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Research article

Hazardous waste management system design under population and environmental impact considerations

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ABSTRACT

This paper presents a multi objective mixed integer location/routing model that aims to minimize transportation cost and risks for large-scale hazardous waste management systems (HWMSs). Risks induced by hazardous wastes (HWs) on both public and the environment are addressed. For this purpose, a new environmental impact definition is proposed that considers the environmentally vulnerable elements including water bodies, agricultural areas, coastal regions and forestlands located within a certain bandwidth around transportation routes. The solution procedure yields to Pareto optimal curve for two conflicting objectives. The conceptual model developed prior to mathematical formulation addresses waste-to-technology compatibility and HW processing residues to assure applicability of the model to real-life HWMSs. The suggested model was used in a case study targeting HWMS in Turkey. Based on the proposed solution, it was possible to identify not only the transportation routes but also a set of information on HW handling facilities including the types, locations, capacities, and investment/operational cost. The HWMS of this study can be utilized both by public authorities and private sector investors for planning purposes.

1. Introduction

A hazardous waste (HW) is defined as any waste that possesses hazard properties (such as toxicity, flammability, carcinogenicity, reactivity, corrosivity, etc.) that make it a substantial present or potential hazard to humans and the environment and thus requires strict controls in the course of handling, transportation, processing and disposal. Hazardous waste management systems (HWMS) entail collection of HWs, their transportation to facilities with proper processing technologies or final disposal.

Due to the various risks involved, safety is the foremost priority for all HWMSs however; inherent complexities to the design and operation of these systems bring challenges. Every HWMS should address handling of many wastes classified as hazardous with various chemical and physical properties, which may impact humans and environment in different ways and require a specific type of processing. Due to these complexities of handling HWs, there are several issues involved in modeling entire HWMSs. Firstly; HWs can possess diverse characteristics limiting their compatibility with certain types of processes (waste-to-technology compatibility) (Alamur and Kara, 2007; Nema and Gupta, 1999; List and Mirchandani, 1991; Jennings and Sholar, 1984). Second, significant risk of HWs to humans and the environment influences stakeholder perceptions and priorities of decision makers. Last, even when HWs are processed properly, hazardous process residues may arise as a result of waste handling operations, which may need further processing.

Previous studies modeling HWMSs has various levels of complexity in terms of their coverage of the range of HWs and management options. Some studies included only a single type of HW with a single technology, which presents a non-inclusive approach to complicated HW management problem (Alcada-Almeida et al., 2009; Rakas et al., 2004; Cappanera et al., 2004; Killmer et al., 2001; Sihimizu, 1999; Giannikos, 1998; Jacobs and Warmerdam, 1994; Stowers and Palekar, 1993; ReVelle et al., 1991). Other studies improved their coverage by handling single HW/limited number of technologies (Wyman and Kuby, 1995), multiple HWs/single process (Hu et al., 2002; Wang et al., 2008) and multiple HWs with limited number of technologies (Emek and Kara, 2007). A more realistic representation of HWMSs is provided by Nema and Gupta (1999), Koo et al. (1991), and Jennings and

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Suresh (1986) who investigated multiple HW/multiple technology systems. In an early study, the model of Jennings and Sholar (1984) allowed generation of multiple waste types from individual sources and co-location of facilities of different technologies (i.e. integrated facilities). Processing residues of HW treatment operations, which themselves can be classified as hazardous were considered only in a small number of studies (Alamur and Kara, 2007; Nema and Gupta, 1999; Hu et al., 2002; Jennings and Suresh, 1986).

Another important aspect of HWMS aside from waste-to-technology compatibility is the risk associated with transportation of HWs and operation of HW facilities. Hazardous wastes need to be safely transported from each point of generation to appropriate facilities for processing and disposal. Moreover, process residues arising from hazardous waste facilities should also be directed to proper destinations. This makes transportation to be one of the fundamental components of a HWMS that requires careful consideration during planning. Although incidents involving hazardous materials are not frequent, consequences can be severe (Erkut et al., 2007; Brown et al., 2000). It is highly possible that the effects of an incident would extend beyond human receptors. In the case of an incident, possible impacts include injuries and death, clean-up costs, property damage, product loss, and environmental damage (Federal Motor Carrier Safety Administration, 2001). Although risks on population are addressed in all hazardous wastes/hazmat routing studies (Table 1), environmental risks associated with the HWMSs are overlooked.

Previously, environmental risks were suggested as relevant decision-making criteria by Jennings and Sholar (1984) and Martinez-Alegria et al. (2003). Few attempts to quantify environmental risks were based on exceedance of the time needed by ecosystems to recover from damage (Jonkman et al., 2003), cost to mitigate environmental pollution (Anand, 2006), clean-up costs (Saat et al., 2014), and the area of environmental components within a certain bandwidth (Jennings and Suresh, 1986). Pradhananga et al. (2014) obtained the Pareto optimal solutions for a hazardous material transportation problem and compared CO_2, NO_x and particulate matter emissions originating from transportation.

In order to ensure economic and technical feasibility as well as safety for both public and the environment; locations, technologies and capacities of hazardous waste processing and disposal facilities need to be carefully selected. In the course of the decision-making process, sources that might create multiple types of hazardous wastes with diverse characteristics should be considered. Further; the type, location, size of waste transfer, treatment and disposal facilities and shipment routes should be determined. In the planning phase, it is crucial to recognize the above complications to comprehend aspects that differentiate HW management from non-HW management. Similarly, while modeling a HWMS, simplifying assumptions that may contradict the nature of HW management or its underlying principles, including the precautionary, proximity, waste hierarchy and polluter-pays should be avoided.

Aim of this study is to develop a mathematical model that is capable of representing a complex HWMS, which takes cost and risks of HW management operations and their trade-offs into account. This model intends to present a better understanding of the practical concerns of HW management and be applicable to existent HWMSs. During development of the conceptual model, a number of aspects including waste classes, waste management principles, and waste-to-technology compatibilities were taken into consideration. Based on our conceptual model; we develop a multi-objective mixed integer location/routing model for a national HWMS. This model is capable of determining HW transportation routes, facility locations and capacities. Effects of different HW management strategies and stakeholder priorities can be assessed through scenario development and comparison. To test its effectiveness, the model is applied to Turkey to plan an economical and safe HWMS. Within the scope of the case study, minimum cost, environmental risk, population risk and total risk scenarios are evaluated.

Table 1
Population risk models utilized.

	Risk model								
	Traditional risk	Population exposure	Incident probability	Perceived risk	Conditional risk	Maximum population exposure	Expected disutility	Mean variance	Demand satisfaction
Erkut et al. (2007)	✓	✓	✓	✓	✓	✓	✓	✓	✓
Jonkman et al. (2003)	✓	✓	✓	✓	✓	✓	✓	✓	✓
Kara et al. (2003)	✓	✓							
Nema and Gupta (1999)	✓								
List and Mirchandani (1991)	✓								
Zhang et al. (2000)	✓								
Fabiano et al. (2002)	✓								
Carotenuto et al. (2007)	✓								
Alamur and Kara (2007)		✓							
Stowers and Palekar (1993)		✓							
ReVelle et al. (1991)		✓							
Verter and Kara (2001)		✓							
Verter and Kara (2008)		✓							
Current and Ratick (1995)		✓							
Pradhananga et al. (2014)		✓							
Lovett et al. (1997)		✓	✓						
Huang et al. (2005)		✓	✓						
Jacobs and Warmerdam (1994)			✓						
Giannikos (1998)				✓					
Erkut and Ingolfsson (2005)									✓

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2. Material and methods

2.1. Conceptual model for the hazardous waste management system

European List of Waste includes 843 distinct waste entries of which 409 of them are classified as hazardous (EC, 2014). Although, all of these waste streams actually present a different waste class, incorporation of this high number of waste classes into models significantly increases the model complexity. Waste classification in mathematical models should be refined enough to account for differences in characteristics of the wastes yet simple enough to avoid such complexity issues. This matter was resolved by aggregating 6-digit wastes into seven broader waste classes based on their technological compatibility. While assigning each waste to suitable technologies not only primary waste handling option but also management of residues from hazardous waste treatment processes were taken into consideration.

In order to determine waste-to-technology compatibilities, an extensive analysis of entire European List of Waste was carried out, keeping "waste hierarchy" principle in mind. Whenever multiple handling procedures were applicable for a specific 6-digit entry, waste quantities were allocated between different options based on current field practices. During this analysis, the process residues were identified and necessary processes for their suitable management were decided. Recovery, chemical physical treatment (CPT), incineration and landfilling were considered as waste handling options for both HWs and process residues in line with the waste hierarchy principle. The resulting seven classes are presented in Fig. 1. Further detail on waste types under each class and allocation percentages can be found on Supporting Information (SI) section.

The conceptual model of the HWMS presented in Fig. 2 displays the relationships among the system components. According to this model, different types of hazardous wastes are collected at point of origin some of which may be subject to waste prevention and minimization practices on site. This fact makes them difficult to be incorporated into transportation/location problems. Therefore, any waste minimization, on-site recovery or on-site transfer of wastes is omitted from system boundaries of the conceptual model. Furthermore, non-hazardous portions separated from HWs and non-hazardous residues are excluded from the HWMS system boundary.

Upon collection at the source, hazardous wastes are transported to the appropriate processing facility according to their type (blue lines in Fig. 2). The model allows co-location or establishment of integrated facilities at the same node. It is especially important that incinerators and landfills be integrated since residues from hazardous waste incineration are likely to be hazardous and must be sent to a hazardous waste landfill.

The proportions of treatment and incineration residues with respect to total amount of waste entering a process step are obtained from the literature and current practices. They are incorporated into the model by means of mass reduction ratios (denoted by upper case M in Fig. 1) provided in SI Table S1. These coefficients represent the relation between the amount of waste and the amount of residues entering the process and are needed for flow balance constraints.

2.2. Costs and impacts of a HWMS

2.2.1. Cost

The HWMS model in this study considers both economical and safety aspects of a HWMS. The economical aspects are included in the model by including transportation and processing costs that are the main cost components of the developed HWMS model. Transportation costs, as seen in Equation (1), are calculated depending on the distance traveled and number of shipments (amount of

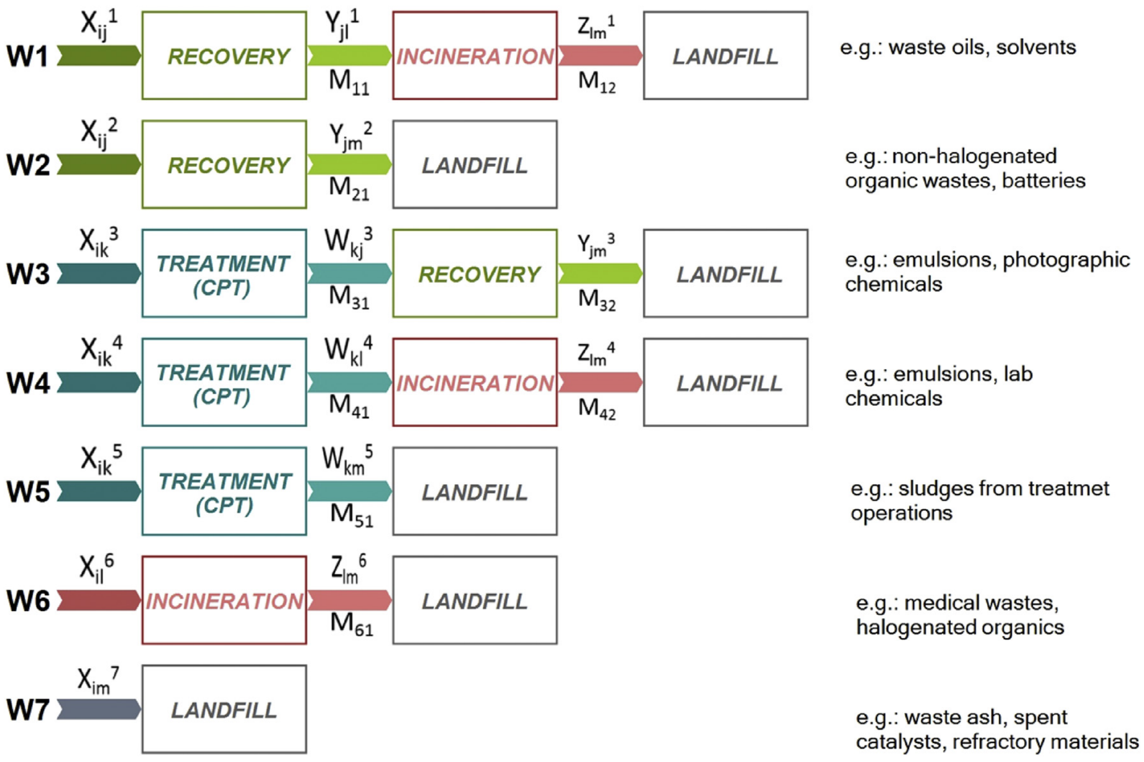

Fig. 1. Waste/residue classification and decision variables.

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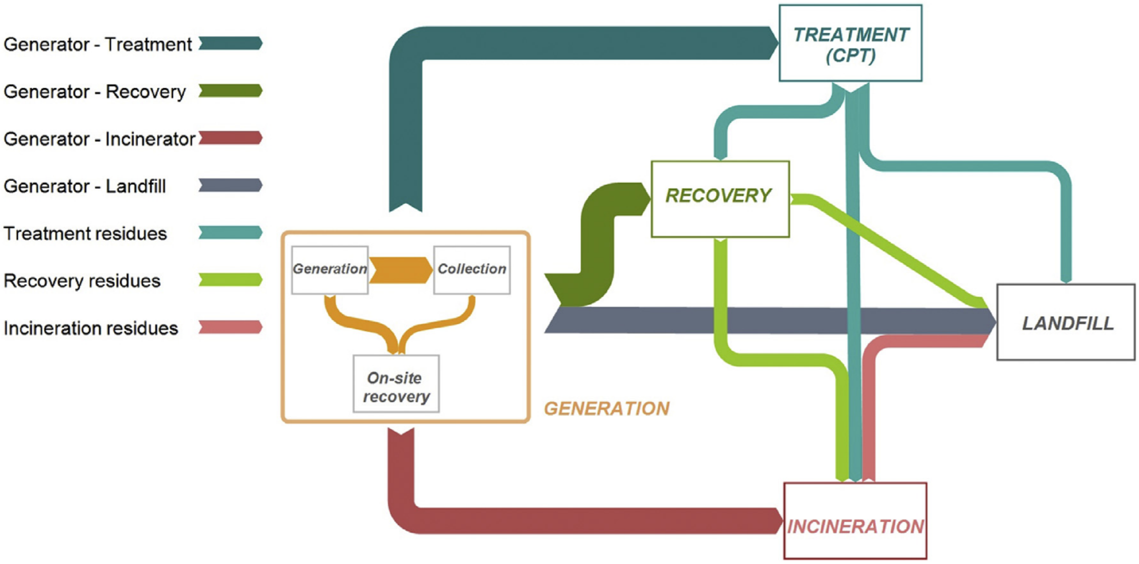

Fig. 2. Conceptual model for the HWMS.

hazardous waste transported and the payloads of the vehicles). Average cost of transportation was estimated assuming that unit cost of transportation does not vary significantly according to the waste type and a fullness ratio of 1.00 for all shipments.

$$TC = UC \times D \times X/PL \tag{1}$$

where,

TC = Transportation cost (TL/yr)
UC = Unit transportation cost (TL/km)
D = Distance traveled (km)
X = Amount of hazardous waste transported (ton/yr)
PL = Payload of the truck used (ton/shipment)

For investment and operational costs of the HW facilities, we used capacity-dependent data to reflect economies of scale principle. Based on the cost data from Yetis and Lenkaitis (2005), the relation between facility capacity and unit investment costs are defined as:

$$\text{For incinerators}: y = 12.19 \times x^{-0.39} \quad \text{with } R^2 = 0.998 \tag{2}$$

where

y: unit investment cost (1000 €s/ton capacity)
x: capacity (1000 tons/yr)

$$\text{For landfills}: y = 12.28 \times x^{-0.35} \quad \text{with } R^2 = 0.998 \tag{3}$$

where

y: unit investment cost (€/ton capacity)
x: capacity (10^6 ton)

Owing to the similarities of the processing equipment, we assume the investment costs of recovery and treatment facilities to be 40% of the incineration costs. We also estimate operational costs to be 8% for incineration, 25% for landfills and 10% for recovery and treatment facilities (Yetis and Lenkaitis, 2005).

2.2.2. Impact

The “risk” objectives used in location/routing models in the literature do not fully reflect the quantitative EU risk assessment methodology, which is comprised of risk identification, exposure assessment and risk characterization steps. Conventional environmental risk assessment methodologies require an extensive amount of information and are difficult to apply to the entirety of complex HWMSs. Rather, all the risk models use surrogate definitions that does not fully quantify the risks but approximates it for scenario comparison purposes. The risk terms in our model are also in line with this approach. In order not to avoid any confusion, in the remainder of the text, the term “impact” is used instead of “risk”.

In order to represent potential public impacts, we adopt the population exposure model used in Alamur and Kara (2007); Stowers and Palekar, (1993); Verter and Kara, (2008); and Madala, (2000). In this study, population impact is defined as the total population of residential units whose center falls within a 1600 m bandwidth around a hazardous waste transportation route. This definition leads us to determine the total number of inhabitants (in capita) along the route between an origin-destination (O-D) pair who can potentially be affected from an incident.

Taking public risk models in the literature as a starting point, we define the environmental impacts between an O-D pair as the length of the road that is in contact with environmentally vulnerable elements, which fall within a 1600 m bandwidth on each side of a hazardous waste transportation route. Environmentally vulnerable elements are selected to be water bodies such as rivers, lakes and dams (used for public consumption and irrigation purposes), coastlines, forests and agricultural lands. Environmental impact value between any O-D pair is the summation of the extent of road (in km) passing by or intersecting environmental components of concern located within the bandwidth.

For both type of impacts and all HW classes, the maximum bandwidth of 1600 m was selected based on the U.S. DOT Emergency Response Guidebook (U.S. Department of Transportation, 2008).

In order to obtain the population and environmental impact matrices, the shortest paths in terms of distance between each O-D pairs are determined (Verter and Kara, 2008). Here the origin nodes are waste generators and all HW facilities except for landfills, which

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are always nodes for final disposal according to our conceptual model. The destination nodes are all possible types of waste handling facilities.

Next, the residential units and environmentally vulnerable elements within the 1600 m bandwidth are identified. While identifying residential units is straightforward, environmental components can interact with the route in various ways as shown in Fig. 3. When an element is located along the road, its impact value is obtained by projecting the length of the environmental member on to the road (Fig. 3a-b, d-f). If a water body intersects

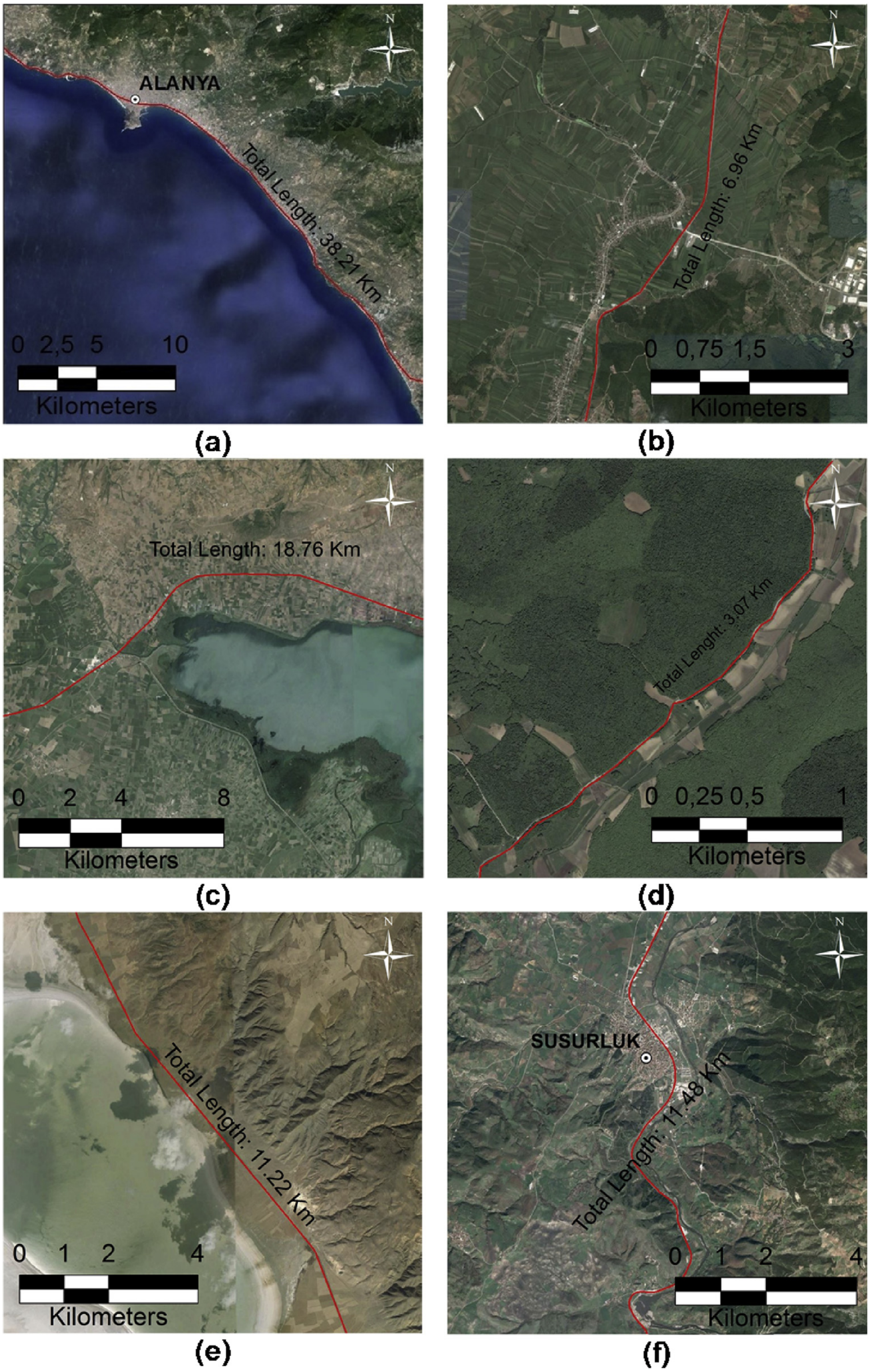

Fig. 3. Illustrations of environmental elements: (a) Mediterranean Shore, (b) Agricultural Area, (c) River Crossing, (d) Forest, (e) Salt Lake (Tuz Gölü), (f) Susurluk River.

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with the transportation route briefly (Fig. 3c), a penalty is added to the environmental impact value to account for the possible mobilization of contaminants as a result of the water flow. These penalties are (i) 20 km for rivers, lakes, dams and reservoirs used for drinking water supply, (ii) 15 km for rivers used as irrigation water source and lakes within specially protected areas, and (iii) 7.5 km for other water bodies.

The cumulative populations of all residential units whose center fall within the bandwidth correspond to the population impact value between a given O-D pair. For each alternative route, length of every environmental element that falls within 1600 m band is added in order to determine total length of vulnerable elements that has the potential to be adversely affected from an incident. As this procedure is repeated for every O-D pair, matrices for population and environmental impacts data are obtained. These matrices are utilized as parameter values in the mathematical model that is presented in Section 2.3.

2.3. Mathematical modeling

The mathematical representation of the conceptual model for the case study is a multi-objective mixed-integer model that considers transporting hazardous wastes and siting hazardous waste facilities. To represent stakeholders' possibly conflicting priorities, population and environmental impacts, and cost are selected as the objectives of the mathematical model. The decision variables in the form of waste and residue quantities are presented in Fig. 1 on the upper side of the arrows connecting the processes.

The mathematical formula for the HWMS model is represented as,

Model indices:

G(i) = set of generators.
R(j) = set of candidate sites for recovery facilities.
T(k) = set of candidate sites for treatment facilities.
I(l) = set of candidate sites for incinerators.
L(m) = set of candidate sites for landfills.
c = type of hazardous waste and residues according to Fig. 1, c = {1,2,…,7}.
u = origin/destination, u ∈ U = {*R*,*T*,*I*,*L*}.
o = origin/destination, o ∈ O = {*R*,*T*,*I*,*L*}.
v = step of hazardous waste processing, v = {1,2}.

E_{ij} = environmental impact between O-D pairs (i,j).

Decision variables:

X^c_{iu}: amount of waste of type c sent from generator (i) ∈ G to facility (u) ∈ U.

$$\begin{array}{lll} \text{For } c = 1,2 & U = R \\ \text{For } c = 3,4,5 & U = T \\ \text{For } c = 6 & U = I \\ \text{For } c = 7 & U = L \end{array}$$

Y^c_{ju}: amount of residue of type c sent from recovery facility (j) ∈ R to facility (u) ∈ U.

$$\begin{array}{ll} \text{For } c = 1 & U = I \\ \text{For } c = 2,3 & U = L \end{array}$$

W^c_{ku}: amount of residue of type c sent from treatment facility (k) ∈ T to facility (u) ∈ U.

$$\begin{array}{ll} \text{For } c = 3 & U = R \\ \text{For } c = 4 & U = I \\ \text{For } c = 5 & U = L \end{array}$$

Z^c_{lu}: amount of residue of type c sent from incinerator (l) ∈ I to landfill (u) ∈ U.
For c = 1, 4, 6 U = L.

$$QR_j = \left\{\begin{array}{ll} 1 & \text{if recovery facility is opened on node j} \\ 0 & \text{otherwise} \end{array}\right\}$$

$$QT_k = \left\{\begin{array}{ll} 1 & \text{if treatment plant is opened on node k} \\ 0 & \text{otherwise} \end{array}\right\}$$

$$QI_l = \left\{\begin{array}{ll} 1 & \text{if incienrator is opened on node 1} \\ 0 & \text{otherwise} \end{array}\right\}$$

$$QL_m = \left\{\begin{array}{ll} 1 & \text{if landfill is opened on node k} \\ & \text{otherwise} \end{array}\right\}$$

The proposed model:

Minimize;

$$Z_1 = \sum_{i\in G}\sum_{u\in U}\left(\frac{C_{iu}}{PL}+C_{Fu}\right)*X^c_{iu} + \sum_{j\in R}\sum_{u\in U}\left(\frac{C_{ju}}{PL}+C_{Fu}\right)*Y^c_{ju} + \sum_{k\in T}\sum_{u\in U}\left(\frac{C_{ku}}{PL}+C_{Fu}\right)*W^c_{ku} + \sum_{l\in I}\sum_{u\in U}\left(\frac{C_{lu}}{PL}+C_{Fu}\right)*Z^c_{lu}$$
$$Z_2 = \sum_{i\in G}\sum_{u\in U}\left(\frac{P_{iu}+E_{iu}}{PL}\right)*X^c_{iu} + \sum_{j\in R}\sum_{u\in U}\left(\frac{P_{ju}+E_{ju}}{PL}\right)*Y^c_{ju} + \sum_{k\in T}\sum_{u\in U}\left(\frac{P_{ku}+E_{ku}}{PL}\right)*W^c_{ku} + \sum_{l\in I}\sum_{u\in U}\left(\frac{P_{lu}+E_{lu}}{PL}\right)*Z^c_{lu} \tag{4}$$

Parameters:

A^c_i: amount hazardous waste generated of type c in province (i) in tons per year.
PL = payload.
D_{ij} = distance between O-D pairs (i,j).
C_{ij} = cost of transportation = unit transportation cost * D_{ij}.
C_{Fu} = facility cost.
M_{cv} = ratio of mass remaining for type c at step v (ton/ton).

$$\begin{array}{ll} \text{For } c = 1,3,4 & v = 1,2 \\ \text{For } c = 2,5,6 & v = 1 \end{array}$$

P_{ij} = population impact between O-D pairs (i,j).

s.t.

$$A^c_i = \sum_{u\in U} X^c_{iu} \tag{5}$$

$$\sum_{i\in G} M_{cv}*X^c_{iu} \sum_{o\in O} Y^c_{uo} \quad \forall \mathrm{u}\in\mathrm{R} \tag{6}$$

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For c = 1, v = 1, O = I
For c = 2, v = 1, O = L

$$\sum_{i\in G} M_{cv}*X_{iu}^{c} = \sum_{o\in O} W_{uo}^{c} \quad \forall u\in T \tag{7}$$

For c = 3, v = 1, O = R
For c = 4, v = 1, O = I
For c = 5, v = 1, O = L

$$\sum_{i\in G} M_{cv}*X_{iu}^{c} = \sum_{o\in O} Z_{uo}^{c} \quad u\in I \tag{8}$$

For c = 6, v = 1, O = L

$$\sum_{j\in R} M_{cv}*X_{ju}^{c} = \sum_{o\in O} Z_{uo}^{c} \quad u\in I \tag{9}$$

For c = 1, v = 2, O = L

$$\sum_{k\in T} M_{cv}*X_{ku}^{c} = \sum_{o\in O} Y_{uo}^{c} \quad u\in R \tag{10}$$

For c = 3, v = 2, O = L

$$\sum_{k\in T} M_{cv}*W_{ku}^{c} = \sum_{o\in O} Z_{uo}^{c} \quad u\in I \tag{11}$$

For c = 4, v = 2, O = L

Table 2
Hazardous waste generation in Turkey according to waste types (Yilmaz, 2011).

Waste classes	Generation[a] (ton/yr)
W1	250,388
W2	140,740
W3	14,136
W4	21,226
W5	16,250
W6	576,466
W7	361,359
TOTAL	**1,380,500**

[a] Excluding mining waste.

$$QR_j, QT_k, QI_l, QL_m \in \{1,0\}$$

$$\begin{array}{lll}
X_{iu}^{c} \geq 0 & \text{for } c = 1,2 & u\in R \\
 & c = 3,4,5 & u\in T \\
 & c = 6 & u\in I \\
 & c = 7 & u\in L \\
Y_{ju}^{c} \geq 0 & \text{for } c = 1 & u\in I \\
 & c = 2 & u\in L \\
W_{ku}^{c} \geq 0 & \text{for } c = 3 & u\in R \\
 & c = 4 & u\in I \\
 & c = 5 & u\in L \\
Z_{lm}^{c} \geq 0 & \text{for } c = 1,4,6 & u\in L
\end{array}$$

$$\begin{array}{l}
X_{ij}^{W1} + X_{ij}^{W2} + W_{kj}^{W3} \leq QR_j*F \quad \forall i\in G,\ j\in R,\ k\in T \\
X_{ik}^{W3} + X_{ik}^{W4} + X_{ik}^{W5} \leq QR_k*F \quad \forall i\in G,\ k\in T \\
X_{il}^{W6} + Y_{jl}^{W1} + W_{kl}^{W4} \leq QR_l*F \quad \forall i\in G,\ j\in R,\ k\in T, 1\in I \\
X_{im}^{W7} + Y_{jm}^{W2} + Y_{jm}^{W3} + W_{km}^{W5} + Z_{lm}^{W1} + Z_{lm}^{W4} + X_{lm}^{W6} \leq QL_m*F \quad \forall i\in G,\ j\in R,\ k\in T, m\in L
\end{array} \tag{12}$$

$$\begin{array}{l}
\sum_{j\in R} QR_j = P_j \\
\sum_{k\in T} QR_k = P_k \\
\sum_{l\in I} QR_l = P_l \\
\sum_{m\in L} QR_m = P_m
\end{array} \tag{13}$$

The first set of constraints (5) ensures that all wastes generated are included in the system. All wastes originating from generators must be sent to hazardous waste facilities with compatible technologies. The second set of constraints (6–12; the flow balance constraints), demands that total amount of hazardous residues (that is, the portion of waste remaining after processing) equals the amount of waste entering the facility times the mass reduction ratios. The third set of constraints (13), which ensures that wastes are sent to a node only if there is a facility established, makes use of binary variables. For this constraint set, no upper capacities are assigned to facilities. Last, the numbers of facilities are parametrically set (13).

Fig. 4. Distribution of hazardous waste generation in Turkey.

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Table 3
Cost information summary (based on Yetis and Lenkaitis, 2005).

	Investment cost (€/ton)	Operational cost (€/ton * yr)
Incineration	2000–6500	160–250
Landfill	9–22	2.25–5.50
Treatment	800–2600	80–260
Recovery	800–2600	80–260

3. Case study: Turkey

3.1. Background information and model inputs

The HMWS model considers 81 provinces with varying hazardous waste types and generation rates (Fig. 4). All 81 provinces are taken as generation nodes. Establishment of HW handling facilities in 19 provinces in Turkey are identified as not probable in real life due to their low hazardous waste generation, high tourism activity or poor highway network. These provinces are omitted from the candidate HW locations (i.e. destination nodes) in order to simplify the mathematical model. The Thrace Region, which includes the part of Istanbul on the European continent, Tekirdag, Edirne, and Kirklareli provinces is handled separately from the rest of the country because transporting HWs through the Bosphorus and Dardanelles Straits would create extensive risk to the public and the environment. This is in line with the Turkish Ministry of Environment and Urbanization's decision to limit hazmat transportation across the Straits.

Currently, a number of small-to medium-sized recovery plants is already been established around the country instead of few large-scale facilities. To represent this existing situation, we assume that recovery facilities to serve each province (generator node) are already available. Therefore, we set the number of recovery facilities to 82 (78 in the Anatolia and four in the Thrace Region) in the model.

Based on waste generation data and technical feasibilities, we decided that establishing ten facilities each for treatment, incineration and landfilling, would be suitable for Anatolia. In addition to these facilities, at least one treatment, incineration and landfilling facility should be located in the Thrace Region to avoid high-risk transportation across Bosphorus and Dardanelles straits. Existing hazardous waste facilities (an incinerator and a landfill in Kocaeli, an incinerator in İzmir and a landfill in Manisa) are not taken into consideration to verify appropriateness of their locations.

Table 4
Optimal solutions for single objective model (minimized objectives are underlined).

Conditions				
Number of generators	Anatolia: 78, Thrace: 4			
Number of candidate sites	Anatolia: 59, Thrace: 4			
Number of recovery facilities	Anatolia: 78, Thrace: 4			
Number of treatment facilities	Anatolia: 10, Thrace: 1			
Number of incinerators	Anatolia: 10, Thrace: 1			
Number of landfills	Anatolia: 10, Thrace: 1			
Objective	Minimum cost	Minimum population impact	Minimum environmental impact	Minimum total impact
Solution				
Population impact (normalized)	2506.90	340.03	1689.96	404.63
Environmental impact (normalized)	802.77	2260.14	1251.30	1481.50
Total normalized impacts	3309.67	2600	2941.26	1886.14
Transportation costs (€/yr)	1,809,758	3,434,659	2,175,955	2,411,981

Due to the lack of a detailed hazardous waste inventory in Turkey, we used the provincial waste generation data estimated through waste generation factors by Yilmaz (2011) (Table 2). The HW generation is concentrated in Western Turkey. Certain provinces with high industrial activity, such as Istanbul and Izmir, significantly contribute to the country's HW generation (Fig. 4).

The ranges of investment and operational costs used in the study are listed in Table 3. The population and environmental impact matrices for the Turkish case study can be found in the SI section.

3.2. Solution procedure

The solution procedure for the HWMS model of Turkish case study can be seen on Fig. 5. The procedure starts with solution of two single objective models for minimizing transportation cost and combined population and environmental impacts. Beside these, two more single-objective models, minimizing population and environmental impacts alone, were considered. Consequently, the solution procedure involves four different scenarios investigating

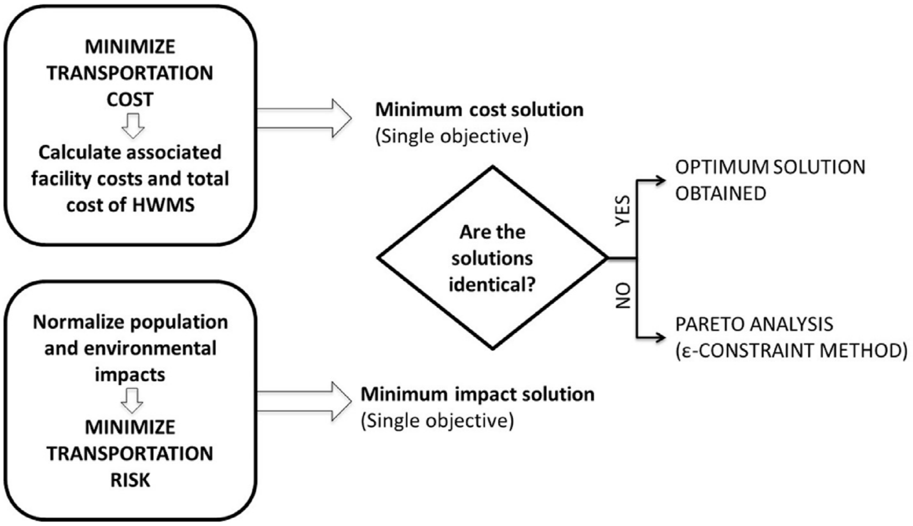

Fig. 5. Solution procedure.

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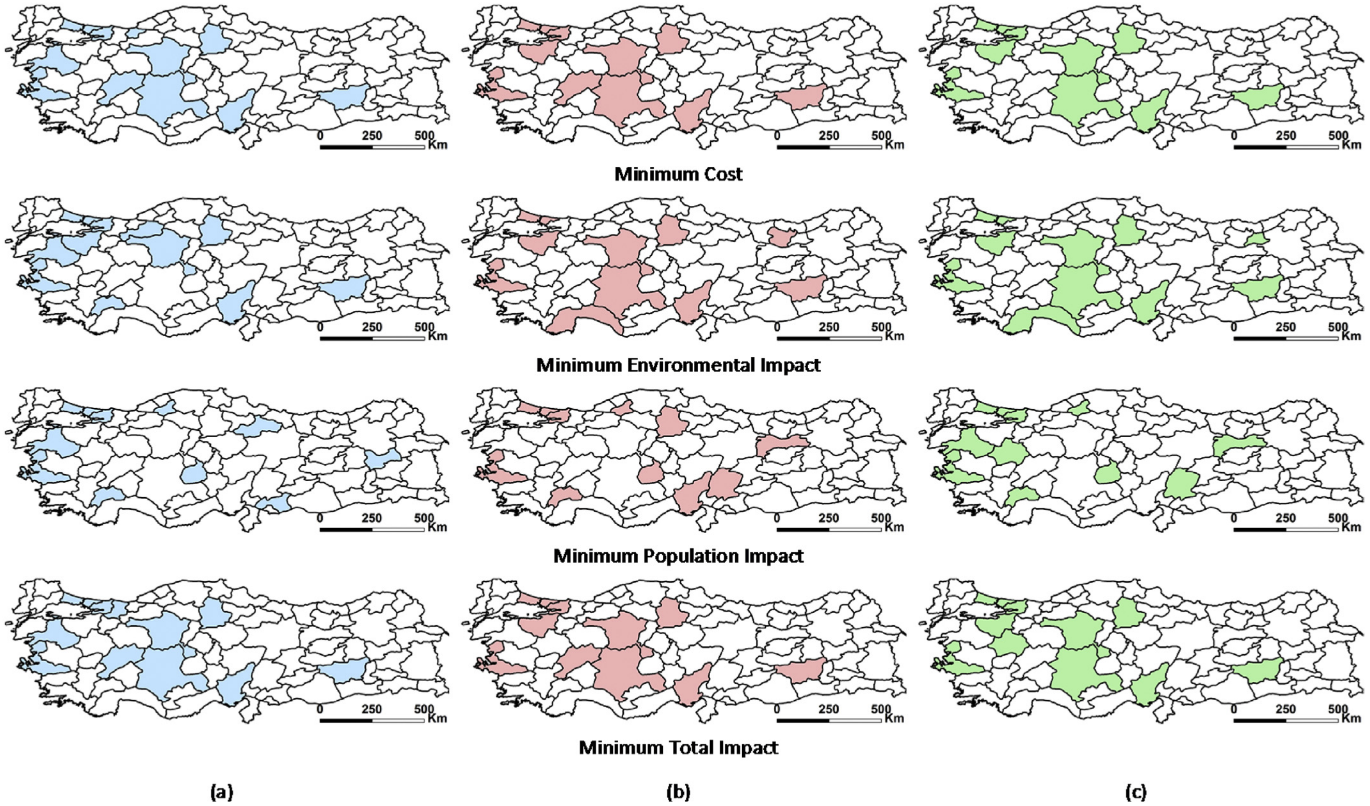

Fig. 6. Facility locations according to single objective scenarios; (a) treatment facilities, (b) incineration facilities, (c) landfills.

(1) minimum cost, (2) only population impacts where public safety is prioritized over environmental aspects, (3) only environmental impacts to determine most environmental friendly solution, and (4) both population and environmental impacts that follow a more holistic approach then two previous scenarios. Main aim here is to observe the variation of facility locations and capacities as a result of public authorities' and private sector HWMS operators' varying priorities.

To be able to obtain a total impact score, population and environmental impacts, which have different units, are normalized by the maximum values in population and environmental impact matrices respectively.

The solutions obtained from single objective models not only reveal the impact scores and transportation costs but also the locations and capacities of the hazardous waste facilities. Facility capacities are obtained from the total waste flow assigned to each facility and the associated unit costs were determined based on Equations (2) and (3). The investment and operational costs of facilities, which depend on capacities according to the economies of scale principle, are calculated separately.

When the minimum cost and minimum impact solutions were identical, the solution procedure was terminated as the optimum solution is reached. While this is valid for smaller domains such as Thrace region, as the problem domain gets larger, the conflicting objective function values begin to diverge. In this case, the ε-constraint method was utilized that involves converting *(n-1)* objective functions to constraints in a multi objective problem with *n* objective functions. In this study, the right hand side of the newly introduced constraint is changed incrementally between its minimum and the maximum values where the minimum is the optimal value of that objective in its single objective model form and maximum value is the value that former objective assumes when the conflicting objective is minimized.

With every incremental change in the right hand side value the new constraint, a solution is obtained. The entire set of solutions comprise the Pareto optimal solution curve since in case of a multi objective formulations with conflicting objectives, there is no single optimal solution. The Pareto optimal curve reveals the changing objective function values due to the trade-off between conflicting objectives, which in our case are cost and impacts.

Solutions for the model were obtained on a computer with an Intel® Core ™ 2 Quad Processor @ 2.66 GHz with 3.25 GB RAM using IBM's OPL 6.3 Development Studio.[1]

3.3. Results and discussion

Table 4 shows the results obtained from single objective optimization of four scenarios. The trade-offs between cost and impact objectives can easily be observed. Furthermore, there seems to be trade-offs between environmental and population impacts. Interestingly, the highest environmental impact value is obtained not under the minimum cost scenario but minimum population impact scenario. Still, it is not advisable to split these two impact measures into separate objective functions since any incident involving hazardous materials would have impacts on both environment and the public. Furthermore, in another case study, depending on the distribution of population and environmentally vulnerable elements geographically, this situation may lose its validity.

The most pronounced difference in facility locations is also observed between minimum environmental and population impact solutions (Fig. 6). The model establishes HW facilities in less populated provinces in case of minimum population impact solution in expense of higher transportation distances. Consequently,

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[1] http://www-03.ibm.com/software/products/en/ibmilogcpleoptistud.

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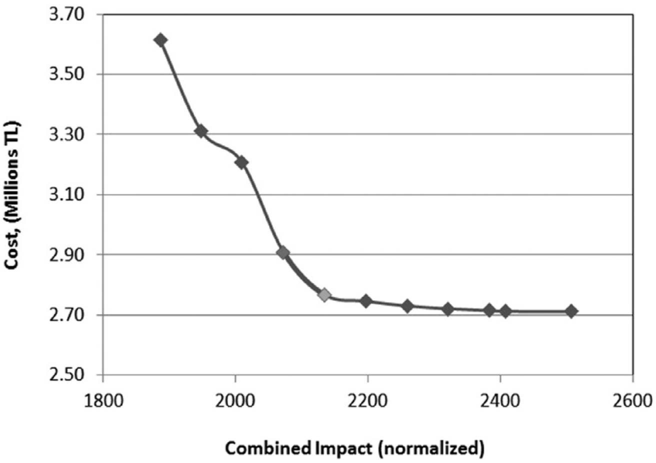

Fig. 7. Trade-off curve for combined population and environmental impact case.

Table 5
Details for the proposed solution.

Conditions	Anatolia	Thrace[a]
Number of generators	78	4
Number of candidate sites	59	4
Number of recovery facilities	78	4
Number of treatment plants	10	1
Number of incinerators	10	1
Number of landfills	10	1
	Solution	
Population impact, point	597	347
Environmental impact, point	1537	1399
Facility cost (€/yr)		
Recovery – investment	31,138,550	3,939,900
Recovery – operational	63,845,650	14,049,650
Treatment – investment	5,916,600	434,500
Treatment – operational	11,833,200	869,000
Incinerator – investment	72,918,050	9,020,950
Incinerator – operational	116,668,900	14,433,500
Landfill – investment	5,990,200	1,081,600
Landfill – operational	1,497,550	270,400
Transportation cost, €/yr	*1,847,450*	*205,750*
Cost, €/yr	**301,656,150**	**44,305,250**
Total HWMS cost, €/yr		**345,961,400**

[a] Anatolia and the European side of Istanbul were considered separate nodes. For this reason, the total number of generators in Anatolia and Thrace add up to 82 although there are only 81 provinces in Turkey.

the transportation cost for minimum population impact scenario is the highest among four in Table 4. On the other hand, locations much closer to high generation nodes are selected to minimize environmental impacts. This stems from the dispersed nature of environmentally vulnerable areas throughout the transportation routes. When adverse environmental effects of hazardous waste transportation are prioritized, shipping distances shorten, which in term reduces the transportation costs. It can be observed that when environmental and public impacts are considered in combination, selected locations show more similarity to minimum environmental impact solution than that of population impact. These locations are also almost identical to the ones chosen for minimum cost scenario since transportation distance is the main parameter that determines the cost.

Still, due to difference in the amount of HWs transported, thus number of trips required, the impact score and transportation costs are disparate in minimum impact and minimum cost solutions. Therefore, it is not possible to minimize both total impacts and total cost simultaneously. The trade-off between these two objectives can be observed in Fig. 7. Each solution point on the Pareto optimal curve was obtained by switching minimum impact objective to a constraint and changing its the right hand side value by increments of 10% between its minimum and maximum values. All the points on the Pareto front in Fig. 7 represent possible solutions and the selection is up to the decision makers' to choose one possible solution based on their priorities.

Table 5 summarizes the main results and the associated facility costs for the proposed solution chosen among the set of Pareto solutions. For estimation of annual cost figures, investment costs are assumed to be linearly depreciated for a 20-year period. According to the proposed solution, total annual cost of HW management in Turkey is approximately 230 million €/yr, which corresponds to 170 €/ton of waste/yr. Main contribution to total cost is associated with incineration (nearly 60% share) depending on high unit costs as well as high combustible waste generation. Around 32% of total cost arises from recovery operations due to higher unit investment costs of small-scale decentralized recovery plants around the country. Finally, the locations of the treatment (CPT), incineration and landfilling facilities with required capacities are presented in Table 6.

The locations of the facilities given in Table 6 show that integrated facilities are favored. In exception to two provinces, model solution suggest establishment of treatment, incineration and final disposal facilities at the same locations. Furthermore, in addition to proposing locations for future facilities, the locations of existing

Table 6
Facility locations and required capacities (The existing facilities in Turkey are shown underlined. Recovery facilities are located at each province – not shown here).

Treatment		Incineration		Landfill	
Province	Capacity (ton/yr)	Province	Capacity (ton/yr)	Province	Capacity (ton/yr)
Adana	4100	Adana	86,200	Adana	53,600
Afyon	4400	Afyon	56,200	Afyon	45,800
Ankara	9300	Ankara	57,200	Ankara	52,800
Balıkesir	6200	Bursa	43,400	Bursa	33,300
Bursa	2300	Corum	55,700	Corum	24,000
Çorum	2100	Diyarbakır	48,100	Diyarbakır	28,800
Diyarbakır	1900	Istanbul (Anatolia)	31,900	Istanbul	67,200
Istanbul (Thrace)	3340	Istanbul (Thrace)	81,900	Istanbul (Thrace)	116,781
Izmir	6900	İzmir	116,700	Izmir	105,900
Kocaeli	10,100	Kocaeli	42,200	Kocaeli	62,300
Konya	2900	Konya	28,400	Konya	35,200
Total	**53,540**	**Total**	**647,900**	**Total**	**625,681**

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facilities in Turkey are confirmed. Although Manisa province is not among proposed locations, it is closely located to İzmir where a treatment plant, an incinerator and a landfill are suggested to be built by the model. According to the results, more than 115,000 ton/yr of incineration capacity is required in İzmir. However, this amount is beyond technically feasible for a single facility. Either two facilities with 60,000 tons/yr capacity can be established or a second incineration facility can be located in close vicinity of İzmir.

Locations such as Istanbul, Kocaeli and Izmir with high waste generation are strong candidates for facilities. Still, we suggest locating at least one facility in the eastern part of Turkey, even though HW generation is not significant in the area. This decision was based on the impact created by transporting HWs from eastern Turkey to facilities in western provinces.

Although we have assumed that recovery facilities to serve each province (generator node) are already available, the waste flows to and from the recovery facilities are still included in the model so as to account for the recovery residues. Cumulative capacity of recovery facilities established by the model around the country is equal to the total amount of recoverable wastes generated. However, this is case is not valid for other facility types due to residue input from other waste processing technologies. Especially the capacities required for incineration and landfilling are much higher than the generation of combustible and disposable wastes within the country. This underlines the importance of including residue flows within the conceptual model in order not to underestimate facility capacities.

4. Conclusions

We present a multi objective model for large scale HWMSs capable of addressing safety and economical concerns. Furthermore, diverse HW classes, waste-to-technology compatibility and HW process residues are also considered in the formulation in order to represent a model applicable to real-life waste management systems.

An important addition of this study to the literature is the introduction of a surrogate definition of potential environmental impacts for HW transportation. This definition shares a similar basis with widely used population exposure model to represent public risks for transportation and involves identification of environmentally vulnerable areas within a constant bandwidth. The results of the case study suggest the environmental impacts can affect the facility location decisions to a great extent, therefore should be taken in to account along public risks.

The case study related to the HWMS of Turkey also demonstrated the importance of including process residues in the conceptual model and among model flows as the total required capacity for the facilities receiving residues are higher than the generation potential.

This model provides valuable insight for decision makers and facility developers. HWMS model proposed in this study confirmed the site selection for already existing plants in Turkey. Locations of future facilities and their capacities are the most substantial information sets provided by the model. The benefits if establishing integrated facilities are proven and should be considered by the decision-makers during elaboration of HW management strategies.

The ability to estimate hazardous waste management costs is another important provision. In addition to total cost, it is possible to draw conclusions on regional and provincial investment needs. Results obtained would help authorities to set priorities and shape their action plans in terms of the missing and inadequate components that needs attention.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.jenvman.2016.06.015.

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