wiley & Sons, New York.

Turkish Statistical Institute (TSI), 2004. <http://www.tuik.gov.tr> (accessed 19.09.12).

T.R. Prime Ministry State Planning Organization. (2003). İllerin ve bölgelerin sosyo-ekonomik gelişmişlik sıralaması araştırması, DPT 2671.

Verter, V., Kara, B.Y., 2001. A GIS-based framework for hazardous materials transport risk assessment. Risk Analysis 21 (6), 1109–1120.

Zhang, J., Hodgson, J., Erkut, E., 2000. Using GIS to assess the risks of hazardous materials transport in networks. European Journal of Operational Research 121, 316–329.

Zhang, M., Ma, Y., Weng, K., 2005. Location-routing model of hazardous materials distribution system based on risk bottleneck. In: Proceedings of the 2005 IEEE International Conference on Services Systems and Services Management (ICSSSM), vol. 1, pp. 362-368.

Zhao, J., Zhao, J., 2010. Model and algorithm for hazardous waste location-routing problem. In: Proceedings of the ICLEM 2010: Logistics for Sustained Economic Development, 2010 ASCE, pp. 2846–2852.