

Hazardous Waste Management

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Abstract

This paper deals with the waste stream of household hazardous waste (HHW) presenting existing management systems, legislation overview and other relevant quantitative and qualitative information. European Union legislation and international management schemes are summarized and presented in a concise manner by the use of diagrams in order to provide crucial information on HHW. Furthermore, sources and types, numerical figures about generation, collection and relevant management costs are within the scope of the present paper. The review shows that the term used to refer to hazardous waste generated in households is not clearly defined in legislation, while there is absence of specific acts regulating the management of HHW. The lack of obligation to segregate HHW from the household waste and the different terminology used makes it difficult to determine the quantities and composition of this waste stream, while its generation amount is relatively small and, therefore, is commonly overlooked in waste statistics. The paper aims to cover the gap in the related literature on a subject that is included within the crucial waste management challenges at world level, considering that HHW can also have impact on other waste streams by altering the redox conditions or causing direct reactions with other non-hazardous waste substances.

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 [1-3]. 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 [4-5]. 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 [6].

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; Capanera 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 [7-9].

Material and methods

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 [10-11] 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 [12-13]. 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 [14].

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 [15].

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.

Costs and impacts of a HWMS

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

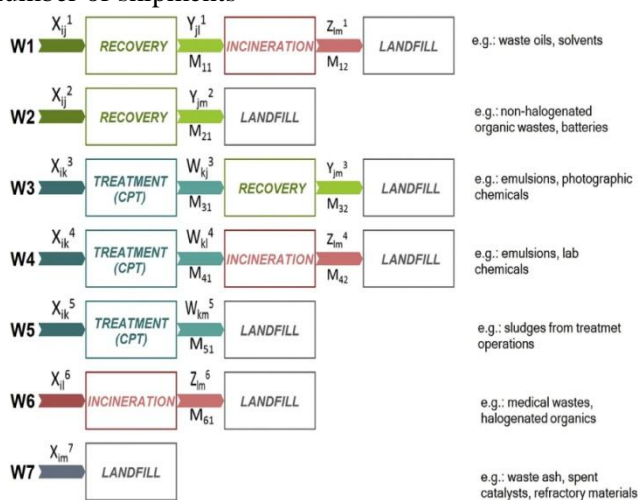


Fig. 1. Waste/residue classification and decision variables.

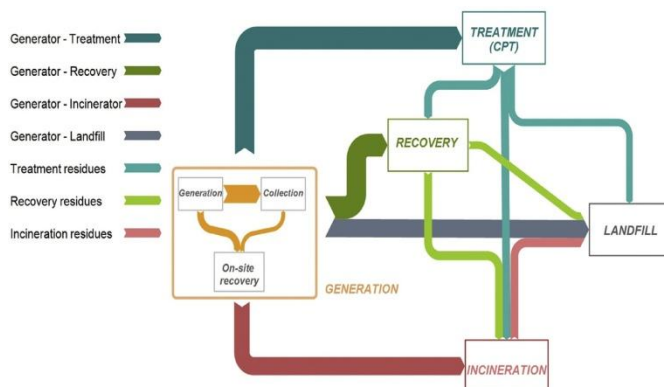


Fig. 2. Conceptual model for the HWMS.

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.

$$TC = UC \cdot D \cdot X = PL \quad (1)$$

where,

TC $\frac{1}{4}$ Transportation cost (TL/yr)

UC $\frac{1}{4}$ Unit transportation cost (TL/km)

D $\frac{1}{4}$ Distance traveled (km)

X $\frac{1}{4}$ Amount of hazardous waste transported (ton/yr) PL

$\frac{1}{4}$ 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:

For incinerators : $y = 12.19 \cdot x^{0.39}$ with $R^2 = 0.998$ (2) where

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

For landfills : $y = 12.28 \cdot x^{0.35}$ with $R^2 = 0.998$ (3) where y: unit investment cost (V/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).

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 [16-17]. 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 are always nodes for final disposal according to our conceptual model. The destination nodes are all possible types of waste handling facilities.

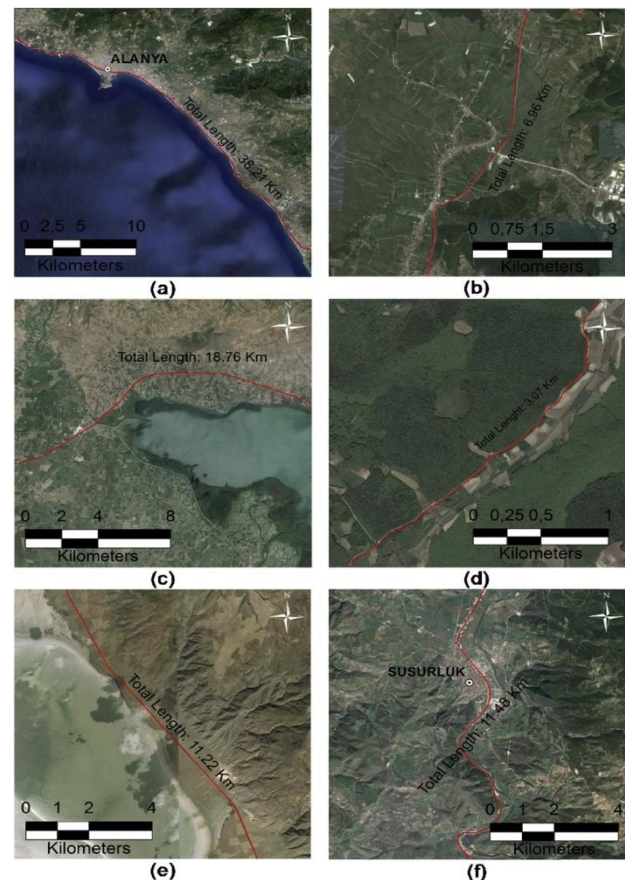


Fig. 3. Illustrations of environmental elements: (a) Mediterranean Shore, (b) Agricultural Area, (c) River Crossing, (d) Forest, (e) Salt Lake (Tuz Golü), (f) Susurluk River.€

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 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.

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:

$G(i) \frac{1}{4}$ set of generators.

$R(j) \frac{1}{4}$ set of candidate sites for recovery facilities.

$T(k) \frac{1}{4}$ set of candidate sites for treatment facilities.

$I(l) \frac{1}{4}$ set of candidate sites for incinerators.

$L(m) \frac{1}{4}$ set of candidate sites for landfills.

$c \frac{1}{4}$ type of hazardous waste and residues according to Fig. 1,

$c \frac{1}{4} \{1,2,\dots,7\}$. $u \frac{1}{4}$ origin/destination, $u \in U \frac{1}{4} \{R,T,I,L\}$. $o \frac{1}{4}$ origin/destination, $o \in O \frac{1}{4} \{R,T,I,L\}$. $v \frac{1}{4}$ step of hazardous waste processing, $v \in \{1,2\}$.

$E_{ij} \frac{1}{4}$ environmental impact between O-D pairs (i,j) .

Decision variables:

X_{iu}^c : amount of waste of type c sent from generator $(i) \in G$ to facility $(u) \in U$.

For $c \frac{1}{4} 1; 2 \quad U \frac{1}{4} R$

For $c \frac{1}{4} 3; 4; 5 \quad U \frac{1}{4} T$

For $c \frac{1}{4} 6 \quad U \frac{1}{4} I$

For $c \frac{1}{4} 7 \quad U \frac{1}{4} L$

Y_{ju}^c : amount of residue of type c sent from recovery facility $(j) \in R$ to facility $(u) \in U$.

For $c \frac{1}{4} 12; 3 \quad UU \frac{1}{4} IL$

For $c \frac{1}{4}$

W_{ku}^c : amount of residue of type c sent from treatment facility $(k) \in T$ to facility $(u) \in U$.

For $c \frac{1}{4} 3 \quad U \frac{1}{4} R$

For $c \frac{1}{4} 4_5 \quad UU \frac{1}{4} LI$

For $c \frac{1}{4}$

Z_{lu}^c : amount of residue of type c sent from incinerator $(l) \in I$ to landfill $(u) \in U$.

For $c \frac{1}{4} 1, 4, 6 \quad U \frac{1}{4} L$.

1 if recovery facility is opened on node j
 $QR_j \frac{1}{4} 0$ otherwise

1 if treatment plant is opened on node k
 $QTr_k \frac{1}{4} 0$ otherwise

1 if incinerator is opened on node l
 $QIl \frac{1}{4} 0$ otherwise

1 if landfill is opened on node k
 $QLm \frac{1}{4} 0$ otherwise

III. Case study: Turkey

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 Kırklareli 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 largescale 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 Izmir and a land_ fill in Manisa) are not taken into consideration to verify appropriateness of their locations.

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). 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.

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

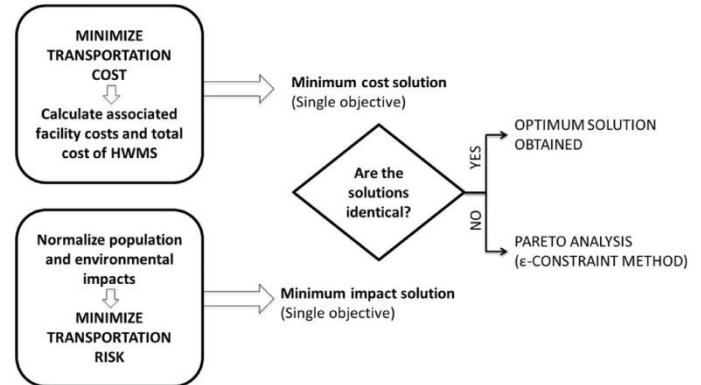


Fig. 4. Solution procedure.

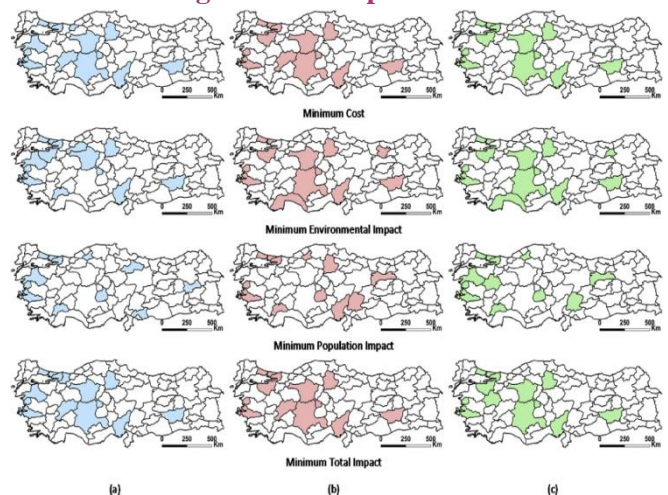


Fig. 5. Facility locations according to single objective scenarios; (a) treatment facilities, (b) incineration facilities, (c) landfills.

IV. 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,

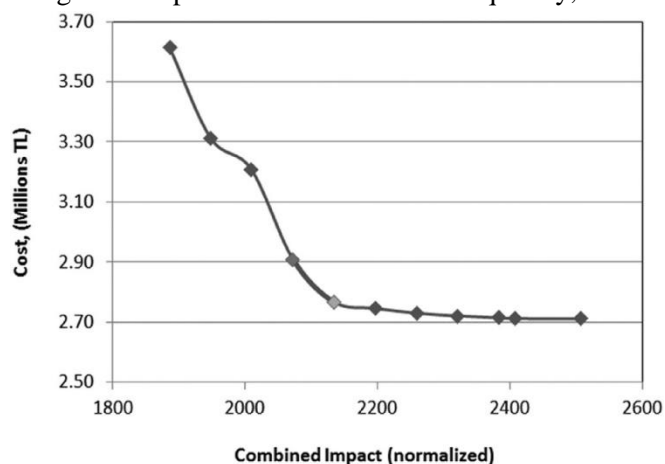


Fig. 6. Trade-off curve for combined population and environmental impact case.

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 (V/yr)		
Recovery e investment	31,138,550	3,939,900

Recovery e operational	63,845,650	14,049,650
Treatment e investment	5,916,600	434,500
Treatment e operational	11,833,200	869,000
Incinerator e investment	72,918,050	9,020,950
Incinerator e operational	116,668,900	14,433,500
Landfill e investment	5,990,200	1,081,600
Landfill e operational	1,497,550	270,400
Transportation cost, V/yr	1,847,450	205,750
Cost, V/yr	301,656,150	44,305,250
Total HWMS cost, V/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.

Table 6

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 V/yr, which corresponds to 170 V/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 facilities in Turkey are confirmed. Although Manisa province is not among proposed locations, it is closely located to Izmir 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 Izmir. 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 Izmir._

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.

V. 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 of 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. The WEEE Directive signals a change of approach, necessitating separate collection of all municipal WEEE and it is possible that other elements of household waste will similarly require separate collection, as further producer responsibility legislation comes into force, such as the Batteries and Accumulators Directive and the End-of-life Vehicles (ELVs) Directive, which has placed responsibility on the last registered owner for the disposal of domestic vehicles, thus rendering certain ELVs a household fraction (Slack et al., 2009).

A European Commission study of 2002 concluded the list of priority hazardous household chemicals, as shown in Table 2 (Gendebien et al., 2002). Household hazardous products which pose the highest risk to health and environment have been identified and classified into a three-tier priority list; Tier 1 products are those which exhibit a proven hazardous potential, Tier 2 products are those which are banned or strictly controlled within the

EU and Tier 3 products are those their hazardous potential cannot be determined, as there is a lack of information or which cannot be labelled as hazardous (Gendebien et al., 2002).

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