HAZARDOUS WASTE MANAGEMENT SYSTEM DESIGN FOR TURKEY

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ABSTRACT

HAZARDOUS WASTE MANAGEMENT SYSTEM DESIGN FOR TURKEY

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Hazardous waste management demands detailed planning due to the risks posed by hazardous wastes on public and environment and high investments required. This study aims to provide a framework that leads Ministry of Environment and Forestry (MoEF) in planning of hazardous waste facilities to be built. This framework considers the facility and transport cost along with impacts of hazardous waste management. The linear optimization models for several scenarios are developed in order to evaluate possible approaches in management of hazardous wastes. During cost calculations economy of scale principle is considered. Estimation of impact includes not only population impact but also environmental impact for which a methodology is developed in the scope of this study. This methodology considers the effect of hazardous waste transportation on lakes, rivers, dams, seashores, forests and agricultural areas, which are defined as vulnerable environmental elements.

Evaluation of the results suggests that establishment of designated hazardous waste facilities with co-incineration practices and use of transfer stations give most satisfactory outcome. Co-incineration practices decrease incineration costs, which has the highest contribution to overall cost while transfer stations provide great improvement in total impact. Locations for recovery, treatment, incineration facilities and landfills are selected. These selections both confirm decisions made in the past regarding existing locations and become suggestions for locations for new facilities. It is observed that integrated facilities are favored. The importance of countrywide planning should also be underlined.

It is believed that results of this study provides a basis to evaluate possible alternatives for further improvement of hazardous waste management system in Turkey that would be most useful to MoEF.

Keywords: Hazardous waste, optimization, transportation, impact, risk

ÖZ

TÜRKİYE İÇİN TEHLİKELİ ATIK YÖNETİM SİSTEMİ TASARIMI

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Tehlikeli atık yönetimi, tehlikeli atıkların kamu ve çevre üzerinde yarattığı risklerden ve yüksek yatırım ihtiyacından dolayı ayrıntılı planlama gerektirmektedir. Bu çalışma Çevre ve Orman Bakanlığı (ÇOB)'na kurulacak tehlikeli atık tesislerini planlarken yol gösterecek bir çerçeve oluşturmayı amaçlamaktadır. Bu çerçeve, tesis ve taşımacılık maliyetleri ile tehlikeli atık yönetimin etkilerini göz önünde bulundurmaktadır. Tehlikeli atıkların yönetiminde olası yaklaşımların değerlendirilebilmesi amacıyla çeşitli senaryolar için doğrusal optimizasyon modelleri geliştirilmiştir. Maliyet hesaplamaları sırasında ölçek ekonomisi prensibi göz önünde bulundurulmuştur. Etkinin belirlenmesi sırasında sadece nüfus üzerindeki etki değil çevresel etkide göz önünde bulundurulmuş ve çevresel etki için bir metodoloji geliştirilmiştir. Bu metodoloji, tehlikeli atık taşımacılığının, hassas çevresel elementler olarak tanımlanan göller, akarsular, barajlar, kıyı kesimleri, ormanlar ve tarım alanları üzerindeki etkisini kapsamaktadır.

Sonuçların değerlendirmesi tehlikeli atık tesislerinin kurulmalarının yanında beraber yakma uygulamaları ve transfer istasyonlarının kullanılmasının en tatminkar sonuçları verdiğini göstermektedir. Beraber yakma uygulamaları toplam maliyet içerisinde en yüksek paya sahip olan yakma maliyetlerini düşürürken, transfer istasyonları toplam etkinin iyileştirilmesini sağlamaktadır. Geri kazanım, arıtma, yakma ve depolama tesisleri için yer seçimi de yapılmıştır. Bu seçimler, geçmişte kurulmuş olan tesislerin yerlerini doğrulamakta ve gelecekte kurulacak tesislerin konumları için öneri oluşturmaktadır. Entegre tesislerin kurulmasının tercih edildiği gözlemlenmiştir. Ayrıca, ülke çapında planlama yapmanın de öneminin altı çizilmektedir.

Yapılan çalışmanın sonuçlarının Türkiye'deki tehlikeli atık yönetim sisteminin iyileştirilmesi sırsında olası alternatiflerin değerlendirilmesi için bir dayanak oluşturacağına ve ÇOB'a üst düzeyde fayda sağlayacağına inanılmaktadır.

Anahtar Kelimeler: Tehlikeli atık, optimizasyon, taşımacılık, etki, risk

To my grandparents,

Münevver Yazar, Halim Yazar, Cavit Yılmaz and Zehra Yılmaz

who are dearly missed

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LIST OF SYMBOLS AND ABBREVIATIONS

ADR:	European Agreement on the International Carriage of Dangerous Goods by Road
BREF:	Best available techniques reference document
CPT:	Chemical physical treatment
DARE:	Decision Alternative Ratio Evaluation
EHS:	Environmental Health and Safety
EMS:	Environmentally sound management
EU:	European Union
GIS:	Geographical Information System
HWMS:	Hazardous waste management system
IFC:	International Finance Corporation
IPPC:	Integrated Pollution Prevention and Control
LP:	Linear programming
MoEF:	Ministry of Environment and Forestry
MS:	Management Sciences
NPV:	Net present value
O-D:	Origin destination
OR:	Operational research
RGPWM:	Regulation on General Principals of Waste Management
TOBB:	The Union of Chambers and Commodity Exchanges of Turkey
TurkStat:	Turkish Statistical Institute
USEPA:	U.S. Environmental Protection Agency

CHAPTER 1

INTRODUCTION

Environmental issues are drawing more and more attraction in Turkey as a result of increasing awareness towards environment and numerous legislations entering into force recently; owing to accession period of Turkey to European Union (EU). One of these environmental issues is the hazardous waste management problem, which is now addressed by various parties. Ministry of Environment and Forestry (MoEF) as the regulatory agency, not only established the legal framework for hazardous wastes but also conducts or participates in multiple projects related to hazardous waste management in Turkey.

On the other hand, industry seeks for sustainable solutions for its hazardous wastes due to release of more stringent regulations on hazardous wastes and also thanks to increase in environmental consciousness. Research institutes and universities play their part by developing and participating in new projects towards more effective hazardous waste management systems in pursuit of supporting the decision makers scientifically.

Environmentally sound management (EMS) of hazardous wastes as underlined in Basel Convention, is a necessity originating from risks created by these wastes on human health and environment. Therefore, from the point of generation to the point of disposal, hazardous wastes must be handled with care. This can only be achieved by implementing complete set of procedures and rules related to handling of hazardous wastes; in other words a *hazardous waste management system* (HWMS).

1.1 Motivation and aim of the study

Although the set of rules or the legislative framework regarding hazardous wastes is well established in Turkey, there are important problems in implementation of the HWMS. Among these problems, there are lack of waste generation data, lack of infrastructure, insufficient enforcement of the regulations and deficiencies in management decisions.

Currently, Turkey does not have a set of hazardous waste generation data in satisfactory detail in terms of types and distribution. For a long period of time, exact potential of hazardous waste generation was unknown to both the MoEF and investors of the private sector. Although the necessity of establishing hazardous waste facilities was obvious to the MoEF, this unknown delayed the investments that are to be made for establishment of facilities. As a consequence, the established capacities created by two commercially available hazardous waste incinerators (in Kocaeli and İzmir) and two landfills (Kocaeli and Manisa) are still way below the generation potential. The gap between established and required capacities can be seen in Table 1.1. (Required capacities are obtained from the hazardous waste generation data compiled for this study presented in Section 4.4). This table clearly shows that additional facilities must be established to handle all hazardous wastes generated in Turkey.

The discordance between actual and necessary handling capacities means that the MoEF should have an implementation plan for new facilities capable of handling various types of wastes. Even if additional facilities are not constructed by the government, the MoEF, as the regulatory body, must have a comprehension of regional and country-wide demands related to capacity and handling technology.

Table 1.1 Comparison of established and required capacities according to technology

Technology	Required Capacity (tons/yr)	Established Capacity [1]
Recovery/Recycling	367,550	263,660 tons/yr
Chemical-Physical Treatment	471,250	--
Incineration	429,900	43,750 tons/yr * + 29,000 tons/yr ** +75,000 tons/yr ***
Landfilling	424,600	4,135,000 m^3

*incineration
**gasification
***co-incineration

In Turkey, hazardous waste management is becoming a market. This is due to the fact that most of the hazardous waste generators do not have the proper technical expertise and infrastructure to deal with their hazardous wastes and are compelled to take service from providers such as hazardous waste carriers, treatment, disposal and storage facility operators. Presently, private sector is ready to make investments in the area since current capacity of hazardous waste handling is not sufficient and the market seems profitable.

One main problem with this high pace of market development is that without proper planning, most of the capacity established for hazardous waste handling might become idle or quality of hazardous waste handling services provided may worsen to decrease costs in the competitive market. One more possibility is to make poor decisions in terms of facility locations chosen by using little real hazardous waste generation data we have today for Turkey.

These concerns further necessitate action to be taken towards development of implementation plan for additional facilities. This action should at least include analysis of waste generation data in terms of technology requirement and geographical distribution and evaluation of most suitable locations for establishment of new facilities along with their capacities. It is important to underline that waste generation distribution cannot be the only criteria in location selection. Although hazardous waste generation data collected in Turkey is in insufficient detail currently, it is possible to come to conclusions about geographical distribution. Assuming industrial hazardous wastes comprise a large portion of total hazardous wastes and geographic distribution of gross domestic product is a representative of distribution of industrial activities in Turkey, highest hazardous waste generating regions are located in Western parts of Turkey. It may easily seem that hazardous waste facilities should be established in Western parts as much as possible. However, only concentrating on these regions creates hardship for generators located in Eastern part of the country especially in terms of transportation costs.

The decisions on locating facilities must be made according to different practical considerations such as costs arising as a result of transportation and facility construction and risks posed on public and environment. Suggestions made in previous projects of the MoEF underline an integrated approach in the sense that facility siting and transportation are considered in unison [2]. Moreover, whole infrastructure should be able to handle not only the wastes buts also the residues generated as a result of hazardous waste processing. It is obvious that there are numerous aspects affecting the decision making process. Therefore, decision only based on common sense would result in an inadequate implementation. A more systematic approach that can handle complexity of hazardous waste handling problem is required.

Unfortunately, current investment projects undertaken generally by private sector consider facility siting as an independent problem. In order for the MoEF to evaluate these projects in terms of conformity to the integrated approach, the Ministry should have a grasp on overall picture to verify that the proposed sites for facilities are indeed suitable when transportation is also considered. The first aim of this study is to provide such a framework that would present location, capacity and technology suggestions for additional facilities. In detail, the proposed framework in this study involves selection of suitable candidate locations for different hazardous waste facilities by assessing transportation and transfer station network and considering distribution of hazardous wastes in Turkey in terms of types and amounts. With this framework it becomes possible to provide a basis for future planning of HWMS and investments related.

Whether countywide or regional management is enforced, transportation of hazardous wastes needs attention. Given that the distribution of hazardous waste generation is not uniform throughout the country, need for travel of wastes in long distances arises. Risk and costs associated with long distance travels may be decreased with a transfer station network. Up to now, this possibility has not drawn much attention and establishment of a transfer station network has not been studied in detail. With a transfer station network, it may be possible to achieve a decrease in transportation risk in addition to the decrease in transportation cost. This decrease in risk mainly originates from the fact that larger capacity vehicles can be used for further transfer of wastes from transfer stations to facilities which means fewer trips to be made when compared to transportation without transfer stations. Moreover, presence of chemical physical treatment (CPT) units would enable processing of treatable hazardous wastes in transfer stations. As a result, amount of treatable wastes that should be sent to subsequent facilities would decrease which in turn would decrease the amount of wastes to be transported. It is presumed that both of these conditions will have a decreasing effect on hazardous waste transportation risk. Therefore, the second aim of this study is to investigate the effect of a transfer station network on overall cost and risk of HWMS.

As mentioned before risk is an inevitable component and a major concern for any HWMS. Although the presence of risk is well known to all stakeholders of the system, more detailed studies are required especially for the MoEF. By this way, it is possible for the MoEF to integrate risk concept in decision-making process. As discussed in more detail in Chapter 3, the impacts posed to humans are already studied in literature. Unfortunately, the impacts posed on environment have not been adequately covered and environmental impacts of hazardous waste management require further investigation. Assessment of risk concept that involves both public and environmental impacts of HWMS is the third aim of the study.

In summary, the overall aim of the study is to propose a framework considering both cost and impact issues for management of hazardous waste transportation and establishment of hazardous waste recovery, treatment, incineration and disposal facilities that would support the decision making process of authorities and investors. Overall objective will be to contribute to establishment of a more effective and applicable HWMS in Turkey.

1.2 Scope of the study

Operations research approaches are being used in various areas including environmental planning that involves facility location and transportation network analysis [3]. For modeling the HWMS in Turkey, linear programming (LP) is utilized in this study. The facility location decisions and transportation considerations are both involved in the models.

Roughly, the problem to be dealt with involves the allocation of hazardous wastes generated from various generators throughout Turkey to hazardous waste facilities (recovery/treatment/incineration/landfill) around the country via highways possibly through transfer stations. The objectives to be achieved are selected as minimizing both the cost and total impact of the system.

In order to provide the decision-aiding framework to the MoEF, it is important to cover whole country and use realistic hazardous waste generation data as much as possible. The study covers all types of hazardous wastes (for whichever the information can be obtained) generated from 81 provinces of Turkey and deals with all major types of processes that can be applied to hazardous waste (recovery/recycling, treatment, incineration and landfilling).

Since it is nearly impossible to handle all aspects of HWMS in a single model, these aspects are considered under four different scenarios. These scenarios are summarized below:

- **Scenario 1**: *Hazardous waste generators can send their wastes to facilities located around Turkey*
  This first scenario is the base scenario. It assumes that there is no preexisting facility established in Turkey. Wastes from 81 provinces can be sent to facilities around Turkey, which will be located as a result of solution of the first multi-objective model related to this scenario. By assuming absence of all facilities, this scenario aims to assess the decisions made in the past regarding existing facilities (capacities and locations).
- **Scenario 2:** *Additional capacity requirement is met by capacity increase in existing facilities or establishment of new facilities*

Second scenario considers the presence of already established facilities in the country and investigates the most feasible way to meet the demand for additional capacity for hazardous waste facilities. Existing facilities include both designated hazardous waste facilities as well as cement kilns used for co-incineration. Capacity increase in existing facilities and establishment of new facilities are assessed in terms of their effects on cost and impacts of the HWMS.

- **Scenario 3**: *Regional hazardous waste management plan is implemented*

  This option involves the implementation of regional hazardous waste management plan as advised in "Technical Assistance for Environmental Heavy-Cost Investment Planning Directive-Specific Investment Plan for Council Directive on Hazardous Waste (91/689/EEC)"[2]. It involves restriction on hazardous waste generators to send their wastes to facilities within their region. If the generators are not covered in a region they can send their wastes to facilities of their own choice. Results of this scenario are compared with results of the base scenario (Scenario 1). By evaluation of these two options, the MoEF can assess effectiveness of countrywide and regional management approaches.
- **Scenario 4:** *Transfer station network is established*

  In this last scenario, establishment of transfer station network is studied. The transfer stations to be constructed are assumed to all involve CPT units. Establishment of such a network is expected to decrease both transportation cost and impact of the system and can be an important investment that would improve the HWMS in regions where hazardous waste generation is low but distances to nearest hazardous waste facilities are high.

In order to be able to represent HWMS by using linear optimization models, conceptual models for all abovementioned scenarios are developed (Chapter 5.1). This conceptual model is in fact essential in laying down main components of HWMS to be included in mathematical models and their interaction with each other.

The next step is the development of multi-objective mathematical models that aim to minimize cost and impact of HWMS based on these conceptual models (Chapter 5). Clear definitions of cost and impact aspects of HWMS are required to be able to reach mathematical statements. These definitions are given in Chapter 4.2.

There are two main sets of decision variables used in all models; waste flows for each type of wastes and residues and binary variables for locating facilities. Due to the fact that, waste types laid down in RGPWM cannot be used directly because of their excessive number, a new classification need to be developed. Details on this classification system are given in Chapter 4.3.

Another vital issue in the development of the optimum HWMS is the data on waste generation. Provincial waste generation data is needed in order to locate waste treatment/transfer/disposal facilities. As such a data set detailed enough to be used in this study is not available, a theoretical approach, which is presented in Chapter 4.4 along with the results, is adopted.

Shortly, constraints of models are the requirement to include all wastes generated, flow balances, preventing sending waste to provinces, which do not have right kind of hazardous waste facility and number of facilities (of each type). Moreover, some scenarios included capacity constraints. For flow balance constraints to be set properly, the relation between waste flows and residue flows should be provided. This relation involves use of mass reduction ratios whose specifics can be found in Chapter 4.5. At this point, all the information required to form mathematical statements are obtained. For each scenario the solution procedure that outlined in Chapter 4.1 is followed and results are obtained.

The text is organized in a way that in Chapter 2 basics of hazardous waste management and HWMS in Turkey are introduced. Chapter 3 presents a review of the Literature related to subject. Chapter 4 involves an overview of solution procedure and methodology followed for gathering necessary information for the study. In Chapter 5, conceptual model of HWMS and definitions of the scenarios are elaborated and detailed models in terms of mathematical formulations for various scenarios are given. The next chapter that is Chapter 6 gives the results obtained as a result of the solution process and along with the discussion of these results in the context of HWMS in Turkey. Finally, conclusions are drawn in Chapter 7 and recommendations for further studies are made in Chapter 8.

CHAPTER 2

HAZARDOUS WASTE MANAGEMENT

2.1 Definition of hazardous wastes

Hazardous waste management problem is first addressed by *The Basel Convention* (verbose: Basel Convention on the Control of Transboundary Movements of Hazardous Wastes and Their Disposal); an international treaty that aims to reduce the movement of hazardous waste between nations, and specifically to prevent uncontrolled transfer of hazardous wastes from developed to less developed countries. The Convention was opened for signature on March 22, 1989, and entered into force on May 5, 1992 [4].

Basel Convention lists the properties (hazard properties from H1 – H13) that render a waste hazardous [4]. These hazard properties are still in use with minor modifications. According to this definition,

" Wastes that are

- Explosive (H1)
- Oxidizing (H2)
- Flammable (H3)
- Irritant (H4)
- Harmful (H5)
- Toxic (H6)
- Carcinogenic (H7)
- Corrosive (H8)

- Infectious (H9)
- Teratogenic (H10)
- Mutagenic (H11)
- Ecotoxic (H14)

and that

- release toxic or very toxic gases in contact with water, air or an acid (H12)
- capable by any means, after disposal, of yielding another substance, e.g. a leachate, which possesses any of the characteristics listed above (H13)

are classified as hazardous wastes" [4,5].

2.2 Basics of HWMS

Main components of the HWMS include generation, storage, collection, transportation, recovery/treatment (whenever possible) and disposal of hazardous wastes. Generation of hazardous wastes should involve on-site waste prevention and waste minimization activities aside from the hazardous waste generating processes. Storage involves temporary storage of hazardous wastes either in the location of generation or specially designed temporary storage facilities suitable for hazardous wastes. Storage should not be confused with landfilling of hazardous wastes. Collection by definition means to gather objects together which in the context of hazardous waste management refer to the step where hazardous wastes are accumulated before being sent to temporary storage facilities, treatment or disposal sites. Transportation part of HWMS is the one where the wastes are conveyed to transfer stations, treatment or disposal facilities following collection of wastes. According to waste hierarchy whenever possible wastes should be recovered/reused/recycled and/or treated. It is important to note that not all the hazardous wastes are suitable for treatment or recycle. Disposal is the ultimate fate of most of the hazardous wastes and usually residues originating from processes applied on hazardous wastes.

In any HWMS, stakeholders include hazardous waste generators involved both in industrial and household hazardous waste generation, collectors, carriers, individuals linked to treatment and disposal of hazardous wastes, policy makers and parties responsible for implementation of the system (i.e. administrative chiefs etc.).By bearing the adverse effects of improper hazardous waste management, public becomes one of the most important stakeholders. However, it is not directly involved with management system. Rather public is represented by governmental bodies like the MoEF or governors. In Turkey, parties directly involved in HWMS are the MoEF, governorships, local administrations (municipalities in smaller provinces and greater municipalities in bigger provinces), hazardous waste generators, and companies that are responsible for transportation, treatment, recovery and disposal of hazardous wastes. Duties, responsibilities and jurisdiction of the MoEF, governorships, local administrations and waste generators are shown in Figure 2.1.

Every step of a HWMS demands great care. All the components of the system should be carefully planned and implemented. Enforcement and supervision are also important for every HWMS. The reason for giving close attention to each step originates from safety issues. Compared to other types of wastes, hazardous wastes pose greater dangers not only for mankind but also for environment. There exists potential for pollution release at every step of HWMS and therefore, possible environmental effects and the risks to public health and the environment are indispensible aspects of dealing with hazardous wastes.

Hazardous waste management system: Duties, responsibilities and jurisdiction

Ministry of Environment and Forestry

- Program and policy making , country-wise and/or region-based
- To obtain regional annual reports, and notices of permits, facility shut downs etc. and carry out inspections
- To monitor trans-boundary movement of hazardous wastes
- To confirm the location selections of disposal facilities, to give necessary permits. To organize regular inspections and additional ones whenever extensions are construtced. To inspect disposal facilities 20 years after their closure.
- To determine the the basis of the contingency plans that should be prepared for the facilities.
- To get involved in cooperations for the establishment of technology and management systems for environmental friendly mangement of hazardous wastes

Administrative chiefs

- To enforce province based waste management plans
- To deliver applications for disposal facilities within the province to MoEF.
- To inspect temporary storage areas storing not more than 1000 kg/month. to notify MoEF such facilities.
- To realize necessary procedure on waste transportation forms.

Local administrations

- To prepare plans and programs for municipal hazardous wastes
- To enforce or establish waste disposal facilities with or without the coperation of waste generators and disposers
- To enforce and take necessary precautions during construction and operation of disposal facilities within the municipal and adjacent areas
- To enforce declaration of conformity of hazardous waste disposal to legislation during licencing of hazardous waste generating facilities within municipal area and adjacent areas

Waste generator

- Unless he can prove that generated wastes are non-hazardous to ensure that wates are managed according to legislation and to cover all related expenses
- To take necessary measures for waste minimization
- To take necessary permits from governorate for interim storage within the facility. To take safety measures during storage within the facility
- To hold records for the generated hazardous wastes, to packand label them accordingly and inform MoEF annually through waste declaration forms.
- To fill out and keep necessary forms during transportation of wastes
- To use licensed carriers and recovery, treatment and disposal facilities
- In case that waste is not accepted by a disposal facilityto send the hazardous waste to another one or accept the waste back and dispose it properly
- To prevent contamination in case of accidental or deliberate spill and depending on the type of waste to take nesessary measures for the contaminated site to return to its original state. To submit a detailed report to governorate on the issue
- During licensing for construction and operation, to prove that hazardous wastes are being managed according to legislation

Figure 2.1 Main duties, responsibilities and jurisdiction in theHWMS

Presence of adverse affects also influences the perspectives of the stakeholders. Due to public health concerns, individuals who are in close contact with hazardous wastes and people located in the close vicinity of transportation routes, storage areas and disposal facilities should always be looked out for. This mainly falls within the responsibility of regulating and inspecting bodies. To make sure that part of the population involved with hazardous wastes and environment itself is not harmed from hazardous wastes, policy makers should plan the system carefully and enforce its proper implementation. Naturally, risk is not the only driving force behind motivations of stakeholders. Financial issues also play role. Generators want to dispose of their hazardous wastes in most cost effective way. Due to polluter pays principle generators are responsible for their waste to be collected, transported, treated and disposed of properly and must cover the expenses. Given that managing hazardous wastes are more expensive than managing non-hazardous wastes, generators seek low expense solutions. This situation also results in reluctance of generators to participate in the system. Likewise, operators of treatment and disposal facilities and carriers aim to maximize their profits while providing hazardous waste handling services, which cannot be fulfilled by the generators.

2.3 HWMS in Turkey

2.3.1 Legislative framework

The development of HWMS in Turkey was initiated with the ratification of Basel Convention and gained impetus with the accession period to EU. In this period, rapid harmonization studies were undertaken and Turkish legislative framework has been harmonized with the EU legislation on hazardous wastes.

In this section, a brief introduction to legislative framework related to hazardous wastes is given. Two aspects of legislative framework that are management and transportation of hazardous wastes are covered in separate subsections.

2.3.1.1 Legislation related to management of hazardous wastes

As mentioned in the previous chapter, the main international legislative document related to management of hazardous wastes is the Basel Convention, which is mainly concerned with minimization of hazardous waste generated, treatment and disposal of hazardous wastes at locations as close to source of generation as possible and finally minimization of transboundary movement of these wastes. EMS concept introduced in the Basel Convention is built upon international waste management policies such as precautionary principle, waste hierarchy, cradle-to-grave approach and polluter pays principle [4].

According to Basel Secretariat, the Basel Convention currently has 173 parties [6]. Some of these countries including many EU member states and Turkey have ratified the Convention while others are in periods of accession, acceptance or approval [6]. Since the proper management of hazardous wastes is mandated by the Convention, parties ratified the Convention introduced regulations regarding hazardous wastes. Since the beginning of the accession period of Turkey to EU, Turkish legislation is being harmonized with EU legislation. Due to these harmonization efforts, on international level, EU legislation on hazardous wastes is also very important.

EU legislation on waste management is shaped by *Directive 2008/98/EC of the European Parliament and of the Council of 19 November 2008 on waste*(Waste Framework Directive) [7]. This core directive repealed *Council Directive 91/689/EEC* *of 12 December 1991 on hazardous waste* that specifically covers the rules for hazardous waste management at the end of 2010 as well as *Council Directive 75/439/EEC of 16 June 1975 on the disposal of waste oils*.

Waste Framework Directive refers to *Commission Decision of 3 May 2000 replacing "Decision 94/3/EC establishing a list of wastes pursuant to Article 1(a) of Council Directive 75/442/EEC on waste"* and "*Council Decision 94/904/EC establishing a list of hazardous waste pursuant to Article 1(4) of Council Directive 91/689/EEC on hazardous waste (2000/532/EC)"* [8]. This document basically lists and classifies both hazardous and non-hazardous wastes and should be used as a reference in identification and classification of wastes.

Beside the directives that lay down general management principles, there exist a set of directives that is concerned with hazardous/non-hazardous waste operations such as landfilling or incineration.

List of Turkish regulations prepared based on same principals with the Basel Convention and EU Directives on hazardous wastes and their EU counterparts are presented in Table 2.1. Turkish legislative documents on hazardous wastes can be considered in three groups. The ones related to general management concepts such as Regulation on General Principals of Waste Management (RGPWM), the ones related to specific types of wastes like medical wastes and waste oils and finally the ones that is related to hazardous waste handling operations such as landfilling or incineration of waste.

RGPWM is the core regulation laying down the outline of waste management similar to its counterpart Waste Framework Directive. The Annexes of RGPWM include lists of recovery and disposal operations, properties that render a waste hazardous and threshold concentrations for mirror wastes [5]. The last Annex of the Regulation (Annex 4) is the counter part of Commission Decision 2000/532/EC that is the list of wastes [5].

Table 2.1 List of Turkish legislation on hazardous wastes

Turkish Legislation	EU Counterpart
Regulation on General Principles of Waste Management	Directive 2008/98/EC on waste
Regulation on Control of Hazardous Wastes	Directive 91/689/EEC on hazardous waste
Regulation on Control of Waste Oils	Directive 75/439/EEC on the disposal of waste oils
Regulation on Control of Waste Vegetable Oils	Under Directive 2008/98/EC on waste
Regulation on the Control of Used Batteries and Accumulators	Directive 2006/66/EC on batteries and accumulators and waste batteries and accumulators
Regulation on the Control of Packaging and Packaging Waste	Directive 94/62/EC on packaging and packaging waste
Regulation for Control of the Tyres Which Have Completed Their Life-Cycles (TCL)	Under Directive 2008/98/EC on waste
Regulation on the Restriction of the use of Certain Hazardous Substances in Electrical and Electronic Equipment	Directive 2002/95/EC on the restriction of the use of certain hazardous substances in electrical and electronic equipment
Regulation for Control of Medical Waste	Under Directive 2008/98/EC on waste
Regulation on Control of Polychlorinated Biphenyls and Polychlorinated Terphenyls	Directive 96/59/EC on the disposal of polychlorinated biphenyls and polychlorinated terphenyls (PCB/PCT)
Regulation on Control of End-Of-Life Vehicles	Directive 2000/53/EC on End-Of-Life Vehicles
Regulation on Landfill of Waste	Directive 1999/31/EC on the landfill of waste
Regulation on Incineration of Waste (Draft)	Directive 2000/76/EC on the incineration of waste.
Regulation on Control of Waste Electrical and Electronic Equipment (Draft)	Directive 2002/96/EC on waste electrical and electronic equipment

As in the case of Commission Decision 2000/532/EC, Annex 4 of RGPWM should be used as the basis of identification and classification of wastes and includes both hazardous and non-hazardous wastes. Main properties of Annex 4 are summarized below:

- Wastes are introduced in three levels. Two-digit level that is the most general one contains 20 entries often representing source and branch generating the waste. Two-digit level is followed by four-digit level that often describes process generating the waste. Finally under every four-digit entry listed the six-digit codes that specify distinct types of wastes.

- Hazardous wastes are indicated with an asterix.
- There are two main types of wastes; absolute and mirror wastes. *Absolute wastes* are the ones that are accepted as hazardous regardless of their constituents. *Mirror wastes* are the ones that are accepted as hazardous only if the concentrations of certain constituents are above the threshold level given in Annex III-B of the regulation.

2.3.1.2 Legislation related to transportation

Transportation of hazardous wastes is generally handled under the rule of legislation on transportation of dangerous goods. For this reason, main agreements and regulations related to transportation of dangerous goods are presented in this subchapter.

The most important legislative document on transportation of dangerous goods is European Agreement on the International Carriage of Dangerous Goods by Road abbreviated as ADR [9].

ADR is composed of a short main body and two annexes; Annex A and B. Annex A is concerned with classification of dangerous goods along with packaging and labeling procedures. Second annex specifies the rules for dangerous good carrying vehicles. Classification introduced in Annex A is important in the sense ADR aims to minimize the risks created during transportation of dangerous goods of which hazardous wastes is a subset and classification of dangerous goods is based on these risks. Consequently, classification provided in ADR is a starting point for classification of hazardous wastes in terms of transportation risk. Further discussion on classification of wastes is provided in following sections.

Classes of dangerous goods as given by ADR are as follows:

Class 1	Explosive substances and articles
Class 2	Gases
Class 3	Flammable liquids
Class 4.1	Flammable solids, self-reactive substances and solid desensitized explosives
Class 4.2	Substances liable to spontaneous combustion
Class 4.3	Substances, which in contact with water, emit flammable gases
Class 5.1	Oxidizing substances
Class 5.2	Organic peroxides
Class 6.1	Toxic substances
Class 6.2	Infectious substances
Class 7	Radioactive materials
Class 8	Corrosive substances
Class 9	Miscellaneous dangerous substances and articles [9]

Each entry in the abovementioned classes is assigned a four-digit UN number either based on single substances (such as acetone) or a group of substances (such as adhesives). According to classes of dangerous goods packing and transportation requirements show variety.

The abovementioned agreement only cover the rules for international transportation meaning that as in the case of Basel Convention countries that sign or ratified this agreement need their own regulations on the subject. At EU level the legislation related to transportation of dangerous goods is comprised of:

- Council Directive 94/55/EC of 21 November 1994 on the approximation of the laws of the Member States with regard to the transport of dangerous goods by road [10],
- Council Directive 95/50/EC of 6 October 1995 on uniform procedures for checks on the transport of dangerous goods by road [11],
- Council Directive 96/35/EEC of 3 June 1996 on the appointment and vocational qualification of safety advisers for the transport of dangerous goods by road, rail and inland waterway [12],

Turkish legislation on transportation of hazardous wastes/dangerous goods involves several decrees and circulars. Transportation of hazardous wastes is mentioned in RGPWM. However; it only specifies the requirement for permit to be taken for transportation of these wastes. The MoEF has published a circular specifically related to transport of hazardous wastes [13]. This circular refers to Regulation on Carriage of Dangerous Goods by Road published by Ministry of Transport and Communication for technical specifications of vehicles and supervision issues [14]. This regulation was prepared in parallel with ADR and numerous articles refer to provisions given in ADR.

2.3.2 Implementation

Following establishment of legal framework affords for implementation of HWMS in Turkey started in mid-90s. Until that time various facilities were constructed and entered into business to meet the demand for hazardous waste processing capacity.

According to the data of November 2007, number of the recycle/recovery plants with ad-hoc working permit and license was 89 [1]. As of July 2010, this number reached up to 135 [15]. The classification of those plants according to recycling methods indicated in Annex 2B of RGPWM can be seen in Table 2.2. As can be seen, highest recovery in terms of tonnage occurs in metal wastes followed by reclamation of waste oils. Recently, a hazardous waste recovery plant with gasification has come into operation in Istanbul Kemerburgaz with a 29,000 tons/year capacity. Energy recovery indicated in Annex 2B of RGPWM is another method for waste recovery. This type of recovery can be implemented in cement industry through co-incineration practices. Currently, 22 cement plants have license in R1 category (Table 2.2). Although co-incineration in cement factories seems to have a considerable capacity, it is worth mentioning that the realized capacity is much lower than full capacity. In 2008; 85,000 tons of hazardous and non-hazardous of wastes were incinerated in cement factories of which 60,000 ton was hazardous(data obtained by personal communication). In 2010, this value increased to approximately 150,000 tons (data obtained by personal communication).

Table 2.2 Number of plants and recycle/recovery activities(2007) [1]

Code of recycle/recovery	Number of plants with license	Total capacity (ton/year)
R1(Cement factories)	22+1	527,460
R2 (Solvents)	3	9,350
R3 (Organics other than solvents)	7	17,477
R4 (Metals and metal compounds)	17	113,442
R5 (Inorganic materials)	4	1,955
R9 (Waste oils)	11	82,452
R11 (Use of wastes from R1-R10 operations)	3	14,570
R12 (Change of one of R1-R11 operations)	7	24,415
TOTAL	**75**	**791,121**

In Table 2.3, locations and capacities of hazardous waste disposal facilities in Turkey are given. Currently, total disposal capacity in Turkey is 60,250 ton/yr (of which 43,750 ton/yr is commercially available) for incineration and 4,135,000 m^3 for landfilling [1].

Table 2.3 Current capacities of disposal facilities [1]

Name of the facility	**Location**	**Capacity**
İZAYDAŞ (landfill)	Kocaeli	790,000 m^3 (occupancy ratio %20)
İZAYDAŞ (incineration)	Kocaeli	35,000 ton/year
PETKİM (incineration)	İzmir	17,500 ton/year
Aegean Region Industrial Waste Disposal Complex(landfill)	Manisa	3,230,000 m^3
TÜPRAŞ (incineration) (for own wastes)	İzmir	7,750 ton/year
ERDEMİR (landfill) (for own wastes)	Hatay	6,084 ton/year
İSKEN (landfill) (for own wastes)	Hatay	115,000 m^3

The insufficiency of capacities seen on Table 2.2 and Table 2.3 to meet the demand and necessity to build additional facilities were mentioned in Chapter 1. The MoEF's approach for locating new hazardous waste facilities is towards considering both cost and effectiveness of the system as shaped by "Technical Assistance for Environmental Heavy-Cost Investment Planning Directive-Specific Investment Plan for Council Directive on Hazardous Waste (91/689/EEC)" Project [2]. As outlined in the final project report, according to "economy of scale" principle, up to a certain point as the capacities of waste processing and disposal facilities intended for regional service increase, the unit costs per ton decrease. As the trend shifts to regional waste handling facilities with high capacities, the transportation distances and consequently, the transportation costs increase. For this reason, establishment of an interim storage network in the form of transfer stations was advised. The main idea is to provide temporary storage in transfer stations for small sized companies until amount of hazardous wastes to be transferred increases up to a point where the amount is suitable for transportation with larger vehicles [2].

In order to demonstrate the applicability of above-mentioned approach three scenarios were evaluated during the project. The first scenario is the establishment of large-scale facilities having regional coverage and transfer stations where industrial activity is concentrated. The transfer stations under this scenario involve basic CPT processes such as separation of oil/water mixtures, neutralization of acid or alkaline solutions etc [2]. The reason for including these CPT units in transfer stations is to decrease the volume of hazardous wastes to be further transported to the facilities. Regional coverage suggested for the facilities is presented in Figure 2.2. Second scenario is similar to the first one however, in this one instead of low number of large-scale facilities to serve for regions, high number of smaller scale facilities serving for smaller areas is considered. This scenario also includes the network and transfer station but again in smaller number and scale. Third scenario involves implementation of first or second scenario along with co-incineration practices in cement kilns [2].

Among these three scenarios; the first one was chosen by technical workgroup involved in the project, which will be referred as regional hazardous waste management plan from now on. The MoEF was inclined to use the results of this project for future planning decision however, up to now no further cost or risk assessment was conducted for realization of this scenario.

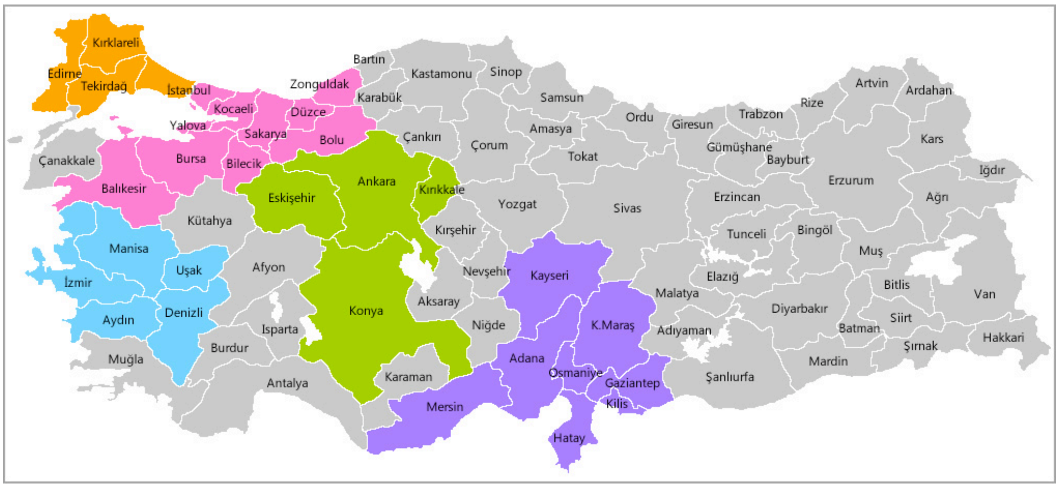


Figure 2.2Hazardous waste management regions [1,2]

This chapter is intended to present the fundamental concepts that shape HWMS in Turkey along with the current practices. In the next chapter, a selection of previous studies concerned with operations research and hazardous waste/hazardous materials (hazmat) is given.

CHAPTER 3

OPERATIONS RESEARCH AND WASTE MANAGEMENT PROBLEM

Operational research (OR) or management sciences (MS) involve the use of advanced analytical methods in order to provide aid in decision making process through consideration of all available options [16]. As mentioned earlier, OR techniques have become useful in topics related to environmental planning. Among these topics there are risk assessment/management, location analysis for noxious and obnoxious facilities, environmental impact assessment and waste management [3].

Daniel et al. [3] states that in terms of risk assessment, risk related to transportation of hazardous materials has drawn attention. Main aim of studies on this area is related to identification of incident probabilities and the extend of human and environmental exposure resulting from an incident during transportation. On the context of OR, location analysis which aims to determine the optimal locations for various types of facilities is another well-studied topic [3]. There are many examples on hazardous waste facility location problem, which is introduced in following sections.

Hazardous waste management problem investigated in this study has numerous facets including generation and transportation of hazardous waste as well as determination of most suitable locations and techniques for hazardous waste facilities. Given the ability of OR techniques to handle these topics successfully, they have been chosen to be applied in this research.

The literature survey revealed that many of the mathematical models concerning transportation and facility location have involved linear relationships. In the case of hazmat routing models, Boffey and Karzakis [17] points out that as long as probability of incident on an arc is small, which is the case most of the time, linear models can be used. *Linear programming* (LP) is one of the tools for optimization. It was first proposed by George B. Dantzig in 1947 in order to aid decision-making process by decreasing the complexity. By introduction of LP, objectives desired to be achieved are expressed explicitly and this proves to be one of the most important advantages of using LP [18]. As the name implies, for a model to be linear, all the equations in the model need to be linear and can be stated as follows [19]:

Min (or Max) $c\mathbf{X}$

Subject to

$$A\mathbf{X} \le a,$$
$$B\mathbf{X} \ge b,$$
$$D\mathbf{X} = d,$$
$$\mathbf{X_i \ge 0,\ i = 1,\ldots,j} \qquad \textbf{Eqn 1}$$

In Eqn 1, the formulation aims only to minimize (or maximize) a single objective. Models that address more than one objective to be met can be defined as *multi-objective models*.

Following sections aim to present an overview of the literature related to how hazardous waste management problem is handled in previous studies. First of all, the scope of the studies is discussed. Next, the most commonly used objectives in the models along with introduction of multi-objective programming are given.

Lastly, other considerations such as coverage, waste types and residues are investigated.

3.1 Scope of the studies

3.1.1 Routing only

This class of studies covers only the aspect of transportation of hazmat/hazardous wastes in the form of routing or network design for fixed facility locations. Routing problems try to optimize the network for transportation of a material for single or multiple objectives and under given constraints. List et al. [20] define the routing problem as "shortest route problem that finds the routes between an origin destination (O-D) pair minimizing a single measure". Routing models are similar for both hazmat and hazardous waste except that hazmat routing is a "many to many" problem whereas hazardous waste routing problem is "many to few" [21].

One of the main distinctions between the routing models is the perspective of the models. As pointed in Chapter 2, hazardous waste management system has multiple stakeholders. In terms of transportation of hazardous wastes, main stakeholders include public, authorities, hazardous waste generators and hazardous waste carriers. The first two is mainly concerned with the risks or impacts of the hazardous waste transportation while main agenda of latter two is the cost of transportation. As mentioned earlier, although the main bearer of risk created by transportation and disposal of hazardous wastes is public, it is represented by the ***authorities***. Moreover, since hazardous waste generators and carriers share the same aims, it is customary to consider only ***carriers*** in the models.

It is obvious that the difference in concerns of authorities and carriers causes these two stakeholders to have different perspectives. Therefore, according to the perspective adopted, the objective of the model or the measure being minimized changes. Another difference comes from the fact that carriers are only interested in deciding the best routes for their own carriage. However, authorities have to regulate all hazardous waste or hazmat shipments [22]. Bianco et al. [23] identifies carriers' perspective as local routing planning problem and authorities' as global routing planning.

The models that consider carriers' perspective aims to minimize the distance traveled or cost of transportation. When hazardous waste/hazmats are not involved in transportation, the network design models only include cost as objective. An example is presented in Caramia and Guerriero [24], in which the model is composed of minimization of cost and travel time and maximization of transport sharing index that allows use of multimodal transport. Although this model includes multiple objectives all of them reflects carriers' perspective.

On the other hand, authorities' perspective requires consideration of transportation risk in the objective formulation [22,23,25,27]. According to Verter and Kara [22], authorities try to prevent risk of hazmat transportation. They developed a model that would minimize societal risk, population exposure and incident risk (Detailed discussion on different risk definitions is presented in Chapter 3.2.2.). Likewise, Carotenuto et al. [25] minimize total risk and consider risk equity over the network in their model, which falls within the focus of authorities.

In their later study, Kara and Verter [26] used a bi-level formulation that aims decreasing the transportation risk. Outer level of the formulation belongs to authorities enabling them to determine the road links to be used, which ultimately creates the transportation network while the inner level belongs to carrier. In this model, the authority makes the decisions on transportation network and carrier has to follow the restrictions. Erkut and Alp [27] argued that the model belonging to Kara and Verter [26] is quite large and this creates computational challenges. They proposed simplification of hazmat network design problem to a tree selection problem which involves assigning a single route for each O-D pair instead of giving freedom to carrier to select a route from a given network as in the case of Kara and Verter [26]. The authors argue that by this way the authorities can ensure that minimum risk routes are always chosen. Bi-level formulation in this study contains an outer problem dealing with selection of hazmat links and inner one dealing with carriers.

Bianco et al. [23] also employed a bi-level model that considers only the authorities. This time they consider a hierarchy with two levels of authority; regional and local ones. In the outer level the local authority tries to minimize the maximum link risk and in inner level the lower authority (regional) tries to minimize the total risk.

Except the case that all hazardous waste management services are provided by government, private sector or carriers are crucial to the system. That is why economic consequences of the decisions given by authorities should also be taken into consideration. This means that in order for the models to give realistic results, priority of carriers that is cost of transportation should also be taken into account. In order to reflect the perspectives of both authorities and carriers, the models should include all the objectives that need to be fulfilled by different stakeholders.

Studies that cover perspectives of both stakeholders can be classified under two groups; ones that consider multiple objectives separately and ones that handles multiple objectives at the same time. Ashur [28] determined separate routes for three objectives namely population, environmental risk and transportation cost. Eno [29] also used shortest path concept to obtain minimum shipment distance, minimum population and environmental exposure paths. Later Madala [30] followed a similar method to obtain different routes for four objectives; shortest distance, minimum population exposure, minimum probability and minimum risk exposure. Another study that considers various objectives separately belongs to Bonvicini and Spadoni [31]. Their model includes minimization of accident frequency, travel distance, exposed population density, out-of-pocket expenses, risk-related costs, total arc costs, traveling time and brings limits on societal and individual risks.

Other group of studies that consider perspectives of conflicting stakeholders considered both cost and risk objectives at the same time leading to multi-objective formulations for which a short definition was given in previous section. Ümit and Kara [32] combined risk and cost objectives in a multi-objective formulation for a hazmat transportation problem. Verter and Kara [33] reconsidered their bi-level formulation presented in Kara and Verter [26] so that it can reflect carriers' perspective better. In Verter and Kara [33], the authors came up with a path-based formulation that includes carriers' cost concerns.

Zografos and Androutsopoulos handled hazmat routing and scheduling problem twice. In their earlier study, a multi-objective formulation was used to address risk and travel time [34]. Minimization of travel time serves the purposes of carriers as minimization of cost does. In their later study, Zografos and Androutsopoulos [35] again dealt with routing scheduling problem with the same objectives and added emergency response unit location aspect in a separate formulation.

Castillo [36] used a stepwise approach. First, travel distance and travel time was considered in the formulation, which reflects carriers' perspective only. In the second phase, population risk was included in addition to travel time and distance. In next phases, urban risk and earthquake building risks are added one by one. By this way in last phases, the authorities' perspective is also included in the model.

Routing problem is handled in the Literature for both hazmat and hazardous wastes. Two conflicting stakeholders have determined the perspectives of the models developed. The models that adopt the perspective of carriers' has cost as their primary objective. On the other hand, in order to reflect the perspective of authorities, risk must be included in the objective. As presented above, there are studies that consider only the perspective of authorities. As involvement of carriers in hazardous waste transportation is inevitable, the system cannot function without regulation of authorities. This means that routing models should include interest of both parties in the form of multiple objectives. In the Literature, models constructed either to obtain separate results for multiple objectives or handle them at the same time. These models widely use risk and cost as conflicting objectives. More elaborate definitions of risk and cost concepts used in the models will be discussed in further sections.

3.1.2 Location only

Another aspect of hazardous waste management system studied is location selection for hazardous waste facilities with consideration of routes used for hazardous waste transportation. ***Siting*** or ***location*** problem is defined as selection of sites among a previously selected set with a network connected which can provide required capacity to handle the waste generated and minimize adverse affects [20]. In the Literature, hazardous waste facilities are usually classified under "undesirable" facilities mainly due to the risk associated with the operation of these facilities. According to the level risk created, plants under undesirable facilities can be noxious or obnoxious. Noxious facilities are accepted to create considerable public risk like nuclear power plants. Though not as much as noxious facilities, obnoxious ones such as hazardous waste facilities still pose some level of risk and are still not desired in close vicinity [37,38]. Gottinger [39] puts this forward as people in the close vicinity to treatment, storage and disposal facilities cannot take advantages of full benefits of the facilities however, they bear most of its costs. As a result most of the facility location literature concentrates on trying to minimize the adverse effects of the facilities while selecting the locations of the facilities [40]. Another outcome of people's reluctance to have an obnoxious facility around is the necessity for authorities to assure equity in order to bring fairness. Gottinger [39] underlines the importance of equity claiming that the people around the facility should be compensated for their disadvantaged position.

As in the case of routing problem, location models can show variety according to the perspective they adopt. Gottinger [39] studied location model from perspective of different stakeholders. From the point of view of the hazardous waste generators, the objective is to maximize the profit. On the other hand, treatment, storage, disposal facility developers try to choose the best waste management option for their facility, which involves best location of the facility, level of safety of the technology chosen and minimum expected cost. Perspective of the regulating authorities requires again a multi-objective approach. The objectives include minimizing the social cost and minimizing the risk, which upon solution gives an efficient or non-inferior set of alternatives.

Killmer et al. [41] differentiate between deterministic and stochastic models. In deterministic types of models there is little uncertainty i.e. the amount of wastes generated and the necessary capacities for the disposal, storage and treatment facilities are known in advanced. The deterministic model of their study has the objective of minimizing the cost comprised of fixed and variables cost. Stochastic models account for the uncertainty. For this purpose, penalties for unstored waste are included in the formulation of objective function.

While minimizing risk, there are several considerations in deciding the locations of hazardous waste facilities. They can be listed as maximizing the minimum distance between facilities and nearest population centers (*maximin*), maximizing the sum of weighted distances between facilities and population centers or other facilities (*maxisum*) and determining number and locations of facilities in a manner that populations centers are not closer to facilities than a specified distance (*anticovering*) [20,40]. Or and Akgül [42] applied maximin objective on siting a hazardous waste disposal facility in İstanbul.

It is also possible to formulate location problems so as to respond to multiple criteria. List et al. [20] identify two approaches to handle multiple criteria. First one is the multi-attribute decision analysis model that is more suitable when the set of possible locations are small and multi-objective programming when there are numerous alternatives to choose the location of the facility. Tuzkaya et al. [38] applied analytic network process that is a multi-attribute decision analysis method for selecting the site for undesirable facilities in İstanbul. The multi-objective model of Jenning and Sholar [43] minimizes cost and risk penalty functions are incorporated to account for external impacts due to shipment, treatment and disposal. Location model of Alçada-Almeida et al. [44] included minimization of investment cost, processing cost, total impact, maximum average impact and maximum individual impact as its objectives.

Emek and Kara [40] developed a model to determine the locations of incinerators that have sufficient capacity to dispose all the hazardous wastes generated which also satisfies the air pollution standards.

Location or siting problem involves selection of most suitable places for hazardous waste facilities. The criteria according to which the sites are selected show variation regarding the perspective adopted by the model. Similar to routing problems authorities are more interested in minimizing the risk and assuring equity rather than minimizing the cost as facility developers do.

3.1.3 Combined location routing

Components of hazardous waste management system always interact with each other. It is impossible to plan a nation-wide HWMS based on individual components without regarding their effects on one another. If only transportation routes are optimized, hazardous waste facilities have to be established along the route regardless of risk and equity concerns related to facilities. Of course as ReVelle et al. [45] pointed out if there is a single source of waste and single destination, problem becomes selecting the transportation route based of risk or cost. Similarly if only location problem is handled alone, only routes leading to decided location could be used; again without considering risk and cost of the routes. In this sense developing models only for transportation of hazardous wastes or locating hazardous waste facilities does not serve the purpose of HWMS planning since they are not realistic. The dependence between routing and location problems are underlined in many combined location – routing studies including Alumur and Kara [49], Cappanera et al. [48], Giannikos [47], List and Mirchandani [21], ReVelle et al. [45], List et al. [20] and Zografos and Samara [46].

Stowers and Palekar [50] considered both location and routing problem for an obnoxious facility. Their model, adopting the perspective of authorities, minimizes risk posed by transportation and location risks at the same time. On the other hand, Jacobs and Warmerdam [51] minimizes cost of disposal in their simultaneous routing and siting model. Similarly, the model of Cappanera et al. [48] minimizes cost that is composed of cost of opening facilities and transportation.

Zografos and Samara [46] studied combined location – routing model that minimizes transportation risk, travel time and disposal risk. Each of these objectives is formulated in the form of inequality constraints in a goal programming model. Objective of the model is to minimize the deviation from specified target of objectives. Giannikos [47] also employed a weighted goal programming model that aims to minimize operational cost, perceived risk, and assures equity and even distribution of disutility. ReVelle et al. [45] developed a multi-objective zero-one programming model that keeps the transportation burden (in ton-miles) and risk (in ton-past people).

Multi-objective models of List and Mirchandani [21] and Wyman and Kuby [52] and minimizes cost, risk and brings disequity. Current and Ratick [53] used five objectives for assisting decision makers in analyzing locating – routing decisions which are minimization of risk associated with transportation and facility siting, exposure to transportation risk, individual risk due to presence of hazardous waste facility and finally transportation plus disposal costs. Exposure to transportation risk and individual risk due to presence of facility is incorporated into the model to present equity constraint.

Nema and Modak [54] and Nema and Gupta [55] obtained a composite objective function consisting of cost (treatment, disposal and transportation) and risk (again treatment, disposal and transportation) by using weighting method. Alumur and Kara [49] used cost and risk objectives for their combine location – routing model. They avoided using equity objective claiming that incorporation of this objective leads to opening more facilities than required to achieve equal distribution of risk among population. Models presented in last three studies are very close to simulating a realistic HWMS.

Overview of the Literature shows that a considerable number of models developed for routing, location or combination of them aim to assist decision-making process of authorities. It is clear that in order for the models to serve their purpose they need to be realistic. As discussed above, models that handle routing or location alone are far from representing the interactions between different components of HWMS. This is why it was decided to address both location and routing aspect of HWMS in the scenarios covered in this study.

In the next section, the Literature according to the scope of models is investigated.

3.2 Objectives of the studies

Main distinction between studies covered under this section is whether they are single or multi-objective models. As the name implies, single objective models aim to minimize or maximize a single objective whereas, in multi-objective problems, there exist more than one objective function to be optimized at the same instance by minimization or maximization, which from time to time conflicts with each other. In some of the studies, more than one model has been developed, each having a single objective. These studies are also included in multi-objective model category.

In the case of conflicting objective functions, there is no single optimal solution that optimizes all of the objective functions at the same time [56]. Since the solution procedure cannot provide a single optimum solution, the decision maker searches for most "acceptable" or "preferred" solution from a set of solutions so called ***Pareto optimal*** (or efficient, non-dominated, non-inferior) solutions [56,57]. A Pareto optimal solution can be defined as "a solution where there exists no other feasible solution that improves the value of at least one objective function without deteriorating and other objective" [58].

Although every Pareto optimal solution is "acceptable" as put forward by Grodzevich and Romanko [58], but for the results of the model to be applied a single solution should be chosen. This is where the decision makers step in and express their preferences. Mavrotas [56] classifies expression of decision makers' preferences as priori, interactive and generation or posteriori methods. In priori methods, preferences of decision makers are established before the solution process by means of goals or weights for objective functions. In interactive methods, decision maker is consulted throughout the solution procedure so as to involve the preferences, which might be changing in the course of obtaining desired solution. Finally, generation or posteriori solution methods set of Pareto optimal solutions (all of them if applicable) are presented and decision maker selects the most appropriate one according to his/her preferences. Each approach has its drawbacks such as difficulties met by decision makers in setting preferences at the beginning of the process or throughout the process without seeing the great picture in priori methods and interactive methods.

Whether single or multi-objective, the most popular objectives used in models are cost and risk. This is valid for routing and location problems and combination of these two. For location problems another widely used objective is equity. In following subsections more detailed information on these first two classes of objectives is given.

3.2.1 Cost

Economics is the inevitable concern for any management system. Although cost and profit is the main agenda for carriers or facility developers in HWMS, it is also important for the authorities. If economic burden of the management system is not carefully considered by planners, it can easily result in reluctance of hazardous waste generators, carriers or facility developers to join the system.

Cost function shows variation according to the type of problem handled. Transportation cost is considered in routing problem whereas; operation and maintenance cost show up in location models.

Emek and Kara [40] used transportation cost which is composed of distance traveled and amount of waste carried in their single objective location problem. This definition of cost is also used in works of Alumur and Kara [49], Cappanera et al. [48], Nema and Gupta [55], Nema and Modak [54], Giannikos [47], Wyman and Kuby [52], Current and Ratick [53] and List and Mirchandani [21].

Three models are developed by Killmer et al. [41]. Their deterministic model contains fixed and variable cost of disposal. In stochastic model, which incorporates uncertainty, they considered cost of establishing the facility, transportation and processing. Lastly, the robust location problem minimizes expected cost and deviations from optimal costs.

In combined location – routing models of Cappanera et al. [48], Giannikos [47] and Wyman and Kuby [52] fixed cost of opening a facility aside from transportation cost are considered. Alumur and Kara [49] defined a fixed annual cost in order to determine yearly cost of operating the facility. In cost definition of Nema and Modak [54], investment and operating costs are combined which are both proportional to the amount of waste treated or disposed in a facility. Nema and Gupta [55] later followed the same approach for definition of cost. Facility cost in terms of fixed and variable cost defined in the same way in Current and Ratick [53] and Alçada-Almeida [44].

In the studies mentioned in the previous paragraph, total fixed cost of facilities is multiplied by binary variable of opening facilities. Jacobs and Warmerdam [51] assigned unit cost for investment as similar to unit cost of processing wastes and makes investment cost dependent on amount of waste processed. They also considered time value of the money and incorporated net present value (NPV) into their model.

Caramia and Guerriero [24], Zografos and Androutsapoulos [35], Bonvicini and Spadoni [31], Zografos and Androutsapoulos [34] and Zografos and Samara [46] used travel time as a surrogate for cost. Like the abovementioned definition of transport cost, travel time also depends on distance, which means that in order to minimize both it is enough to consider shortest path problem as Ümit and Kara [32] did. Other cost definitions include transportation burden (ReVelle et al. [45]) and penalty functions (Jennings and Sholar [43]).

When literature is overviewed, it can be seen that definition of transportation cost is straightforward in terms of direct cost or travel distance which are the most popular transportation cost definitions. However, for facility cost it is observed that the models lack realistic interpretation. As emphasized in "Technical Assistance for Environmental Heavy-Cost Investment Planning Directive-Specific Investment Plan for Council Directive on Hazardous Waste (91/689/EEC)" Project, "economy of scale" principle is effective in hazardous waste facilities [2]. This means that up to a certain point as the capacities of waste processing and disposal facilities intended for regional service increase, the unit costs per ton decrease. The fixed cost concept provided in literature fails to reflect economies of scale principle. In most of the articles, there is no mention of variation in fixed cost according to range of capacities. These studies assumed that no matter how much waste is received to a facility; same fixed cost could be used in calculations. The only study that involves variable fixed costs depending on capacity is Jennings and Sholar [43] which states that use of piecewise linear approximation of a concave cost function is more appropriate. Economy of scale principle needs to be taken into consideration since the difference between unit costs of high, medium and low capacity facilities can be significant.

A detailed discussion on determination of facility costs is presented in "Technical Assistance for Environmental Heavy-Cost Investment Planning Directive-Specific Investment Plan for Council Directive on Hazardous Waste (91/689/EEC)" Project [2] and this discussion on incinerators, landfills, treatment plants and transfer stations are summarized below.

The investment cost of hazardous waste facilities depend on amount of waste received (i.e. capacity of the facility), nature and composition waste and selected site and its infrastructure (access roads, power and water supply etc.). For the sake of simplicity only the effect of capacity can be considered. The effect on size of the facility on investment cost is as follows. Relative investment per ton of installed capacity decreases with increasing capacity leading to a negatively proportional relationship. Of course, it is technically infeasible to build very high capacity facilities which mean that the relation would be similar to one given in Figure 3.1. Therefore, construction of larger plants is always economically more feasible given that transportation costs are not excessively high.

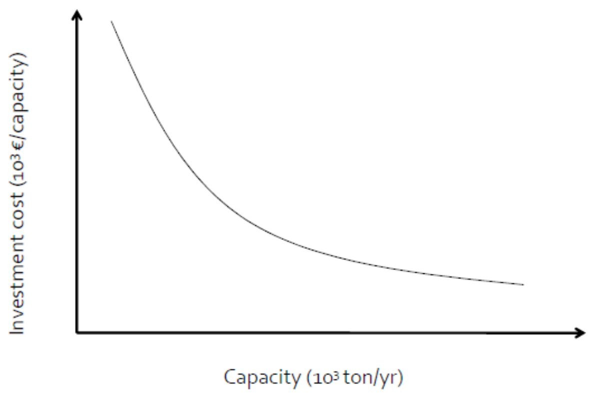


Figure 3.1 Relation between unit investment cost and capacity

Incinerators

The equipment cost for incinerators are calculated according to the formula given below [2]:

$$EC = 1.026 * e^{0.064*Ln(HI)} \qquad \textbf{Eqn 2}$$

Where EC = equipment cost in million Euros

HI = heat input in GJ/h

Equipment cost given in Eqn 2 is assumed to be 100% and values are set for following items depending on equipment cost.

- Boiler and turbine: 25% of EC
- Flue gas treatment: 33% of EC
- Electrical instrumentation: 25% of EC
- Buildings, structures and foundations: 30% of EC
- Piping: 40% of EC
- Installation: 15% of EC

Based on this reasoning, installed plant cost becomes 268% of equipment cost. Another 45% of installed plant cost should be added to present capital investment including planning, design and supervision, land purchase and site preparation. Range of investment cost for incinerators is between €2000 /ton capacity (for 100,000 ton/yr capacity) and €6500 /ton capacity (for 2000 ton/yr capacity). Figure 3.2 shows the relation between unit investment cost and capacity for incinerators.

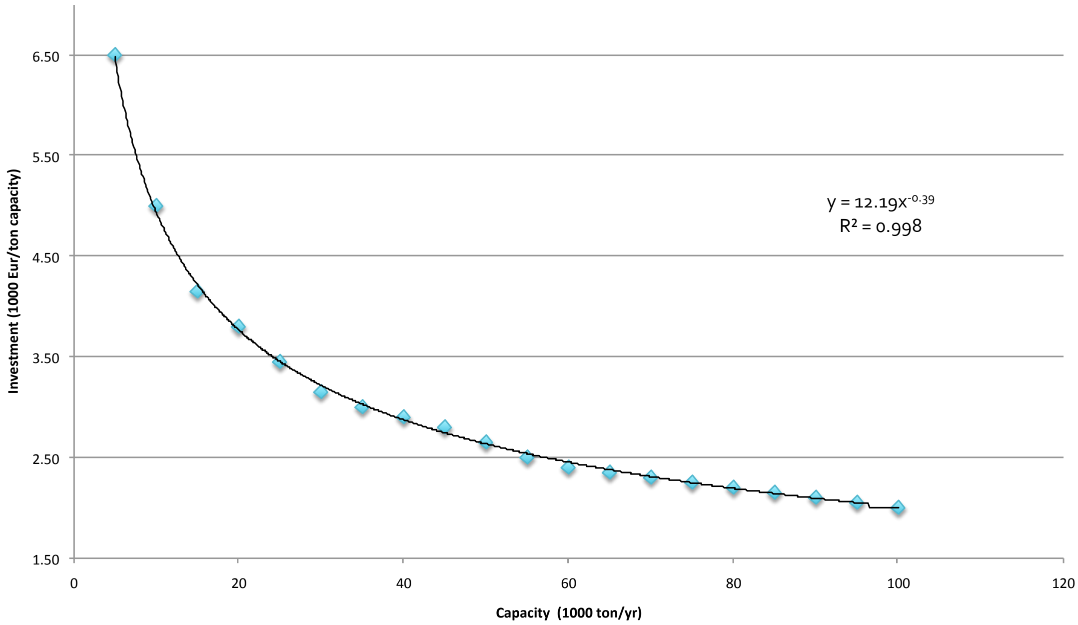


Figure 3.2 Investment cost vs capacity for incinerators (derived from[2])

Landfills

To estimate landfill cost it is assumed that the landfill is rectangular with sides two times the length and one time in width and with an average slope of 1:8. Cost items are as listed below [2]:

- Clay liner and drainage: €400,000 per ha
- Plastic liner: €150,000 per ha
- Leachate collection and treatment: €120,000 per ha
- Buildings and fencing: €100,000 + 0.1 € per m^3 capacity
- Weigh bridge: €50,000 + 0.02 per m^3 capacity
- Equipment and machinery: €200,000 + €0.5 per m^3 capacity

After calculation of these items, 15% of investment cost is added for landfill infrastructure and 10% for contingencies. Range for landfills is between €8.5 /ton capacity (for 3 million ton capacity) and €22 /ton capacity (for 0.25 million ton capacity). The figure for cost capacity relation is given in Figure 3.3.

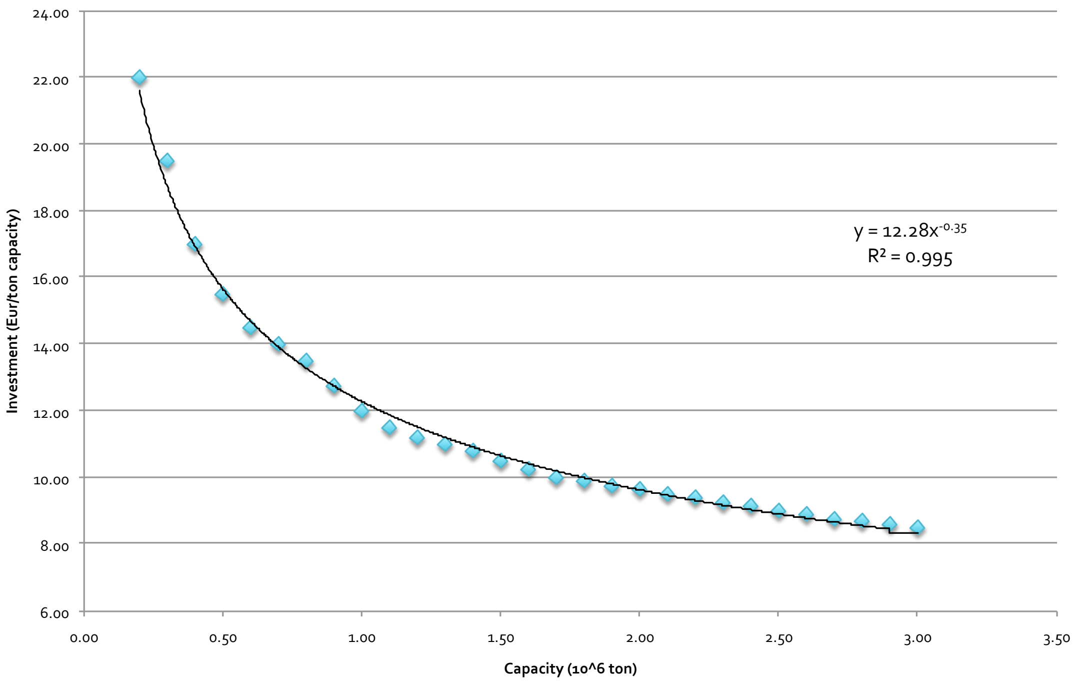


Figure 3.3 Investment cost vs capacity for landfills (derived from [2])

<u>Treatment facilities and transfer stations</u>

Although treatment plants are not separately handled in the report, it is mentioned under incinerators with the assumption that treatment plants with reception, control, storage and monitoring will be established with every incinerator. Cost of treatment plant itself is estimated to be 40% of installed incinerator plant cost. In this study, calculation of treatment plant investment cost is done by taking 40% of investment cost of incinerator with the same capacity as the treatment plant in question.

Transfer stations are expected to perform pre-treatment, repackaging, separation of oil/water mixture and physical/chemical treatment for treatable wastes and simple storage for other types of hazardous wastes. Therefore, for transfer stations there are two cost considerations; cost of treatment units for treatable wastes and cost of storage units for the rest. Cost of treatment units are assumed to be the same as the cost of treatment plants mentioned above. For storage units which only involve construction of buildings for storage and necessary infrastructure for safety, associated cost is assumed to be similar to building, structure and foundation cost of an incinerator of the same capacity that is 30% of equipment cost and 7.7% of the overall cost [2]. Consequently, transfer station investment costs are calculated as the summation of cost of treatment facilities (40% of investment cost of incinerator) and cost of storage (7.7% of investment cost of incinerator).

Recovery facilities

On the contrary to incinerators and landfills, which utilize more or less the same types of processes and similar equipment, there are many different recovery operations that can be applied on hazardous wastes. When RGPWM is inspected, it can be seen that there are fourteen possible recovery operations that aims at recovery of different components in hazardous wastes including metals, oils etc. There are various cost estimates presented in IPPC Reference Document on Best Available Techniques for the Waste Industries [59] regarding these different recovery operations. Unfortunately, it is difficult to use one of these numbers so that all recovery operations can be represented. However, waste classification used in this study demands use of a single set of cost data that only depends on capacity. As a result, for the sake of simplicity recovery costs are assumed to be same as treatment cost.

Operation costs of facilities are also taken from "Technical Assistance for Environmental Heavy-Cost Investment Planning Directive-Specific Investment Plan for Council Directive on Hazardous Waste (91/689/EEC)" Project Report [2]. Annual operational costs for incineration, landfill and recovery/treatment/transfer stations are 8%, 25% and 10% of investment costs respectively.

3.2.2 Risk

As mentioned a couple of times before, risk must somehow be addressed in hazardous waste management problem. Erkut et al. [60] identify the main difference of hazmat (or hazardous waste) transportation problem from other transportation problem as the presence of risk. According to Alp [61], what constitutes risk is the measure of probability along with severity of harm posed on receptor as a result of an undesired event in a hazardous facility. Kellman [62] presents a collection of risk definitions that has been used in the Literature. As can be seen in Table 3.1, these definitions can be simple or more detailed.

Obviously, for risk to be addressed in hazardous waste management decisions, qualitative risk assessment approach would be inadequate. Decision makers need to have an understanding about the quantity of risk in order to be able to compare different alternatives and scenarios. The value of quantitative risk assessment as a basis for decision-making process is also underlined by Jonkman et al. [72].

The next question is how to quantify risk? The EU risk assessment methodology involves three steps for quantification of risk. In the first step, identification of the hazard or adverse effects of a substance and determination of relationship between concentration of this substance and its effects (so called dose-response relationship) is carried out. In the second step, exposure assessment which is the estimation of concentration of substance that humans or environment may be exposed to is undertaken. Lastly, the extent of adverse effects on humans and environment as a result of exposure to the substance in question is determined in risk characterization step [73,74].

Table 3.1 Definitions of risk

Risk Definition	Reference*
Total risk = Impact of hazard * elements at risk * vulnerability of elements at risk	[63]
"'Risk' is the probability of a loss, and this depends on three elements, hazard, vulnerability and exposure"	[64]
Risk = Hazard * Vulnerability * Value (of the threatened area) * Preparedness	[65]
$Risk_{(total)}$ = Hazard * Elements at Risk * Vulnerability	[66]
Risk = Probability * Consequences	[67]
"Risk is a combination of the chance of a particular event, with the impact that the event would cause if it occurred. Risk therefore has two components – the chance (or probability) of an event occurring and the impact (or consequence) associated with that event. Risk = Probability * Consequence."	[68]
"Risk is the actual exposure of something of human value to a hazard and is often regarded as the combination of probability and loss".	[69]
"Risk might be defined simply as the probability of the occurrence of an undesired event [but] be better described as the probability of a hazard contributing to a potential disaster…importantly, it involves consideration of vulnerability to the hazard".	[70]
Risk is "Expected losses (of lives, persons injured, property damaged, and economic activity disrupted) due to a particular hazard for a given area and reference period. Based on mathematical calculations, risk is the product of hazard and vulnerability".	[71]

* cited in [62]

Whenever a complete HWMS is covered, abovementioned methodology is very difficult to apply. First reason is the number of different types of substances that is regulated under hazardous management legislation. The risk assessment should be applied for each substance and the assessment should include exposure on humans through various pathways including dermal, ingestion and inhalation. It is a fact that previous studies exist in the Literature for many substance/products; however, when the substances in question are "wastes", due to their complicated nature, previous studies are hardly useful and a massive amount of additional ones are required.

Second challenge in applying detailed risk assessment is the need to model environmental exposure. In order to do so, it is crucial to have information on partition coefficients, abiotic and biotic degradation rates etc. For a large-scale hazardous waste management problem, even if these data is available for all types of waste, it is impossible to quantify risk for all exposed media (including, air, water, groundwater and soil) in every possible O-D pairs.

It is clear that implementation of a detailed quantitative risk assessment cannot be the case for modeling a problem of the magnitude handled in this study. Mostly for this reason, the OR Literature used surrogate "risk" definitions instead. It is important to stress the word "surrogate". In an OR problem like the one handled in this thesis, the main aim is to be able to compare different alternatives and scenarios. Jennings and Scholar [43] puts this forward as unlike cost, the magnitude for any single number for risk has no true meaning.

Following discussion outlines how "risk" concept is handled in the Literature.

When Alp [61] defined the risk as measure of probability along with severity of harm posed on receptor as a result of an undesired event in a hazardous facility, he specifies the exposed receptors as human beings. This risk posed on humans or population risk is categorized as individual and societal risk. ***Individual risk*** is defined as probability of an individual present at a certain distance from a road segment or facility being adversely affected as a result of an incident [61,72,75]. The definition of individual risk requires the person to be within a certain distance meaning that beyond a distance the risk diminishes. Similarly if the individual were very close to the point of incident the risk would be higher. Following this reasoning it can be incurred that magnitude of individual risk depends on the distance. This relationship is represented by risk contours [72].

Societal risk as stated by Saccomanno and Shortreed [75] is the average of all possible damages over an area posed by not only a single person but on a group of people. Individual risk represents the risk created at a certain location whereas; societal risk represents risk created over a whole area [72]. In Alp [61], it is mentioned that individual and societal risks are also differentiated as per person impact and total impact respectively. Bubbico et al. [76] emphasizes that the components that constitute risk (frequency of events, exposed population etc.) is subject to change along a route which creates complexity in calculation of risk and states that the route is divided into manageable segments to simplify quantification. For this reason societal risk is determined for each segment which has a uniform accident probability and population density [61].

Whether it is individual or societal, risk will diminish beyond a certain distance. As mentioned above, in calculation of individual risk this concept is reflected by determination of risk contours. For societal risk, it is important to establish the "distance" of interest in order to specify the area of interest or in other words impact area. One of the most widely used approaches to determine the impact area is to assume that an incident occurring at a point will effect an area of a circle around it self. This circle is named as the ***danger circle*** [60,77,78]. As the vehicle moves along the route, this danger circle moves too creating a ***semicircular exposure zone*** [78]. This concept is shown in Figure 3.4. This approach also named as λ-neighborhood concept is used in many studies including Zografos and

Androutsopoulos [35], Alumur and Kara [49], Carotenuto et al. [25], Zografos and Androutsopoulos [34], Ümit and Kara [32], Lovett et al. [79], Verter and Kara [22] and ReVelle et al [45].

The radius of the circle (λ) depends on the type hazmat being transported and assumed to be constant throughout the shipment. Selection bandwidth of impact area is based on ADR. According to classification given in ADR, impact distances are determined. These impact distances present the distances that require safety precautions to be taken in case of an incident. These safety precautions include the initial evacuation distances for public health. These distances present the danger zones or impact areas around the road segment in which all population is assumed to be effected by the incident that involves hazardous waste. The evacuation distances are presented in APPENDIX A, at the end of thesis [80]. As can be seen from Table A. 1 in APPENDIX A, the evacuation distances of bandwidth falls within the range of 50 – 1600 meters.

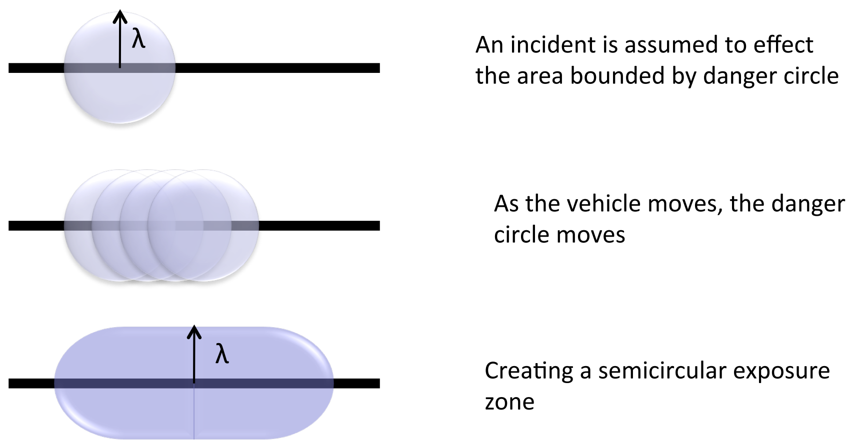


Figure 3.4 Danger circle and exposure zone concept

Following the determination of borders of risk assessment, next step is to decide on the risk model to be utilized. At the beginning of this subsection various definitions of risk has been presented. What is common in all the definitions is the presence of probability and consequences. Although definition of risk as ***probability*consequence*** which is also called ***traditional model*** is straightforward, still different models have been presented in literature [60,77]. The reasons for having various models for risk are scarcity of information and public's perception of risk.

The traditional risk model is;

$$TR(P) = \sum_{i \in P} p_i C_i \qquad \textbf{Eqn 3}$$

where TR(P): total risk along the path

p_i : probability of incident on egde i

C_i : the number of people within the impact area along edge [77].

Alternative models to traditional model include [59,77]:

- Population exposure: based on total number of people exposed to risks during a transport activity

$$TR(P) = \sum_{j=1}^{n} C_i \qquad \textbf{Eqn 4}$$

where Ci : the number of people within the danger circle along edge

- Incident probability: based on the probability of incident only

$$TR(P) = \sum_{i=1}^{n} p_i \qquad \textbf{Eqn 5}$$

where pi : probability of incident on egde i

- Perceived risk: Throughout the decision making process people's perceptions on a particular risk may be quite important. By perception of a risk it is meant by peoples may regard low probability-high consequence incidents (such as a plane crash) a catastrophe whereas be unresponsive to a high probability-low consequence incidences (such as traffic accidents). Perceived risk model considers this issue by adding a tolerance factor to the traditional risk model.

$$TR(P) = \sum_{i=1}^{n} p_i (C_i)^{\alpha} \qquad \textbf{Eqn 6}$$

where α : tolerance factor

For α = 1, the model is the same as the traditional risk model. For α>1, the risk is perceived more than it actually is; therefore, it models risk aversion. For α <1, the risk is perceived less than it actually is; therefore, it models risk-taking behavior.

- Conditional risk: When a catastrophic incident occurs, it is unlikely that the same road will be used for further transportation unless an assessment is conducted for use of that path. Conditional risk models expected consequence given the occurrence of the first incident.

$$TR(P) = \frac{\sum_{i=1}^{n} p_i C_i}{\sum_{i=1}^{n} p_i} \qquad \textbf{Eqn 7}$$

- Expected disutility: This model considers the risk aversion of the society towards incidents as in the case of perceived risk model.

$$TR(P)=\sum_{i=1}^{n}p_i\left(\exp\left(\alpha C_i\right)-1\right) \qquad \textbf{Eqn 8}$$

- <u>Mean-variance</u>: This model considers the deviance from the mean value.

$$TR(P)=\sum_{i=1}^{n}\left(p_iC_i+\beta p_iC_i^2\right) \qquad \textbf{Eqn 9}$$

- <u>Demand satisfaction</u>: In case of an incident, the need for the hazmat to be delivered to the destination does not vanishes. A second trip may be required for to fulfill the task, which means that the demand must be satisfied.

$$TR(P)=\sum_{i=1}^{n}\left(1-\exp\left(-p_i\right)\right)C_i\prod_{j=i}^{n}\exp\left(p_j\right) \qquad \textbf{Eqn 10}$$

Verter and Kara [33] , Alumur and Kara [49], Carotenuto et al. [25], Verma and Verter [81], Kara and Verter [26], Ümit and Kara [32], Madala [30], Ashur [28], Stowers and Palekar [50] are examples of studies that utilized population exposure model. On the other hand; Giannikos [47] and ReVelle et al.[45] used perceived risk, Castillo [36], Zhang et al.[82], Nema and Gupta [55] and List and Mirchandani [21]used traditional risk. Up to now only one study that involves use of incident probability was encountered [83].

According to EU risk assessment methodology, while determining the risk, not only risk on human health but also risk on environment should be considered. In the OR Literature, although public risks are well studied, environmental risks are overlooked. Yet the risks created by any HWMS on environment cannot be ignored. Currently, HWMS are being designed focusing on humans but it is also necessary to consider the environmental burdens of the system. It is obvious that a HWMS can never focus only on environmental aspects but it should also not focus only on human aspect since risks on humans and environment are not independent from each other. For example, when an incident happens leading to an environmental contamination, costs for clean up and remediation of contaminated media is almost always very high. According to polluter pays principle, these costs should be borne by polluter however, in certain circumstances, the costs of so high that it becomes impossible for polluter to bear the entire burden. In this case, governmental subsidy is often required which means that public eventually faces cost of pollution. This is the cost aspect of problem. On risk side of the problem, the area or media being contaminated becomes important. For example if the contaminated environmental component is used as water resource or agricultural area, it is inevitable that this pollution would reach to humans by certain mechanisms. Even if the risks and costs never affect public, environmental consciousness demands protection of environment from adverse anthropogenic effects as much as possible.

Unfortunately, environmental risk has not drawn much attention. Zografos and Androutsopoulos [34] reasoned that although transportation of hazmat creates various risk such as injuries, fatalities, property damages and environmental impacts, population risks are considered to have priority above others. Nevertheless, environmental risk is mentioned in many articles but there is limited number of studies that fully considered estimation of environmental risk. Alumur and Kara [49], Cappanera et al. [48] and Jacobs and Warmerdam [51]underlined the necessity to locate facilities far from rivers, lakes and groundwater supplies due to risk created by hazardous waste facilities. In Talınlı et al. [84], very brief description of environmental risk is given that only includes environmental risk being calculated as LC_{50}. In Verter and Kara [22] in which Geographical Information System (GIS) is used for quantification of risks, environmental risk is considered under environmental equity. Bianco et al. [23], Verter and Kara [33], Kara and

Verter [26] and Alp [61] mention the presence of environmental risk but they did not made any attempt to quantify it.

Verro et al. [85] used a tiered approach to determine the risk posed by pesticides to aquatic ecosystem of River Meolo Basin in Italy. This approach is very detailed however; it is not applicable for large-scale applications, which involve many types of different chemicals or wastes and a much greater area. It is obvious that a more simplistic approach is required. Moreover, this study only included impacts on aquatic ecosystem. Examples of other studies that include single medium are Verma [86], Verma and Verter [81] and Emek and Kara [40] in which Gaussian Plume Model is used in order to represent the air pollution created by hazardous waste incineration.

Jenning and Sholar [43] used DARE (Decision Alternative Ratio Evaluation) method that involves selection of an initial set of decision factors and factor weights and follows by a pair-wise evaluation to obtain cardinal risk. Risk consideration included acute and chronic health hazard and environmental consequences. Weights are assigned for these four factors. According to checklists developed for facility and transportation risk, scores are given to disposal alternatives and transportation of different types of wastes. Next, according to the weights assigned to each factor, an overall DARE rating is obtained. Authors point out that the units of facility and transportation risks are different (risk per quantity processed and risk per unit distance respectively) from each other, which prevent them to be compared. They should be scaled and some additional weights should be assigned to transportation and facility risks to be analyzed together. DARE methodology was later adopted by Nema and Gupta [55], Nema and Modak [54] and Jenning and Suresh [87].

In NORSOK standards developed by Norwegian petroleum industry, it was proposed that probability of exceedance of the time needed by the ecosystem to recover from the damage can be used as a measure for environmental risk [72].

Martinez-Alegria et al. [88] suggested a semi quantitative methodology to assess risk. They adopted traditional risk model that considers event probability and potential damage, which they call gravity. Gravity is composed of hazard and potential damage inherent to product along with vulnerability. Both population vulnerability and environmental vulnerability is considered. Hazard term depends on type of accident according to which hazard value is assigned. Accidents that do not involve loss of containment assume a smaller hazard value but accidents with explosion for example are assigned with a higher hazard value. Inherent damage of the product is related to its hazard properties; flammability, reactivity, toxicity/corrosion and oxidation. Based on properties of product, inherent damage index is obtained. For population and environmental vulnerability, some criteria Martinez-Alegria et al. [88] chose some criteria. Population vulnerability includes social (populated areas, educational centers, hospitals, hotels etc.) and technological criteria (industry, communication infrastructure, petrol stations etc.). In decreasing priority criteria for environmental vulnerability are;

- Main and secondary water sources
- Lakes and reservoirs
- Alluvial plains
- Aquifers
- Forestry lands
- Specially protected areas
- Sandy terrain
- Historical and artistic heritage

For both type of vulnerabilities impact matrices are prepared by assigning values that are only based on experiences of the researchers. Therefore, these matrices are highly subjective. In the next step, according to the values that are assigned to indices, risk maps are obtained on GIS. As a result, risk maps are obtained. This method although attempts to deal with environmental risk, it is highly subjective and does not lead to magnitude of risk which is required to be incorporated into mathematical models.

Anand [89] included environmental risk by calculating the cost to mitigate environmental pollution created in case of an accident. The clean-up cost is based on treatment or disposal options to clean contaminated soil and groundwater. The quantitative risk assessment model belonging to Inter_Industry Rail Safety Task Force was used for hazard assessment.

Eno [29] considered ;

- Farmlands
- Fauna
- Lakes and rivers
- Touristic, recreational and historical sites
- Forests
- Mining sites
- Soil contamination

for determination of environmental risks. As in the case of population risk, a constant bandwidth around the road assumed to be affected from an event. Areas of exposed environmental elements were determined which becomes the measure of environmental risk. No attempt was made to combine population and environmental exposure under a single risk term. Instead exposure to population and environmental exposure are minimized in separate single objective models. This study is important in that quantity of environmental risk is obtained and it is incorporated into the model. The only problem with this approach is to limit the area exposed to risk with a certain bandwidth. It makes sense to set boundaries on environmental risk since as in the case of population exposure, beyond a certain distance the risk would diminish. However, especially in the case of rivers, lakes and sea, it is not reasonable to assume the consequences will be retained within the boundaries of constant bandwidth area. In case of a spill, most probably the chemical will move and continue to effect area beyond the band.

Two main components that should be covered under the concept of risk are population and environmental. Population risk has been studied well. Main attempts were made in order to assess individual and societal risk. In many studies the area of interest for which the risk was estimated has been determined according to danger circle concept, which leads to an area around the road with constant bandwidth. The width of band depends on the type of hazmat or hazardous waste being transported. Whether it is population or environmental risk, risk is composed of probably of an incident and its consequence. This definition of risk is named as traditional risk. Other versions of risk model have also been developed but they will be discussed in following chapter.

The screening of literature the reveals environmental risk has been overlooked. There are several studies that go beyond mentioning environmental risk and try to develop a methodology to quantify it. Only one study worth mentioning is Eno [29], which has been helpful in developing the approach that was used in this study.

When risk assessment methodologies and risk surrogates used in the Literature is considered together, it is believed that to name the surrogate definitions risk is misleading. For this reason, since detailed assessments cannot be made, throughout the study the surrogate definitions either taken from Literature or developed within the scope of this studyare not considered as risk. Instead these concepts are mentioned as ***population*** and ***environmental impact*** in order to avoid any confusion with actual risk quantification.

3.3 Commodity type

According to the definition of hazardous wastes introduced at the beginning of this chapter, any waste that shows one of fourteen hazard properties are regarded as hazardous wastes. These hazard properties are diverse in nature from explosiveness to ecotoxicity which leads to possession of different types and magnitudes of risk on humans and environmental.

Another diversity we encounter is physical and chemical properties of hazardous wastes. These attributes not only determine the hazard properties those wastes show but also directly affect the type of processes that should be applied on wastes for recovery, treatment or disposal purposes.

Whether it is hazmat or hazardous wastes only a portion of studies covered different types of commodity. Carotenuto [25], Erkut and Alp [27], Castillo [36] Cappanera et al. [48], Ümit and Kara [32], Killmer et al. [41], Madala [30], Giannikos [47], Wyman and Kuby [52], Current and Ratick [53], Jacobs and Warmerdam [51] and ReVelle et al. [45] developed models for single commodity case.

Multiple commodity case should be considered in the models that handle hazardous waste management problem for a number of reasons. For routing models, unless routing of a single type of waste is not being optimized, waste-to-waste compatibilities issues should be borne in mind. Alumur and Kara [49] defined waste-to-waste compatibility as transportation of a certain type of waste only with compatible wastes. Compatibility criteria can be selected as dangerous goods classes in ADR. The MoEF circular on transport of hazardous wastes bans mixing of different kinds on hazardous wastes in same container [13]. However, there is no restriction for transporting hazardous wastes in different containers but in same vehicle. For this reason, waste-to-waste compatibility can be neglected. For facility location problem, second compatibility issue that is waste-to-technology should be taken into consideration. Waste-to-technology compatibility requires that every type of waste should be processed with a technology suitable for the physical and chemical characteristics of that waste [43,49]. There is no single assumption that leads to neglecting different types of processes that can be applied to hazardous wastes and that not every process is suited to every type of hazardous waste. Therefore, the location-routing problem handled in this study must consider waste-to-technology compatibility. This means that different types of hazardous wastes at least according to type of processes suitable for them should be considered, leading to a multi-commodity problem. There are examples of multi-commodity problems in literature as tabulated in Table 3.2.

Table 3.2 Commodity types in multi-commodity problems

Study	Example problem	Reference
List and Mirchandani	Multiple – not specified	[21]
Verter and Kara	Gasoline, fuel-oil, petroleum, alcohol	[22]
Kara and Verter	Gasoline, fuel-oil, petroleum and coal tar, alcohol	[26]
Verter and Kara	Gasoline, fuel-oil, petroleum and coal tar, alcohol	[33]
Göttinger	Multiple – not specified	[39]
Emek and Kara	Recyclable, unrecyclable, clinical waste	[40]
Jennings and Sholar	Organic and inorganic solids, organic and inorganic sludge, inorganic acid, caustic, oil and oily wastes, metal sludge, aqueous organics, metal solutions, organic liquids, halogenated organic liquids	[43]
Alumur and Kara	Suitable for incineration, suitable for chemical treatment, suitable for both	[49]
Nema and Modak	Metal plating waste, petrochemical waste, pesticide waste, waste residue	[54]
Nema and Gupta	Metal plating waste, petrochemical waste, pesticide waste, waste residue	[55]

A model simulating any component of HWMS should reflect the diversity of hazardous wastes. Concentrating on hazardous waste models, it is obvious that except for the work of Jennings and Sholar [43], no study comes close to reflecting this diversity. The classes of hazardous wastes should be decided so that all types of hazardous wastes and all types of processes can be represented in the model. Classification of hazardous wastes will be further discussed in Chapter 4.

In order to fully reflect waste-to-technology compatibility, it is not enough to consider multiple types of wastes. It is also necessary to represent all types of technologies that are needed in a HWMS. In the Literature, there are studies that considered only single type of facilities and multiple types of facilities as this study do. List of these studies is given below:

- Single type facility as destination;
    - Alçada-Almeida et al. [44]: Incineration
    - Killmer et al. [41]: Disposal
    - Giannikos [47]: Treatment
    - Or and Akgül [42]: Disposal
    - Jacobs and Warmerdam [51]: Single facility of storage or disposal
    - ReVelle et al. [45]: Disposal
    - Zografos and Samara [46]: Single integrated facility containing treatment and disposal
    - List and Mirchandani [21]: Single integrated facility containing treatment, storage and disposal
- Multiple types of facilities as destination;
    - Emek and Kara [40]: Recycling and incineration

- Alumur and Kara [49]: Chemical treatment, incinerator, recycling and disposal (which assumed to accept non-hazardous residues) facilities
- Nema and Gupta [55]: Treatment and disposal facilities
- Nema and Modak [54]: Treatment and disposal facilities
- Göttinger [39]: Treatment, storage and disposal facilities
- Jennings and Sholar [43]: Treatment and disposal facilities

As can be seen from the list, there is only one study that belongs to Alumur and Kara [49] that covers all types of facilities. However; in this one final disposal facilities assumed to accept only non-hazardous residues and the fact that some hazardous wastes should be sent to landfills directly was overseen along with the possibility of residues being hazardous. Therefore, it can be concluded that no study was encountered in the literature that managed to reflect processing component of HWMS fully.

Except for the few, the models in the Literature fail to present the fate of hazardous wastes after they are processed. For example, when a halogenated waste is incinerated, the resulting ash is also regarded as hazardous and must be sent to a hazardous waste landfill for final disposal. If a model ignores the fact that process ***residues of hazardous waste handling*** can also be hazardous, processing component of HWMS cannot be reflected realistic manner in the model. Examples that realize necessity to incorporate residue concept include works of Alumur and Kara [49], Nema and Modak [54] and Jennings and Sholar [43]. In Chapter 4, how residues are incorporated into mathematical models is presented.

CHAPTER 4

MATERIALS AND METHODS

In this chapter, the methodology used throughout the thesis work is presented. Firstly, the solution procedure is overviewed. Next the objectives of the models developed are defined along with the methods to quantify these objectives. In the next subsection, multi-commodity nature of the models is elaborated by introducing hazardous waste classification. In the rest of the chapter, information necessary to construct realistic model including hazardous waste generation data and mass reduction ratios follow.

4.1 Overview of solution procedure

As introduced earlier, in multi-objective problems, there exists more than one objective function to be optimized simultaneously by minimization or maximization. It is common to encounter situations where optimal solutions for different objectives can contradict with each other. In the case of conflicting objective functions, there is no single optimal solution that optimizes all of the objective functions at the same time [56]. Since the solution procedure cannot provide a single optimum solution, the decision maker searches for most "acceptable" or "preferred" solution from a set of solutions so called Pareto optimal (or efficient, non-dominated, non-inferior) solutions [56,57]. A Pareto optimal solution can be defined as "a solution where there exist no other feasible solution that improves the value of at least one objective function without deteriorating and other objective" [58].

Since solver engines are not equipped to solve multi-objective problems simultaneously; in order to obtain solutions for a multi-objective problem in IBM ILOG OPL Development Studio, it is necessary to convert multiple objective problem into a single objective model. Three widely applied methods to obtain single objective function are weighted sum (utility function), ε-constraint (bounded objective function) and hierarchical (goal programming) methods [56,57, 121].

ε-constraint method, which is used for current study involves keeping only one objective function and converting the rest into constraints. Generic formulation for ε-constraint method is given below [121].

$$\min \left(f_1(x), f_2(x), \ldots, f_n(x)\right)$$
$$st$$
$$x \in S$$
$$where\ f_1(x), \ldots, f_n(x)\ are\ the\ objective\ functions\ and\ S\ is\ the\ feasible\ region$$

$$\varepsilon\text{-}constaint\ method\ is\ stated\ as$$

$$\min f_1(x)$$
$$st$$
$$f_2(x) \le e_2$$
$$f_3(x) \le e_3$$
$$\ldots$$
$$f_n(x) \le e_n$$
$$x \in S$$

For a minimization problem the objective functions converted into constraints and upper bounds are assigned for this constraint [57]. As the right hand side values are changed, separate conditions are obtained and solutions of each determine on

Pareto optimal solution [121,122]. Steps of solution procedure applied for every scenario can be found in Figure 4.1. Details of the steps are explained below.

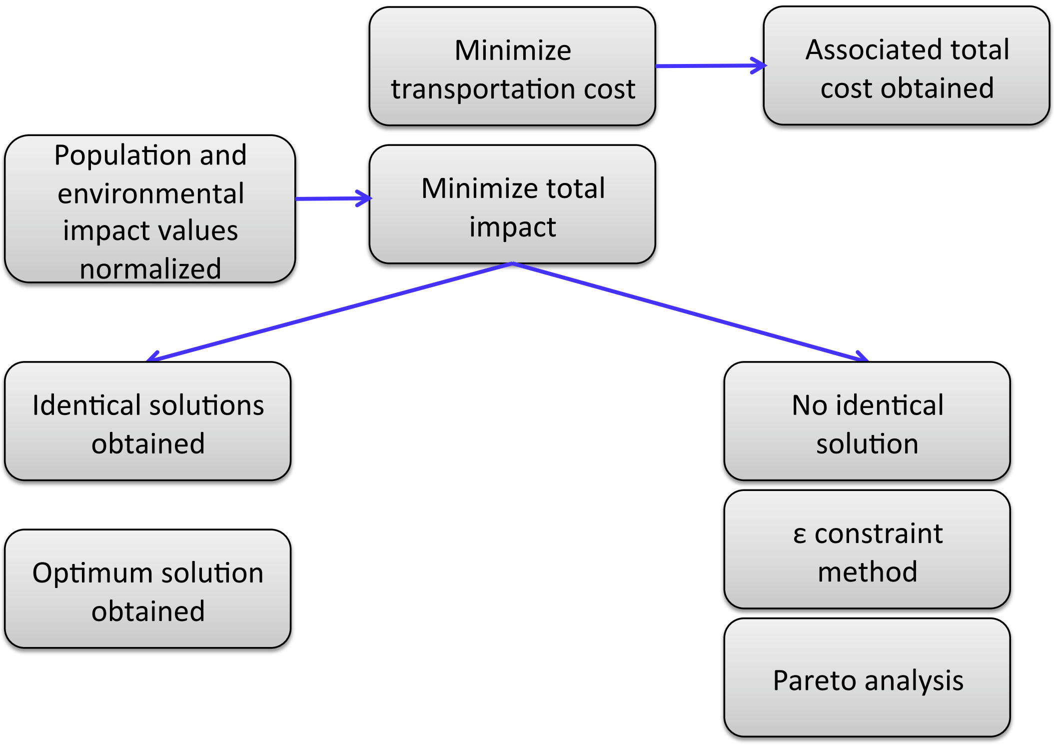


Figure 4.1 Steps of solution procedure followed

1. First of all, the models are solved as single objective models that minimize cost and impact separately. Constraints are common for these single objective models. The model that minimizes cost includes transportation cost as objective function. As mentioned in Chapter 3, facility costs are determined based on economy of scale principle. According to this principle, there is an inverse relation between facility capacities and unit investment and operational costs. Therefore, constant investment and

operational unit costs cannot be incorporated into mathematical statements. The cost figures used for various capacities are obtained from Figure 3.2 and Figure 3.3. As apparent from these figures the inverse relations are not linear therefore, when facility costs are included in the objective function, the model becomes non-linear. Given that this situation changes the solution procedure completely, it is decided to calculate facility costs after solutions are obtained according to minimization of transportation cost. By this way, both linearity of the models is kept and facility costs are considered in calculation of total cost.

2. As a result of cost and impact being contradicting objectives, the solution of minimum transportation costs also determines maximum impact value. Additionally, capacities of facilities are determined based on the amounts of wastes allocated to each facility established in the solutions. These capacities determine which unit investment and operation cost figures should be used on Figure 3.2 and Figure 3.3. As a result, total cost of the system is calculated.
3. The next step of solution procedure involves solution of single objective model that minimization of total impact. Total impact is calculated from summation of population impact and environmental impact for each O-D pair. These two impact components have different units so they cannot be added directly. Population impact is in the form persons, while environmental impact is in the form of kilometers. Normalization is done by dividing each term by its maximum value in the data set [49]. In order to obtain data sets for total impact, normalization of population and environmental impact values are required. Combined impact formulation becomes

$$\frac{Population\ impact_{ij}}{Max\,population\ impact_{ij}}+\frac{Environmental\ impact_{ij}}{Max\,environmental\ impact_{ij}}$$

4. If the solutions for cost and impact objectives are identical, optimal solution is found and solution procedure is terminated. However, if minimization of cost and impact produce conflicting results, ε-constraint method is applied. Cost objective is kept as the objective function and impact objective is shifted to constraints. The minimum and maximum impact values are previously obtained from step 1 and 2. Various right hand side values between minimum and maximum assigned to impact constraint as upper boundaries. Right hand side values change by 10% increments within the range between minimum cost (maximum risk) and minimum risk solution. By this way nine more solutions are obtained in addition to minimum cost and minimum risk cases. Each solution corresponding to a different cost and impact value becomes a point on Pareto optimal curve, which is graphically constructed.
5. The decision on proposed Pareto solutions presented in Chapter 5 is guided by analysis of percent changes in both objectives and their trade-off.

For nearly every scenario, several sub-scenarios or alternatives covered. The alternatives covered for the scenarios are presented in Figure 4.2. As can be seen in this figure, main aim is to obtain a single solution for each scenario that can be compared. As mentioned before, these solutions give idea about effect of different management approaches. Final recommendation for future implementation of HWMS in Turkey is obtained from comparison of proposed solutions of each scenario.

Two strategic decisions made at the beginning of solution procedure including the types of wastes covered under the models and ban on wastes being transported across Bosphorus.

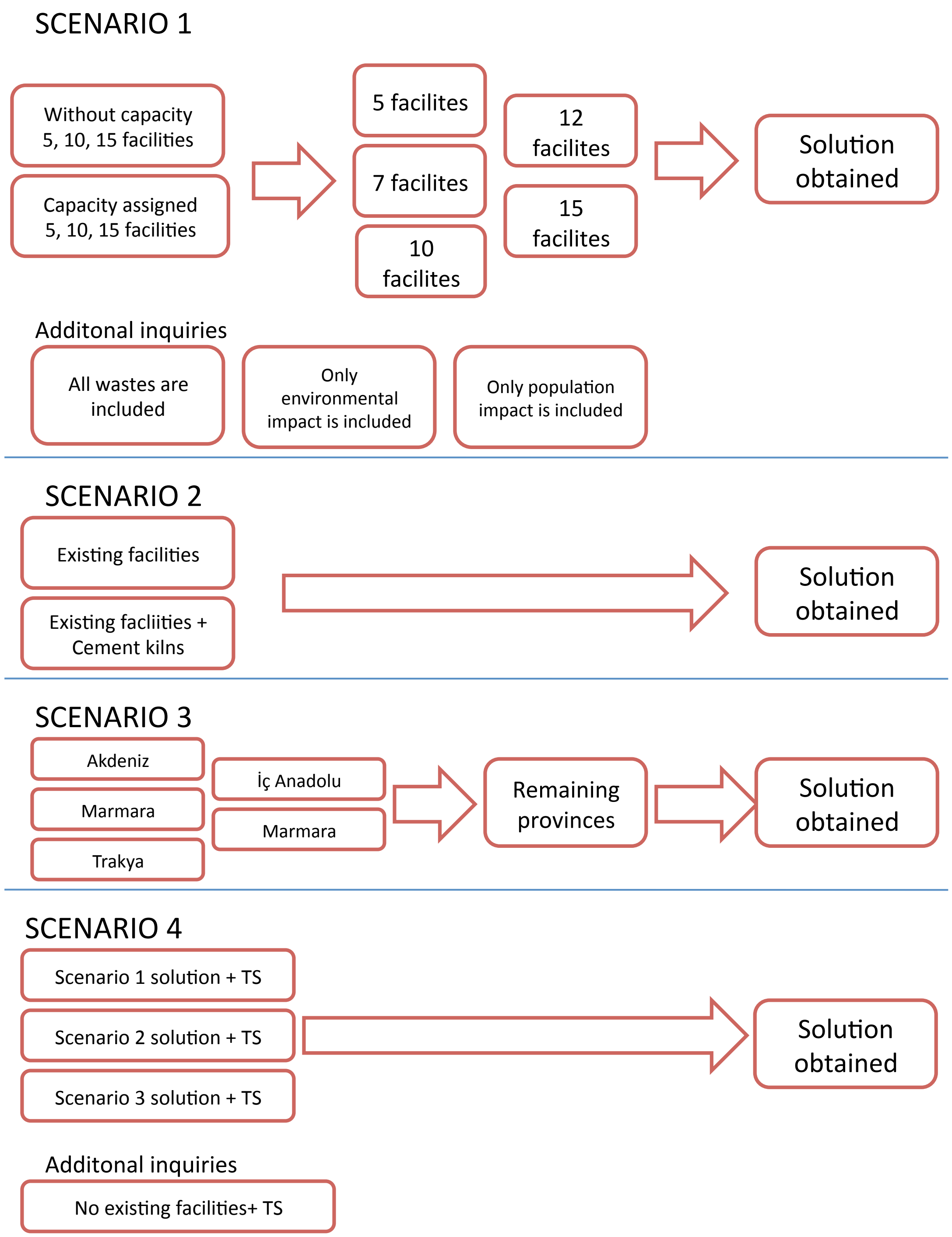


Figure 4.2 Alternatives covered for scenarios

This study aims to include all types of wastes as much as possible and waste generation estimation is done accordingly. When waste generation is inspected approximately 215,000 tons/yr of mining wastes draws attention. These wastes seem to constitute an important portion of wastes generated in Turkey and in practice they usually are collected in huge ponds in mining sites. Due to their excessive volume, mining wastes are not sent to off-site treatment plants. Consequently, it is decided to exclude mining wastes from total waste generation and total amount of wastes handled in this study becomes 1.38 million tons/yr. Nevertheless, solutions are obtained for the case where mining wastes are sent to treatment plants for comparison purposes only.

Transportation of wastes between Thrace Region and Anatolia means transportation of wastes across the city of İstanbul and from one of two bridges on Bosphorus. With nearly 12 million residents, İstanbul is the biggest city in Turkey. The possible adverse impacts of such transportation especially on population are decided to be excessive and Thrace Region handled separately from Anatolia. According to this approach, hazardous wastes generated in Edirne, Kırklareli, Tekirdağ and İstanbul (covers part of İstanbul on Thrace Region) are to be managed separately in facilities established on this region only. Transportation of wastes to and from Thrace Region to Anatolia is banned and vice versa. Therefore, in all scenarios countrywide solutions of model always consider 78 generators instead of 81. However, the cost of regional management in Thrace Region is added to total cost as proposed solutions of each model.

Scenario 1 that is the basic scenario, involves location of four types of facilities without considering existing facilities. First alternative covered under Scenario 1 is whether to assign maximum capacities to facilities or not. As mentioned before in cost discussion, construction of facilities is bounded with technical feasibility. Capacities are calculated by dividing amount of total wastes with number of corresponding facilities. Two cases are compared for various numbers of facilities where number of facilities is kept constant and capacities are assigned or not.

Secondly, decision should be made in terms of total number of facilities for each facility type. Establishment of 5, 7, 10, 12 and 15 treatment plants, incinerators and landfills are investigated and results are compared. It is expected to see an inverse relation between cost and impact values as numbers are changed. According to the data obtained as a result of the trials with varying facility numbers most appropriate number of facilities is determined. It is worth repeating that facility numbers are assumed to be equal to number of generators for recovery facilities. Therefore, this analysis omits recovery facilities.

Second scenario aims to determine locations for new facilities to be constructed in addition to existing ones. Two alternatives are studied under this scenario. In the first alternative, four existing commercially available facilities (Table 2.3) are included in the system. Secondly, cement factories that are used for co-incineration purposes are added to the system in order to see their effect on overall cost and impact of the system as well as waste allocation. Capacities of cement kilns are assigned based on provincial distribution of the amounts incinerated in kilns in 2010 (data obtained by personal communication). Total number of facilities is kept as the same decided for Scenario 1.

Third scenario assumes implementation of regional hazardous waste management system (Chapter 2). Initially, solutions are obtained for regions determined in [2]. At this point the locations of facilities are determined. Later, waste allocation is obtained for remaining provinces where facility locations are set according to first step. As a result of the second step final capacities of facilities are obtained. Costs of facilities are calculated according to final capacities.

Last scenario involves establishment of a transfer station network along with hazardous waste facilities. This scenario investigates the effect of transfer station on proposed solutions of previous scenarios. To be more specific, three alternatives are investigated under this scenario; combinations of base scenario and transfer stations, regional management and transfer stations and finally existing facilities and transfer stations. The locations of facilities are assumed to be as decided in proposed solutions of scenarios. Scenario 4 solutions present locations of transfer stations, waste allocations in case of a transfer station network existing and cost and impact of the system. An additional inquiry of Scenario 4 is simultaneous siting of hazardous waste facilities and transfer stations.

4.2 Definition of objectives

In the proceeding sections, approach used for the evaluation of ***transportation cost and impact*** of hazardous waste management system are described.

4.2.1 Costs

Main components of the conceptual model that constitutes to cost are transportation and processing of hazardous wastes. Although both of these costs are covered by hazardous waste generator due to his obligations according to polluter pays principle, in models carriers and facility developers are mentioned as stakeholders. As given in Section 2.5.1, definitions of transportation costs used by various studies are always dependent on amount of waste carried. Similar definition is used for this study. However, there is an important point that should be taken into consideration. When transfer stations are used there will be a reduction in number of trips since wastes are stored in transfer stations temporarily and are sent to facilities after they increase in amount. This situation creates the opportunity to use vehicles with larger capacities for transportation between transfer stations and facilities.

For the first scenario where no transfer stations are established, using waste amounts and number of trips yield same results. However, when transfer stations are established (Scenario 4) change in number of trips affects cost and impact of the system considerably. This situation is explained with and example in Figure 4.3.

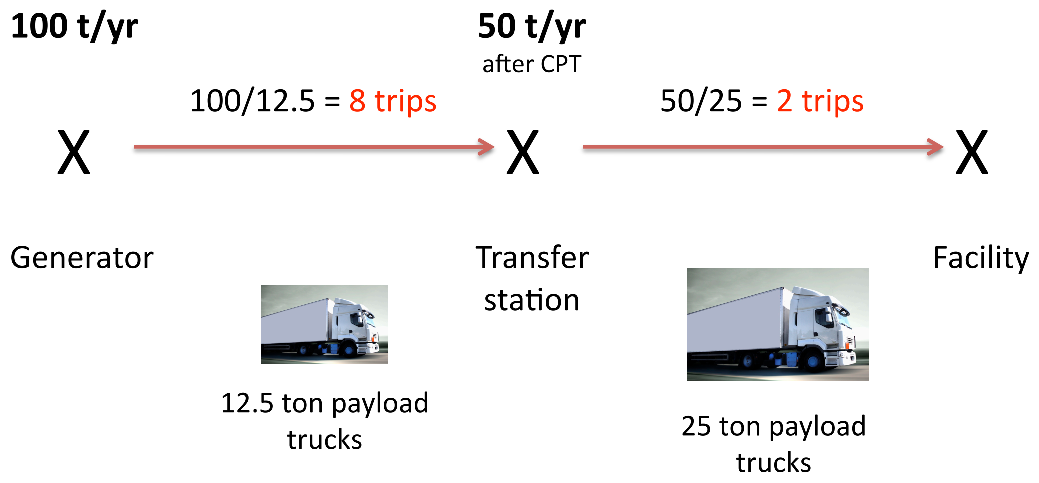


Figure 4.3 Example case for Scenario 4

This example shows a case where 100 tons/yr of waste is sent to a transfer station first. After CPT the amount of waste that must be further transported is reduced to 50 tons/yr. Considering different payload trucks would be used, the number of trips required from generator to transfer station and from transfer station to facility are 8 and 2 respectively. Therefore, the amount of waste is decreased to half but number of trips is reduced to ¼. If only waste amount is taken into account, the full effect of establishment of transfer stations cannot be reflected to the model. Especially, this becomes important for impact of the system where it is calculated per travel. For this reason, a modification for cost definition is required. Number of trips is used in objective function instead of waste amount as seen below.

$$TC = UC * D * X/PL \qquad \text{Eqn 11}$$

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/trip)

Unfortunately, estimation of unit cost of transportation is not straightforward. There are many parameters that affect this cost including, type of waste, type of vehicle used, amount of payload, fullness ratio, driver requirement etc. For this reason, some simplifying assumptions must be made.

- Unit cost of transportation does not change according to waste type.
- Same types of engines used for different payloads.
- Two separate payloads are used (12.5 ton in Scenarios 1,2,3 and 4 (for transportation origins other than transfer stations) and 25 ton in Scenario 4 (for transportation origins that are transfer stations). Payloads are decided based on actual trucks used in hazardous waste transportation)
- Fullness ratio is 1 for all shipments.
- Driver requirements do not change according to distance of travel.

- Fuel consumption for 12.5 ton payload truck is 31.4 L/100 km which is equivalent to 102 TL/100 km or 0.102 TL/km (February 2011 prices in Ankara [91,91])
- Fuel consumption for 25 ton payload truck is 39.8 L/100 km which is equivalent to 129.35 TL/100 km or 0.129 TL/km (February 2011 prices in Ankara [91,92])
- Fuel costs constitute 20% of total transportation cost [93]

Based on these assumptions, average cost of transportation for voluminous solid hazardous wastes and liquid hazardous wastes, unit price is around 0.51 TL/km for 12.5 ton payload trucks and 0.645 TL/km for 25 ton payload.

Processing costs are related to facilities and include both investment costs and operational costs as in the case of Alçada-Almeida et al. [44], Nema and Gupta [55], Nema and Modak [54] and Current and Ratick [53]. Both investment costs depend on the size of the facility. Assuming that all the wastes assigned to a facility by the model is actually sent there, for recovery, treatment and incineration facilities size of the capacity is identical to annual amount of waste that is received. For landfills the capacity is the total amount or volume of waste that a landfill can take until the end of its useful lifetime, which is assumed as 20 years in this study.

As discussed in the previous chapter, different definitions of investment and operational cost are used in the Literature. Even though only a limited number of studies considered economy of scale principle it needs to be taken into consideration since the difference between unit costs of high, medium and low capacity facilities can be significant. The determination of processing costs is carried out according to information given in "Technical Assistance for Environmental Heavy-Cost Investment Planning Directive-Specific Investment Plan for Council Directive on Hazardous Waste (91/689/EEC)" Project [2]. A summary of cost information is presented in Table 4.1.

Table 4.1 Cost information summary

	Investment Cost (€/ton)	Operational cost (€/ton*yr)
Incineration	2000 – 6500	160 – 250
Landfill	9 – 22	2.25 – 5.5
Treatment	800 – 2600	80 – 260
Recovery	800 – 2600	80 – 260
Transfer station		
treatment	800 – 2600	80 – 260
storage	154 – 500	15 – 50

According to required capacities obtained in solutions, the corresponding unit investment and operational costs are determined from Figure 3.2 and Figure 3.3 and facility costs are calculated. It should be noted that the investment costs given in these figures are linearly depreciated based on the assumption that useful lifetime of facilities are 20-years. This means that cost values obtained from Figure 3.2 and Figure 3.3 are divided by 20 in order to obtain yearly based investment costs. Only by this way, it becomes possible to add investment and operation costs to obtain total facility costs.

For instance, if three incinerators decided to be built and model results suggest that 100,000 tons/yr, 25,000 tons/yr and 60,000 tons/yr of wastes are sent to these three facilities, associated unit costs of investment are determined from Figure 3.2 as 2000, 3450 and 2400 €/ton*yr respectively. Associated unit operation costs for these facilities are 160, 276 and 192 €/ton*yr. Facility cost is determined by multiplying capacities with unit costs and summing all cost values as given in Table 4.2.

Table 4.2 Example for facility cost calculation

Facilities	1	2	3
Capacities (tons/yr)	100,000	25,000	60,000
Unit investment cost (€/ton*yr)	2000	3450	2400
Investment cost (million €/yr)	10	4.3	7.2
Unit operational cost (€/ton*yr)	160	276	192
Operational cost (million €/yr)	16	6.9	11.5
Total investment costs (million €/yr)		21.5	
Total operational costs (million €/yr)		34.4	
Facility cost (million €/yr)		**55.9**	

When annual transportation costs obtained from model results are added to facility costs, yearly hazardous waste management costs can be found.

4.2.2 Impacts

The second objective of the models is to minimize impact. Survey of literature shows that the most popular risk model is ***population exposure*** and is decided to be used in this study. Therefore, the number of people within a certain bandwidth around every transport route is the surrogate for risk measure and is termed as ***population impact***.

Although the population exposure concept is used in the study, quantification of population impact differs from the one used in the Literature. In many studies after specification of the bandwidth within which the total number of people is sought, number of people within band is calculated by multiplying a constant population density (ca/area) with the area of the settlement falling within the band.

In this study, above methodology is not applied due to the fact that when only the population that falls within the area inside the band is considered, it is assumed that people are fixed where they are all the time. It is obvious that this is not the case since people keep moving all the time. They go to work, school, shopping etc. It is possible that some areas of concentration such as schools or hospitals can be within the area that falls inside the band. Calculation based on constant population density and area inside the band underestimates the number of people that possibly be affected from an incident.

To overcome the problem of underestimation, worst-case scenario approach is adopted. Verma and Verter [81] also adopted similar strategy. Instead of considering some of population inside the band, it is assumed that whole population of any settlement that falls within the band have the potential to be adversely affected. Consequently, total population of that settlement should be included in impact calculations. The boundaries of settlements are not easy to determine and can be quite subjective so the criterion of a settlement being within the band is selected as the population center being within the band.

For choosing the bandwidth(s) to be used, two options are considered. First one is to categorize hazardous wastes according to their bandwidths. This can be done by linking ADR classes to hazard properties of hazardous wastes, determine the hazardous properties of hazardous wastes one by one and assign each type of hazardous waste to an ADR class and finally obtain an evacuation distance. According to evacuation distances a classification of hazardous wastes can be done. Actually, hazardous wastes can have more than one hazard property, which makes it impossible to assign them to a single ADR class. Also, hazardous wastes are also classified in this study according to their destinations. A second classification according to impact brings huge computational burden on solution of models.

For these reasons, more simplistic method is selected which is in accordance with worst-case approach. Maximum bandwidth that is ***1600 m*** is selected for all types of wastes.

One important bottleneck of the study was the absence of digital data with which impact calculation could be made using GIS software. Although data needed could not be retrieved, it was obtained from through Google Earth and Google Maps services provided by Google. Google Earth is a GIS-based software that allows the user to view satellite imagery. The imagery is one to three years old and contains information around the globe. Download of Google Earth and use of Google Maps via internet is free of charge. Another advantage of these two services is that wide range of resolutions is accessible.

The estimation of population impact is achieved according to following steps:

1. For each O-D pair; shortest path in terms of distance is determined. As Verter and Kara [33] pointed out, carriers would always prefer to use shortest paths unless the authority intervenes the paths or manifest preference. In Turkey, the MoEF does not have the jurisdiction to influence the paths selected by carriers. Therefore, it is logical to assume that between provinces (O-D pairs) carriers will choose to use shortest paths. By applying worst-case scenario on shortest paths, preferences of both authorities and carriers are considered without giving priority to any of them. Therefore, it can be said that assuming use of shortest paths between provinces makes the models more realistic.
2. For each O-D pair, the settlements that fall within 1600 m from each side of the road are determined. The centers of the settlements are already marked on Google Earth and these center points are used unless there are important offsets. Distance between road and population center is measured with line measurement property of Google Earth. Obviously no

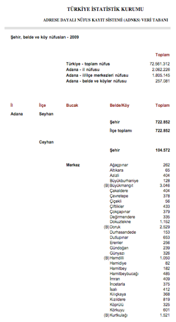
hazardous waste facility will be constructed at city centers. Hence, no settlement closer than 10 km to origin and destination is included in the list. Of course, if a city center is passed throughout the route, because it is the vehicle that goes through it creating a risk, population of that center is included.

3. Populations of each settlement are obtained from Turkish Statistical Institute (TurkStat). TurkStat publishes census each year under a program called "Address Based Population Registration System". The reports for every province can be obtained from the website of TurkStat [90].
4. Populations of every settlement that falls within 1600 m band is added in order to determine total number of people that have the potential to be adversely affected from an incident across the length of one trip. Population of every settlement is taken into account regardless of the size.
5. As this procedure is repeated for every O-D pair, a 81 x 81 matrix of population exposure data is obtained. A sample data set is presented in APPENDIX B. In Figure 4.4 a representation of above steps can be seen.

Another concern is the quantification of environmental impact. As discussed in Chapter 2, there are no satisfactory environmental risk models in the Literature. For this reason it is necessary to develop a method to determine environmental impact. The method developed is similar to that of population impact. Only instead of number of people exposed in a given impact area, the environmentally vulnerable elements inside the band is determined.

Step 1: shortest distance paths are determined

Step 2: settlement within 1600 m bandwith from each side of the road are determined

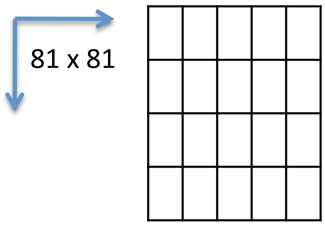


Step 3: census data is obtained from TurkStat

ADANA - ADIYAMAN

			P/E	Uzaklık -m	Kişi
		ADANA - MERKEZ			
1	ADANA	Yıldırım Bayezid Mh.	P	350	
2		Buruk Cumhuriyet Mh.	P	1030	
3		Kürkçüler	P	1170	
4		Tarım alanı	E	0	
5		Ceyhan Nehri			
6		Altıkara	P	200	65
7		Tarım alanı	E	0	
8		Sirkeli	P	250	485
9		Toktamış	P	1400	886
10		Sulama kanalı	E	0	
11		Sarıkeçili	P	1400	
12		Değirmendere	P	1000	335
13		Dokuztekne	P	150	1152
14		Dutlupınar	P	500	653
		Orman/yeşillik alan	E	1200	
15		Tüysüz	P	1000	2595
16		Tarım alanı	E	0	
17		Alahanlı	P	400	660
18		Tarım alanı	E	0	
19		Ceyhan Nehri	E	0	
20	OSMANİYE	Dervişli	P	450	1655
21		Tehçi	P	400	1348
22		Orman/yeşillik alan	E	0	
23		Şekerdere	P	500	1058
24		Orman/yeşillik alan	E	0	
25		Ellek	P	900	6634
26		Tarım alanı	E	0	
27		Arıklıkaş	P	750	761
28		Nohut	P	1250	495
29		Orman/yeşillik alan	E	0	
30		Bahçe	P	1000	12917
31		Orman/yeşillik alan	E	0	
32		Arıcaklı	P	50	132

Step 4: population along the route is added to obtain population impact for a single trip between a given O-D pair



Step 5: population exposure matrix is obtained

Figure 4.4Steps followed for population exposure estimation

These ***vulnerable elements*** are identified as

- Rivers
- Lakes
- Reservoirs and dams
- Sea shores
- Forests
- Agricultural areas

All of these elements are easily identifiable on Google Earth software.

Steps followed for estimation of environmental risk as follows:

1. Shortest paths identified for population impact estimation are used for environmental impact estimation.
2. For each O-D pair, environmentally vulnerable elements that fall within 1600 m from each side of the road are determined.
3. Interaction between the route and environmental elements can be different as seen in Figure 4.5. They can be either located along the road or can intersect with the road at a single point. Intersection is usually valid for rivers, which are crossed by bridges or small lakes/reservoirs and dams. When an environmental element continues along the road, there is a risk of environmental contamination throughout its length. Based on this reasoning "distance" is selected as measure of environmental impact. So ***environmental impact*** is defined as the length of route that is in contact with the environmentally vulnerable elements specified above. When environmental elements go along the road, length of the element is measured by path length measurement property of Google Earth. The measured piece is the distance between borders of the element as shown in red in Figure 4.5. Intersection of road with rivers and water bodies being short does make the risk negligible. If an accident occurs over a bridge or

near a water body, the pollution created can easily be transported downstream in river or contaminate whole water body in a lake or reservoir. In the case that intersection is very short, a certain amount of distance is added to total distance according to the scheme presented below:

Rivers used as drinking water supply: 20 km

Rivers used as irrigation water source: 15 km

Other rivers: 7.5 km

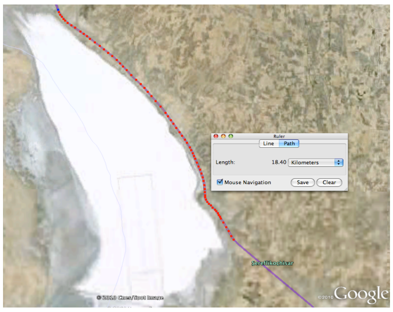
Lakes, dams and reservoirs used as drinking water supply: 20 km

Lakes fall within specially protected areas: 15 km

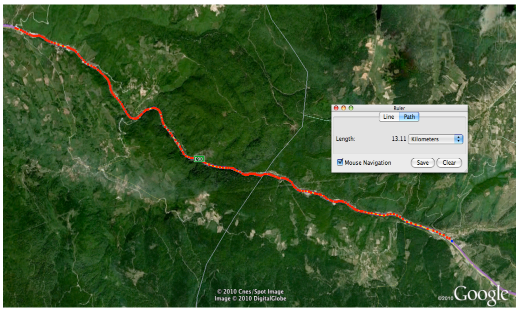
Other lakes, reservoirs and dams: 7.5 km

These extra distances are added in order to reflect the nature of water bodies and to avoid underestimation of environmental impact.

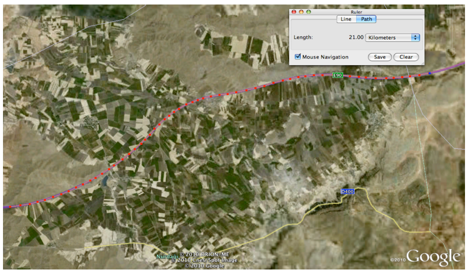
4. Distance values for every environmental element that falls within 1600 m band is added in order to determine total length of environmental elements exposed that have the potential to be adversely affected from an incident.
5. As this procedure is repeated for every O-D pair, a 81 x 81 matrix of population exposure data is obtained. A sample data set is presented in APPENDIX B.



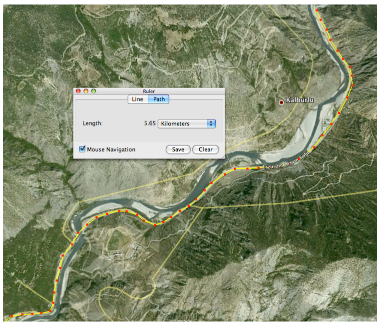
a- Salt Lake



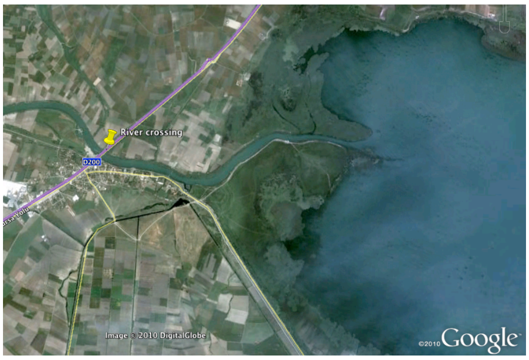
b- Forest



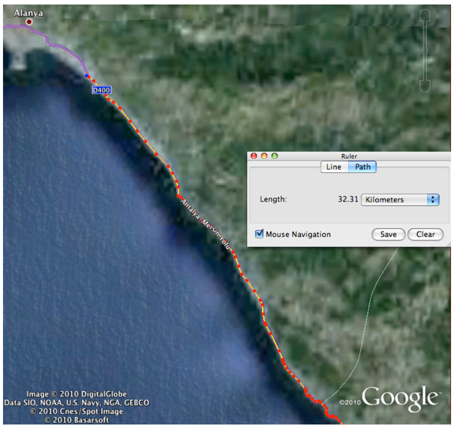
c- Agricultural area



d- Çoruh River



e- River crossing and Ulubat Lake



f- Mediterannean Shore

Figure 4.5 Samples of environmentally vulnerable elements

4.3 Waste classification

As discussed in pervious chapter, it is essential to take different types of hazardous wastes into account. Models developed for this thesis aims to minimize cost and impact of HWMS. Based on both of the objectives, hazardous wastes can be classified. Transportation fee is assumed to be constant for all types of wastes. On the other hand, since not every process is suitable for all types of hazardous wastes, some wastes can only go through certain processes, which will generate various types of residues. Consequently, most important considerations are waste-to-technology compatibility and processing residues. Second possible classification can be based on impact. As mentioned in risk definition, worst-case approach is adopted for impact, which eliminates the necessity for the second classification.

The best starting point for deciding the classification scheme is the legislation. RGPWM Annex 4 contains 480 six-digit code listed under 99 four-digit code. This means that the regulation defines 480 separate hazardous waste types. Due to the fact that this many of waste type increases model complexity significantly an alternative classification is required.

Two criteria should be considered for classification; process types (waste-to-technology compatibility) and destinations for the residues generated. For the base scenario, four types of processes are identified as recovery, treatment, incineration and landfill. Not only the wastes but also the residues are sent to either of these processes. If only wastes were included, recoverable, treatable, incinerable and landfillable would suffice as the classification. But the residues should also continue their way through HWMS so this complicates the situation.

As a baseline for waste classification, Annex 3 of RCHW is selected since it contains two lists that are simpler than Annex 4 of RGPWM and more complex than four-item process type classification. Annex 3 is provided in APPENDIX C of this study. Annex 3 classes are matched with six-digit codes of RGPWM Annex 4. In order to make these classes reflect the wastes in Annex 4 better, some alterations are made and final list of classes are obtained. This list includes 31 items of Annex 3 and five new groups, a total of 36 classes. Table A. 6 in APPENDIX C contains information on these classes and six digit coded wastes that are assigned to them.

Main aim is to group wastes according to the processes suitable for them and residues generated. When these 36 classes are evaluated based on this issue, it becomes possible to simplify the list further. As a result of this evaluation; seven main classes of hazardous wastes are identified. These seven classes are not actual classes; they involve the main destinations for the waste and possible destinations for the residues forming a process scheme. General process schemes for main classes of wastes can be seen in Figure 4.6.

Information on main groups of waste classes is given below. Some Annex 3 classes can fall into more than one these 7 groups. In that case, it is assumed that some percent is handled under one group and the rest under another. Percent values are given inside parentheses.

- Waste category 1 (W1): includes
    1. Wood preservatives (50%)
    2. Waste oils and oily wastes (50%)
    3. Waste solvents (50%)
- Waste category 2 (W2): includes
    4. Photographic chemicals (25%)
    5. Non-halogenated organic wastes (50%)
    6. Contaminated equipment (25%)
    7. Contaminated containers and packaging (50%)
    8. Waste batteries and accumulators (60%)

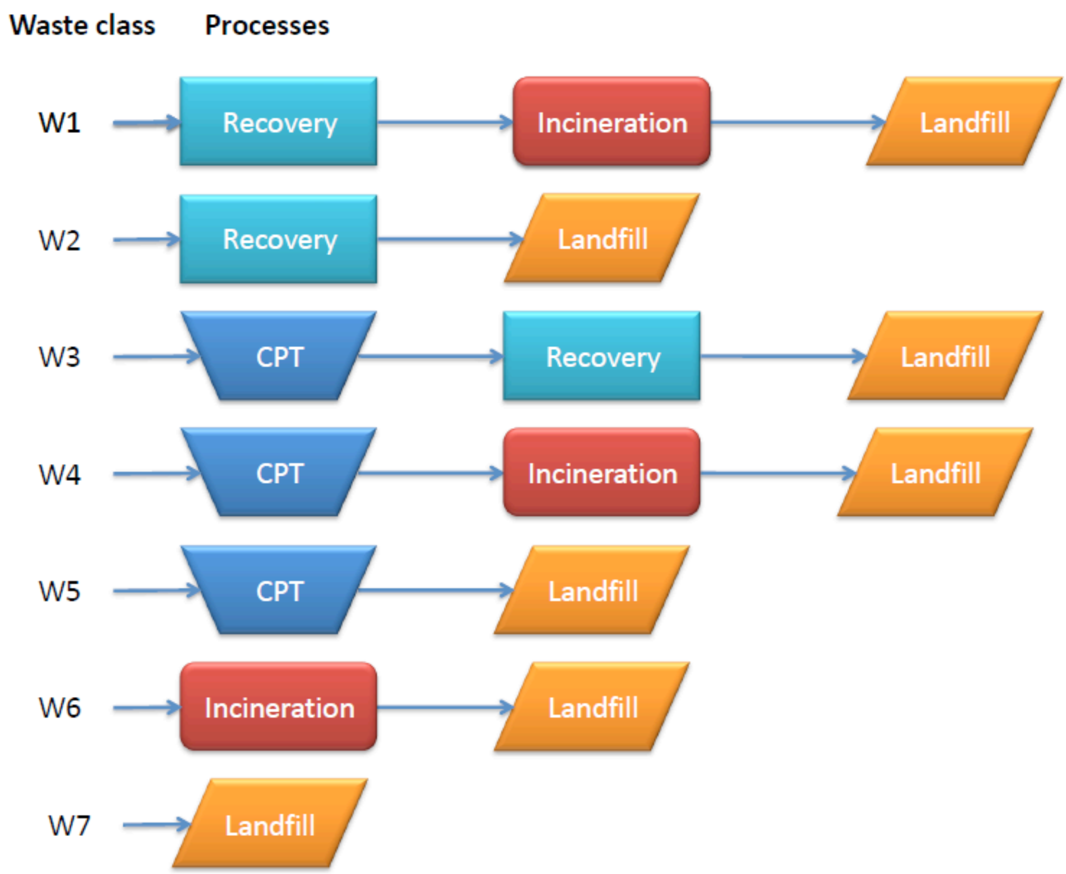


Figure 4.6 Waste classes according to process schemes

- Waste category 3 (W3): includes
  9. Oil/water, hydrocarbon/water emulsions (50%)
  10. Photographic chemicals (25%)
- Waste category 4 (W4): includes
  11. Oil/water, hydrocarbon/water emulsions (50%)
  12. Laboratory chemicals (50%)
  13. Sludges from treatment operations (50%)
  14. Liquid hazardous wastes sent to off-site treatment (50%)
- Waste category 5 (W5): includes
  15. Tempering salts containing cyanide (50%)

16. Liquids or sludges containing metals and metal compounds
17. Sludges and filter cakes from gas treatment (50%)
18. Sludges from treatment operations (50%)
19. Liquid hazardous wastes sent to off-site treatment (50%)
20. Household hazardous wastes not otherwise specified

- Waste category 6 (W6): includes

21. Medical wastes
22. Waste pharmaceuticals, medicines and wastes from manufacture of pharmaceuticals and medicines
23. Waste wood preservatives (50%)
24. Waste solvents (50%)
25. Waste biocide and phyto-pharmaceutical substances
26. Halogenated organics including solvents, wood preservatives, oils, organic chemical industry wastes
27. Waste oils and oily wastes (50%)
28. PCB containing wastes
29. Tarry wastes
30. Waste inks, varnishes etc.
31. Laboratory chemicals (50%)
32. Non-halogenated organic wastes except solvents (50%)
33. Ion exchange residues
34. Tank bottom sludges
35. Contaminated equipment (25%)
36. Contaminated containers and packaging (25%)
37. Waste refractory materials (50%)
38. Other solid wastes (50%)

- Waste category 7 (W7): includes

39. Tempering salts containing cyanide (50%)
40. Explosive wastes

41. Inorganic wastes that do not contain heavy metals
42. Waste ash and cinder
43. Waste soil and sand
44. Non-cyanic tempering salts
45. Spent catalysts
46. Solid wastes from pollution control operations
47. Sludges and filter cakes from gas treatment (50%)
48. Contaminated equipment (50%)
49. Contaminated containers and packaging (25%)
50. Waste batteries and accumulators (40%)
51. Solid wastes containing metals and metal compounds
52. Waste gases from pressurized tanks containing dangerous substances
53. Waste refractory materials (50%)
54. Other solid wastes (50%)

Definition of classification of hazardous wastes is therefore finalized. Next step is to estimate hazardous waste generation data that is one of the most important inputs of models.

4.4 Waste generation

In this section, information on waste generation data is provided. Unfortunately, obtaining hazardous waste generation data has always been problematic. Most important issue on data collection is to obtain complete set of data periodically. This situation is obvious from results published by UN Statistics Division on hazardous waste generation [95]. According to the results, among 87 countries from which information was obtained, only 10% managed to present complete data set for the period of 1995 – 2007 while the percent of countries that provided single data for this period is 31%.

Data scarcity is an issue for Turkey too. There are two official information sources for hazardous waste generation; statistics published by TurkStat and waste declaration forms complied by the MoEF. TurkStat has released three statistics related to hazardous waste generation from manufacturing industry belonging to years 2000, 2004 and 2008. According to these statistics, total hazardous waste generation from manufacturing industry is 1.31, 1.20 and 1.14 million tons/yr, respectively [96]. In these releases, distribution based only on major industrial sectors was presented. Moreover, they lack geographical distribution and distribution according to waste types.

Waste declaration forms submitted by hazardous waste generators to the MoEF on an annual basis is the second source for hazardous waste generation information. Recently, the MoEF started the internet-based declaration system. Before, the new internet-based declaration system, the return ratio of waste declaration forms was very low. In addition to that the forms contained insufficient and inconsistent data and were far from providing sufficient data on industrial hazardous waste generation. With the new system, the return ratio shows an increasing trend however; still information flow from all hazardous waste generators is not established. According to 2008 numbers, total hazardous waste generation reported to the MoEF is approximately 4.6 million tons/yr [90]. This amount is nearly four times the total hazardous waste generation announced by TurkStat.

Official resources for hazardous waste generation are far from providing data with required characteristics. Most important aspects missing in both sources are level of detail and reliability. Mere numbers for hazardous wastes amounts is not sufficient to create a model that aims to optimize transportation and facility location. At minimum waste generation data should include information on distribution of waste amount in terms of point of generation (i.e. geographic distribution) and waste types. Moreover, conflicting data from different sources makes it difficult to take one source as baseline.

Instead of adopting unsatisfactory inventories, it is decided to use the methodology laid down in Yılmaz [97]. This approach involves use of a theoretical method for estimation of waste generation. Main idea behind theoretical estimations to construct an inventory is using ***waste generation factors*** and capacity information to reach hazardous waste generation data.

In its most simplistic form ***waste generation factors*** can be defined as coefficients that enable the user to calculate amount of waste generated in terms of various multipliers such as a product unit (amount of raw material or product), number of people (number of employees or population) or economic unit (GDP unit etc.)

It is possible to classify waste generation factors under two groups. First group is the waste generation factors developed based on number of employees working in a given industrial facility. Differences in production process used and automation level of facilities turn out to be important variables for waste generation factors based on employee numbers. Unfortunately; the employee number based waste generation factors cannot reflect this variation adequately. Consequently, direct use of employee number based waste generation factors obtained from the Literature does not deem suitable for construction of hazardous waste inventories.

The second group that is production or process based waste generation factors that present waste generation in terms of amount of product or raw material utilized. Basis of process based waste generation factors is the material balance concept. Inputs (feedstocks, operating substances, water, air etc.) for any process are converted to some output (products, residues etc.) based on conservation of mass [98]. As a result, it becomes possible to relate the amount of residues or wastes with the amount of inputs or products. By the help of material balances constructed, the amount of waste generated can also be related to the amount of production or capacity utilized.

The most important point to be considered while using production based waste generation factors is that factors show variation according to the type of process installed even if the end product of processes are the same. As long as production processes are the same, it is convenient to apply production based waste generation factors obtained from the Literature to other facilities.

Applicable waste generation factors can be obtained from various sources. Waste generation factors have been developed and being used by international organizations for some time. Moreover, these factors are published by these organizations for public use through reports and reference documents.

One of the most extensive references for these factors is the Best Available Techniques Reference Documents (BREFs) that are published by the European Integrated Pollution Prevention and Control (IPPC) Bureau [99]. These studies are conducted by Technical Working Groups composed of experts from Member States, European Free Trade Association countries, Accession countries, industry and environmental non-governmental organizations. Consequently, industrial facilities from different countries were analyzed and waste generation factors developed represent industry better than waste generation factors developed for single facilities. Within the context of BREFs, general information on the sector around Europe and current production processes are given. BREFs also concentrate on range of currently observed emission and consumption levels for the overall process and its sub-processes. In this scope, waste generation factors for industry in question are presented if there is any. In addition to European IPPC Bureau, International Finance Corporation (IFC) has published Environmental Health and Safety (EHS) Guidelines as reference documents to promote internationally accepted standards on pollution prevention and control. In the context of these EHS Guidelines, waste generation factors are presented [100]. Emission factors have also been developed by U.S. Environmental Protection Agency (USEPA) especially for air emissions. As in the case of BREFs, reports presenting waste generation factors are published for various industrial sectors [101].

For the case study, 120 different hazardous waste generation factors were used for various waste types. Since it is inconvenient to present all waste generation factors, they are inspected in terms of contribution to total hazardous waste generation. The results indicate that some waste steams have major contribution whereas share of others are insignificant. At four-digit level 38 waste generation factors given in Table A. 7 of APPENDIX D become prominent leading to nearly 75% of total generation.

After valid waste generation factors are obtained next step is to gather information on the utilized capacity or amount of raw material used in industrial sector from which the particular hazardous waste is generated. Capacity information should be detailed enough to reveal hazardous waste generation distribution countrywide. Capacity information is mainly obtained from The Union of Chambers and Commodity Exchanges of Turkey (TOBB), Industrial Database which is accessible via internet [113]. This database is one of the most detailed and up-to-date information sources on industrial capacities in Turkey. One alternative source for capacity information is VIII. and IX. Five Year Development Plan Special Commission Reports prepared by T.R. Prime Ministry State Planning Organization [114,115]. Other relevant statistical information was provided from TurkStat [96].

Application of theoretical methodology resulted in total hazardous waste generation of approximately 1.7 million tons/yr throughout Turkey. Unfortunately, waste generation factors are not available for each type of wastes in the Literature. Yet highest waste generating sectors are universal around the world, which makes research to concentrate on them, making waste generation factors available. Therefore, it is believed that most important waste streams are covered. Coverage information given in Table 4.3 is calculated from the number of four- and six-digit entries for which calculations are made, under the covered two-digit entries and four-digit entries respectively.

Table 4.3 Brief summary of theoretical estimation of hazardous waste generation

Total generation (tons/yr)	1,693,300
Absolute entries (%)	80.5
Mirror entries (%)	19.5
Coverage (%)	
Two-digit level	80.0
Four-digit level under covered entries	35.2
Six-digit level under covered entries	21.0

The amount of waste generation calculated for six-digit entries are summed up according to waste classification scheme revealing total amounts of waste generated for seven hazardous waste classes. The summary table is presented below in Table 4.4. The distribution of wastes is presented in Figure 4.7. This figure shows that Marmara Region has the highest hazardous waste generation potential, İstanbul being the leader. Kocaeli, İzmir, Bursa, Tekirdağ, Ankara and Konya are among important waste generation centers. Malatya, Kastamonu and Rize also produce high amounts of wastes due to mining activities. Another important finding is that majority of hazardous wastes originate from western part of Turkey. This situation justifies establishment of facilities in Western provinces. Despite the fact that waste generation in Eastern parts is smaller compared to generation in Western part, these wastes still need to be managed properly. More detailed information is included in Table A. 8 of APPENDIX E, which includes distribution of each type of waste in terms of provinces.

Table 4.4 Country-wide hazardous waste generation according to waste classes

	Waste classes	TURKEY (ton/yr)
W1	G-R-I-L	250,388
W2	G-R-L	140,740
W3	G-T-R-L	14,136
W4	G-T-I-L	21,226
W5	G-T-L	234,815
W6	G-I-L	576,466
W7	G-L	361,359
	TOTAL	**1,599,130**

The total amount calculated is 1,693,300 tons/yr but as it can be seen Table 4.4, around 1,6 million of could be distributed among the provinces. Distribution of waste generation is based on the capacities obtained for every province mainly from TOBB industrial database [113]. The capacity information for missing amount could not be obtained with provincial distribution. For this reason it was not possible to obtain geographical distribution for these wastes, only total amount for Turkey could be calculated.

HWMS should ensure proper management of not only hazardous wastes but also hazardous residues that are generated as a result of processing of hazardous wastes. The necessity makes the amount and distribution of residues as important as of wastes'. Therefore, models should be developed in a manner that takes this necessity into consideration. Amounts of residues are calculated by means of waste reduction ratios, which enable the model to integrate residue amounts from hazardous waste amounts. Next section is dedicated to waste reduction ratios.

Figure 4.7 Distribution of hazardous waste generation around Turkey

4.5 Waste reduction ratios

Another aspect of models that deserve attention is the mass reduction ratios. These ratios are the amount of reduction in terms of mass achieved as a result of processes applied on hazardous wastes. Mass reduction ratios are derived from mass balances as in the case of waste generation factors.

Correct estimation of mass reduction ratios is as important as estimation of waste generation since the amount and distribution of residues are calculated by model using mass reduction ratios entered into models as constants. For this purpose both literature on processes and actual facility mass balances are used. Facility mass balances are obtained from the MoEF who collects mass balance forms from hazardous waste facilities periodically. Attention is given to processes for which mass reduction values are missing in literature. In Table 4.5 more detailed information on mass balance forms obtained from the MoEF can be found. It should be kept in mind that the availability of mass balance forms are bounded by presence of facilities of a given R-codes and operational status of the facilities. There are certain facilities that do not accept any waste for long periods though they have the license for a given R-code to processes the waste.

Table 4.5 Information on mass balance forms used for the study

R code*	Explanation	Number of facilities
R2	Solvent reclamation/regeneration	4
R3	Recycling/reclamation of organic substances which are not used as solvents (including composting and other biological transformation processes)	1
R4	Recycling/reclamation of metals and metal compounds	4
R5	Recycling/reclamation of other inorganic materials	1

* as specified in RGPWM

According to classification method introduced in previous section, each waste class involves a process scheme, which is applicable to wastes which are categorized under that particular class. These process schemes are a collection of different recovery, treatment and disposal operations. Since the wastes classified under each group is diverse in chemical and physical nature, recovery, treatment and disposal processes of different classes would not be the same. For example the recovery process of W1 under which waste solvents are classified would be R2 – solvent reclamation/generation whereas the recovery process for organics that are grouped under W2 would be R3 – recycling of organic substances, which are not used as solvents. Taking theses differences into consideration, process schemes are evaluated and R and D codes corresponding to each waste type is determined. R codes for recovery operations and D codes for disposal operations are taken from RGPWM Annex 2. Later mass reduction ratios are obtained from literature and/or mass balance forms.Table 4.6 presents a summary table for the findings regarding mass reduction ratios.

In this chapter the conceptual HWMS model is presented. It includes all possible types of hazardous wastes laid down in legislation and various processes that are applicable to these wastes. Moreover, the model also includes transportation and processing of residues.

Table 4.6 Mass reduction ratios used in the study

Waste type	Corresponding R-D codes	Mass reduction ratio (literature)	Mass reduction ratio (mass balance forms)	Selected mass reduction ratio
W1: R-I-L	R2: Solvent reclamation/regeneration R9: Oil re-refining or other reuses of oil D10: Incineration on land D1: Deposit into or on to land (e.g. landfill, etc.)	R2: 60 – 99.5 % [116] R9: 70 – 90% [117,118] D1: 65 – 70% [119,120]	R2: 74.5 – 97.7% R2: 53.5 – 90.8% R2: 87.1 – 95.8% R2: 100%	R2 & R9: 75% D1: 65%
W2: R-L	R1: Use principally as a fuel or other means to generate energy R3: Recycling/reclamation of organic substances which are not used as solvents R4: Recycling/reclamation of metals and metal compounds R5: Recycling/reclamation of other inorganic materials D1: Deposit into or on to land (e.g. landfill, etc.)	R1: 65 – 70% [119,120]	R3: 100% R4: 50% R4: 90 – 99 % R4: 83 – 86% R4: 39% R5: 100%	R1,3,4 &5 : 75%
W3: T-R-L	D9: Physico-chemical treatment not specified elsewhere in this Annex which results in final compounds or mixtures which are discarded by means of any of the operations numbered D 1 to D 8 and D 10 to D 12 R4: Recycling/reclamation of metals and metal compounds R9: Oil re-refining or other reuses of oil D1: Deposit into or on to land (e.g. landfill, etc.)	R9: 70 – 90% [117,118]	R4: 50% R4: 90 – 99 % R4: 83 – 86% R4: 39%	D9: 60% R4 & R9: 70%

Table 4.6 continued

Waste type	Corresponding R-D codes	Mass reduction ratio (literature)	Mass reduction ratio (mass balance forms)	Selected mass reduction ratio
W4: T-I-L	D9: Physico-chemical treatment not specified elsewhere in this Annex which results in final compounds or mixtures which are discarded by means of any of the operations numbered D 1 to D 8 and D 10 to D 12 D10: Incineration on land D1: Deposit into or on to land (e.g. landfill, etc.)	D1: 65 – 70% [119,120]		D9: 60% D1: 65%
W5: T-L	D9: Physico-chemical treatment not specified elsewhere in this Annex which results in final compounds or mixtures which are discarded by means of any of the operations numbered D 1 to D 8 and D 10 to D 12 D1: Deposit into or on to land (e.g. landfill, etc.)			D9: 60%
W6: I-L	D10: Incineration on land D1: Deposit into or on to land (e.g. landfill, etc.)	D1: 65 – 70% [119,120]		D1: 65%
W7: L	D1: Deposit into or on to land (e.g. landfill, etc.)	NA	NA	NA

Conceptual model aims to include all possible types of wastes. Certain classification schemes are considered like classification according to legislation and according to major process types. First one involved more number of waste types that can be handled by models and the latter one is too simplistic to reflect the complexity brought by residues. Instead a waste classification based on process schemes that target both wastes and residues is selected. As a result seven different waste classes are defined. Six-digit wastes in legislation are assigned to these seven classes.

Two important considerations of models that are information on amounts and distributions of wastes and residues are also handled in this chapter. Hazardous waste generation is estimated based on theoretical approach that involves use of waste generation factors and capacity information. This method is selected due to absence of a formal hazardous waste inventory in Turkey that contains sufficient detail in terms of distribution and is adequately reliable. Amount of residues are calculated by model based on the amount of wastes received using waste reduction ratios. These ratios derived from mass balances of processes. Both literature and actual facility data is used in order to obtain representative ratios for various processes.

Lastly, the solution procedure that involves use of ε-constraint method whenever conflicting results from optimization of cost and impact objectives is introduced. Solution procedure also involves evaluations of alternatives under each scenario and selection of a single solution for each scenario. At the end, scenarios are compared with each other.

Next chapter presents the mathematical formulations for the scenarios defined in Chapter 1.

CHAPTER 5

MATHEMATICAL FORMULATION

This chapter starts by presenting the conceptual model. As conceptual model is elaborated, next step is to develop the mathematical models that will be implemented in solver software. As mentioned in Chapter 1, there are several scenarios handled in the scope of this study. These scenarios handle different aspects of HWMS and possible alternatives in terms of management approach. In this chapter, the mathematical models and software used for obtaining the solutions are introduced.

5.1 Problem definition and conceptual model

Before elaborating the problem definition and presenting conceptual model, boundaries of the system covered should be decided. Components of HWMS that are introduced in Chapter 2 are considered in this study.

Processing of hazardous wastes includes handling of both ***hazardous wastes*** and ***hazardous residues*** that originate from processing of these wastes. Moreover, as processing component; recovery, CPT, incineration and landfilling, different types of facilities that undertake these different types of processes is covered.

Conceptual model of HWMS displays the relationships among them. As Scenario 1 given in Chapter 1 is selected as the base scenario, the conceptual model is developed for this scenario (Figure 5.1) and the model development based on this scenario is described below.

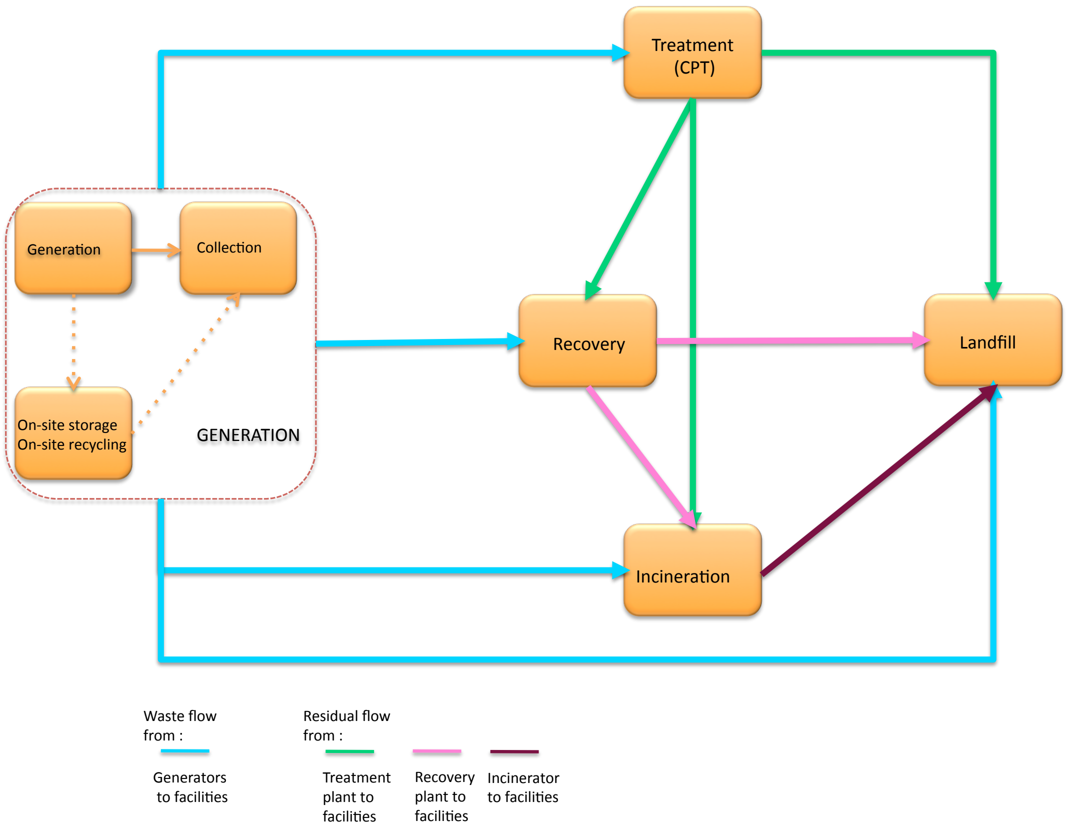


Figure 5.1 Conceptual model for Scenario 1

According to the conceptual model developed for Scenario 1, different types of hazardous wastes are collected at designated places at the point of origin. It is possible that some portion of these wastes is recycled in-situ without reaching the collection points and entering the HWMS. This is in accordance with waste hierarchy concept. Wastes are assumed to enter HWMS as they reach collection points at generators' premises. Hazardous wastes are picked up from collection points at the origin of generation by hazardous waste carriers periodically or on demand. These wastes are transported to either recovery, treatment, incineration and landfilling according to their types. The waste classification which is introduced in forthcoming sections depends on this concept.

The aims of processes applied on hazardous wastes can be to separate the portions of hazardous wastes that might be reclaimed (recovery), to render it non-hazardous (chemical) or to reduce its mass or volume such as dewatering (physical treatment), obtain energy and achieve mass and volume reduction at the same time (incineration) or to store it for long periods of time under engineered conditions (landfilling). Ideally, establishment of integrated facilities are preferred [90]. Especially incineration and landfilling facilities should be integrated since almost always hazardous waste incineration ash is also classified as hazardous and should be sent to a hazardous waste landfill.

On the other hand, recovery facilities are distributed around Turkey with lower capacities when compared to an incineration plant or a landfill (Table 2.2). Moreover, these recovery plants cannot process all types of recoverable hazardous wastes; rather the concentrate on a group of waste, such as waste solvent, oils etc. The boundary of conceptual model does not include on-site recovery carried out by waste generators since the methodology used for estimation of waste generation cannot predict the amounts recovered at points of generation. For the conceptual model to reflect the current situation in Turkey, it is decided to avoid large-scale recovery facilities where all types of recoverable wastes arrive. Instead it is assumed that recovery capacity required in each province is already established. This assumption also enables the model to account for on-site recovery practices.

Whichever process is applied, hazardous and non-hazardous residues will be formed. For example, the wastes that are rendered non-hazardous or recovered portions would not continue their way through HWMS. Instead they would be disposed of as non-hazardous wastes or would be directed to suitable clients that can reuse them. Therefore, non-hazardous residues or wastes are not included in the conceptual model seen in Figure 5.1. Nevertheless, rest of residues that are hazardous cannot be left out. They must be included in the system by being send to facilities suitable to their chemical and physical properties like hazardous wastes.

Residues from treatment plants including hazardous sludges are expected to be sent to incineration or landfilling after dewatering. Residues from recovery facilities also have the potential to be sent to treatment, incineration or landfilling according to their properties. Ash originating from incinerators can only be sent to landfilling.

5.2 Scenario 1

First scenario or the base scenario involves the case that is most close to the current situation of HWMS in Turkey. Different types of hazardous wastes as defined in the previous chapter are generated from 81 provinces and they should be sent to facilities that offer suitable processes for handling of these wastes. It assumes that there are no facilities established in Turkey and aims to determine the location and capacities of facilities. The conceptual model is developed based on this scenario. A detailed discussion on conceptual model is given in previous section and can be seen in Figure 5.1 graphically.

The model developed for Scenario 1 is a multi-objective mixed integer model. The objectives are minimization of cost and impact of transportation and processing of hazardous wastes (Eqns 12& 13). The mixed integer nature of model comes from binary decision variables that will be introduced in a short while.

For minimization of transportation cost, many models in the Literature used shipment volume or amount of hazardous waste transported as a decision variable since unit transportation costs are in terms of monetary unit per amount of shipment per distance [21,23,40,43,47-49,51,52,53,54,55]. In this study, shipment volume is used as well; however, as mentioned earlier in order to reflect changes in cost and impact properly, shipment volume is converted to number of shipments by dividing the amount transported by constant payloads. When hazardous wastes arrive at facilities volume of transport becomes the amount processed. In location models, the amount processed is used as decision variable instead of amount transported [40,41,44,49,51,54,55]. When amounts arriving at facilities are summed up, the capacity requirement of facilities can be found. Therefore, the shipment volume not only determines the transportation cost but also investment cost for facilities since investment cost change with capacity.

Second set of decision variables is related to whether a facility is opened in a node or not. This is a widely used decision variable in location models [40,44,47-49,52,53,54,55]. Decision on opening a facility can be represented with a binary variable which takes the value of "1" if facility is opened and "0" if not. Presence of this variable causes the model to be a mixed integer model.

Constraints to the problem include involvement of all hazardous wastes generated in the system, flow balance for both wastes and residues, sending wastes to a node only if a facility is established there and number of facilities.

First constraint that ensures all generated wastes is included in system is a common one also used by Killmer et al. [41], Giannikos [47], Current and Ratick [53], Gottinger [39], List and Mirchandani [21] and Jennings and Scholar [43]. All types of wastes originating from generators must be sent to hazardous waste facilities with compatible technologies. This constraint is important in that all waste should be covered by hazardous waste management system meaning that all wastes should be managed properly (Eqns 14 - 20).

Also almost all models except the ones that are concerned with network design include flow balance constraint [23,49,55]. Flow balance constraints demand that total amount of hazardous residuals which is the portion remaining after processing (amount of hazardous wastes entering * mass reduction ratio) a facility should be sent to proper facilities. This constraint aims to prevent transfer stations, treatment, recovery and incineration facilities to function as landfills. This constraint is not valid for generators and landfills (Eqn 21 - 29).

Third constraint that ensures wastes are sent to a node only if there is a facility there makes use of binary variable on opening a facility (Eqn 30 - 33). Lastly, the numbers of facilities are parametrically set (Eqn 34 - 37). Models that are constructed in a way that facilities have predetermined capacities, a constraint that prevents acceptance of more amount of waste than the capacity is used [39,41,43,44,49,51-53]. In this scenario first no capacity is assigned to facilities. By this the total capacity requirement is determined from the total amount of waste sent to a node. When capacities are not set, in order to prevent the model to open every node a facility which is impossible in reality, the numbers of facilities are parametrically set. This approach is also used by Emek and Kara [40], ReVelle et al. [45] and Zografos and Samara [46]. Obviously there is technical limit to capacity above which establishment of facilities becomes infeasible. For this reason, capacities of facilities are set in the second case.

Mathematical expression for above-mentioned problem is given below.

MODEL INDICES:

N = set of provinces (generators) in Turkey,

R = set of candidate provinces for recovery facilities

T = set of candidate provinces for treatment facilities

In = set of candidate provinces for incinerators

La = set of candidate provinces for landfills

PARAMETERS:

A_i^{W1}: amount of type W1 hazardous waste generated in province (i) in tons per year

A_i^{W2}: amount of type W2 hazardous waste generated in province (i) in tons per year

A_i^{W3}: amount of type W3 hazardous waste generated in province (i) in tons per year

A_i^{W4}: amount of type W4 hazardous waste generated in province (i) in tons per year

A_i^{W5}: amount of type W5 hazardous waste generated in province (i) in tons per year

A_i^{W6}: amount of type W6 hazardous waste generated in province (i) in tons per year

A_i^{W7}: amount of type W7 hazardous waste generated in province (i) in tons per year

PL = payload = 12.5 ton/trip

D_{ij}= distance between O-D pairs

C_{ij} = cost of transportation= D_{ij} * 0.51 TL/km

C_{Fj} = recoveryfacility cost = investment cost + operational cost in T/ton/yr

C_{Fk} = treatment facility cost = investment cost + operational cost in T/ton/yr

C_{Fl} = incineration facility cost = investment cost + operational cost in T/ton/yr

C_{Fm} = landfill facility cost = investment cost + operational cost in T/ton/yr

M_{11}= ratio of mass remaining for type W1 in recovery facility (ton/ton) = 0.25

M_{12} = ratio of mass remaining for type W1 in incineration facility (ton/ton) = 0.35

M_{21}= ratio of mass remaining for type W2 in recovery facility (ton/ton) = 0.25

M_{31}= ratio of mass remaining for type W3 in treatment facility (ton/ton) = 0.40

M_{32}= ratio of mass remaining for type W3 in recovery facility (ton/ton) = 0.30

M_{41}= ratio of mass remaining for type W4 in treatment facility (ton/ton) = 0.40

M_{42}= ratio of mass remaining for type W4 in incineration facility (ton/ton) = 0.35

M_{51}= ratio of mass remaining for type W5 in treatment facility (ton/ton) = 0.40

M_{61}= ratio of mass remaining for type W6 in incineration facility (ton/ton) = 0.35

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

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

DECISION VARIABLES:

Generators to facilities

X_{ij}^{W1} : amount of waste of type W1 sent from generator (i) to recovery facility (j)

X_{ij}^{W2} : amount of waste of type W2 sent from generator (i) to recovery facility(j)

X_{ik}^{W3} : amount of waste of type W3 sent from generator (i) to treatment facility (k)

X_{ik}^{W4} : amount of waste of type W4 sent from generator (i) to treatment facility (k)

X_{ik}^{W5} : amount of waste of type W5 sent from generator (i) to treatment facility (k)

X_{il}^{W6} : amount of waste of type W6 sent from generator (i) to incineration facility (l)

X_{im}^{W7} : amount of waste of type W4 sent from generator (i) to landfill (m)

Recovery facilities to other facilities

Y_{jl}^{W1} : amount of residue of type W1 sent from recovery facility (j) to incinerator (l)

Y_{jm}^{W2} : amount of residue of type W2 sent from recovery facility (j) to landfill (m)

Y_{jm}^{W3} : amount of residue of type W3 sent from recovery facility (j) to landfill (m)

Treatment facilities to other facilities

W_{kj}^{W3} : amount of residue of type W3 sent from treatment facility (k) to recovery facility (j)

W_{kl}^{W4} : amount of residue of type W4 sent from treatment facility (k) to incinerator (l)

W_{km}^{W5} : amount of residue of type W3 sent from treatment facility (k) to landfill (m)

Incinerators to other facilities

Z_{lm}^{W1} : amount of residue of type W1 sent from incinerator (l) to landfill (m)

Z_{lm}^{W4} : amount of residue of type W4 sent from incinerator (l) to landfill (m)

Z_{lm}^{W6} : amount of residue of type W6 sent from incinerator (l) to landfill (m)

Binary variables

$$QR_j = \begin{Bmatrix} 1 \text{ if recovery facility on node } j \text{ is used} \\ 0 \text{ otherwise} \end{Bmatrix}$$

$$QT_k = \begin{Bmatrix} 1 \text{ if treatment plant on node } k \text{ is used} \\ 0 \text{ otherwise} \end{Bmatrix}$$

$$QI_l = \begin{Bmatrix} 1 \text{ if incinerator on node } l \text{ is used} \\ 0 \text{ otherwise} \end{Bmatrix}$$

$$QL_m = \begin{Bmatrix} 1 \text{ if landfill on node } m \text{ is used} \\ 0 \text{ otherwise} \end{Bmatrix}$$

MODEL FORMULATION:

Minimize

$$Z_1 = \sum_{i\in N}\sum_{j\in R} C_{ij} * \frac{\left(X_{ij}^{W1} + X_{ij}^{W2}\right)}{PL} + \sum_{i\in N}\sum_{k\in T} C_{ik} * \frac{\left(X_{ik}^{W3} + X_{ik}^{W4} + X_{ik}^{W5}\right)}{PL} + \sum_{i\in N}\sum_{l\in In} C_{il} * \frac{X_{il}^{W6}}{PL} +$$

$$\sum_{i\in N}\sum_{m\in La} C_{im} * \frac{X_{im}^{W7}}{PL} + \sum_{j\in R}\sum_{l\in In} C_{jl} * \frac{Y_{jl}^{W1}}{PL} + \sum_{j\in R}\sum_{m\in La} C_{jm} * \frac{\left(Y_{jm}^{W2} + Y_{jm}^{W3}\right)}{PL} + \sum_{k\in T}\sum_{j\in R} C_{kj} * \frac{W_{kj}^{W3}}{PL} +$$

$$\sum_{k\in T}\sum_{l\in In} C_{kl} * \frac{W_{kl}^{W4}}{PL} + \sum_{k\in T}\sum_{m\in La} C_{km} * \frac{W_{km}^{W5}}{PL} + \sum_{l\in In}\sum_{m\in La} C_{lm} * \frac{\left(Z_{lm}^{W1} + Z_{lm}^{W4} + Z_{lm}^{W6}\right)}{PL} +$$

$$\sum_{i\in N}\sum_{j\in R} C_{Fj} * \left(X_{ij}^{W1} + X_{ij}^{W2}\right) + \sum_{i\in N}\sum_{k\in T} C_{Fk} * \left(X_{ik}^{W3} + X_{ik}^{W4} + X_{ik}^{W5}\right) + \sum_{i\in N}\sum_{l\in In} C_{Fl} * X_{il}^{W6} +$$

$$\sum_{i\in N}\sum_{m\in La} C_{Fm} * X_{im}^{W7} + \sum_{j\in R}\sum_{l\in In} C_{Fl} * Y_{jl}^{W1} + \sum_{j\in R}\sum_{m\in La} C_{Fm} * \left(Y_{jm}^{W2} + Y_{jm}^{W3}\right) + \sum_{k\in T}\sum_{j\in R} C_{Fj} * W_{kj}^{W3} +$$

$$\sum_{k\in T}\sum_{l\in In} C_{Fl} * W_{kl}^{W4} + \sum_{k\in T}\sum_{m\in La} C_{Fm} * W_{km}^{W5} + \sum_{l\in In}\sum_{m\in La} C_{Fm} * \left(Z_{lm}^{W1} + Z_{lm}^{W4} + Z_{lm}^{W6}\right)$$

Eqn 12

$$Z_2 = \sum_{i\in N}\sum_{j\in R} \left(P_{ij} + E_{ij}\right) * \frac{\left(X_{ij}^{W1} + X_{ij}^{W2}\right)}{PL} + \sum_{i\in N}\sum_{k\in T} \left(P_{ik} + E_{ik}\right) * \frac{\left(X_{ik}^{W3} + X_{ik}^{W4} + X_{ik}^{W5}\right)}{PL} +$$

$$\sum_{i\in N}\sum_{l\in In} \left(P_{il} + E_{il}\right) * \frac{X_{il}^{W6}}{PL} + \sum_{i\in N}\sum_{m\in La} \left(P_{im} + E_{im}\right) * \frac{X_{im}^{W7}}{PL} + \sum_{j\in R}\sum_{l\in In} \left(P_{jl} + E_{jl}\right) * \frac{Y_{jl}^{W1}}{PL} +$$

$$\sum_{j\in R}\sum_{m\in La} \left(P_{jm} + E_{jm}\right) * \frac{\left(Y_{jm}^{W2} + Y_{jm}^{W3}\right)}{PL} + \sum_{k\in T}\sum_{j\in R} \left(P_{kj} + E_{kj}\right) * \frac{W_{kj}^{W3}}{PL} + \sum_{k\in T}\sum_{l\in In} \left(P_{kl} + E_{kl}\right) * \frac{W_{kl}^{W4}}{PL} +$$

$$\sum_{k\in T}\sum_{m\in La} \left(P_{km} + E_{km}\right) * \frac{W_{km}^{W5}}{PL} + \sum_{l\in In}\sum_{m\in La} \left(P_{lm} + E_{lm}\right) * \frac{\left(Z_{lm}^{W1} + Z_{lm}^{W4} + Z_{lm}^{W6}\right)}{PL}$$

Eqn 13

s.t.

$$A_i^{W1} = \sum_{j \in R} X_{ij}^{W1} \quad \forall i$$ Eqn 14

$$A_i^{W2} = \sum_{j \in R} X_{ij}^{W2} \quad \forall i$$ Eqn 15

$$A_i^{W3} = \sum_{k \in T} X_{ik}^{W3} \quad \forall i$$ Eqn 16

$$A_i^{W4} = \sum_{k \in T} X_{ik}^{W4} \quad \forall i$$ Eqn 17

$$A_i^{W5} = \sum_{k \in T} X_{ik}^{W5} \quad \forall i$$ Eqn 18

$$A_i^{W6} = \sum_{l \in In} X_{il}^{W6} \quad \forall i$$ Eqn 19

$$A_i^{W7} = \sum_{m \in La} X_{im}^{W7} \quad \forall i$$ Eqn 20

$$\sum_{i \in N} M_{11} * X_{ij}^{W1} = \sum_{l \in In} Y_{jl}^{W1} \quad \forall j$$ Eqn 21

$$\sum_{j \in R} M_{12} * Y_{jl}^{W1} = \sum_{m \in La} Z_{lm}^{W1} \quad \forall l$$ Eqn 22

$$\sum_{i \in N} M_{21} * X_{ij}^{W2} = \sum_{m \in La} Y_{jm}^{W2} \quad \forall j$$ Eqn 23

$$\sum_{i \in N} M_{31} * X_{ik}^{W3} = \sum_{j \in R} W_{kj}^{W3} \quad \forall k$$ Eqn 24

$$\sum_{k \in T} M_{32} * W_{kj}^{W3} = \sum_{m \in La} Y_{jm}^{W3} \quad \forall j$$ Eqn 25

$$\sum_{i \in N} M_{41} * X_{ik}^{W4} = \sum_{l \in In} W_{kl}^{W4} \quad \forall k$$ Eqn 26

$$\sum_{k \in T} M_{42} * W_{kl}^{W4} = \sum_{m \in La} Z_{lm}^{W4} \quad \forall l$$ Eqn 27

$$\sum_{i \in N} M_{51} * X_{ik}^{W5} = \sum_{m \in La} W_{km}^{W5} \quad \forall k$$ Eqn 28

$$\sum_{i \in N} M_{61} * X_{il}^{W6} = \sum_{m \in La} Z_{lm}^{W6} \quad \forall l$$ Eqn 29

$$X_{ij}^{W1} + X_{ij}^{W2} + W_{kj}^{W3} \leq QR_j * 1000000 \quad \forall ijk$$ Eqn 30

$$X_{ik}^{W3} + X_{ik}^{W4} + X_{ik}^{W5} \leq QT_k * 1000000 \quad \forall ik$$ Eqn 31

$$X_{il}^{W6} + Y_{jl}^{W1} + W_{kl}^{W4} \leq QI_l * 1000000 \quad \forall ijkl$$ Eqn 32

$$X_{im}^{W7} + Y_{jm}^{W2} + Y_{jm}^{W3} + W_{km}^{W5} + Z_{lm}^{W1} + Z_{lm}^{W4} + Z_{lm}^{W6} \leq QL_m * 1000000 \quad \forall ijklm$$ Eqn 33

$$\sum_{j \in R} QR_j = P_j$$ Eqn 34

$$\sum_{k \in T} QT_k = P_k$$ Eqn 35

$$\sum_{l \in In} QI_l = P_l$$ Eqn 36

$$\sum_{m \in La} QL_m = P_m$$ Eqn 37

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

$$X_{ij}^{W1}, X_{ij}^{W2}, X_{ik}^{W3}, X_{ik}^{W4}, X_{ik}^{W5}, X_{il}^{W6}, X_{im}^{W7}, Y_{jl}^{W1}, Y_{jm}^{W2}, Y_{jm}^{W2}, W_{kj}^{W3}, W_{kl}^{W4}, W_{km}^{W5},$$
$$Z_{lm}^{W1}, Z_{lm}^{W4}, Z_{lm}^{W6} \geq 0$$

5.3 Scenario 2

Second scenario involves the investigation of additional capacity demand. As opposed to the first scenario, this one considers already established facilities (designated hazardous waste facilities alone and with cement factories) in Turkey and aims to determine the locations and capacities of new facilities. Mathematical formulation of this scenario is the similar to the one presented for Scenario 1.

Constraints for existing facilities and cement kilns are added to the formulation while the total number of facilities is kept the same as decided in Scenario 1.

5.4 Scenario 3

Third scenario considers the implementation of regional hazardous waste management outline in "Technical Assistance for Environmental Heavy-Cost Investment Planning Directive-Specific Investment Plan for Council Directive on Hazardous Waste (91/689/EEC)" [2]. In this alternative, five regions are determined where hazardous waste generation is concentrated (Figure 2.2). These regions and their coverage is give below:

1. Thrace region: Edirne, Tekirdağ, Kırklareli, İstanbul (European part)
2. Marmara region: İstanbul (Anatolian part), Kocaeli, Sakarya, Düzce, Zonguldak, Bolu, Bilecik, Bursa, Balıkesir
3. Aegean region: İzmir, Manisa, Uşak, Aydın, Denizli
4. Central Anatolian region: Eskişehir, Ankara, Kırıkkale, Konya
5. Mediterranean region: Mersin, Adana, Kayseri, Kahramanmaraş, Osmaniye, Hatay, Gaziantep, Kilis

These provinces grouped under each region are determined to have high potential of hazardous waste management. The generators in provinces that are not covered under any region are not obliged to sent their wastes to a predestined one.

Mathematical formulation of Scenario 3 is identical to the base scenario. For regional solutions the set of generators and candidate provinces are set to the number of provinces in each region. For remaining provinces the constraints of the model is adjusted to reflect locations of facilities decided in regional solutions without any capacity constraints.

5.5 Scenario 4

The last scenario involves establishment of a transfer station network as well as hazardous waste facilities. Transfer stations are assumed to be constructed in a way that they involve CPT units for treatment of treatable hazardous wastes. By this way the need for separate treatment plants are satisfied. Other waste types that do not require treatment may or may not be sent to transfer stations. With the addition of transfer stations, the conceptual model becomes as shown in Figure 5.2.

In the case of Scenario 4, waste generators can send their wastes directly to facilities or may chose to use transfer stations. Treatable wastes must be sent to transfer stations first, since establishment of transfer stations eliminate the requirement for large-scale CPT facilities. The main idea behind this assumption is to compare construction of large scale treatment facilities that give nation-wide or region-wide service (Scenario 1 and Scenario 3 respectively) with more localized small capacity treatment units in transfer stations. In Scenario 4, strategy applied for treatment of hazardous wastes becomes similar to the approach followed in recovery of wastes. In previous scenarios, treatment strategy was more similar to incineration and landfilling of wastes.

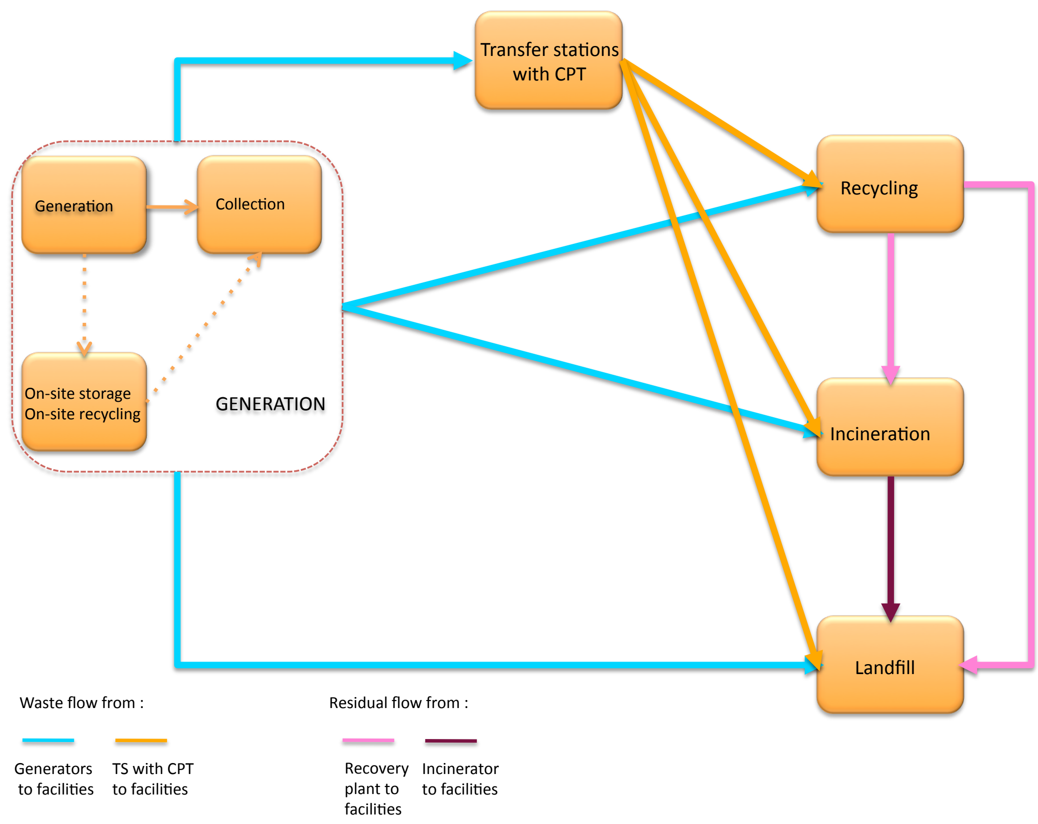


Figure 5.2 Conceptual model for Scenario 4

Except for the treatable wastes for which processing occurs, no mass reduction occurs.

Use of transfer stations are not foreseen for residue flow since it is more practical to use temporary storage areas of facilities than sent the residues to transfer stations.

As discussed in previous chapter, one of the most important outcomes of using transfer stations is the reduction in transportation cost. This reduction in cost is a result of wastes being transported in larger vehicles after the amount stored in transfer station reaches the desired amount. By this way the number of required travels decreases which in turn decreases transportation cost. Although the duration of storage is limited according to RGPWM, it is accepted that this duration is never exceeded. Moreover, the fact that treatable wastes are handled in transfer stations means these bulk wastes will not require further transport. The cost reduction is reflected in the model by use of number of trips required.

Mathematical formulation including constraints of Scenario 4 is similar to previous models. Some new variables are added to model in order to include transfer station siting decisions and can be seen below. Facility locations decided in Scenario 1,2, and 3 are included in constraints in separate solutions.

CHANGES IN MODEL INDICES:

Deleted:

T = set of candidate provinces for treatment facilities

Inserted:

TS = set of provinces in which a transfer station without CPT exist

CHANGES IN PARAMETERS:

Inserted:

$C2_{ij}$ = unit cost of of transportation where transfer stations are used

= 0.645 TL/km * D_{ij}

PL_2: payload for trucks transporting wastes from transfer stations to facilities

= 25 ton

C_{F1r} = transfer station cost – treatment units= investment cost + operational cost in T/ton/yr

C_{F2r} = transfer station cost – storage units= investment cost + operational cost in T/ton/yr

CHANGES IN DECISION VARIABLES:

Deleted:

X_{ik}^{W3} : amount of waste of type W3 sent from generator (i) to treatment facility (k)

X_{ik}^{W4} : amount of waste of type W4 sent from generator (i) to treatment facility (k)

X_{ik}^{W5} : amount of waste of type W5 sent from generator (i) to treatment facility (k)

W_{kj}^{W3} : amount of residue of type W3 sent from treatment facility (k) to recovery facility (j)

W_{kl}^{W4} : amount of residue of type W4 sent from treatment facility (k) to incinerator (l)

W_{km}^{W5} : amount of residue of type W3 sent from treatment facility (k) to landfill (m)

$$QT_k = \begin{Bmatrix} 1 \text{ if treatment plant on node k is used} \\ 0 \text{ otherwise} \end{Bmatrix}$$

Inserted:

X_{ir}^{W1} : amount of waste of type W1 sent from generator (i) to transfer station (r)

X_{ir}^{W2} : amount of waste of type W2 sent from generator (i) to transfer station (r)

X_{ir}^{W3} : amount of waste of type W3 sent from generator (i) to transfer station (r)

X_{ir}^{W4} : amount of waste of type W4 sent from generator (i) to transfer station (r)

X_{ir}^{W5} : amount of waste of type W5 sent from generator (i) to transfer station (r)

X_{ir}^{W6} : amount of waste of type W6 sent from generator (i) to transfer station (r)

X_{ir}^{W7} : amount of waste of type W7 sent from generator (i) to transfer station (r)

Q_{rj}^{W1}: amount of waste of type W1 sent from transfer station (r) to recovery facilities (j)

Q_{rj}^{W2}: amount of waste of type W2 sent from transfer station (r) to recovery facility (j)

Q_{rj}^{W3}: amount of residue of type W3 sent from transfer station (r) to recovery facility (j)

Q_{rl}^{W4}: amount of residue of type W4 sent from transfer station (r) to incinerator (l)

Q_{rm}^{W5}: amount of residue of type W5 sent from transfer station (r) to landfill (m)
Q_{rl}^{W6}: amount of waste of type W6 sent from transfer station (r) to incinerator (l)
Q_{rm}^{W7}: amount of waste of type W7 sent from transfer station (r) to landfill (m)

$$QTS_r = \begin{Bmatrix} 1 \textit{ if transfer station on node r is used} \\ 0 \textit{ otherwise} \end{Bmatrix}$$

MODEL FORMULATION:

Minimize

$$\begin{aligned} Z_1 = & \sum_{i\in N}\sum_{j\in R} C1_{ij} * \frac{\left(X_{ij}^{W1} + X_{ij}^{W2}\right)}{PL_1} + \sum_{i\in N}\sum_{l\in In} C1_{il} * \frac{X_{il}^{W6}}{PL_1} + \sum_{i\in N}\sum_{m\in La} C1_{im} * \frac{X_{im}^{W7}}{PL_1} + \\ & \sum_{i\in N}\sum_{r\in TS} C1_{ir} * \frac{\left(X_{ir}^{W1} + X_{ir}^{W2} + X_{ir}^{W3} + X_{ir}^{W4} + X_{ir}^{W5} + X_{ir}^{W6} + X_{ir}^{W7}\right)}{PL_1} + \\ & \sum_{r\in TS}\sum_{j\in R} C2_{rj} * \frac{\left(Q_{rj}^{W1} + Q_{rj}^{W2} + Q_{rj}^{W3}\right)}{PL_2} + \sum_{r\in TS}\sum_{l\in In} C2_{rl} * \frac{\left(Q_{rl}^{W4} + Q_{rl}^{W6}\right)}{PL_2} + \\ & \sum_{r\in TS}\sum_{l\in In} C2_{rl} * \frac{\left(Q_{rm}^{W5} + Q_{rm}^{W7}\right)}{PL_2} + \sum_{j\in R}\sum_{l\in In} C1_{jl} * \frac{Y_{jl}^{W1}}{PL_1} + \sum_{j\in R}\sum_{m\in La} C1_{jm} * \frac{\left(Y_{jm}^{W2} + Y_{jm}^{W3}\right)}{PL_1} + \\ & \sum_{l\in In}\sum_{m\in La} C1_{lm} * \frac{\left(Z_{lm}^{W1} + Z_{lm}^{W4} + Z_{lm}^{W6}\right)}{PL_1} + \sum_{i\in N}\sum_{j\in R} C_{Fj} * \left(X_{ij}^{W1} + X_{ij}^{W2}\right) + \\ & \sum_{r\in TS}\sum_{j\in R} C_{Fj} * \left(Q_{rj}^{W1} + Q_{rj}^{W2} + Q_{rj}^{W3}\right) + \sum_{i\in N}\sum_{l\in In} C_{Fl} * X_{il}^{W6} + \sum_{j\in R}\sum_{l\in In} C_{Fl} * Y_{jl}^{W1} + \\ & \sum_{r\in TS}\sum_{l\in In} C_{Fl} * \left(Q_{rl}^{W4} + Q_{rl}^{W6}\right) + \sum_{i\in N}\sum_{m\in La} C_{Fm} * X_{im}^{W7} + \sum_{j\in R}\sum_{m\in La} C_{Fm} * \left(Y_{jm}^{W2} + Y_{jm}^{W3}\right) + \\ & \sum_{l\in In}\sum_{m\in La} C_{Fm} * \left(Z_{lm}^{W1} + Z_{lm}^{W4} + Z_{lm}^{W6}\right) + \sum_{r\in TS}\sum_{m\in La} C_{Fm} * \left(Q_{rm}^{W5} + Q_{rm}^{W7}\right) + \\ & \sum_{i\in N}\sum_{r\in TS} C_{F1r} * \left(X_{ir}^{W1} + X_{ir}^{W2} + X_{ir}^{W6} + X_{ir}^{W7}\right) + \sum_{i\in N}\sum_{r\in TS} C_{F2r} * \left(X_{ir}^{W3} + X_{ir}^{W4} + X_{ir}^{W5}\right) \end{aligned}$$

Eqn 38

$$
\begin{aligned}
Z_2 = &\sum_{i\in N}\sum_{j\in R}\left(P_{ij}+E_{ij}\right)*\frac{\left(X_{ij}^{W1}+X_{ij}^{W2}\right)}{PL_1}+\sum_{i\in N}\sum_{l\in In}\left(P_{il}+E_{il}\right)*\frac{X_{il}^{W6}}{PL_1}+\\
&\sum_{i\in N}\sum_{m\in La}\left(P_{im}+E_{im}\right)*\frac{X_{im}^{W7}}{PL_1}+\\
&\sum_{i\in N}\sum_{r\in TS}\left(P_{ir}+E_{ir}\right)*\frac{\left(X_{ir}^{W1}+X_{ir}^{W2}+X_{ir}^{W3}+X_{ir}^{W4}+X_{ir}^{W5}+X_{ir}^{W6}X_{ir}^{W7}\right)}{PL_1}+\\
&\sum_{r\in TS}\sum_{j\in R}\left(P_{rj}+E_{rj}\right)*\frac{\left(Q_{rj}^{W1}+Q_{rj}^{W2}+Q_{rj}^{W3}\right)}{PL_2}+\sum_{r\in TS}\sum_{l\in In}\left(P_{rl}+E_{rl}\right)*\frac{\left(Q_{rl}^{W4}+Q_{rl}^{W6}\right)}{PL_2}+\\
&\sum_{r\in TS}\sum_{m\in La}\left(P_{rm}+E_{rm}\right)*\frac{\left(Q_{rm}^{W5}+Q_{rm}^{W7}\right)}{PL_2}+\sum_{j\in R}\sum_{l\in In}\left(P_{jl}+E_{jl}\right)*\frac{Y_{jl}^{W1}}{PL_1}+\\
&\sum_{j\in R}\sum_{m\in La}\left(P_{jm}+E_{jm}\right)*\frac{\left(Y_{jm}^{W2}+Y_{jm}^{W3}\right)}{PL_1}+\sum_{l\in In}\sum_{m\in La}\left(P_{lm}+E_{lm}\right)*\frac{\left(Z_{lm}^{W1}+Z_{lm}^{W4}+Z_{lm}^{W6}\right)}{PL_1}
\end{aligned}
$$

Eqn 39

s.t.

$$A_i^{W1} = \sum_{j\in R} X_{ij}^{W1} + \sum_{r\in TS} X_{ir}^{W1} \qquad \forall i$$ **Eqn 40**

$$A_i^{W2} = \sum_{j\in R} X_{ij}^{W2} + \sum_{r\in TS} X_{ir}^{W2} \qquad \forall i$$ **Eqn 41**

$$A_i^{W3} = \sum_{r\in TS} X_{ir}^{W3} \qquad \forall i$$ **Eqn 42**

$$A_i^{W4} = \sum_{r\in TS} X_{ir}^{W4} \qquad \forall i$$ **Eqn 43**

$$A_i^{W5} = \sum_{r\in TS} X_{ir}^{W5} \qquad \forall i$$ **Eqn 44**

$$A_i^{W6} = \sum_{l\in In} X_{il}^{W6} + \sum_{r\in TS} X_{ir}^{W6} \qquad \forall i$$ **Eqn 45**

$$A_i^{W7} = \sum_{m\in La} X_{im}^{W7} + \sum_{r\in TS} X_{ir}^{W7} \qquad \forall i$$ **Eqn 46**

$$\sum_{i\in N} M_{11} * X_{ij}^{W1} + \sum_{r\in TS} M_{11} * Q_{rj}^{W1} = \sum_{l\in In} Y_{jl}^{W1} \quad \forall j$$ **Eqn 47**

$$\sum_{j\in R} M_{12} * Y_{jl}^{W1} = \sum_{m\in La} Z_{lm}^{W1} \quad \forall l$$ **Eqn 48**

$$\sum_{i\in N} X_{ir}^{W1} = \sum_{j\in R} Q_{rj}^{W1} \quad \forall r$$ **Eqn 49**

$$\sum_{i\in N} M_{21} * X_{ij}^{W2} + \sum_{r\in TS} M_{21} * Q_{rj}^{W2} = \sum_{m\in La} Y_{jm}^{W2} \quad \forall j$$ **Eqn 50**

$$\sum_{i\in N} X_{ir}^{W2} = \sum_{j\in R} Q_{rj}^{W2} \quad \forall r$$ **Eqn 51**

$$\sum_{i\in N} M_{31} * X_{ir}^{W3} = \sum_{j\in R} Q_{rj}^{W3} \quad \forall r$$ **Eqn 52**

$$\sum_{r\in TS} M_{32} * Q_{rj}^{W3} = \sum_{m\in La} Y_{jm}^{W3} \quad \forall j$$ **Eqn 53**

$$\sum_{i\in N} M_{41} * X_{ir}^{W4} = \sum_{l\in In} Q_{rl}^{W4} \quad \forall r$$ **Eqn 54**

$$\sum_{r\in TS} M_{42} * Q_{rl}^{W4} = \sum_{m\in La} Z_{lm}^{W4} \quad \forall l$$ **Eqn 55**

$$\sum_{i\in N} M_{51} * X_{ir}^{W5} = \sum_{m\in La} Q_{rm}^{W5} \quad \forall r$$ **Eqn 56**

$$\sum_{i\in N} M_{61} * X_{il}^{W6} + \sum_{r\in TS} M_{61} * Q_{rl}^{W6} = \sum_{m\in La} Z_{lm}^{W6} \quad \forall l$$ **Eqn 57**

$$\sum_{i\in N} X_{ir}^{W6} = \sum_{l\in In} Q_{rl}^{W6} \quad \forall r$$ **Eqn 58**

$$\sum_{i\in N} X_{ir}^{W7} = \sum_{m\in La} Q_{rj}^{W7} \quad \forall r$$ **Eqn 59**

$$X_{ij}^{W1} + X_{ij}^{W2} + Q_{rj}^{W1} + Q_{rj}^{W2} + Q_{rj}^{W3} \leq QR_j * 1000000 \quad \forall ijr$$ **Eqn 60**

$$X_{il}^{W6} + Y_{jl}^{W1} + Q_{rl}^{W4} + Q_{rl}^{W6} \leq QI_l * 1000000 \quad \forall ijrl$$ **Eqn 61**

$$X_{im}^{W7} + Y_{jm}^{W2} + Y_{jm}^{W3} + Z_{lm}^{W1} + Z_{lm}^{W4} + Z_{lm}^{W6} + Q_{rm}^{W5} + Q_{rm}^{W7} \leq QL_m * 1000000 \quad \forall ijlm$$

Eqn 62

$$X_{ir}^{W1} + X_{ir}^{W2} + X_{ir}^{W3} + X_{ir}^{W4} + X_{ir}^{W5} + X_{ir}^{W6} + X_{ir}^{W7} \leq QTS_r * 1000000 \quad \forall ir$$

Eqn 63

$$\sum_{j \in R} QR_j = P_j$$

Eqn 64

$$\sum_{l \in In} QI_l = P_l$$

Eqn 65

$$\sum_{m \in La} QL_m = P_m$$

Eqn 66

$$\sum_{r \in TS} QTS_r = P_r$$

Eqn 67

$$QR_{j,} QI_l, QL_m, QTS_r \in \{1,0\}$$

$$X_{ij}^{W1}, X_{ij}^{W2}, X_{il}^{W6}, X_{im}^{W7}, X_{ir}^{W1}, X_{ir}^{W2}, X_{ir}^{W3}, X_{ir}^{W4}, X_{ir}^{W5}, X_{ir}^{W6}, X_{ir}^{W7}, Y_{jl}^{W1},$$

$$Y_{jm}^{W2}, Y_{jm}^{W2}, Z_{lm}^{W1}, Z_{lm}^{W4}, Z_{lm}^{W6}, Q_{rj}^{W1}, Q_{rj}^{W2}, Q_{rj}^{W3}, Q_{rl}^{W4}, Q_{rl}^{W5}, Q_{rl}^{W6}, Q_{rm}^{W7}, \geq 0$$

CHAPTER 6

RESULTS AND DISCUSSION

6.1 Results

Properties of hardware used for this study includes Intel (R) Core ^{TM} 2 Quad CPU Q 8400 Processor @ 2.66 GHz with 1.97 GHz 3.25 GB RAM. For solution of model IBM OPL 6.3 Development Studio is used.

Computational times vary according to the characteristics of models solved. Duration of Scenario 1 solutions varied between 4 minutes to a little over 4 hours for single objective models. It is observed that as facility numbers increased the solutions times decrease up to4 minutes. Regional models are solved in less than a minute. Due to the fact that additional constraint is added in Pareto solutions, durations of runs increase as much as 16 hours. Addition of transfer stations in Scenario 4 increases both decision variables, which results in longer solution times.

6.1.1 Scenario 1

In this scenario, initially the aim was to set candidate final disposal sites to 78 provinces that are all generators in Anatolia. The iterations occurring during solution procedure involve evaluation of wastes originating from a generator to a certain type of facility that can be established in any of 78 provinces. Given that there are four facility types that are defined conceptually, the number of possibilities rises to 78^5 and consequently the complexity of problem increases significantly. Unfortunately, OPL software were not able to handle this complexity and solutions were interrupted due to out of memory status. Performance of the software is increased with several adjustments. However; they were not enough to obtain solutions for 78 candidate province case.

For this reason, the problem at hand had to be downsized. The number of generators is held at 78 so that all generators are covered but number of candidate sites is decreased. It is presumed that unless high waste generation occurs, facilities would be sited in more central locations rather than provinces at the sides of the country. By this reasoning, 19 provinces shown on Figure 6.1 with colored filling are eliminated from the candidate province set in Anatolia. Edirne, Kırklareli and Tekirdağ are eliminated as a result of assumption made on banning hazardous waste transportation across Bosphorus. It should be reminded that regional solution for Thrace covering abovementioned three provinces is obtained separately and cost associated with regional management of Thrace is added to costs determined for other scenarios.

Figure 6.1 Provinces eliminated from the candidate location set

As outlined in Chapter 4, several alternatives are investigated in order to obtain a solution for Scenario 1. First of all, capacity assignment is addressed by comparing the results of the two cases where;

1. no upper limit is specified for the capacities of treatment/incineration/landfilling facilities, and
2. capacities, calculated from total waste generation and number of facilities, are assigned as upper limits (Eqn 30 – 33).

Separate solutions are obtained for minimum cost and minimum impact cases for 5, 10 and 15 treatment/incineration/landfilling facilities. Since the total amount of waste generated does not change, capacities assigned to facilities will vary according to the total number of facilities (Table 6.1 and Table6.2).

When no capacity is assigned to facilities the minimum total cost varies between 411 – 511 million TL/yr (Table 6.1). The total cost is 411 million TL/yr for the case of 5 integrated facilities and it increased to 465 million for 10 facilities and to 551 million TL for 15 facilities. These numbers are 411, 463 and 523 million TL/yr for the capacity assignment case, for 5, 10 and 15 facilities respectively (Table 6.2). As can be seen from these tables, Table 6.1 and Table 6.2, incineration and recovery operations comprise a large portion of the total cost in both situations.

It should be reminded that all the costs presented in Table 6.2 are yearly costs. Moreover, although these values are termed as total or overall cost throughout this chapter, true overall cost can only be calculated after the regional hazardous waste management cost for the Thrace region is calculated.

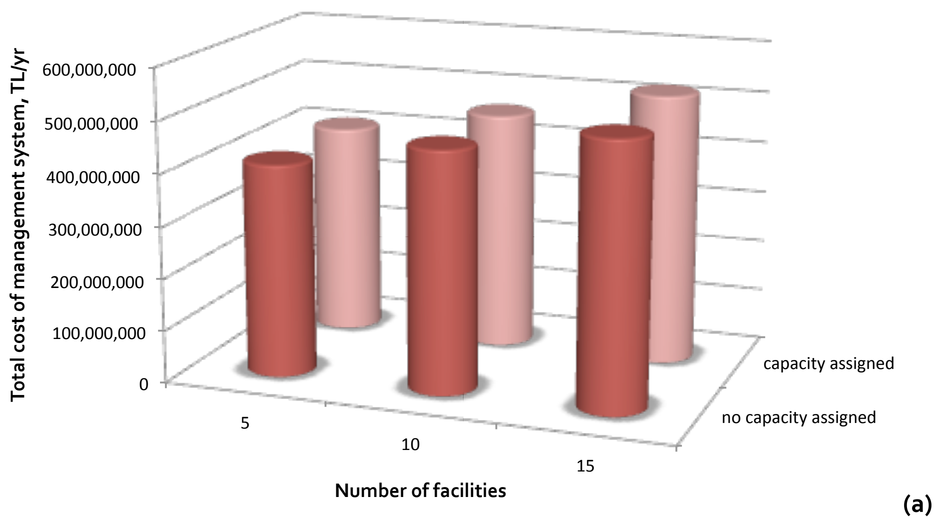
Table 6.1Solution for no capacity assignment case

Conditions						
Number of generators	78			78		
Number of candidate sites	59			59		
Number of recovery fclt	78			78		
Number of treatment plnt	5	10	15	5	10	15
Number of incinerators	5	10	15	5	10	15
Number of landfill	5	10	15	5	10	15
Objective:	**minimize cost**			**minimize impact**		
Solution						
Population impact	3297	803	386	1631	405	203
Environmental impact	2982	1704	954	2733	1482	932
Facility cost, TL/yr						
Recovery – investment	46,724,477	47,199,333	46,744,658	47,955,482	48,044,468	46,027,157
Recovery – operational	95,756,137	96,705,849	95,839,080	98,218,148	98,438,702	94,404,079
Treatment - investment	7,180,455	8,260,500	9,735,765	7,037,682	8,748,272	9,735,765
Treatment - operational	14,360,910	16,521,100	19,471,530	14,075,364	16,235,913	19,471,530
Incinerator - investment	101,350,753	108,994,695	124,924,373	96,676,475	108,554,666	124,782,880
Incinerator - operational	131,099,205	174,391,512	199,878,996	154,682,360	173,687,466	189,244,827
Landfill – investment	7,441,750	8,443,488	10,255,740	7,673,182	8,877,659	9,796,142
Landfill – operational	1,860,438	2,110,872	2,563,935	1,918,295	2,219,415	2,449,035
Transportation cost, TL/yr	5,063,301	2,711,198	1,631,447	6,885,495	3,613,389	2,009,926
TOTAL COST, TL/yr	**411,017,426**	**465,338,447**	**511,045,524**	**435, 122,483**	**468,419,949**	**497,921,342**
TOTAL IMPACT	**6279**	**2507**	**1340**	**4364**	**1886**	**1135**

Table 6.2 Solution for capacity assignment case

Conditions						
Number of generators, candidate sites, facilities	Same as Table 6.1					
Capacity						
Recovery facilities	50,000	25,000	25,000	50,000	25,000	25,000
Treatment plants	not assigned	not assigned	not assigned	not assigned	not assigned	not assigned
Incinerators	130,000	65,000	32,500	130,000	65,000	32,500
Landfills	127,000	130,000	31,500	127,000	130,000	31,500
Objective:	**minimize cost**			**minimize impact**		
Solution						
Population impact	2718	1182	1148	1861	539	818
Environmental impact	3000	1945	1647	2916	1985	1459
Facility cost, TL/yr						
Recovery – investment	46,990,071	47,477,909	50,777,520	47,081,225	47,606,911	50,287,604
Recovery – operational	96,287,326	97,246,654	103,881,540	96,469,633	97,563,587	102,901,709
Treatment – investment	7,636,646	9,011,265	9,272,835	7,400,372	8,844,857	9,735,765
Treatment – operational	12,273,291	18,022,530	17,777,253	14,800,743	16,552,383	19,471,530
Incinerator – investment	101,968,265	105,934,850	125,096,416	101,266,530	104,637,211	124,604,257
Incinerator – operational	128,322,224	169,495,760	200,154,266	162,026,448	167,419,537	199,366,811
Landfill – investment	7,255,962	9,022,553	10,698,522	7,264,374	8,690,932	10,271,508
Landfill – operational	1,813,991	2,255,638	2,674,630	1,816,093	2,240,233	5,244,809
Transportation cost, TL/yr	5,551,855	3,247,274	2,858,354	6,416,1126	4,042,405	3,382,922
TOTAL COST TL/yr)	**411,099,631**	**461,684,432**	**523,191,337**	**444,541,543**	**457,868,055**	**525,266,916**
TOTAL IMPACT	**5718**	**3127**	**2795**	**4777**	**2524**	**2277**

Comparison of the results for the capacity assignment and no capacity assignment cases reveals that capacity assignment improves neither the cost nor the impact (Figure 6.2). On the contrary, as the number of facilities increased, the minimum cost and the environmental impact of the system worsens with respect to capacity assignment due to increased costs of smaller sized facilities. For this reason, it is decided against assigning capacities to facilities.



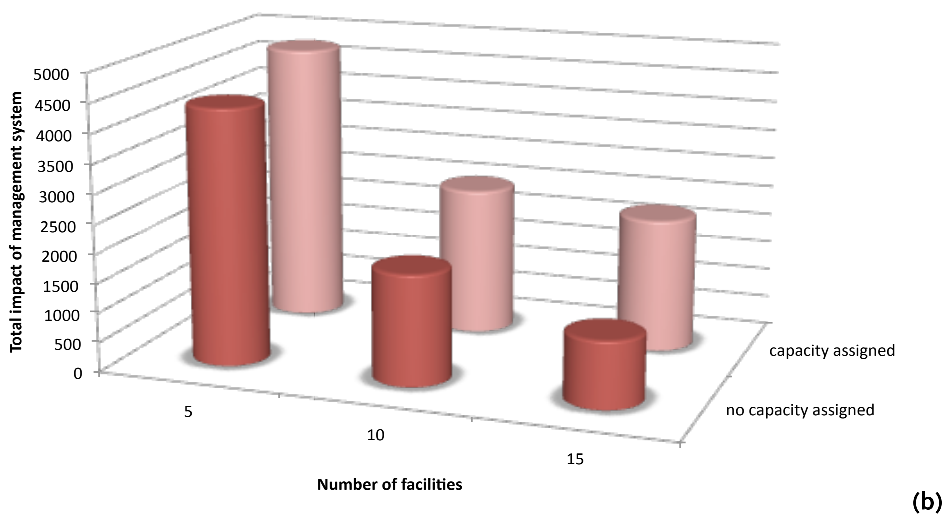


Figure 6.2 Effect of capacity assignment on cost (a) and impact (b)

When total costs for minimum cost and minimum impact cases are inspected. It can be seen that total cost of minimum impact case is smaller than total cost of minimum cost case. It is worth reminding that mathematical formulation optimized includes only transportation cost. Transportation cost of minimum impact case is higher than transportation cost of minimum cost case for same number of facilities. However, due to varying allocations of wastes in different solutions, the facility capacities change and when corresponding unit investment and operational costs are used, results in which total cost of minimum impact case is smaller than total cost of minimum cost situation.

In the next step, solutions are sought for different values in order to decide on numbers of facilities. Trials are conducted for 5, 7, 10, 12 and 15 treatment/incineration/landfilling facilities. Recovery facilities are assumed to be present in each province so the number of recovery facilities is equal to the number of generators. Results for minimum cost and minimum impact runs for the above-mentioned facility numbers are given in Table 6.3.

As can be depicted from Table 6.3, as the number of facilities increases, there is an increase in overall cost and decrease in transportation cost and total impact. The decrease in transportation cost and total impact is related to the reduction in transportation distances due to facilities being distributed throughout the country as their number increases. If only these two aspects were to be considered, high number of facilities would be favored. However, due to economy of scale principle; as the number of facilities increases, capacities are reduced and in turn unit investment and operational costs increase. For this reason total cost should be considered while making a decision on facility numbers.

Table 6.3 Results on cost and risk with changing facility numbers

Number of facilities	Transport cost/ Total cost, TL/year	Impact	% increase in minimum cost	% decrease in maximum impact
MINIMUM COST				
5	5,063,301 411,017,426	6279	0	0
7	3,759,752 442,353,823	4106	7	35
10	2,711,198 465,338,447	2507	12	60
12	2,201,026 482,629,925	1877	15	70
15	1,631,447 511,045,524	1340	20	78
MINIMUM IMPACT				
5	6,885,495 435,122,483	4364	0	0
7	5,027,022 444,701,238	3043	2	30
10	3,613,389 468,419,949	1886	8	57
12	3,011,607 488,442,237	1530	12	65
15	2,009,926 497,921,342	1135	14	74

As a result of the trade-off between impact and total cost which is apparent from the percentage increase and decrease in cost and impact respectively (Table 6.3), neither the minimum cost nor the minimum impact case can be selected. Therefore, the best number of facilities should be somewhere in the middle. As the cost objective worsens there is an improvement in the impact value. Initial rapid improvement slows down towards the minimum cost solution. In both minimum cost and minimum impact solutions the point which corresponds to ten facilities seems to be the breaking point for this slow down. Due to this reasoning, in further solutions the number of treatment/incineration and landfilling facilities are set to ten.

For the solution with ten facilities, the minimization of cost and impact does not yield to identical solutions which lead to Pareto analysis should be obtained. Following ε- constraint method, impact objective is shifted to constraints. Besides minimum cost and impact solutions, additional nine solutions are obtained by assigning values to impact constraint which changes by 10% increments of the difference between minimum and maximum impact values (or maximum and minimum cost solutions). These solutions are presented in Table 6.4 and Figure 6.3. The values tabulated in Table 6.4 show that up to a certain point, solutions close to minimum cost occur with some level of reduction in impact. The solutions close to minimum cost case suggest that initial impact reduction is achieved by changing waste amounts sent to facilities. These solutions do not vary in terms of facility locations meaning that locations are the same with previous solution but waste amounts are changed in order to provide a reduction in cost. As the values assigned to right hand side of impact constraint gets smaller, it becomes impossible for the model to decrease impact value further without changing facility locations. At some point the facility locations selected by the model starts to change and at that point the increase in cost in consecutive solutions starts to get larger. Beyond this point, decreasing impact causes larger increases in cost. The point colored red in Table 6.4 17.5% reduction is achieved with only 2% increase in cost. In further solutions, decrease in impact continues to occur but there is a steep increase in cost. Consequently, the orange point on Figure 6.3 is selected as the proposed solution for Scenario 1.

It is worth mentioning that in all Scenarios, location selected in adjacent solutions does not change significantly. Either one or two locations change or the amount allocated to facilities change. Of course, as these small changes add up as we move from minimum cost to minimum impact solutions more significant differences arise.

Table 6.4 Data points of Pareto optimal curve for Scenario 1 solution

Impact	Transport Cost (Tl/yr)	% decrease in impact	% increase in cost
2507	2,711,198		
2407	2,712,513	4.15	0.05
2383	2,714,703	5.20	0.13
2320	2,721,086	8.06	0.36
2259	2,730,391	10.98	0.70
2196	2,746,025	14.16	1.27
2134	2,767,410	17.48	2.03
2072	2,909,500	20.99	6.83
2009	3,208,953	24.79	15.51
1948	3,312,103	28.70	18.14
1886	3,613,389	32.93	24.97

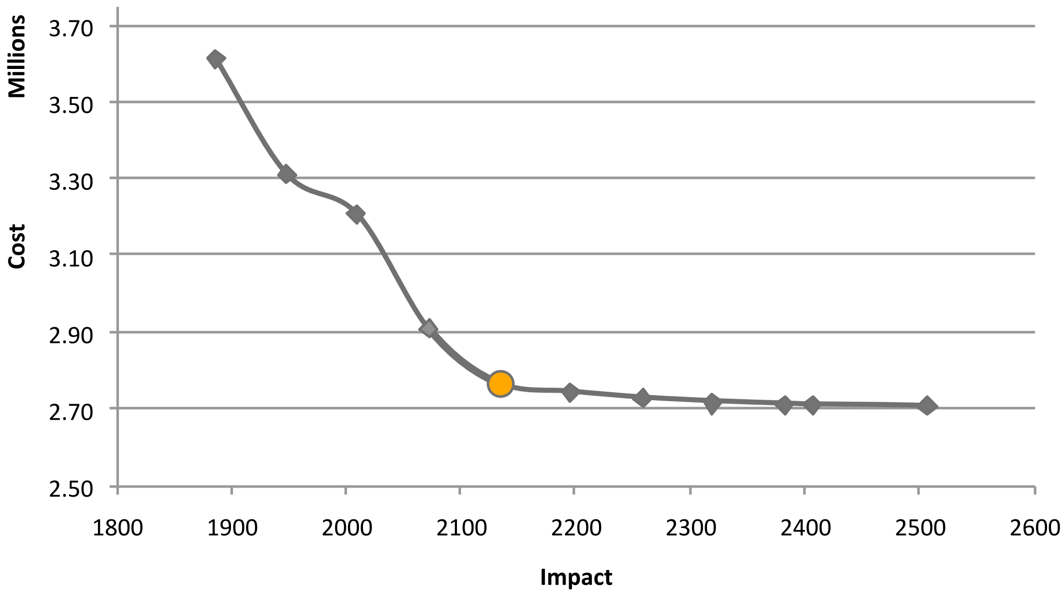


Figure 6.3 Pareto optimal curve for Scenario 1

Detailed results on proposed solution are given in Table 6.5. In terms of cost, major component is facility cost when compared to transportation cost. Among the facilities; highest cost belongs to incineration both due to unit costs of incineration being higher than other facilities and amount of combustible wastes being highest. This situation suggests that incineration investments demand special attention when planning hazardous waste management system. Moreover, it underlines the importance of investigating contribution of cement kilns in Scenario 2.

Table 6.5 Detailed information on the proposed solution of Scenario 1

Conditions	
Number of generators	78
Number of candidate sites	59
Number of recovery facilities	78
Number of treatment plants	10
Number of incinerators	10
Number of landfills	10
Solution	
Population impact	597
Environmental impact	1,537
Facility cost (TL/yr)	
Recovery – investment	46,649,692
Recovery – operational	95,647,149
Treatment - investment	8,863,665
Treatment - operational	17,727,330
Incinerator - investment	109,238,540
Incinerator - operational	174,781,665
Landfill – investment	8,973,882
Landfill – operational	2,243,470
Transportation cost, TL/yr	2,767,628
TOTAL COST, TL/yr	**466,892,023**
TOTAL IMPACT	**2134**

Next highest contributor to the overall system cost is recovery facilities. Although unit costs of recovery facilities is not as high as incinerators, establishment of recovery facilities in every province causes capacities to be small thus investment and operational costs to be high. It can be expected that if integrated recovery facilities could be established, share of recovery in overall cost would be much smaller. Recovery is followed by treatment and landfill respectively. Smallest contribution comes from transportation of wastes.

The locations for facilities associated with selected solution are shown on Figure 6.4 along with minimum cost and impact cases. As it can be seen on Figure 6.4, although two solutions share some of the facility locations, locations in minimum cost and impact cases do not exactly match. Locations suggested in selected Pareto optimal solution is a combination of minimum cost and minimum impact solutions.

Additional inquiries were made for Scenario 1 by including mining wastes and considering population and environmental impacts separately. Table 6.6 presents the minimum cost and the minimum impact solutions for the cases in which mining wastes are included and excluded.

When mining wastes are assumed to be included in the system, the cost of the system is between 480 – 523 million TL/yr. Exclusion of mining wastes causes a decrease in cost. Minimum cost decreases to 465 million TL/yr from 480 million TL/yr and maximum cost is reduced to 468.5 million TL/yr from 523 million TL/yr. These cost reductions correspond to 3% and 10.4% for minimum cost and minimum impact cases respectively. In fact the difference between two cases presents the cost of managing hazardous mining wastes which is 3% at minimum and can go up to 10.4%. Exclusion of mining wastes also causes a reduction in overall impact of the system as expected. Percent decrease in impact for minimum impact and maximum impact cases are 20% and 30% based on total impact values presented in bottom row of Table 6.6.

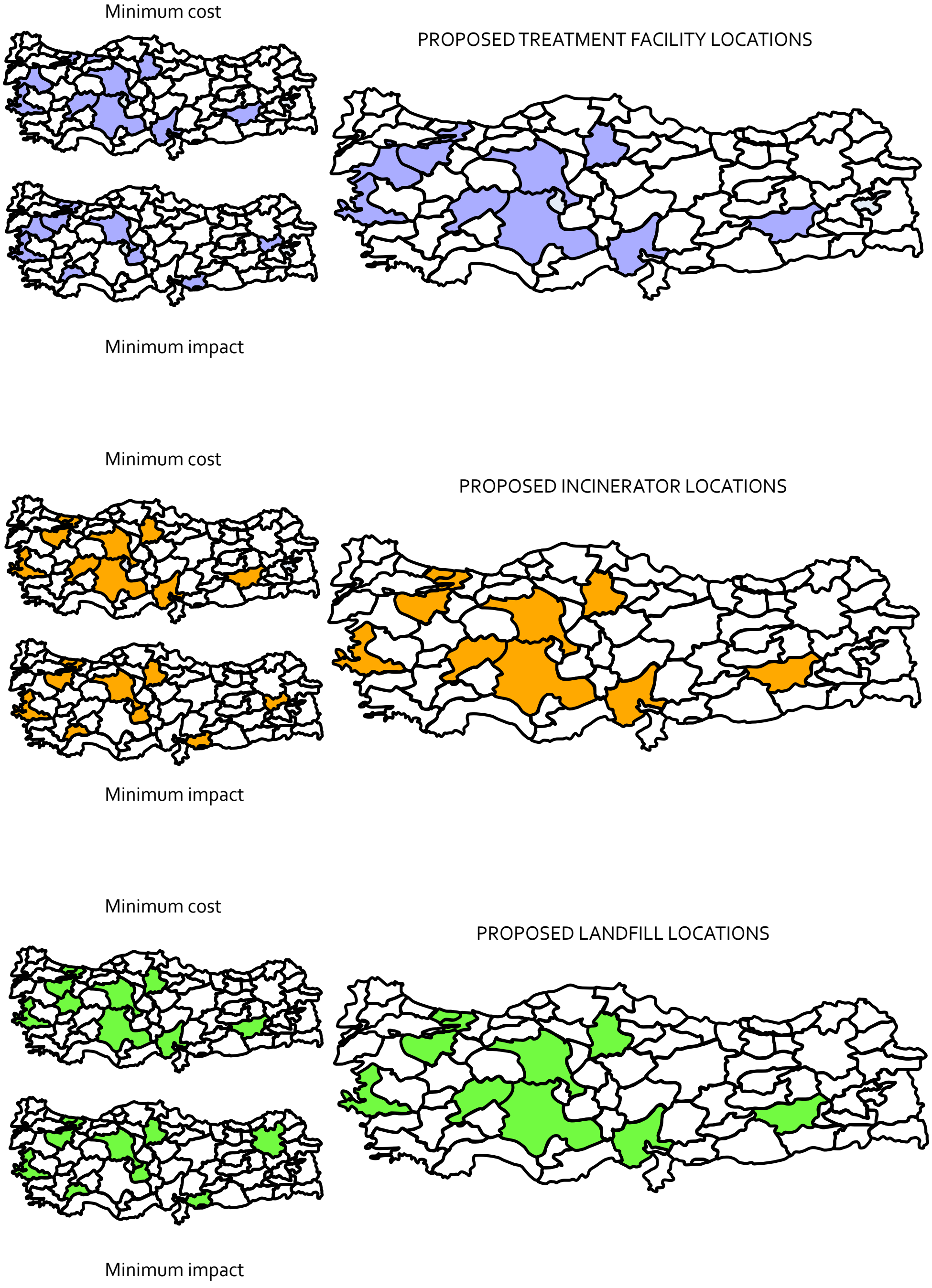


Figure 6.4 Facility locations for minimum cost, minimum impact and proposed solution

Table 6.6 Effect on mining wastes on cost and impact of HWMS

	Mining wastes included		Mining wastes excluded	
Conditions				
Number of generators	78			
Number of candidate sites	59			
Number of recovery fclt	78			
Number of treatment plnt	10			
Number of incinerators	10			
Number of landfills	10			
Solution	**Cost**	**Impact**	**Cost**	**Impact**
Population impact	1422	501	803	405
Environmental impact	2115	1853	1704	1482
Facility cost (TL/yr)				
Recovery - investment	46,708,059	46,710,966	47,199,333	48,044,468
Recovery - operational	95,723,302	95,729,116	96,705,849	98,438,702
Treatment - investment	10,937,862	26,651,108	8,260,500	8,748,272
Treatment - operational	49,728,440	53,302,215	16,521,100	16,235,913
Incinerator - investment	99,889,626	109,575,801	108,994,695	108,554,666
Incinerator - operational	161,850,281	175,321,281	174,391,512	173,687,466
Landfill - investment	8,875,709	8,917,389	8,443,488	8,877,659
Landfill - operational	2,281,927	2,229,347	2,110,872	2,219,415
Transportation cost (TL/yr)	3,391,970	4,621,188	2,711,198	3,613,389
TOTAL COST (TL/yr)	**479,324,175**	**523,058,410**	**465,338,447**	**468,419,949**
TOTAL IMPACT	**3537**	**2353**	**2507**	**1886**

Another point investigated is effect of population and environmental impact on the system. Normalization was performed on both impact items, which enables us to add them and makes comparison with each other possible. The results presented up to now in Table 6.1,

Table 6.2, Table 6.5 and Table 6.6 shows that environmental impact is higher than population impact. This situation is also valid in further scenarios. This situation underlines the importance of including environmental impact into consideration.

Figure 6.5 displays the effect of minimum population impact and minimum environmental impact solutions on facility locations. Minimum impact solution for Scenario 1 is also included to be able to observe the behavior of model when two are considered together. The first column of three shows locations of facilities when environmental impact is at minimum. Later two shows minimum population impact and minimum total impact respectively. When population impact is at its minimum facilities are more dispersed throughout the country compared to minimum environmental impact situation. While achieving minimum total impact, facility locations are set so that both minimum environmental and population impact selections are reflected. However, it is clear from Figure 6.5 that facility locations of minimum total impact case are more similar to minimum environmental impact. This tendency is expected considering higher contribution of environmental impact.

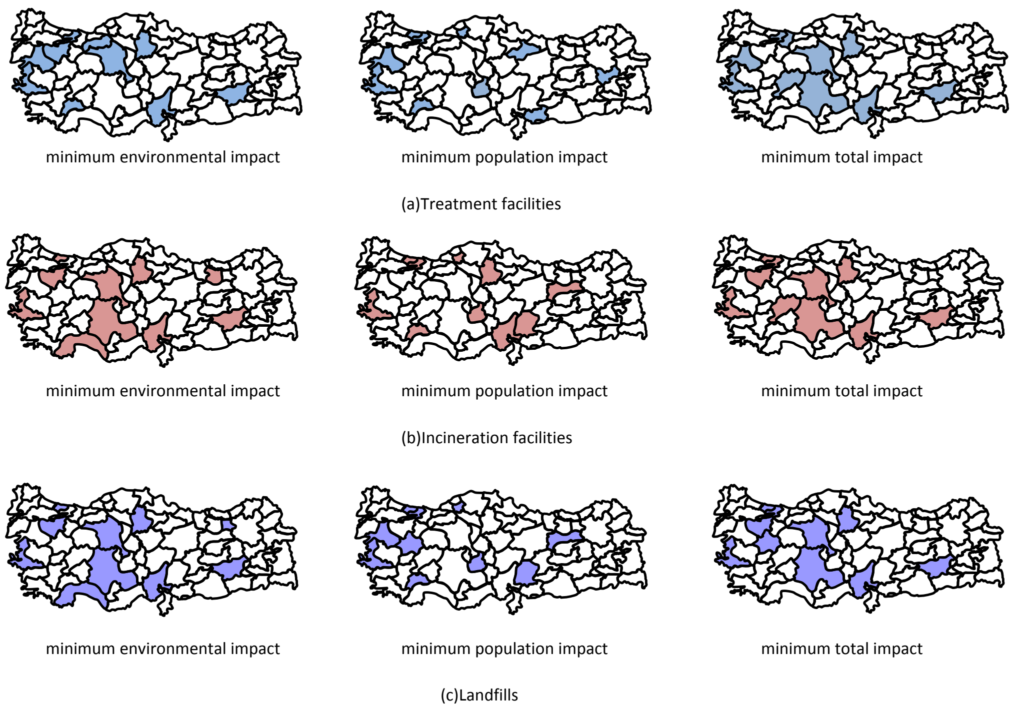


Figure 6.5 Locations of facilities in minimum environmental, population and total impact cases

6.1.2 Scenario 2

In the second scenario, existing facilities in Turkey are included in the model to investigate their effect on locating new facilities. Information on existing facilities is already presented in Table 2.3. Two alternatives are considered under this scenario. In the first alternative, only the facilities that are dedicated for hazardous waste management i.e. hazardous waste treatment plants, incinerators and landfills are defined in the model. Second alternative covers co-incineration practices carried out by cement factories in addition to hazardous waste incinerators and landfills. These existing facilities are introduced to the model by assigning the value of binary variable belonging to the province in which the facility located, to 1. Cement factories are added to the model as a new type of facility in Information on existing facilities is already presented in Table 2.3 (pg 21). Only commercially available hazardous waste facilities to waste generators are taken into account (incinerators in Kocaeli and İzmir and landfills in Kocaeli and Manisa). Capacities for cement plants are also gathered and provincial sums are obtained. The amounts actually incinerated are considered instead of amounts accepted to the plant. Provincial capacities of co-incineration are summarized in Table 6.7. Among these provinces Edirne and Kırklareli has been omitted since they are in Thrace region and cement kilns in İstanbul are all assumed to be on Anatolian side.

Results of the model runs for with and without cement factories is presented in Table 6.8.When figures are inspected it is easily observed that main difference between cost and impact values originate from incineration and landfill costs. Variation in incineration costs mainly occurs due to presence of cement kilns, which reduce the necessary capacity for hazardous waste incinerators. Presence of cement kilns in addition to hazardous waste incinerators affects distribution of hazardous wastes among landfills thus the investment and operational costs.

Table 6.7 Co-incineration capacities

Province	Capacity (tons/yr)	Province	Capacity (tons/yr)
Adana	1400	İstanbul	35000
Ankara	10800	İzmir	5000
Balıkesir	300	Kayseri	2900
Bolu	2150	Kırklareli	650
Çanakkale	11300	Kocaeli	62000
Denizli	880	Konya	13000
Edirne	4350	Samsun	650
Eskişehir	50	Siirt	1230
Gaziantep	430	Yozgat	600
Mersin	1420	**TOTAL**	**154100**

Table 6.8 Scenario 2 results

Minimize:	**With co-incineration**		**Without co-incineration**	
Number of generators	78			
Number of candidate sites	59			
Number of recovery facilities	78			
Number of treatment plant	10			
Number of incinerators	10			
Number of landfills	10			
Number of cement kilns	17		--	
Minimize	**Cost**	**Impact**	**Cost**	**Impact**
Solution				
Population impact	1083	458	1158	525
Environmental impact	1926	1597	1961	1784
Facility cost, TL/yr				
Recovery - investment	46,714,390	46,681,897	46,721,212	46,681,897
Recovery - operational	95,735,963	95,713,559	95,793,262	95,713,559
Treatment - investment	9,253,095	8,748,272	9,010,995	8,748,272
Treatment - operational	18,506,190	17,496,543	18,021,990	17,496,543
Incinerator - investment	81,549,922	81,836,580	94,918,857	98,932,368
Incinerator - operational	151,059,703	145,674,642	172,450,354	178,871,873
Landfill - investment	6,796,570	6,769,984	6,968,640	6,710,661
Landfill - operational	2,275,921	2,228,195	2,277,378	2,214,436
Transportation cost, TL/yr	2,964,152	3,927,638	3,209,661	4,366,666
TOTAL COST, TL/yr	**414,855,349**	**409,077,309**	**449,342,349**	**459,736,274**
TOTAL IMPACT	**3009**	**2055**	**3119**	**2308**

When co-incineration is applied the cost of the system is around 410 – 415 million TL/yr. If co-incineration is not applied, cost values rise up to 450 million TL/yr (minimum cost) to 460 million TL/yr (minimum impact). When minimum cost case is considered, use of co-incineration results in 7.7% decrease. This reduction is achieved in spite of the increased unit incineration facility costs originating from decreased capacity as a result of allocation of some of the wastes to cement kilns. Given that incineration facility costs are higher than unit costs associated with other facilities, promotion of co-incineration is advisable. Similar situation is also valid for the impact case. The minimum impact solutions with and without co-incineration lead to impact values of 2308 and 2055 respectively. That is to say, it is possible to achieve 11% decrease in impact if minimum impact conditions are realized. Use of cement factories causes the incineration facilities to be more distributed, decreasing the distance traveled by wastes thus improving impact values. Decrease in both total cost and impact makes use of cement kilns more preferable than the case where co-incineration is not applied.

Again Pareto optimal analysis should be applied for co-incineration alternative since minimum cost and minimum impact solutions do not give identical results. Solutions for nine points which corresponds to 10% change in difference minimum and maximum impact values are obtained. Data on these solution and Pareto optimal curve is presented in Figure 6.6.

Table 6.9 Data points of Pareto optimal curve for Scenario 2 solution

Impact	Transport Cost (Tl/yr)	% decrease in impact	% increase in cost
3009	2,964,152		
2914	2,960,231	3.26	-0.13
2818	2,966,161	6.78	0.07
2723	2,978,212	10.50	0.47
2627	2,991,828	14.54	0.93
2532	3,007,537	18.84	1.44
2437	3,041,557	23.47	2.54
2341	3,133,417	28.53	5.40
2246	3,213,424	33.97	7.76
2150	3,540,881	39.95	16.29
2055	3,927,638	46.92	24.53

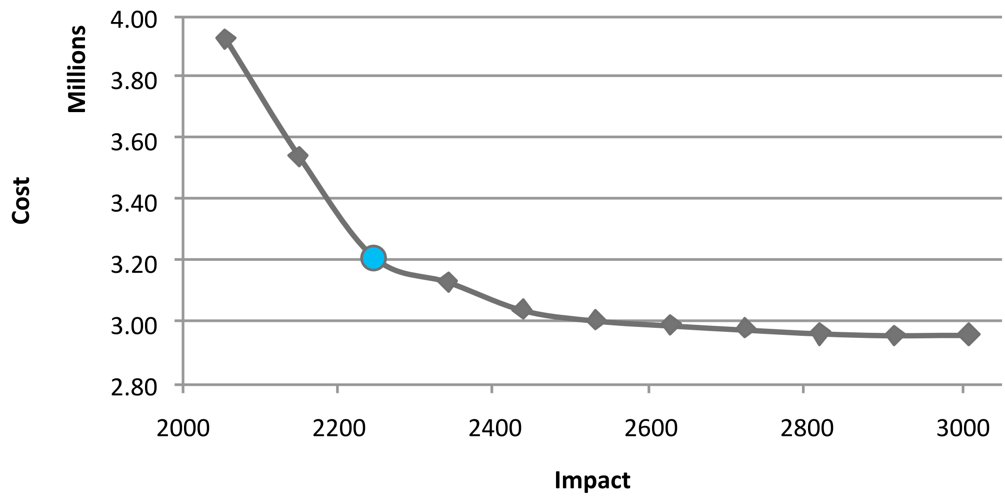


Figure 6.6Pareto optimal curve for Scenario 2

First couples of solutions do not increase the total cost significantly while decreasing the impact, however; this decrease is not satisfactory to select one of these points as proposed solution. After these points come solutions that causes the cost to increase more rapidly but overall decrease in impact becomes more satisfactory. Therefore, one of these middle locations should be preferred. Among these points, after the one colored in red in data table in Table 6.9, there is a step increase in cost with smaller improvement in impact. Consequently, the solution marked with blue color is selected as the proposed solution for Scenario 1. Details of this solution can be found in Table 6.10. Furthermore, facility locations including cement kilns are presented in Figure 6.7.

Table 6.10 Detailed data for proposed solution of Scenario 2

Conditions	
Number of generators	78
Number of candidate sites	59
Number of recovery facilities	78
Number of treatment plants	10
Number of incinerators	10
Number of landfills	10
Number of cement factories	17
Solution	
Population impact	627
Environmental impact	1,619
Facility cost, TL/yr	
Recovery - investment	46,715,728
Recovery - operational	95,781,220
Treatment - investment	9,011,580
Treatment - operational	18,023,160
Incinerator - investment	81,683,573
Incinerator - operational	151,273,766
Landfill - investment	4,772,294
Landfill - operational	2,250,166
Transportation cost, TL/yr	3,192,193
TOTAL COST, TL/yr	**412,703,681**
TOTAL IMPACT	**2,246**

An interesting observation from Figure 6.7 is that unless high generation occurs, the model does not result in opening incinerators in provinces that already have licensed cement kilns. By this way, the incineration facilities become more dispersed and as mentioned earlier, this situation is responsible for the reduction achieved in this scenario.

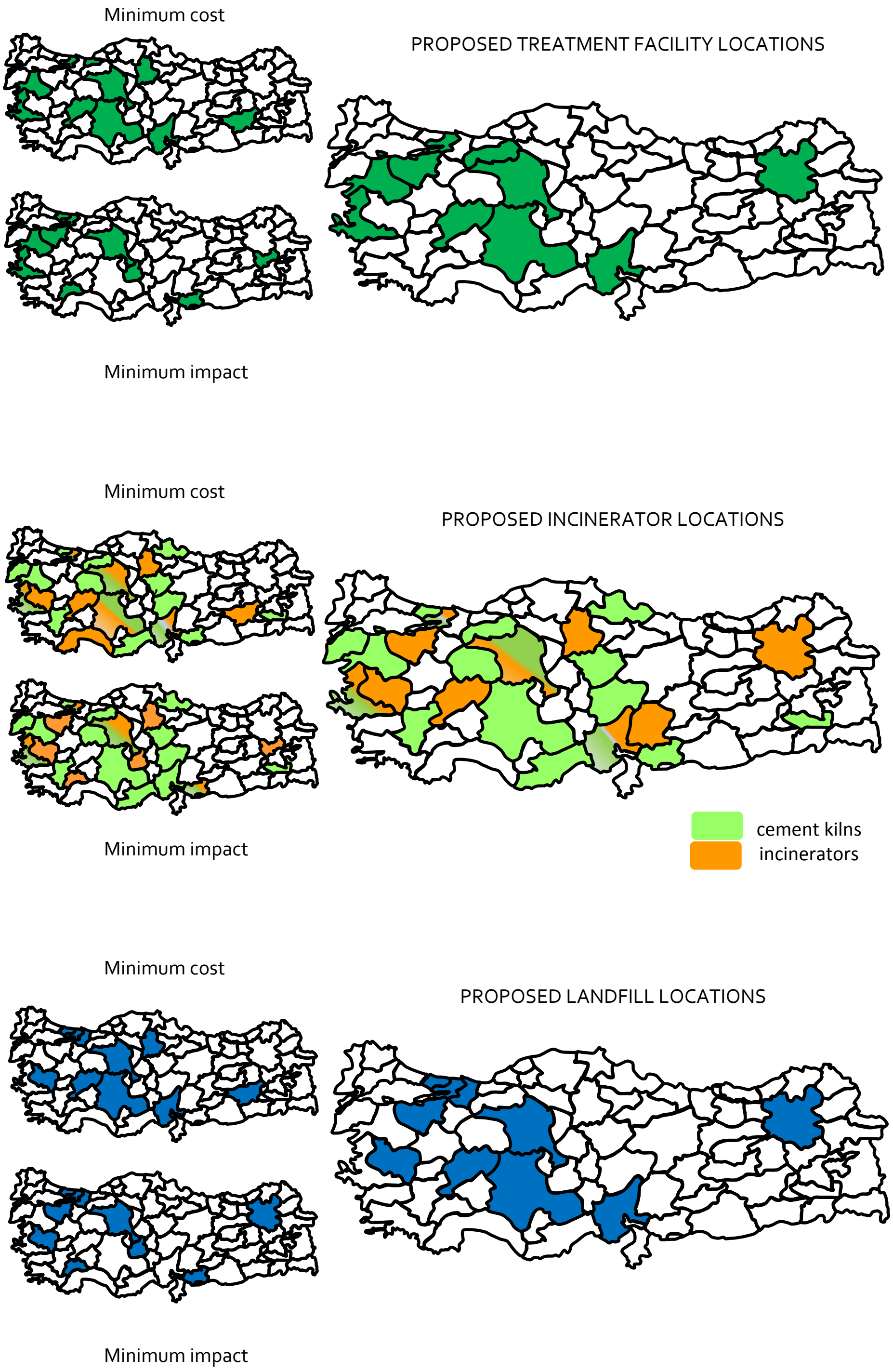


Figure 6.7: Locations of facilities for proposed solution of Scenario 2

6.1.3 Scenario 3

In the third scenario, regional hazardous waste management option outlined in Chapter 2 is evaluated. The regions are shown in Figure 2.2. For solution of this scenario, first of all separate solutions are obtained for each five regions. By this way the facility locations are selected. Facility numbers are adjusted so that every region has two treatment plants, incinerators and landfills except for Thrace region. This corresponds to two integrated facilities if these three types of facilities are located at the same province according to model results. Due to its smaller size it is decided to assign single facility of each type for Thrace Region. Later, allocation of wastes generated from the remaining provinces that do not fall into any region is sought. While obtaining results for remaining provinces, the locations obtained in first step are used without specifying capacities.

In Table 6.11, solutions obtained for five regions are presented. Except for Marmara Region, for all regions, minimum cost and minimum impact objectives yielded same solutions. The "regional" costs are calculated based on the amounts generated within the regions. According to waste generation data highest generation occurs in Marmara Region followed by Aegean region. This situation affects regional management costs and as it can be seen from Table 6.11, highest investments are required in Marmara and Aegean regions, which are approximately 100 and 94 million TL/yr respectively. They are followed by Central Anatolia, Mediterranean and Thrace regions, which are close to each other.

Table 6.11 Regional results or Scenario 3

Conditions	**Region**									
	Aegean		Central Anatolia		Marmara		Mediterranean		Thrace	
Number of generators	5		4		10		8		4	
Number of candidate sites	5		4		10		8		4	
Number of recovery fclt	5		4		10		8		4	
Number of treatment pl	2		2		2		2		1	
Number of incinerators	2		2		2		2		1	
Number of landfills	2		2		2		2		1	
Solution										
Population impact	17		45		1665		170		347	
Env. impact	63		40		2407		159		1399	
Facility cost, TL/yr	Regional	Country-wide	Regional	Country-wide	Regional	Country-wide	Regional	Country-wide	Regional	Country-wide
Recovery - inv	7,859,103		5,010,424		9,396,168		7,409,633		5,991,463	--
Recovery - oper	15,718,206		10,020,847		21,099,519		14,819,266		21,047,769	--
Treatment - inv	1,382,355	1,929135	1,755,195	1,955,775	3,171,957	3,171,957	784,485	1,193,400	650,910	--
Treatment - oper	2,764,710	3,858,270	3,150,390	3,911,550	6,343,914	6,343,908	1,568,970	2,386,800	1,301,820	--
Incinerator - inv	24,655,595	29,894,772	15,798,611	28,956,370	21,473,495	21,473,629	16,137,254	24,200,454	13,514,276	--
Incinerator - oper	39,464,952	47,831,634	25,277,777	46,330,192	34,357,592	34,357,806	25,819,606	38,720,725	21,622,841	--
Landfill - inv	1,611,650	1,962,318	1,619,142	2,014,725	2,636,011	2,733,612	1,274,814	2,425,188	1,620,341	--
Landfill - oper	402,912	490,579	404,785	503,682	659,000	683,403	2,150,718	606,297	405,085	--
Transportation cost, TL/yr	127,446		151,730		787,483		3,192,193		303,138	--
TOTAL COST, TL/yr	93,996,930		63,548,900		99,925,414		68,434,088		66,457,642	--
TOTAL IMPACT	80		85		4071		329		1747	--

High waste generation also results in high transportation impact which is the main reason for high impact values in Marmara Region It should be underlined that each regional impact data is normalized according to maximum value in the data set belonging to that specific region. For other scenarios, since countrywide solutions are sought therefore, normalization is carried out based on the same data set. Hence, the impact values belonging to regions presented in bottom row of Table 6.11 should not be compared with each other.

By adding up regional flows i.e. the amount of waste generated within the region and amount sent from remaining provinces to facilities, total capacity of each facility can be calculated. The cost figures under "countrywide" column are calculated by using total capacities. In addition to these values, a total of 50 million TL/yr is required for recovery facilities in additional provinces as well as 3 million TL/yr for transportation of wastes from other provinces to facilities within regions. In order to calculate total cost of Scenario 3 solution, cost of facilities calculated based on total capacities in "countrywide" column, regional recovery costs, recovery costs of remaining provinces (50 million Tl/yr), regional transportation costs and cost of transportation from remaining provinces to facilities (3 million TL/yr) should all be added up. Consequently, total cost of Scenario 3 solution adds up to approximately 520 million TL/yr.

Facility locations in each province are presented in Figure 6.8. Different colors on figures represent five different regions. For Mediterranean Region, Adana, Gaziantep and Kahramanmaraş, for Central Anatolia, Ankara and Konya, For Aegean Region Denizli and İzmir, for Marmara Region Balıkesir, Kocaeli, Sakarya and İstanbul are selected by model for locating hazardous waste facilities. Only facility in Thrace Region is located at İstanbul, which means that İstanbul needs two integrated facilities at each side of Bosphorus. Among these Adana, Ankara, Konya, Denizli, İstanbul and Kahramanmaraş are integrated facilities in the sense that these facilities should include at least two types of processes.

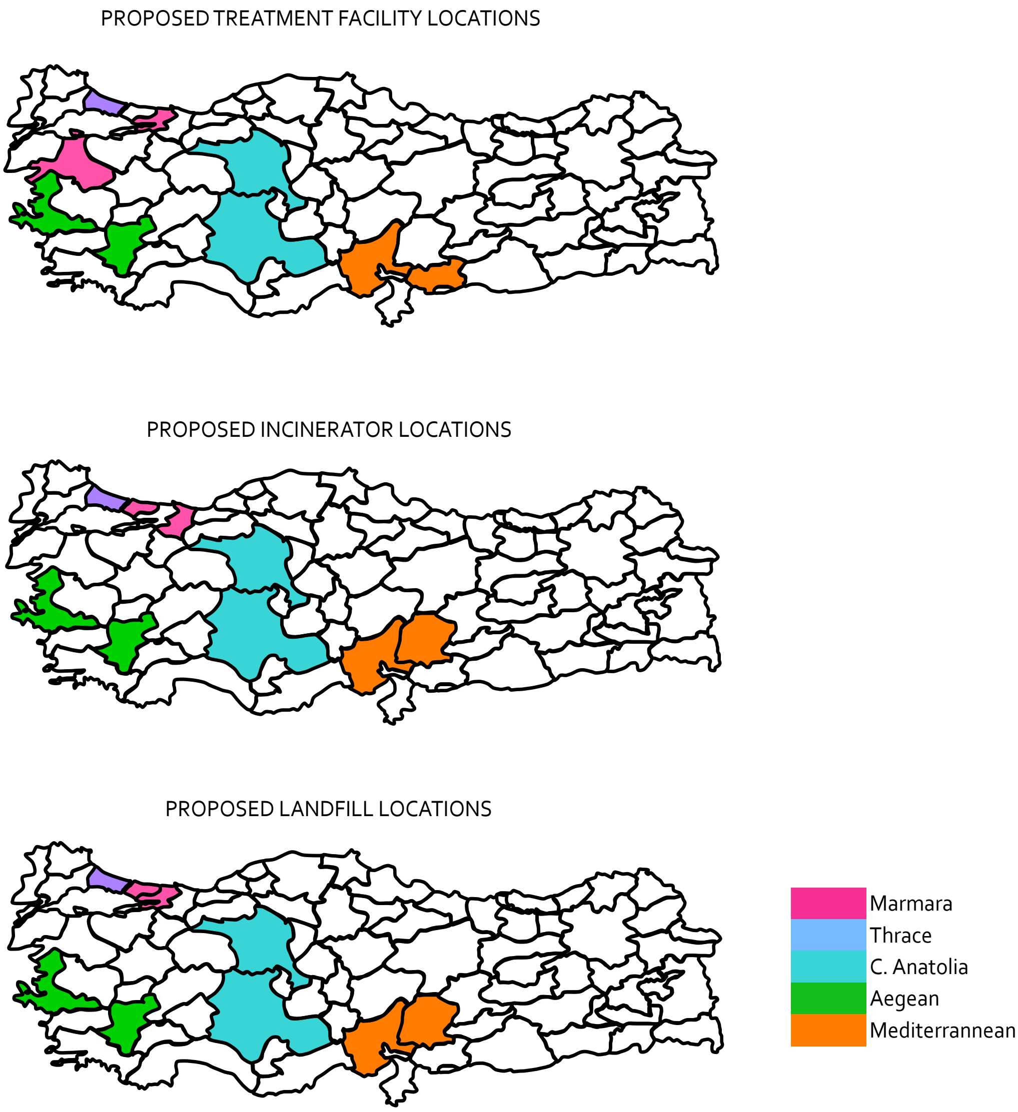


Figure 6.8 Facility locations for Scenario 3 solution

6.1.4 Scenario 4

This scenario concentrates on the effect on transfer stations on hazardous waste management system. As outlined previously, transfer stations have two major purposes; treatment units in transfer stations act as localized treatment facilities and eliminate the necessity to establish dedicated treatment plants for hazardous wastes, and transfer stations provide cost and impact reduction as a result of collection of wastes and enabling further transport by larger capacity vehicles.

Answers to two main alternatives are investigated for Scenario 4;

1. establishment of transfer stations in the presence of facilities whose locations are already decided in previous scenarios and,
2. establishment of hazardous waste facilities and transfer station simultaneously.

For the first alternative, constraints of the Scenario 4 models are adjusted to reflect the facilities already located in previous scenarios by limiting the candidate sets to locations decided. For both alternatives, transfer stations are introduced to the model as a new type of facility as given in Chapter 5.

In Scenario 1, necessity to decrease the candidate set for facility location due to increase in complexity was mentioned. Due to high complexity, solution process was interrupted in OPL software. In Scenario 4, additional decision variables are introduced to the model. This further increases the complexity meaning that set of candidate provinces should be further decreased in order to obtain solutions. This decreased set of candidate sites prevents. Unfortunately, this set should be decreased in a way that it becomes impossible to observe the effect of simultaneous siting of transfer stations and facilities.

Calculation of facility costs for transfer stations is done considering different types of wastes undergoing different procedures. Cost of treatment units are calculated from the amount of treatable wastes arriving at transfer stations (X_{ir}^{W3}, $X_{ir}^{W4}$and X_{ir}^{W5} in Scenario 4 model) and; unit costs presented in Chapter 4. In transfer stations, other wastes that do not require treatment are only stored until they reach necessary amount for transportation. Consequently, the amount of these wastes comprises storage capacity and associated cost is calculated from the unit costs given in Chapter 4 (Table 4.1).

Similar methodology followed for Scenario 1 is followed for Scenario 4, starting from decision on the number of facilities. As presented in Section 6.1.1, incineration and landfill numbers are already decided in Scenario 1 as ten. There are no separate treatment plants and every province is equipped with necessary recovery facilities. Different transfer station numbers (15, 20, 25, 30 and 35) are investigated under these conditions and the cost and impact figures presented in Table 6.12 are obtained. As can be seen from the results, increase in number of transfer stations cause a reduction in both transportation cost and impact as in the case of Scenario 1. Again, similar to Scenario 1, total cost increases with increasing number of transfer stations. However, since only number of transfer stations are changed the increase in total cost is relatively smaller; no more than 2% for the range covered. Decrease in impact with increasing number of transfer stations reaches up to 20% for both minimum impact and minimum cost cases.

It can be inferred from the results presented in Table 6.12 that highest number of transfer station possible should be constructed, even maybe one in every province. However, as will be discussed in detail in forthcoming Sections, scenarios handled in this study should not be considered alone. Instead, it is necessaryto keep a Scenario 4 comparable with the pervious scenarios. A rough comparison with Scenario 1 reveals that above 35 transfer stations, the investments required for transfer station network may become a burden. Therefore, 35 is selected as the number of transfer stations so that nearly one of every two provinces would have a transfer station. The results obtained for the combination of Scenario 4 with the previous scenarios is presented below.

Table 6.12 Results on cost and risk with changing transfer station numbers

Number of facilities	Transport cost/ Total cost, TL/year	Impact	% increase in minimum cost	% decrease in maximum impact
MINIMUM COST				
15	2,260,503 469,038,907	1852	0	0
20	2,134,236 470,280,985	1774	0.26	4.20
25	2,035,090 474,885,093	1584	1.25	14.50
30	1,961,021 476,433,514	1531	1.60	17.30
35	1,903,885 475,479,175	1480	1.37	20.00
MINIMUM IMPACT				
15	2,545,691 467,261,198	1439	0	0
20	2,420,536 470,584,307	1321	0.70	8.20
25	2,294,651 472,747,686	1244	1.17	13.55
30	2,209,481 475,031,921	1197	1.66	16.81
35	2,157,797 475,952,292	1164	1.86	19.10

Scenario 4 in combination with Scenario 1

For this alternative, transfer station locations are selected by model in presence of facilities already been located in Scenario 1. Data of Pareto optimal curve and the curve itself is presented in Table 6.13and Figure 6.9. Proposed solution is marked with color both in Table 6.13 and Figure 6.9. Details on minimum cost, impact and solution proposed for this combination can be found in Table 6.14.

Table 6.13Data points of Pareto optimal curve for Scenario 4+1combination

Impact	Transport Cost (Tl/yr)	% decrease in impact	% increase in cost
1480	1,903,885		
1448	1,904,957	2.21	0.06
1416	1,906,809	4.52	0.15
1385	1,910,207	6.86	0.33
1353	1,914,308	9.39	0.54
1322	1,920,219	11.95	0.85
1290	1,927,923	14.73	1.25
1258	1,937,936	17.65	1.76
1227	1,946,079	20.62	2.27
1195	1,993,312	23.85	4.49
1164	2,157,797	27.15	11.77

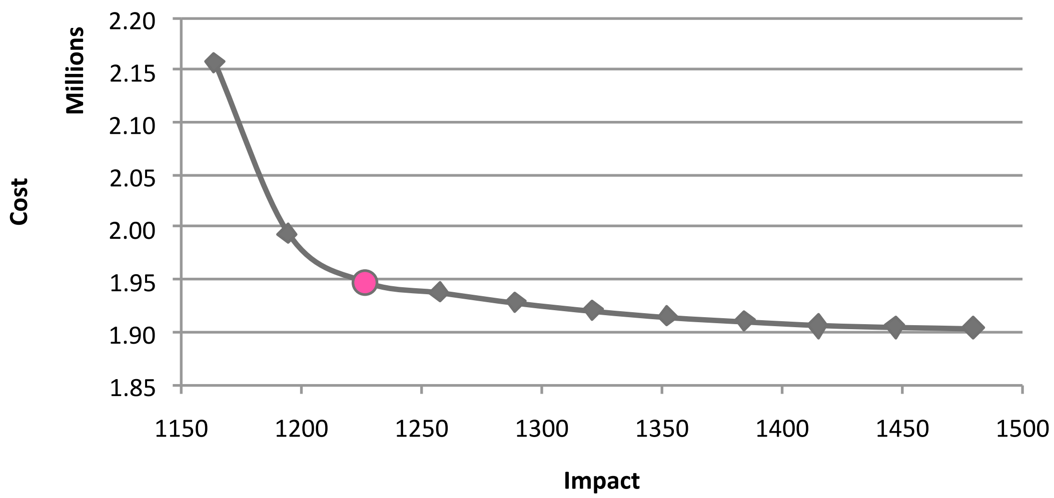


Figure 6.9 Pareto optimal curve for Scenario 1 and 4 combination

Table 6.14Minimum cost, impact and proposed solution details for Scenario 4+1 combination

Conditions			
Number of generators		78	
Number of recovery facilities		78	
Number of treatment plants		10	
Number of incinerators		10	
Number of landfills		10	
Number of transfer stations		35	
	Min cost	Min impact	Proposed soln
Solution			
Population impact	454	297	321
Environmental impact	1026	867	907
Facility cost, TL/yr			
Recovery – investment	46,794,686	47,076,530	47,076,296
Recovery – operational	95,939,136	96,502,826	96,502,357
Incinerator – investment	109,489,253	108,959,246	109,150,313
Incinerator – operational	175,182,805	174,334,793	174,640,501
Landfill – investment	9,197,241	9,160,257	9,116,586
Landfill – operational	2,299,310	2,290,064	2,279,146
Transfer station – investment	11,019,538	11,512,373	11,539,874
Transfer station – operational	22,972,736	23,958,406	24,013,409
Transportation cost, TL/yr	1,903,885	2,157,797	1,948,234
TOTAL COST, TL/yr	**474,798,590**	**475,952,292**	**476,266,720**
TOTAL IMPACT	**1480**	**1164**	**1228**

When cost figures presented in Table 6.14 are inspected it can be seen that total cost of all three cases are very close to each other. Interestingly, total cost of Pareto optimal solution proposed is the highest among three. The difference is very small; approximately 0,31% from the minimum cost solution and occurs due to change in incineration and transfer station costs.

Facility location set for combination of Scenario 4 with Scenario 1 can be viewed in Figure 6.10.

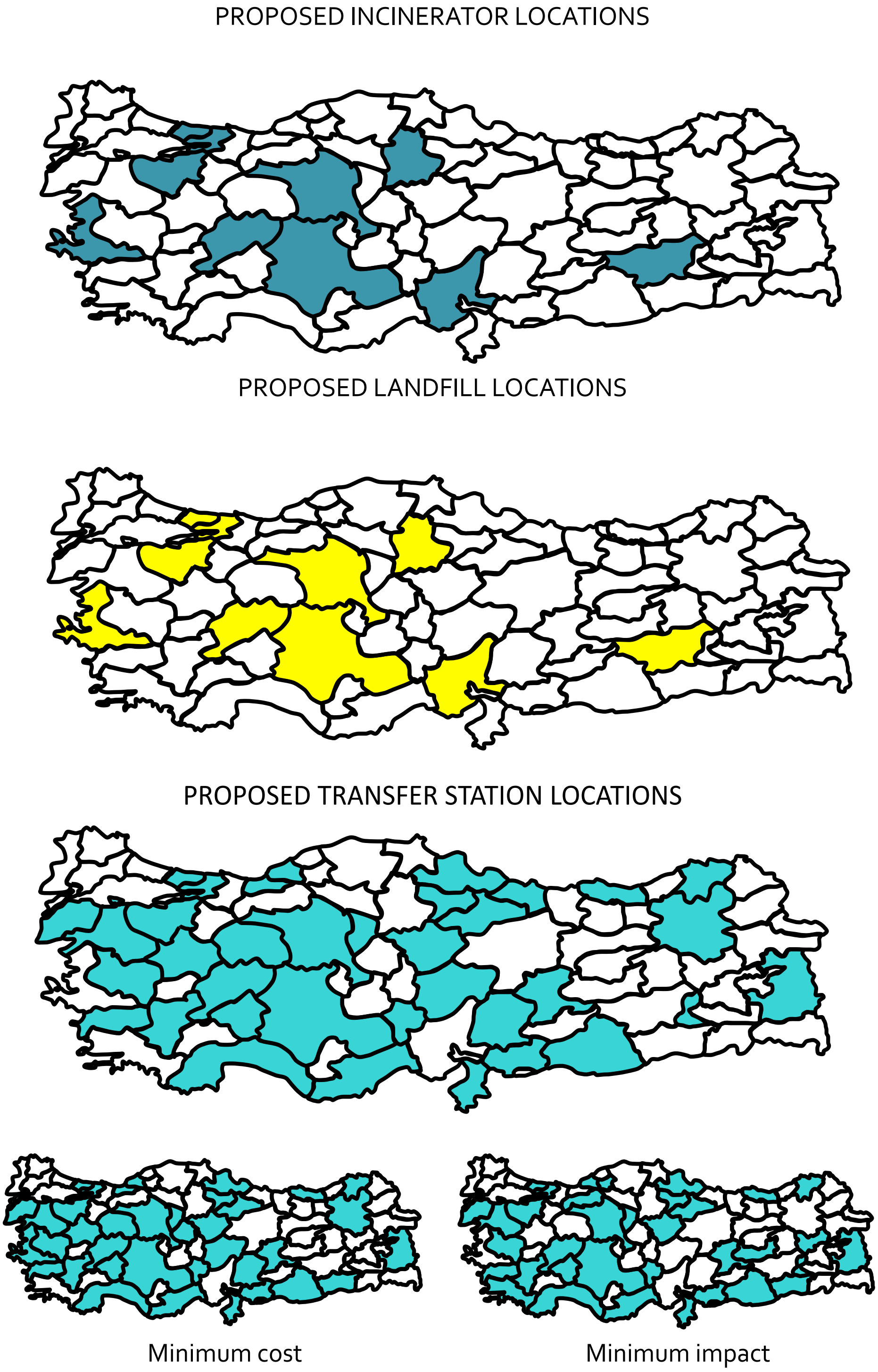


Figure 6.10 Facility locations for Scenario 4 and 1 combination

As can be seen from Figure 6.10, placement of transfer stations are largely influenced by distribution of treatable wastes since these wastes must be sent to transfer stations for treatment. This is also obvious from amounts of waste allocated to facilities. For example, transfer stations in Ankara, Bursa, İstanbul, Konya and Kocaeli receive no wastes other than treatable wastes which means that these transfer stations are established by the model only as treatment plants. These provinces are also high treatable waste generators or neighbors to these high generators.

It can be seen that not only eastern provinces take advantage of transfer stations; but also western provinces are equipped with transfer stations (Figure 6.10). Besides high generation of treatable wastes, overall high waste generation is another important factor affecting the location of transfer stations. Greater reduction in transportation cost can be achieved if transfer stations are established in provinces with high generation potential. Another observation is that where hazardous waste facilities are already established, no transfer stations are required since sending wastes to facilities in the vicinity causes no transportation cost and impact. Following this observation it can be advised that priority in construction of transfer stations should be given to provinces in which no hazardous waste facilities exist unless there is high generation of treatable wastes within that province.

Scenario 4 in combination with Scenario 2

This combination involves the establishment of dedicated hazardous waste facilities, cement kilns for co-incineration and transfer stations. Data points of

Pareto optimal curve can be found in Table 6.15 and minimum cost, impact and proposed solution are given in Figure 6.11 and Table 6.16.

Table 6.15 Data points of Pareto optimal curve for Scenario 4+2 combination

Impact	Transport Cost (Tl/yr)	% decrease in impact	% increase in cost
1577	2,266,049		
1553	2,267,252	1.55	0.05
1528	2,269,646	3.21	0.16
1504	2,273,530	4.85	0.33
1480	2,277,880	6.55	0.52
1455	2,283,698	8.38	0.77
1431	2,293,453	10.20	1.19
1407	2,308,899	12.08	1.86
1353	2,326,240	14.03	2.59
1358	2,373,611	16.13	4.53
1334	2,525,202	18.22	10.26

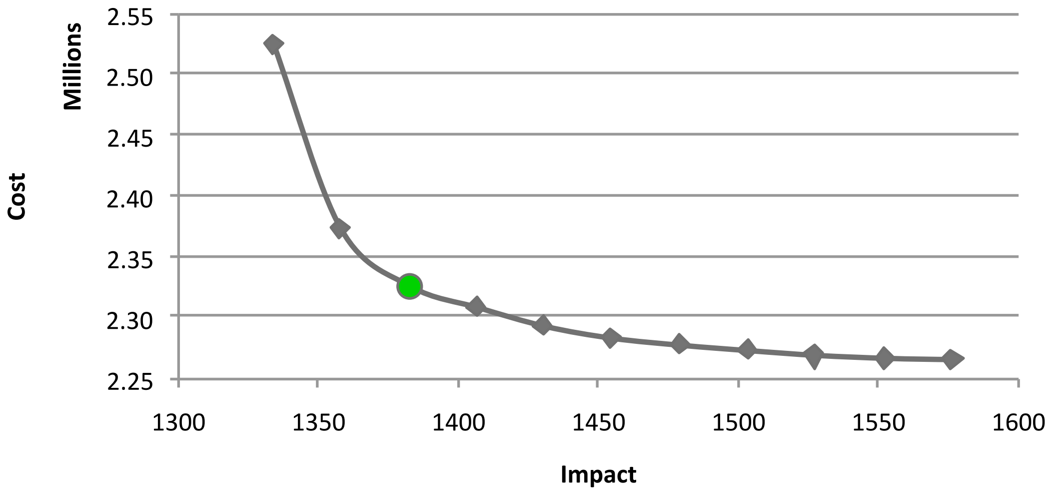


Figure 6.11 Pareto optimal curve for Scenario 2 and 4 combination

Table 6.16 Minimum cost, impact and proposed solution details

Conditions			
Number of generators		78	
Number of recovery facilities		78	
Number of treatment plants		10	
Number of incinerators		10	
Number of landfills		10	
Number of cement factories		17	
Number of transfer stations		35	
	Min cost	Min impact	Proposed soln
Solution			
Population impact	504	341	367
Environmental impact	1073	993	1016
Facility cost, TL/yr			
Recovery – investment	46,794,155	46,568,309	46,767,048
Recovery – operational	95,938,075	95,486,383	95,943,862
Incinerator – investment	85,399,896	82,872,467	82,650,955
Incinerator – operational	157,954,806	153,910,955	153,556,499
Landfill – investment	6,540,220	6,634,292	7,037,720
Landfill – operational	2,138,058	2,184,216	2,175,097
Transfer station – investment	11,908,371	12,722,708	12,590,433
Transfer station – operational	28,874,810	26,379,077	33,259,520
Transportation cost, TL/yr	2,266,502	2,525,202	2,326,566
TOTAL COST, TL/yr	**437,859,895**	**429,283,614**	**436,471,652**
TOTAL IMPACT	**1577**	**1334**	**1383**

When Table 6.14 and Table 6.16 are inspected together it can be seen that the transportation cost of Scenario 4 + 1 combination is smaller than that of Scenario 4 + 2. This can be attributed to the conditions of Scenario 1 being more relaxed than Scenario 2. In Scenario 2, the locations of cement kilns are introduced to the model rather than decided by it. Although in reality this is not possible, if cement kilns were to be located by the model, transportation cost of Scenario 4 + 2 would be less than Scenario 4 + 1. Similar to transportation cost, total impact of Scenario 4 + 2 combination is higher that of Scenario 4 + 1 combination. On the contrary, owing to the reduction of incineration costs by use of cement kilns for co-incineration and presence of existing facilities, total cost of Scenario 4 + 2 is 7.8% lower than previous solution.

Locations of facilities selected in this alternative are presented in Figure 6.12.

Scenario 4 in combination with Scenario 3

Scenario 4 + 3 combination involves the establishment of transfer station network in the presence of regional waste management. Pareto optimal curve and its data can be seen in Table 6.17 and Figure 6.13

Table 6.17 Data points of Pareto optimal curve for Scenario 4+2 combination

Impact	Transport Cost (Tl/yr)	% decrease in impact	% increase in cost
2430	2,848,606		
2379	2,851,718	2.14	0.11
2329	2,857,233	4.34	0.30
2278	2,864,142	6.67	0.54
2227	2,876,227	9.12	0.96
2176	2,891,701	11.67	1.49
2126	2,912,075	14.30	2.18
2075	2,950,018	17.11	3.44
2024	3,000,726	20.06	5.07
1974	3,071,482	23.10	7.26
1923	2,243,426	26.37	12.17

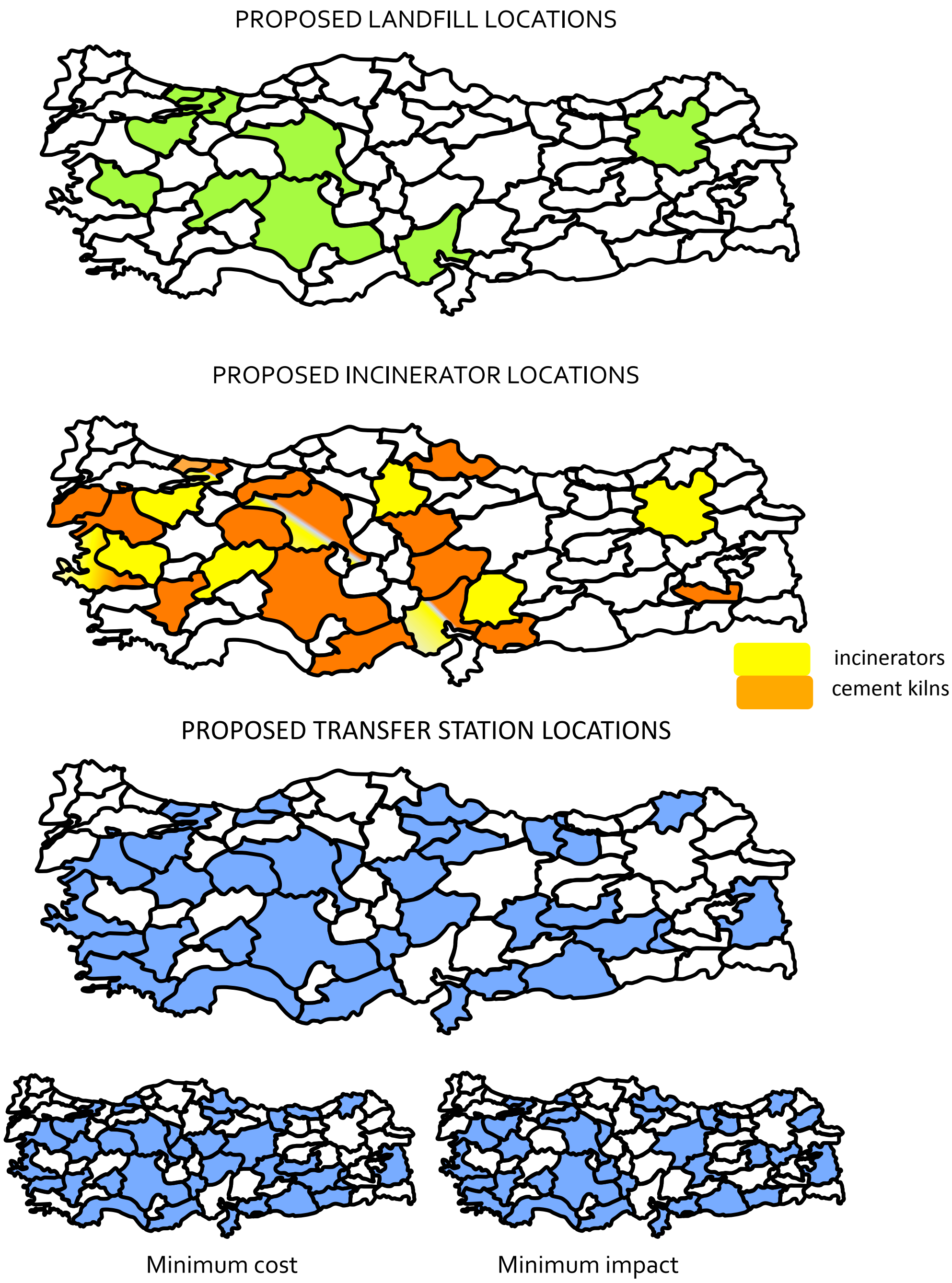


Figure 6.12 Facility locations in Scenario 4 + 2 combination

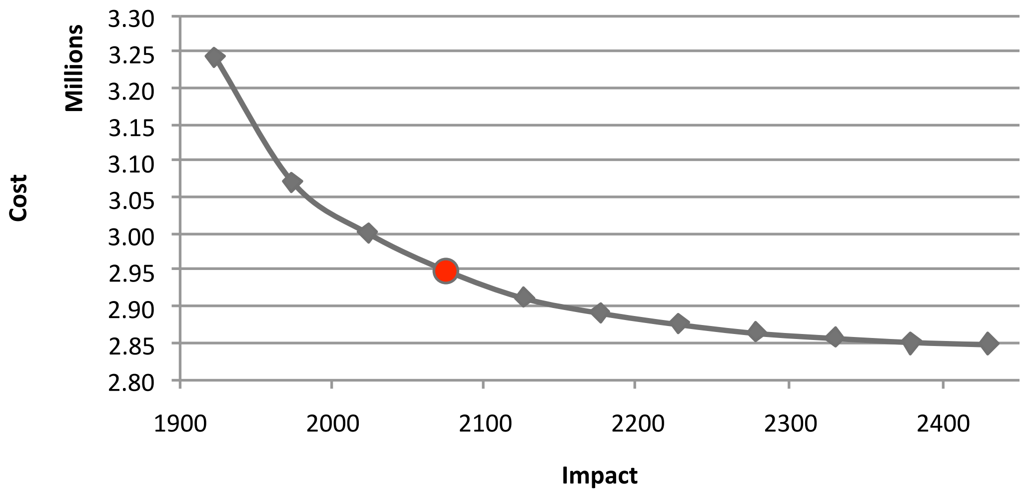


Figure 6.13 Pareto optimal curve for Scenario 3 and 4 combination

When the Pareto optimal curve is inspected it can be seen that the solution points are more uniformly distributed over the curve. This means that the % changes in cost and impact are also uniform which makes harder to propose a point on the curve. Still, the red point on the curve corresponds to a solution where the % increase in cost for the same % decrease in impact is larger than the previous solutions or points on the curve. For this reason solution marked with red is proposed for this scenario. Detailed information is given in Table 6.18.

Comparison of minimum cost, minimum impact and proposed solution gives an interesting result. Trends in transportation cost and impact are as they should. However, the waste allocation in minimum impact solution gives a facility configuration such that minimum total cost is achieved in minimum impact solution. This means that both minimum impact and minimum total cost belongs to minimum impact solution. Consequently, instead of the “proposed” solution selected in Figure 6.13, the minimum impact solution is preferred. Facility locations given in Figure 6.14 are based on this selection.

Table 6.18 Minimum cost, impact and proposed solution details

Conditions			
Number of generators		78	
Number of recovery facilities		78	
Number of treatment plants		8	
Number of incinerators		8	
Number of landfills		8	
Number of transfer stations		35	
	Min cost	Min impact	Proposed solution
Solution			
Population impact	936	575	712
Environmental impact	1494	1348	1248
Facility cost (TL/yr)			
Recovery – investment	46,776,806	46,730,666	46,779,117
Recovery – operational	95,903,378	95,811,097	95,907,999
Incinerator – investment	100,550,062	103,865,654	104,524,811
Incinerator – operational	160,880,100	165,687,365	167,239,698
Landfill – investment	8,466,928	8,351,183	8,451,254
Landfill – operational	2,116,732	2,087,795	2,098,527
Transfer station – investment	12,377,405	12,736,490	12,679,259
Transfer station – operational	25,807,534	26,525,705	26,416,650
Transportation cost (TL/yr)	2,847,969	3,243,426	2,949,504
TOTAL COST	**455,726,917**	**465,039,385**	**467,046,921**
TOTAL IMPACT	**2430**	**1924**	**2075**

Below, the comparison of alternatives handled under Scenario 4 is discussed. In Table 6.19 major cost items and impacts of three combinations is presented.

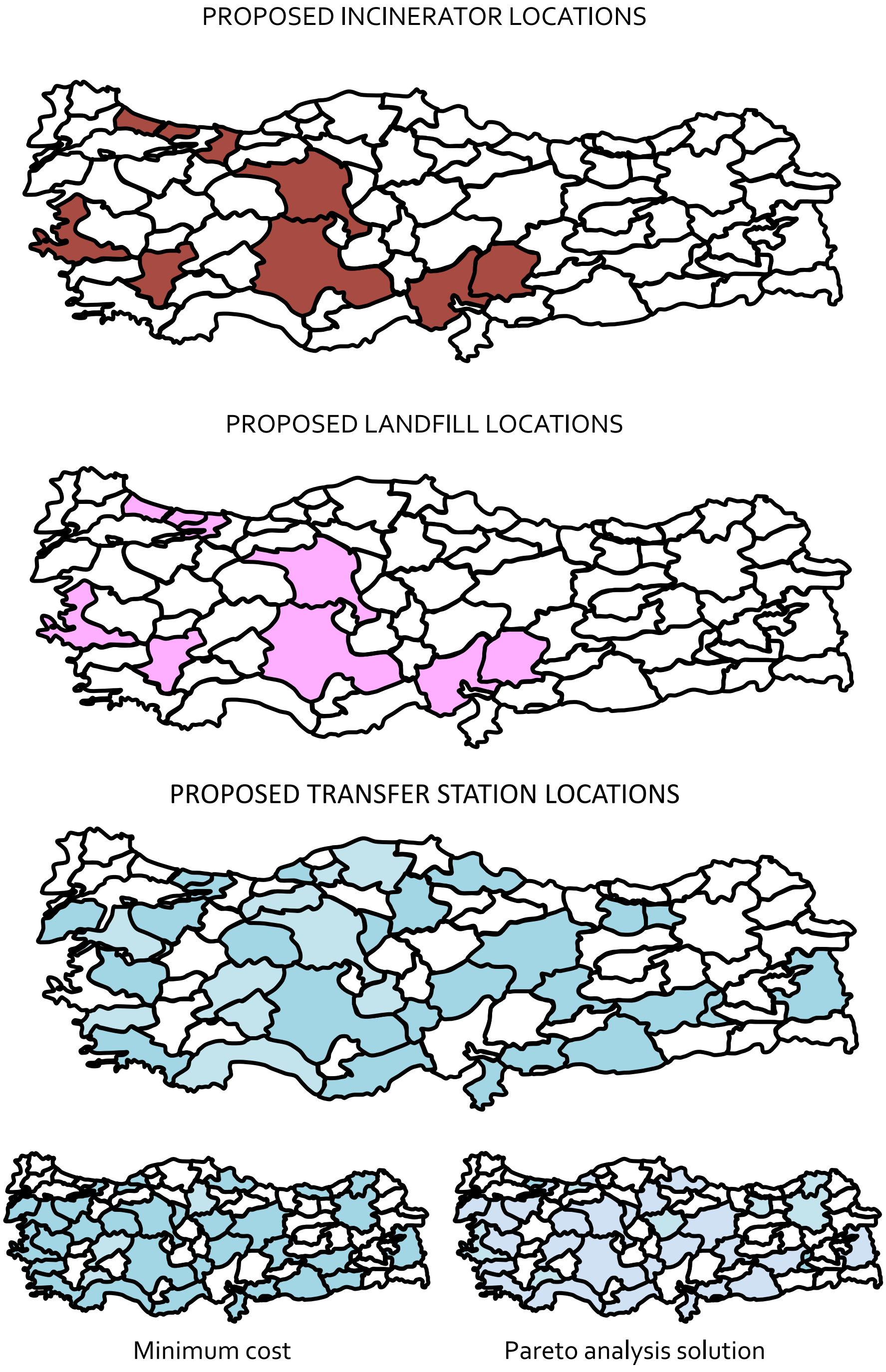


Figure 6.14 locations in Scenario 4 + 3 combination

Table 6.19 Comparison of combinations covered under Scenario 4

	Scenario 4 + 1	Scenario 4 + 2	Scenario 4 + 3
Population impact	321	367	575
Environmental impact	907	1016	1348
Recovery cost(TL/yr)	143,560,000	142,710,000	142,550,000
Incineration cost(TL/yr)	283,790,000	236,200,000	269,550,000
Landfill cost(TL/yr)	11,400,000	10,875,000	10,450,000
Transfer station cost(TL/yr)	35,550,000	45,850,000	39,250,000
Total cost(TL/yr)	474,300,000	435,650,000	461,790,00
Total impact	1228	1383	1924

Obviously, the worst results in term of cost are obtained in combination of transfer station network with the base scenario whereas for the same objective implementation of regional hazardous waste management with transfer station network gives best results with a yearly hazardous waste management cost of 435,6 million TL/yr. In terms of impact Scenario 1 gives the best result that is 1228. It is followed by Scenario 4+2 and 4+1 with values of 1383 and 1924 respectively. In reality implementation of base scenario is not possible since existing facilities must be taken into account, the choice really is to chose between Scenario 4 + 2 and Scenario 4 + 3. Among these two, Scenario 4 + 2 gives best result both in terms of cost and impact. Consequently, proposed solution of Scenario 4 involves use of transfer stations with co-incineration practices.

Capacities of transfer stations for selected alternative are as given in Table 6.20. All treatable wastes are sent to transfer station. In addition 440,000 tons/yr of other types of wastes are sent to facilities by using transfer stations. This amount corresponds nearly to 1/3 of total wastes.

Table 6.20Capacities of transfer stations

Province	Storage capacity	Treatment capacity
Amasya	7400	35
Ankara	16,750	4000
Antalya	6700	250
Artvin	6400	75
Aydın	13,000	100
Balıkesir	5400	6200
Bursa	--	2150
Denizli	10,200	800
Diyarbakır	2400	310
Elazığ	16,500	100
Eskişehir	11,500	660
Gaziantep	3600	1700
Giresun	5900	125
Gümüşhane	5900	340
Hatay	6400	450
Isparta	4600	1150
Mersin	21,400	1740
İstanbul	--	2100
İzmir	115,000	6200
Kayseri	8400	210
Kocaeli	66,000	6400
Konya	9000	2850
Kütahya	12,500	1750
Malatya	7600	100
Muğla	4500	560
Niğde	11,400	125
Samsun	6000	330
Tokat	5900	175
Şanlıurfa	3850	175
Van	2800	225
Yozgat	6400	1375
Zonguldak	13,250	1650
Kırıkkale	17,750	1850
Batman	3500	525
Düzce	1750	3550
TOTAL	**439,650**	**50,500**

In the next section, general remarks on solutions are made. Moreover, four scenarios evaluated up to now are compared in order to propose final recommendations on hazardous waste management system of Turkey.

6.2 General remarks and comparison of scenarios

There are some general remarks on properties of hazardous waste management system that would better be reported while comparing results of all scenarios.

Let us first examine the contribution of cost items to overall management system cost. In Figure 6.15, percent contribution of major cost items (recovery, treatment, incineration, landfilling, transport and transfer stations) are presented.

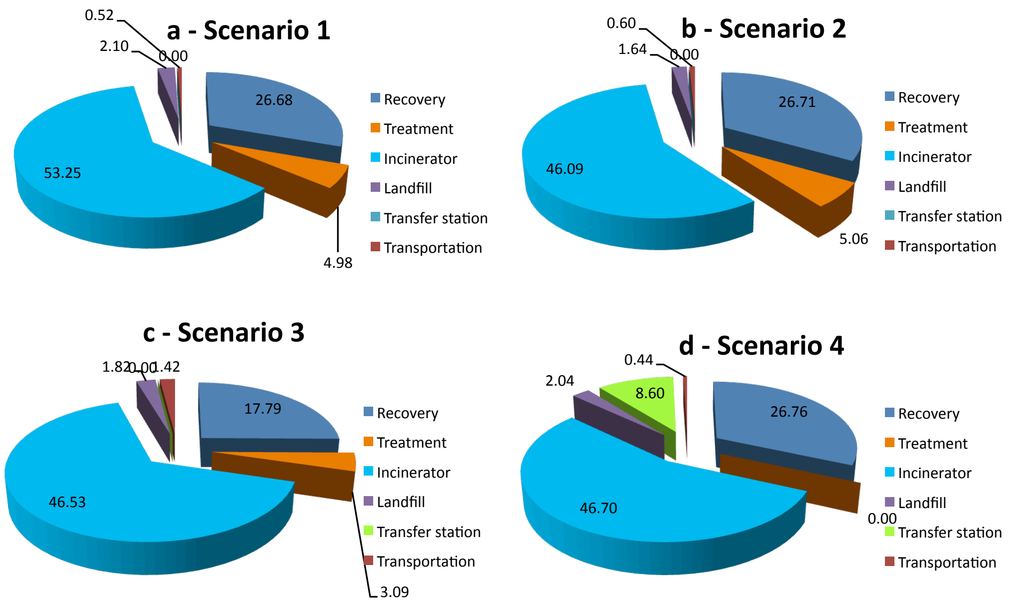


Figure 6.15 Contribution of cost items to overall cost

In all scenarios, almost half of total hazardous waste management costs originate from incineration operations. Incineration is followed by recovery and transfer stations in Scenario 4. The decrease in incineration costs by use of cement kilns is obvious from inspection of Figure 6.15a- and b- . Investment and operational costs of cement kilns are handled by factory management therefore, they are not included in total cost of waste management. Therefore, the percent change in incineration is not a result of change in total amount but the actual decrease in incineration cost which roughly corresponds to 7%. Since incineration is the most expensive component of hazardous waste handling, promotion of co-incineration practices seems like an attractive option.

Second topic to be discussed is related to locations of facilities and their capacities. A summary on facility locations selected in Scenarios along with required capacities is given in Table 6.21. The capacities of these facilities are calculated from the amounts of wastes arriving. It should be reminded that small differences in total amounts of wastes are due to round ups applied for capacities

The first important thing observed in Table 6.21, is that when the locations of different types of facilities are examined, it is seen that the locations match most of the time. For example in Scenario 1, all three types of facilities are located in Adana, Afyon, Ankara, Çorum, Diyarbakır, İzmir, Kocaeli and Konya. This situation is also valid for other scenarios. Only treatment facility locations differ sometimes due to distribution of treatable waste around the country. Especially, incinerators and landfills are located at the same provinces mainly due to the fact that all incineration residues are sent to landfills. Need for integrated facilities are already outlined in Concept Report of LIFE HAWAMAN Project [90]. The results confirm that in a hazardous waste management system that is design considering both cost and impact of the system, ***integrated facilities*** are indeed favored.

Table 6.21 Facility locations and capacities

Scenario 1		Scenario 2		Scenario 3		Scenario 4	
Province	Capacity	Province	Capacity	Province	Capacity	Province	Capacity
TREATMENT							
Adana	4100	Adana	4300	Adana	2700		
Afyon	4400	Afyon	4400	Ankara	8200		
Ankara	9300	Ankara	7700	Balıkesir	6200		
Balıkesir	6200	Balıkesir	6200	Denizli	3600		
Bursa	2300	Bolu	5200	Gaziantep	3500		
Çorum	2100	Bursa	2300	İzmir	6500	NA	
Diyarbakır	1900	Erzurum	1700	Kocaeli	15,600		
İzmir	6900	İzmir	6900	Konya	3800		
Kocaeli	10,100	Kocaeli	8500				
Konya	2900	Konya	3100				
TOTAL	**50,200**	**TOTAL**	**50,300**		**50,100**		
INCINERATION							
Adana	86,200	Adana	62,300	Adana	67,000	Adana	65,400
Afyon	56,200	Afyon	64,100	Ankara	111,200	Afyon	66,000
Ankara	57,200	Ankara	50,000	Denizli	37,000	Ankara	61,500
Bursa	43,400	Bursa	39,900	İstanbul	32,000	Bursa	39,800
Çorum	55,700	Çorum	45,100	İzmir	116,000	Çorum	42,900
Diyarbakır	48,100	Erzurum	37,200	Kocaeli	89,000	Erzurum	37,200
İstanbul	31,900	İzmir	17,500	Konya	39,000	İzmir	17,500
İzmir	116,700	Kocaeli	35,000	K.Maraş	72,000	Kocaeli	35,000
Kocaeli	42,200	Manisa	94,200			Manisa	94,200
Konya	28,400	K.Maraş	39,000			K.Maraş	32,400
TOTAL	**566,000**	**TOTAL**	**484,300**	**TOTAL**	**563,200**	**TOTAL**	**491,900**
LANDFILL							
Adana	53,600	Adana	55,500	Adana	39,500	Adana	62,000
Afyon	45,800	Afyon	48,900	Ankara	78,000	Afyon	50,000
Ankara	52,800	Ankara	73,800	Denizli	18,000	Ankara	73,500
Bursa	33,300	Bursa	33,300	İstanbul	67,200	Bursa	31,400
Çorum	24,000	Erzurum	24,300	İzmir	105,500	Erzurum	24,800
Diyarbakır	28,800	İstanbul	66,000	Konya	39,500	Istanbul	64,000
İstanbul	67,200	Kocaeli	31,500	K.Maraş	47,500	Kocaeli	31,500
İzmir	105,900	Konya	36,000	Sakarya	115,000	Konya	30,000
Kocaeli	62,300	Manisa	105,900			Manisa	105,000
Konya	35,200	Sakarya	32,600			Sakarya	35,000
TOTAL	**508,900**	**TOTAL**	**507,800**	**TOTAL**	**510,200**	**TOTAL**	**507,200**

In the second scenario, there is a difference in total amount of wastes incinerated in hazardous waste incinerators, which is around 82,500 tons/yr. According to the model results, this amount is actually sent to cement kilns for co-incineration. This amount corresponds to 14.5% of total combustible waste generated in Turkey.

Given that this amount allocated for co-incineration is more than already established incineration capacity of Turkey, it is believed that co-incineration practices should play a major role in hazardous waste management system at least until sufficient hazardous waste handling infrastructure is established.

There is another interesting finding about capacities of cement kilns. The amounts of wastes incinerated in last year were introduced to the model as provincial capacities (Table 6.7). The results of the model suggest that not all the capacity of cement kilns are used when minimization of cost and impact is intended. There seems to be idle capacity in Çanakkale, İstanbul and Kocaeli cement kilns. This result may be interpreted as although co-incineration may play an important role in processing of combustible wastes and decreasing cost of the system, if sufficient infrastructure were established in terms of dedicated hazardous waste incinerators at the locations suggested by the model, not all of the licensed capacity would be used for co-incineration.

The locations of the facilities given in Table 6.21 give an insight on justification of locations of existing facilities and provide guidance on locating new ones. There is an incinerator and a landfill in Kocaeli, an incinerator in İzmir and a landfill in Manisa. Soon another incinerator is supposed to become operational in Manisa. When Scenario 1 results are considered which actually resembles the situation in Turkey when İzaydaş in Kocaeli was established before any hazardous waste facility, it can be seen that a treatment plant, an incinerator and a landfill is located in Kocaeli. This decision justifies construction of these facilities in Kocaeli in the first place.

Although Manisa is not among Scenario 1 locations, it is closely located to İzmir where a treatment plant, an incinerator and a landfill are suggested to be built by the model. Moreover, Manisa is also a good candidate for hazardous waste facilities due to high capacity for incineration in İzmir. According to the results, around 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.

This conclusion is backed up by the Scenario 2 solution. Due to the nature of binary decision variables of locating facilities, they can only take 1 or 0 as value. This means that two same types of facilities cannot be located in the same province because if this happens the value of decision variables become two.In other words, a landfill and an incinerator can be located in the same province but two incinerators cannot. The results suggest that if another incinerator in İzmir cannot be established, most suitable choice is to set up a facility in Manisa. Total capacity of incinerators in İzmir and Manisa according to Scenario 2 solution adds up to 111,700 tons/yr, which is close to the capacity required in İzmir according to Scenario 1 results.

Due inability to define a second facility of same types in a province, capacity increase in existing facilities cannot be evaluated only by examining Scenario 2 solutions. Nevertheless, it is possible the make comments on capacity increase by comparing Scenario 2 solution with Scenario 1. In Scenario 1, in which no preexisting facilities are included the amount of wastes sent to a certain province represents the total capacity requirement. When this value is compared with the actual capacities of facilities, additional capacity requirement can be inferred. For İzmir case, if a second facility to be established in İzmir, an additional 100,000 tond/yr capacity is required.

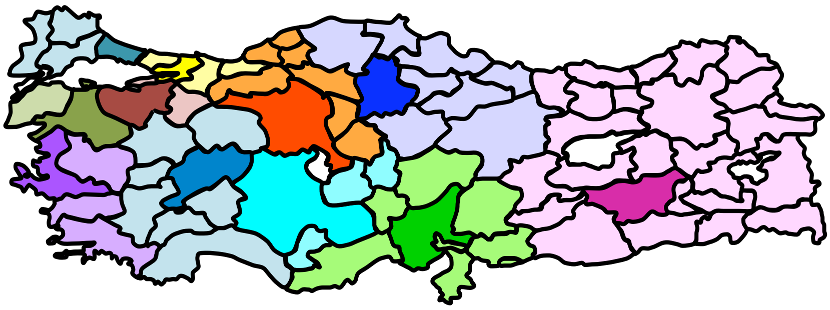
For Kocaeli, this additional capacity requirement is around 10,000 tons/yr. However, in deciding additional capacity in Kocaeli, Kocaeli and İstanbul should be considered in unison. The model suggests that an incinerator and a landfill should be constructed in İstanbul. However, the eligible land on which these facilities can be built is very limited in İstanbul. This means that Kocaeli may be the most suitable location to serve for the wastes allocated to İstanbul. Consequently, additional capacity requirement in Kocaeli rises from 10,000 tons/yr to 42,000 tons/yr.

There are some provinces, which are selected for certain types of facilities in all scenarios. For treatment plants, Adana, Ankara, Balıkesir, İzmir and Koaceli are selected for all scenarios. Adana and Ankara are common choices for incinerators. Moreover, İzmir, Kocaeli and Çorum are locations given by at least three scenarios. Adana and Ankara should also have landfills according all four results. İstanbul and Kocaeli are other provinces in which a landfill should be built.

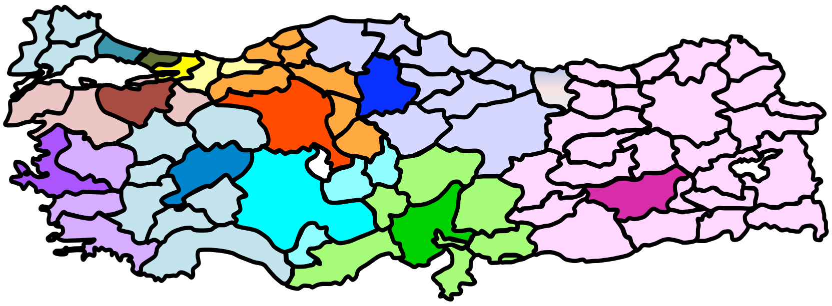
It is also worth examining the service areas of the facilities located in the solutions. Figures 6.16–6.18 show the service areas. Each facility type is shown with a dark color and the province than send their wastes to this facility is shown with lighter shade of the same color. Facility configuration in solution ofthe forth scenario is basically the same as configuration of Scenario 4, therefore it is not separately given.

The figures suggest that integrated facilities that would be established in Ankara, Erzurum / Kahramanmaraş and Adana would serve half of the country in terms or area. It is clear from the figures that where high waste generation occurs, the service areas of the facilities become smaller. For eastern regions of Turkey where waste generation is smaller, a single facility serves 10 – 15 provinces. On the contrary, according to the model results in İstanbul where the waste generation is highest, established facilities usually do not accept wastes from other provinces.

SERVICE AREAS FOR TREATMENT PLANTS



SERVICE AREAS FOR INCINERATOR



SERVICE AREAS FOR LANDFILLS

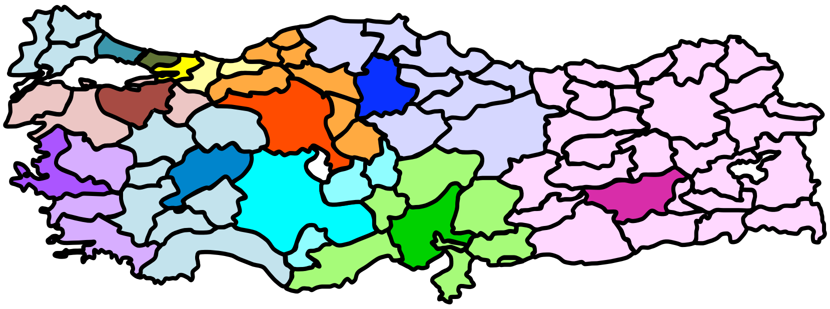


Figure 6.16 Service areas of facilities in Scenario 1

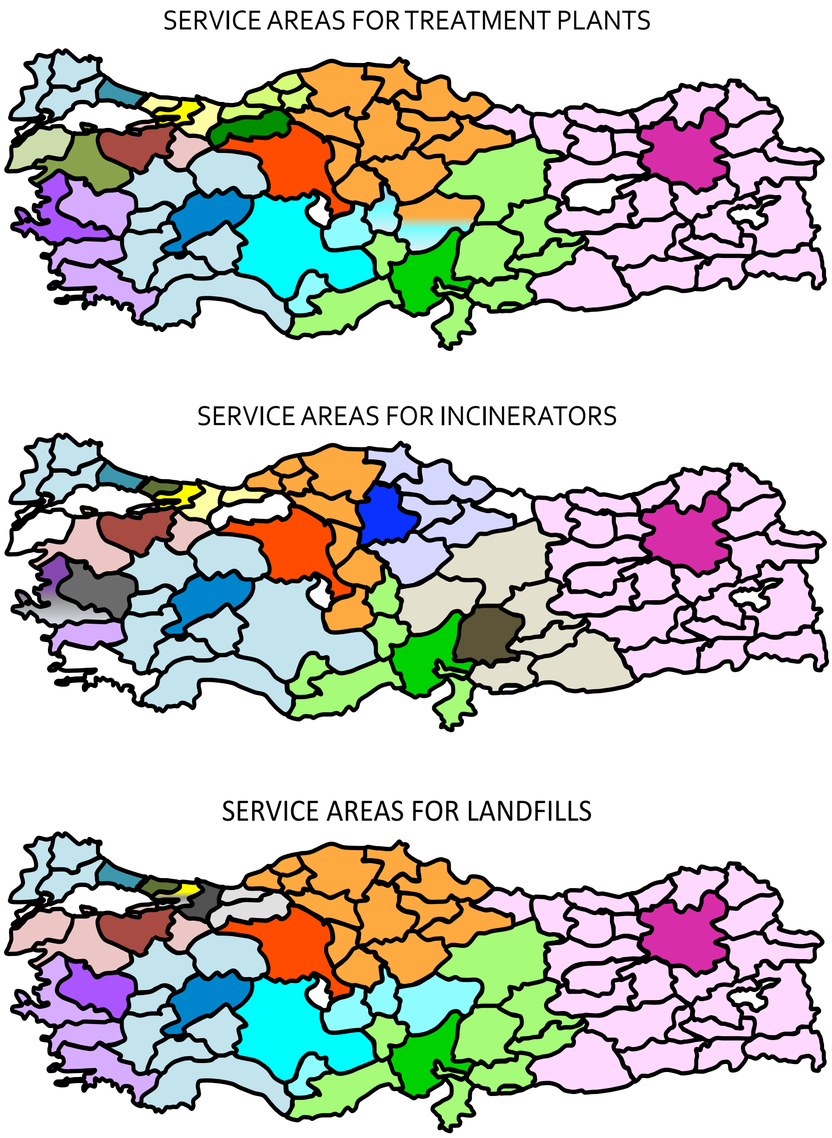


Figure 6.17 Service areas of facilities in Scenario 2

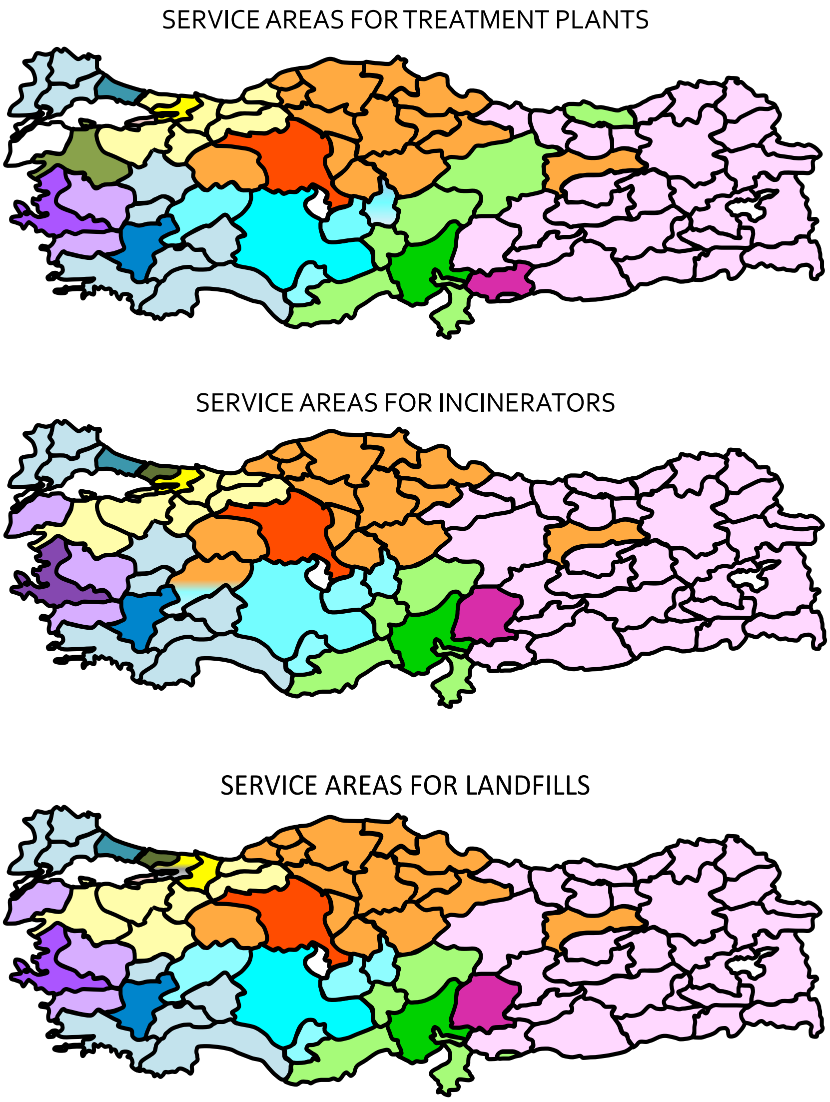


Figure 6.18 Service areas of facilities in Scenario 3

In last sections, results on four scenarios handled in this study are presented. In order to be able to compare these results Table 6.22 is prepared. Each column corresponds to the solution of a scenario selected as the best previously.

A very important point to note that during calculation of impact in regional solution of Scenario 3, normalization was done according to maximum data in each data set meaning that regional impact values are not additive. This situation prevents reporting a single value for impact for selected solution of Scenario 3. Nevertheless, it possible compare possible impact of regional hazardous waste management using the data given in Table 6.3 in which cost and impact values are calculated for different facility numbers in Scenario 1.

Table 6.22Results of four scenarios

	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Solution				
Population impact	597	627		367
Environmental impact	1,537	1,619		1016
Facility cost (TL/yr)				
Recovery - investment	46,650,000	46,700,000	52,600,000	46,750,000
Recovery - operational	95,650,000	95,780,000	116,570,000	95,950,000
Treatment - investment	8,850,000	9,000,000	8,900,000	--
Treatment - operational	17,725,000	18,000,000	17,800,000	--
Incinerator - investment	109,250,000	81,700,000	118,000,000	82,650,000
Incinerator - operational	174,775,000	151,275,000	188,800,000	153,550,000
Landfill - investment	8,975,000	4,770,000	10,756,000	7,000,000
Landfill - operational	2,240,000	2,250,000	2,700,000	2,175,000
Transfer station – investment	--	--	--	12,600,000
Transfer station - operational	--	--	--	33,250,000
Transportation cost (TL/yr)	2,770,000	3,190,000	7,560,000	2,325,000
Regional management cost of Thrace	66,450,000	66,450,000	included	66,450,000
TOTAL COST (TL/yr)	**533,335,000**	**479,115,000**	**525,000,000**	**502,700,000**
TOTAL IMPACT	**2134**	**2246**	**--**	**1383**

It can be observed that total impact value cannot be calculated due to the fact that regional impact data is normalized with maximum value in each regional set. As a result, the impact values obtained for each region and for rest of the provinces should not be added to each other. According to Table 6.3, when number of facilities is set to seven, the minimum achievable cost turns out to be little over 500 million TL/yr when regional management of Thrace Region is included. This value corresponds to an impact value of 4506. This value is calculated from the same data set as the other solutions did. Therefore, it is comparable with other impact values given in Table 6.22.This suggests that impact value of Scenario 3 would be close to the 4506, which is much higher than impact value of other solutions. This outcome underlines the importance of applying countrywide studies as much as possible. When regional optimization is applied first and regional decisions are used for countrywide implementation, the results are worse than countrywide scale case. According to this reasoning and the fact that cost of regional management is the second highest, it is the first option to be eliminated.

Obviously, Scenario 1 is not eligible to be the final recommendation since it can only be used for comparison purposes. This leaves us Scenario 2 in which co-incineration practices are used and Scenario 4 in which co-incineration is applied along with a transfer station network. Scenario 4 solution results in nearly half of the impact value of Scenario 2 solution with only a 5% increase in total cost. This means that co-incineration practices along with establishment of a transfer station network turns out to give most satisfactory results for hazardous waste management of Turkey. Advantage brought by co-incineration practices on incineration costs has already been discussed previously, which creates a second motivation for selection of this alternative.

The unit cost of management for selected Scenario, including establishment of additional facilities with a transfer station network and transportation is 368.75 TL/ton/yr for a 20-year period.

According to the to proposed configuration, **incinerators** in *Adana, Afyon, Ankara, Bursa, Çorum, Erzurum, İzmir, Kocaeli, Manisa* and *Kahramanmaraş* and **landfills** in

Adana, *Afyon*, *Ankara*, *Bursa*, *Erzurum*, *İstanbul*, *Kocaeli*, *Konya*, *Manisa* and *Sakarya* should be established.

Previous studies that suggest facility locations for Turkey are Environmental Heavy-Cost Investment Planning Directive-Specific Investment Plan for Council Directive on Hazardous Waste (91/689/EEC)" Project and LIFE HAWAMAN Project [2, 90]. According to [2], establishment of five incinerators and landfills are suggested with identical locations of Kocaeli, Thrace, Ankara, İzmir and Adana/Mersin. Locations proposed in [90] for integrated facilities are İstanbul, Kocaeli, İzmir, Ankara and Adana. Clearly, the results obtained in current study supports the selections made in previous studies in terms of locations. However, it is shown that small numbers of facilities create high transportation impact, which was not considered in any previous projects.

CHAPTER 7

CONCLUSIONS

In this chapter, a brief summary of the study and major findings and recommendations on hazardous waste management system are summarized. The recommendations as a whole draw the outline of the framework for hazardous waste management system that was intended to be provided for the MoEF. This framework covers hazardous wastes of various types generated in 81 provinces of Turkey to be allocated to four types of facilities (recovery, treatment, incineration and landfilling) through routes with the smallest cost and impact as much as possible.

Four scenarios are evaluated in order to compare different management approaches. First scenario assumes no facilities exist in Turkey. Second scenario considers the existing facilities and cement kilns used for co-incineration purposes. In the third scenario, regional hazardous waste management is evaluated. Lastly, effect of a transfer station network on previous scenarios is inspected.

In order to model HWMS in Turkey, linear programming models are developed for abovementioned scenarios and aim to minimize cost and impact of the system. The models developed include transportation and facility costs as components of total cost. For determination of transportation costs unit transportation costs are used. However, as a result of economy of scale principle, it is decided that single unit investment and operational costs cannot be used. According to this principle, there is an inverse relation between capacities and unit facility costs which is non-linear. Inclusion of these non-linear cost relations in objective function causes the models to lose their linearity. Facility costs cannot be ignored since they have a high share in total hazardous waste management cost. Instead facility costs are calculated manually after models solved only based transportation cost and transportation impact.

Model solutions obtained provides information on total transportation cost and impact, amounts of wastes allocated to each facility i.e. annual capacity requirements of each facility and locations of facilities. After capacities are determined for each facility, by using unit investment and operational costs suitable for that capacity, facility costs are calculated. During comparison of results of both subscenarios and scenarios, always total cost is considered.

Components of impact objective are population impact and environmental impact of transportation. Population impact of hazmat and hazardous waste transportation is well-studied in literature. Unfortunately, environmental impacts of hazardous waste transportation did not draw much attention up to now. A new approach for determination of environmental impacts is proposed in this study. Results suggest that environmental impact has a greater share in total impact and is more influential is selection of facility locations than population impact. This situation underlines the importance of considering both aspects of transportation impact.

A summary of comparison of the scenarios covered in the study is presented in Table 7.1

Table 7.1 Comparison of scenarios

	Scenario 1	Scenario 2	Scenario 4
Total cost (TL/yr)	533,335,000	479,125,000	502,700,000
Total impact	2134	2246	1383
% change in cost – with respect to base scenario	--	10.2%	5.7%
% change in impact – with respect to base scenario	--	5.2 %	- 36.6%

Comparison of results of scenarios indicates that most satisfactory results especially in terms of impact is obtained by combining designated hazardous waste facilities, co-incineration and transfer stations. Risks created by hazardous wastes and resulting high costs are important aspects of HWMS that must be taken into account during planning and implementation stages. A successful planning and implementation process should bring some means to improve these two aspects. Addition of transfer stations provides a significant improvement in transportation impact as much as approximately 40%. On the other hand, co-incineration practices causes incineration costs to decrease when compared to cases where cement kilns are not used. This is an important outcome since incineration costs is the major cost component in overall cost. In summary, with the proposed management approach decrease in both total cost and impact of the system is achieved.

According to the proposed configuration; **incinerators** in *Adana*, *Afyon*, *Ankara*, *Bursa*, *Çorum*, *Erzurum*, *İzmir*, *Kocaeli*, *Manisa* and *Kahramanmaraş* and **landfills** in *Adana*, *Afyon*, *Ankara*, *Bursa*, *Erzurum*, *İstanbul*, *Kocaeli*, *Konya*, *Manisa* and *Sakarya* should be established. Among these Kocaeli and İzmir incinerators and Kocaeli and Manisa landfills already exist and the rest is suggestions for new facilities. Transfer stations that serve, as localized treatment plants are also among the recommendation. As can be observed from the list of facility locations most of the facilities match meaning that integrated facilities are favored.

The intention of this study was to present a framework to MoEF that would be helpful for future implementation and development of HWMS in Turkey. In this study, locations and capacities (Table 6.21) of new facilities are determined. These suggestions would help MoEF to guide future investments and evaluate locations of applications done by facility developers. In addition to this important contribution, additional suggestions include:

- Requirement for capacity increase in exisiting facilities: Results confirm locations of İZAYDAŞ incinerator and landfill in Kocaeli, PETKİM incinerator in İzmir. Additional capacity requirement for Kocaeli is 10,000 tons/yr if an incinerator in İstanbul can be established. Otherwise, the need for additional capacity increases to 42,000 tons/yr. For İzmir case, if a second facility to be established in İzmir, an additional 100,000 capacity is required. Given high amount of additional capacity also establishment of an integrated facility in Manisa can be considered. This alternative is justified according to the results of Scenario 2.
- Common choices for every hazardous waste management approach: Adana, Ankara, Balıkesir and İzmir are locations for treatment plants selected in all scenarios and therefore, are recommended as proposed locations for future treatment plants. For incineration plants, Adana and Ankara are proposed. Moreover, İzmir, Kocaeli and Çorum are locations given by at least three scenarios. Adana and Ankara should also have landfills according all four results. İstanbul and Kocaeli are other provinces in which a landfill should be built. This item is very important in that even if a different management approach is adopted by MoEF, results of this study can still be useful. These common choices decrease the uncertainty up to a certain extend.
- Distribution of facilities across the country: No previous study suggested establishment of an integrated facility in Eastern part of Turkey due to low number of facilities considered. However, it is shown that low number of high capacity facilities help to decrease total cost but associated transportation impacts are very high. As number of facilities increased, the model solutions always include a facility either in Soutern Eastern or Eastern Region of Turkey. This facility that serves high number of low waste generating facilities is believed to play part in decrease in impact as facility numbers increased.

CHAPTER 8

RECOMMENDATIONS FOR FUTURE STUDIES

Possible future studies that based on this study can be listed as follows:

- In this study, it is foreseen that all hazardous waste transportation is carried out via highways. Use of railway as a means of hazardous waste transportation is an attractive alternative given that in Turkey probability of railway accidents are much lower than highway accident probabilities. Moreover, it is possible to transport higher volumes by railway in a single shipment.
- Further inquiries on co-incineration practices is another possible future study. The total potential of co-incineration in Turkey is not being used due to two reasons. First of all, not all cement factories are licenced to incinerate hazardous wastes. Secondly, the amount of wastes incinerated in cement kilns are way below the amount permitted by liceses. More detailed optimization studies that focus on co-incineration would guide both MoEF and cement industry for future practices.
- Due to absence of hazardous waste generation data, an inventory is constructed in the scope of this study. It is believed that when a reliable hazardous waste inventory is compiled with the help of annual declarations of waste generators, models developed in this study can be used by MoEF and the results fo this study can be verified.

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APPENDIX A

EVAUCATION DISTANCES

Table A. 1Distances for impact zones for ADR classes [80]

Class	Definition	Danger Zone (m)	Condition
****	Mixed load / unidenfied cargo	100	isolate spill or leak
		800	if tank, rail car or tank truck is involved in fire
1.1	Explosives	500	isolate spill or leak
1.2		800	large spill
1.3		1600	if rail car or trailer is involved + heavily encased explosives
1.5		800	no heavily encased explosives
1.6A			
1.6B			
1.4	Explosives	100	isolate spill or leak
		250	large spill
		500	if tank, rail car or tank truck is involved in fire
2	Gases - flammable	100	isolate spill or leak
	Gases - flammable - corrosive	800	large spill
		1600	if tank, rail car or tank truck is involved in fire
2	Gases - flammable + toxic	100	isolate spill or leak
		1600	if tank, rail car or tank truck is involved in fire
2	Gases - inert	100	isolate spill or leak
		100	large spill
		800	if tank, rail car or tank truck is involved in fire
2	Gases - oxidizing	100	isolate spill or leak
	Gases - compressed or liquefied	500	large spill
		800	if tank, rail car or tank truck is involved in fire
2	Gases - toxic and/or corrosive	100	isolate spill or leak
	Gases - toxic and/or corrosive - oxidizing	800	if tank, rail car or tank truck is involved in fire

Table A. 1 continued

Class	Definition	Danger Zone (m)	Condition
2	Gases - corrosive	100 1600	isolate spill or leak if tank, rail car or tank truck is involved in fire
3	Flammable liquids - polar/water miscible Flammable liquids - nonpolar/immiscible Flammable liquids - polar/miscible/noxious Flammable liquids - nonpolar/immiscible/noxious	50 300 800	isolate spill or leak large spill if tank, rail car or tank truck is involved in fire
3	Flammable liquids - toxic Flammable liquids - corrosive	50 800	isolate spill or leak if tank, rail car or tank truck is involved in fire
3	Carbon monoxide - refrigerated liquid	100 1600	isolate spill or leak if tank, rail car or tank truck is involved in fire
4.1	Flammable solids Flammable solids - toxic and/or corrosive	100 800	large spill if tank, rail car or tank truck is involved in fire
4.1	Flammable Solids - Toxic	100 500 800	isolate spill or leak large spill if tank, rail car or tank truck is involved in fire
4.1	Substances - self reactive Substances - self reactive - temperature controlled	250 800	large spill if tank, rail car or tank truck is involved in fire
4.2	Substances - spontaneously combustible	800	if tank, rail car or tank truck is involved in fire
4.2	Substances - spontaneously combustible - toxic and/or corrosive	300 800	spill if tank, rail car or tank truck is involved in fire
4.3	Substances - water reactive - emitting flammable gases	50 25 800	isolate spill or leak - liquids isolate spill or leak - solids if tank, rail car or tank truck is involved in fire
4.3	Substances - water reactive - emitting flammable and toxic gases	50 25 800	isolate spill or leak - liquids isolate spill or leak - solids if tank, rail car or tank truck is involved in fire

Table A. 1 continued

Class	Definition	Danger Zone (m)	Condition
5.1	Oxidizers Oxidizers - toxic	50 25 100 800	isolate spill or leak - liquids isolate spill or leak - solids large spill if tank, rail car or tank truck is involved in fire
5.1	Oxidizers - toxic - liquid	50 800	isolate spill or leak - liquids
5.1	Oxidizers - unstable Oxidizers - water reactive	50 25 800	isolate spill or leak - liquids isolate spill or leak - solids if tank, rail car or tank truck is involved in fire
5.2	Organic peroxides - heat and contamination sensitive Organic peroxides - heat, contamination and friction sensitive	50 25 250 800	isolate spill or leak - liquids isolate spill or leak - solids large spill if tank, rail car or tank truck is involved in fire
5.2	Organic peroxides - heat and contamination sensitive / temperature controlled	250 800	large spill if tank, rail car or tank truck is involved in fire
6.1	Substances - toxic - non-combustible Substances - toxic - combustible Substances - toxic and/or corrosive - combustible Substances - toxic and/or corrosive - non-combustible Substances - toxic and/or corrosive - flammable/water sensitive Substances - toxic and/or corrosive - combustible/water sensitive Substances - toxic and/or corrosive - non-combustible/water sensitive	50 25 800	isolate spill or leak - liquids isolate spill or leak - solids if tank, rail car or tank truck is involved in fire
6.1	Halogenated solvents	50 300 800	isolate spill or leak large spill if tank, rail car or tank truck is involved in fire

Table A. 1 continued

Class	Definition	Danger Zone (m)	Condition
6.1	Fluorine - refrigerated liquid	100	isolate spill or leak
		1600	if tank, rail car or tank truck is involved in fire
6.2	Infectious substances	****	
7	Radioactive materials - low level radiation	25	isolate spill or leak
	Radioactive materials - low to moderate level	100	large spill
	Radioactive materials - moderate to high level	300	fire
8	Substances - water reactive - corrosive	50	isolate spill or leak - liquids
		25	isolate spill or leak - solids
		800	if tank, rail car or tank truck is involved in fire
8	Substances - irritating	50	isolate spill or leak - liquids
		25	isolate spill or leak - solids
		800	if tank, rail car or tank truck is involved in fire
9 M4	Lithium ion batteries	100	large spill
		500	if tank, rail car or tank truck is involved in fire
9 M7	Gallium and mercury	50	isolate spill or leak
		100	large spill
		500	fire
9 M11	Metals - powders, dusts, shavings, borings, turnings and cuttings	50	isolate spill or leak - liquids
		25	isolate spill or leak - solids
	Substances - low to moderate hazard	800	if tank, rail car or tank truck is involved in fire

APPENDIX B

IMPACT DATA

Sample data set is presented for population impact Marmara Region specified in Scenario 3 in Table A. 2. In Table A. 3 normalized value for this data set can be found. Normalized set is obtained by dividing every term in Table A. 2 by the maximum value of the data set in the same table that is 1,352,521 people/trip. Similarly, in Table A. 4 and Table A. 5 environmental impact values for Marmara Region and normalized values can be seen.

Table A. 2 Population impact values for Marmara Region (people/trip)

	Balıkesir	Bilecik	Bolu	Bursa	İstanbul	Kocaeli	Sakarya	Zonguldak	Düzce
Balıkesir	0	79633	184205	35625	1352521	487794	141254	425519	153635
Bilecik	79633	0	68573	73464	956901	92174	55190	341476	69105
Bolu	184205	68573	0	181180	944693	79966	41975	49307	21574
Bursa	35625	73464	181180	0	1310125	445398	135916	419920	148036
İstanbul	1352521	956901	944693	1310125	0	571388	899429	1184657	912773
Kocaeli	487794	92174	79966	445398	571388	0	2503	338751	66867
Sakarya	141254	55190	41975	135916	899429	2503	0	191118	64364
Zonguldak	425519	341476	49307	419920	1184657	338751	191118	0	137456
Düzce	153635	69105	21574	148036	912773	66867	64364	137456	0

Table A. 3 Normalized population impact values for Marmara Region

	Balıkesir	Bilecik	Bolu	Bursa	İstanbul	Kocaeli	Sakarya	Zonguldak	Düzce
Balıkesir	0.0000	0.0589	0.1362	0.0263	1.0000	0.3607	0.1044	0.3146	0.1136
Bilecik	0.0589	0.0000	0.0507	0.0543	0.7075	0.0681	0.0408	0.2525	0.0511
Bolu	0.1362	0.0507	0.0000	0.1340	0.6985	0.0591	0.0310	0.0365	0.0160
Bursa	0.0263	0.0543	0.1340	0.0000	0.9687	0.3293	0.1005	0.3105	0.1095
İstanbul	1.0000	0.7075	0.6985	0.9687	0.0000	0.4225	0.6650	0.8759	0.6749
Kocaeli	0.3607	0.0681	0.0591	0.3293	0.4225	0.0000	0.0019	0.2505	0.0494
Sakarya	0.1044	0.0408	0.0310	0.1005	0.6650	0.0019	0.0000	0.1413	0.0476
Zonguldak	0.3146	0.2525	0.0365	0.3105	0.8759	0.2505	0.1413	0.0000	0.1016
Düzce	0.1136	0.0511	0.0160	0.1095	0.6749	0.0494	0.0476	0.1016	0.0000

Table A. 4 Environmental impact values for Marmara Region (m/trip)

	Balıkesir	Bilecik	Bolu	Bursa	İstanbul	Kocaeli	Sakarya	Zonguldak	Düzce
Balıkesir	0	378520	631820	165250	422680	399480	375170	793040	599270
Bilecik	378520	0	345300	129470	179190	155990	134100	429700	204300
Bolu	631820	345300	0	360870	218490	195290	173400	141670	38200
Bursa	165250	129470	360870	0	229700	206500	187470	463070	284470
İstanbul	422680	179190	218490	229700	0	23200	45090	280090	135290
Kocaeli	399480	155990	195290	206500	23200	0	25000	324150	172950
Sakarya	375170	134100	173400	187470	45090	25000	0	359000	120700
Zonguldak	793040	429700	141670	463070	280090	324150	359000	0	170850
Düzce	599270	204300	38200	284470	135290	172950	120700	170850	0

Table A. 5 Normalized environmental impact values for Marmara Region

	Balıkesir	Bilecik	Bolu	Bursa	İstanbul	Kocaeli	Sakarya	Zonguldak	Düzce
Balıkesir	0.0000	0.4773	0.7967	0.2084	0.5330	0.5037	0.4731	1.0000	0.7557
Bilecik	0.4773	0.0000	0.4354	0.1633	0.2260	0.1967	0.1691	0.5418	0.2576
Bolu	0.7967	0.4354	0.0000	0.4550	0.2755	0.2463	0.2187	0.1786	0.0482
Bursa	0.2084	0.1633	0.4550	0.0000	0.2896	0.2604	0.2364	0.5839	0.3587
İstanbul	0.5330	0.2260	0.2755	0.2896	0.0000	0.0293	0.0569	0.3532	0.1706
Kocaeli	0.5037	0.1967	0.2463	0.2604	0.0293	0.0000	0.0315	0.4087	0.2181
Sakarya	0.4731	0.1691	0.2187	0.2364	0.0569	0.0315	0.0000	0.4527	0.1522
Zonguldak	1.0000	0.5418	0.1786	0.5839	0.3532	0.4087	0.4527	0.0000	0.2154
Düzce	0.7557	0.2576	0.0482	0.3587	0.1706	0.2181	0.1522	0.2154	0.0000

APPENDIX C

WASTE CLASSES ACCORDING TO ANNEX 3 OF RCHW

Annex 3-A:

1. anatomical substances; hospital and other clinical wastes;
2. pharmaceuticals, medicines and veterinary compounds;
3. wood preservatives;
4. biocides and phyto-pharmaceutical substances;
5. residue from substances employed as solvents;
6. halogenated organic substances not employed as solvents excluding inert polymerized materials;
7. tempering salts containing cyanides;
8. mineral oils and oily substances (e.g. cutting sludges, etc.);
9. . oil/water, hydrocarbon/water mixtures, emulsions;
10. substances containing PCBs and/or PCTs (e.g. dielectrics etc.);
11. tarry materials arising from refining, distillation and any pyrolytic treatment (e.g. still bottoms, etc.);
12. inks, dyes, pigments, paints, lacquers, varnishes;
13. resins, latex, plasticizers, glues/adhesives;
14. chemical substances arising from research and development or teaching activities which are not identified and/or are new and whose effects on man and/or the environment are not known (e.g. laboratory residues, etc.);
15. pyrotechnics and other explosive materials;
16. photographic chemicals and processing materials;
17. any material contaminated with any congener of polychlorinated dibenzo-furan;
18. any material contaminated with any congener of polychlorinated dibenzo-p-dioxin.

Annex 3-B:

19. animal or vegetable soaps, fats, waxes;
20. non-halogenated organic substances not employed as solvents;
21. inorganic substances without metals or metal compounds;
22. ashes and/or cinders;
23. soil, sand, clay including dredging spoils;
24. non-cyanidic tempering salts;
25. metallic dust, powder;
26. spent catalyst materials;
27. liquids or sludges containing metals or metal compounds;
28. residue from pollution control operations (e.g. baghouse dusts, etc.) except (29), (30) and (33);
29. scrubber sludges;
30. sludges from water purification plants;
31. decarbonization residue;
32. ion-exchange column residue;
33. sewage sludges, untreated or unsuitable for use in agriculture;
34. residue from cleaning of tanks and/or equipment;
35. contaminated equipment;
36. contaminated containers (e.g. packaging, gas cylinders, etc.) whose contents included one or more of the constituents listed in Annex II;
37. batteries and other electrical cells;
38. vegetable oils;
39. materials resulting from selective waste collections from households and which exhibit any of the characteristics listed in Annex III;
40. any other wastes which contain any of the constituents listed in Annex II and any of the properties listed in Annex III.

ADJUSTED WASTE CLASSES

1. Medical wastes
2. Waste pharmaceuticals, medicines and wastes from manufacture of pharmaceuticals and medicines
3. Waste wood preservatives
4. Waste biocides and phyto-pharmaceutical substances
5. Waste solvents
6. Halogenated organics including solvents, wood preservatives, oils, organic chemical industry wastes
7. Tempering salts containing cyanides
8. Waste oils and oily wastes
9. Oil/water, hydrocarbon/water emulsions
10. PCB containing wastes
11. Tarry wastes
12. Waste inks, dyes, pigments, paints, lacquers, varnishes, glues, adhesives and wastes from manufacturing of inks, dyes, pigments, paints, lacquers, varnishes, glues and adhesives
13. Laboratory chemicals
14. Explosive wastes
15. Photographic chemicals and processing materials
16. Non-halogenated organic wastes – excepts solvents
17. Inorganic wastes that do not contain heavy metals
18. Waste ash and cinder
19. Waste soil and sand
20. Non-cyanic tempering salts
21. Spent catalysts
22. Liquids and sludges containing metals or metal compounds

23. Solid wastes from pollution control operations
24. Sludges and filter cakes from gas treatment
25. Ion exchange column residues
26. Sludges from treatment operations
27. Tank bottom sludges
28. Contaminated equipment
29. Contaminated container and packaging
30. Waste batteries and accumulators
31. Solid wastes containing metals and metal compounds
32. Waste gasses from pressurized tanks containing dangerous substances
33. Liquid hazardous wastes sent to off-site treatment
34. Waste refractory materials not otherwise specified
35. Other hazardous solid wastes
36. Household hazardous wastes not classified elsewhere

Table A. 6 Six-digit wastes categorized under Annex 3 classification

Waste class *	Six-digit waste code	Waste class *	Six-digit waste code	Waste class *	Six-digit waste code
1	18 01 03*	6	07 05 09*	8	13 01 11*
	18 01 06*		07 06 03*		13 01 12*
	18 01 08*		07 06 07*		13 01 13*
	18 01 10*		07 06 09*		13 02 05*
	18 02 02*		07 07 03*		13 02 06*
	18 02 05*		07 07 07*		13 02 07*
2	07 05 13*		07 07 09*		13 02 08*
	18 02 07*		12 01 06*		13 03 07*
	20 01 31*		12 01 08*		13 03 08*
3	03 02 01*		13 01 04*		13 03 09*
	03 02 03*		13 01 09*		13 03 10*
	03 02 04*		13 02 04*		13 04 01*
	03 02 05*		13 03 06*		13 04 02*
4	02 01 08*		14 06 02*		13 04 03*
	20 01 19*		14 06 04*		13 07 01*
5	07 01 04*	7	11 03 01*		13 07 02*
	07 02 04*	8	01 05 05*		13 07 03*
	07 03 04*		04 01 03*		16 01 07*
	07 04 04*		05 01 02*		16 07 08*
	07 05 04*		05 01 05*		17 04 10*
	07 06 04*		05 01 06*		19 02 07*
	07 07 04*		05 01 12*		19 08 09*
	14 06 01*		05 01 15*		19 08 10*
	14 06 03*		08 03 19*		19 11 01*
	14 06 05*		08 04 17*		19 11 03*
	20 01 13*		10 02 11*		19 11 04*
6	03 02 02*		10 03 27*		19 11 05*
	07 01 03*		10 04 09*		20 01 26*
	07 01 07*		10 05 08*	9	12 01 09*
	07 01 09*		10 06 09*		13 01 05*
	07 02 03*		10 07 07*		13 05 01*
	07 02 07*		10 08 19*		13 05 02*
	07 02 09*		11 01 13*		13 05 03*
	07 03 03*		12 01 07*		13 05 06*
	07 03 07*		12 01 10*		13 05 07*
	07 03 09*		12 01 12*		13 05 08*
	07 04 03*		12 01 18*		13 08 01*
	07 04 07*		12 01 19*		13 08 02*
	07 04 09*		12 03 01*		
	07 05 03*		12 03 02*		
	07 05 07*		13 01 10*		

* waste class number are same as the previous list

Table A. 6 continued

Waste class *	Six-digit waste code	Waste class *	Six-digit waste code	Waste class *	Six-digit waste code
10	13 01 01*	15	09 01 05*	17	06 01 03*
	13 03 01*		09 01 06*		06 01 04*
	16 01 09*		09 01 11*		06 01 05*
	16 02 09*		09 01 13*		06 01 06*
	16 02 10*		20 01 17*		06 02 01*
	17 09 02*	16	03 01 04*		06 02 03*
11	05 01 07*		04 02 14*		06 02 04*
	05 01 08*		07 01 01*		06 02 05*
	05 06 01*		07 01 08*		06 03 11*
	05 06 03*		07 01 10*		06 06 02*
	10 03 17*		07 02 01*		06 07 01*
	10 08 12*		07 02 08*		06 07 02*
	17 03 03*		07 02 10*		06 07 04*
	19 11 02*		07 02 14*		06 08 02*
12	04 02 16*		07 02 16*		06 09 03*
	08 01 11*		07 03 01*		06 10 02*
	08 01 13*		07 03 08*		06 13 01*
	08 01 15*		07 03 10*		06 13 02*
	08 01 17*		07 04 01*		06 13 04*
	08 01 19*		07 04 08*		08 05 01*
	08 01 21*		07 04 10*		10 01 09*
	08 03 12*		07 04 13*		10 01 22*
	08 03 14*		07 05 01*		10 03 04*
	08 03 16*		07 05 08*		10 03 08*
	08 03 17*		07 05 10*		10 03 09*
	08 04 09*		07 06 01*		10 03 15*
	08 04 11*		07 06 08*		10 04 01*
	08 04 13*		07 06 10*		10 04 02*
	08 04 15*		07 07 01*		10 04 03*
	20 01 27*		07 07 08*		10 05 10*
13	16 05 06*		07 07 10*		10 08 08*
	16 05 07*		16 01 13*		10 08 10*
	16 05 08*		16 03 05*		10 09 05*
14	16 01 10*		19 02 08*		10 09 07*
	16 04 01*		19 02 09*		10 09 13*
	16 04 02*		19 12 06*		10 09 15*
	16 04 03*		20 01 37*		10 10 05*
15	09 01 01*	17	05 01 04*		10 10 07*
	09 01 02*		05 01 11*		10 10 13*
	09 01 03*		06 01 01*		10 10 15*
	09 01 04*		06 01 02*		10 11 09*

[*] waste class number are same as the previous list

Table A. 6 continued

Waste class *	Six-digit waste code	Waste class *	Six-digit waste code	Waste class *	Six-digit waste code
17	10 11 13*	18	10 04 04*	23	11 05 03*
	10 13 09*		10 04 05*		19 01 07*
	11 01 05*		10 05 03*		19 01 10*
	11 01 06*		10 06 03*		19 04 02*
	11 01 07*		10 08 15*		19 11 07*
	11 01 08*		10 09 09*	24	10 02 13*
	11 01 11*		19 01 11*		10 03 25*
	11 01 11*		19 01 13*		10 04 07*
	11 01 98*		19 01 15*		10 05 06*
	11 02 05*		19 01 17*		10 06 07*
	11 02 07*	19	01 05 06*		10 08 17*
	11 03 01*		17 05 03*		10 11 17*
	12 01 16*		19 13 01*		19 01 05*
	12 01 20*	20	11 03 02*	25	11 01 15*
	16 01 11*	21	16 08 02*		11 01 16*
	16 01 14*		16 08 05*		19 08 06*
	16 02 12*		16 08 06*		19 08 07*
	16 02 13*		16 08 07*	26	04 02 19*
	16 03 03*	22	01 03 04*		05 01 09*
	16 09 01*		01 03 05*		06 05 02*
	16 09 02*		01 03 07*		07 01 11*
	16 09 03*		01 04 07*		07 02 11*
	16 09 04*		05 07 01*		07 03 11*
	17 05 05*		10 12 11*		07 04 11*
	17 05 07*		11 01 09*		07 05 11*
	17 06 01*		11 02 02*		07 06 11*
	17 06 03*		10 05 04*		07 07 11*
	17 06 05*		12 01 14*		10 01 20*
	17 08 01*		19 08 08*		19 02 05*
	17 09 03*	23	10 01 18*		19 08 11*
	20 01 14*		10 02 07*		19 08 13*
	20 01 15*		10 03 23*		19 13 03*
18	06 13 05*		10 04 06*		19 13 05*
	10 01 04*		10 05 05*	27	05 01 03*
	10 01 13*		10 06 06*		16 07 09*
	10 01 14*		10 11 15*		
	10 01 16*		10 11 19*		
	10 03 19*		10 12 09*		
	10 03 21*		10 13 12*		
	10 03 29*		10 14 01*		

* waste class number are same as the previous list

Table A. 6 continued

Waste class *	Six-digit waste code	Waste class *	Six-digit waste code	Waste class *	Six-digit waste code
28	16 01 04*	31	06 03 15*	33	19 02 04*
	16 01 21*		06 04 03*		19 07 02*
	16 02 11*		06 04 04*		19 13 07*
	16 02 15*		06 04 05*	34	16 11 01*
	20 01 23*		10 09 11*		16 11 03*
	20 01 35*		10 10 11*		16 11 05*
29	15 01 10*		10 11 11*		17 01 06*
	15 01 11*		17 04 19*		17 02 04*
	15 02 02*		17 09 01*	35	19 03 04*
30	16 06 01*		19 10 03*		19 03 06*
	16 06 02*		19 10 05*		19 04 03*
	16 06 03*		20 01 21*		19 12 11*
	16 06 06*	32	16 05 04*	36	20 01 29*
	20 01 33*	33	16 10 01*		
31	06 03 13*		16 10 03*		

waste class number are same as the previous list

APPENDIX D

WASTE GENERATION FACTORS

Waste generation factors used in determination of hazardous waste generation is compiled from literature and presented in Table A.7 in following pages.

Table A. 7 Collection of waste generation factors used in the study

Waste Entry / Type	Waste generation factor	Unit	Ref	Contribution (%)
13 02	**waste engine, gear and lubricating oils**			**18.58**
Waste engine oil from automobiles	5.28	kg/yr/vehicle	[102]	1.96
Waste engine oil from minibuses	29.48	kg/yr/vehicle	[102]	0.63
Waste engine oil from buses	370.92	kg/yr/vehicle	[102]	3.96
Waste engine oil from small trucks	44.44	kg/yr/vehicle	[102]	4.69
Waste engine oil from trucks	105.60	kg/yr/vehicle	[102]	4.47
Waste engine oil from motorcycles	7.48	kg/yr/vehicle	[102]	0.84
Waste engine oil from tractors	26.14	kg/yr/vehicle	[102]	2.02
01 03	**wastes from physical and chemical processing of metalliferous minerals**			**12.81**
Tailings generated from lead-zinc mining	0.94	ton tailings/ ton of matl handled	[103]	0.80
Tailings generated from copper mining	1.00	ton tailings/ton of matl handled	[103]	6.85
Tailings generated from iron mining	0.46	ton tailings/ ton of matl handled	[103]	4.05
Tailings generated from bauxite mining	0.37	ton tailings/ton of material handled	[104]	1.11
11 01	**wastes from chemical surface treatment and coating of metals and other materials zinc coating processes, pickling processes, etching,**			**9.27**
Phosphatising sludge	2.4*10-4	L/m2 of surface processed	[105]	0.00
Waste emulsion containing oil from degreasing	0.05	kg/ton of metal processed	[106]	0.00
Oily sludge from degreasing in batch galvanization	0.16	kg/ton of metal processed	[106]	0.00
Discarded degreasing bath	1.5	kg/ton of metal processed	[106]	0.00

Table A. 7 continued

Waste Entry / Type	Waste generation factor	Unit	Ref	Contribution (%)
11 01	**wastes from chemical surface treatment and coating of metals and other materials zinc coating processes, pickling processes, etching,**			**9.27**
Spent wet drawing emulsion from wire drawing	100	L/ton of metal processed	[106]	3.50
07 05	**wastes from the MFSU of pharmaceuticals**			**8.60**
Organic solvents	10	kg/kg of active pharm. ingredient	[107]	8.60
07 04	**wastes from the MFSU of organic plant protection products , wood preserving agents and other biocides**			**7.38**
Hazardous waste from active ingredient manufacture of organic biocides	200	kg/ton of active ingredient	[108]	7.22
Hazardous waste from formulation of organic biocides	3.5	kg/ton of formulated product	[108]	0.16
10 01	**wastes from power stations and other combustion plants (except 19)**			**6.09**
Fly-ash from emulsified hydrocarbons used as a fuel	120	t/MW	[109]	6.09
07 02	**wastes from the MFSU of plastics, synthetic rubber and man-made fibres**			**5.82**
Organic sludge from ethylene cracking	1.20	kg/ton of ethylene	[110]	0.03
Hazardous waste from low density polyethylene manufacture	4.60	kg/ton of LDPE	[111]	0.08
Hazardous waste from high density polyethylene manufacture	3.90	kg/ton of HDPE	[111]	0.02
Activated carbon and filter cloth from aromatics manufacture	0.02	kg/ton of aromatics	[110]	Negligible

Table A. 7 continued

Waste Entry / Type	Waste generation factor	Unit	Ref	Contribution (%)
07 02	**wastes from the MFSU of plastics, synthetic rubber and man-made fibres**			**5.82**
Liquid effluent from ethylene oxide recovery	150	kg/ton of EO	[110]	Negligible
Solid effluent from EO recovery	5.25	kg/ton of EO	[110]	Negligible
Heavy glycols	50	kg/ton of EO	[110]	Negligible
Stripper bottom from acrylonitrile manufacture	1	ton/ton of ACN	[110]	5.39
Liquid residues from vinyl chloride monomer manufacture	32.5	kg/ton of VCM	[110]	0.25
Direct chlorination residue from vinyl chloride monomer manufacture	30	g/ton of VCM	[110]	Negligible
Coke from vinyl chloride monomer manufacture	0.15	kg/ton of VCM	[110]	Negligible
Tars from purification of vinyl chloride monomer	0.68	g/ton of VCM	[110]	Negligible
Hazardous wastes from emulsion process of polyvinyl chloride manufacture	1.20	kg/ton of PVC	[111]	Negligible
Hazardous wastes from polypropylene manufacture	3.90	kg/ton of PP	[111]	0.02
Solid wastes from polystyrene manufacture	0.6	kg/ton of PS	[111]	Negligible
Hazardous wastes from styrene butadiene rubber manufacture	3.00	kg/ton of SBR	[111]	0.03
07 03	**wastes from the MFSU of organic dyes and pigments**			**5.56**
Aqueous washing liquids and mother liquids from organic dye and pigment manufacture	7.00	t/ton of product	[112]	5.56

APPENDIX E

WASTE GENERATION

Table A. 8 Waste generation in provinces

Waste classes	W1	W2	W3	W4	W5	W6	W7	TOTAL
Adana	4,300	11,742	13	197	401	22,366	699	39,718
Adıyaman	531	136	0	0	62	1,202	313	2,245
Afyon	13,152	288	0	392	466	14,890	201	29,389
Ağrı	352	90	0	0	57	872	66	1,437
Amasya	1,924	2,007	0	0	35	7219	97	11,281
Ankara	11,052	11,842	771	1,052	2,148	33,046	13,791	73,702
Antalya	5,485	2,895	17	17	199	14,758	1,972	25,342
Artvin	304	51	0	0	18	643	6,036	7,052
Aydın	3,194	729	0	0	103	5,474	890	10,391
Balıkesir	4,042	2,672	18	3,011	14,614	12,427	904	37,688
Bilecik	488	87	0	63	84	913	61	1,696
Bingöl	157	37	0	0	27	463	28	713
Bitlis	210	53	0	0	35	541	39	877
Bolu	821	160	633	938	334	1,708	644	5,237
Burdur	741	152	17	518	528	1,577	351	3,883
Bursa	6,161	10,202	755	825	517	21,186	13,176	52,823
Çanakkale	2,157	296	0	0	51	3,251	225	5,980
Çankırı	300	66	0	0	19	617	46	1,047
Çorum	13,093	2,098	632	632	58	18,851	418	35,781
Denizli	3,388	465	4	339	433	5,652	608	10,889
Diyarbakır	1,107	272	0	0	159	3,231	199	4,968
Edirne	989	275	0	0	42	2,298	213	3,817
Elazığ	679	163	18	18	58	2,014	365	3,316
Erzincan	320	71	0	0	11,522	711	50	12,675
Erzurum	876	203	17	17	83	2,511	394	4,099
Eskişehir	2,764	367	17	216	279	4,992	11,412	20,045
Gaziantep	2,484	1,311	667	667	172	6,082	5,053	16,436
Giresun	597	114	0	0	45	1,339	81	2,176
Gümüşhane	168	36	0	0	14	374	25	617
Hakkari	125	34	0	0	28	350	26	561
Hatay	2,801	498	21	110	240	5,443	890	10,002
Isparta	974	199	17	17	44	2,211	384	3,845
Mersin	5360	5,287	21	476	627	20,440	2,303	34,513
İstanbul	33,186	13,521	1,722	1,847	1,635	71,436	136,535	259,882
İzmir	24,439	27,944	2,756	2,778	427	70,084	49,801	178,229
Kars	358	83	0	0	33	762	59	1,295
Kastamonu	808	177	0	0	100,038	1,632	123	102,778

Table A. 8 continued

Waste classes	W1	W2	W3	W4	W5	W6	W7	TOTAL
Kayseri	2,431	594	39	39	3,651	5,211	6,035	18,000
Kırklareli	1,711	172	2	2	36	2,395	126	4,443
Kırşehir	690	1,942	0	0	24	5,692	67	8,415
Kocaeli	18,751	2,792	2,836	3,044	402	29,671	42,951	100,447
Konya	6,572	4,176	648	648	22,080	19,974	23,433	77,530
Kütahya	1,315	280	2	381	440	2,710	9,862	14,989
Malatya	1,294	2,085	2	2	33,198	7,379	170	44,129
Manisa	16,398	2,507	34	34	141	24,160	5,697	48,971
K.maraş	1,235	9,192	0	0	110	11,593	192	22,322
Mardin	1,139	2,014	0	0	80	6,618	121	9,972
Muğla	2,213	490	0	236	320	4,172	358	7,790
Muş	270	71	0	0	43	716	52	1,153
Nevşehir	750	150	3	3	30	1,350	390	2,675
Niğde	1,998	1,981	0	0	3,561	7,256	91	14,887
Ordu	819	248	0	0	77	1,966	198	3,307
Rize	592	104	0	0	22,614	1,202	85	24,598
Sakarya	1,945	355	3	3	91	3,560	534	6,490
Samsun	3,032	483	18	18	273	5,704	925	10,454
Siirt	163	44	0	0	32	433	33	704
Sinop	306	71	0	0	21	664	50	1,112
Sivas	1,935	230	19	19	10,647	3,388	411	16,648
Tekirdağ	14,226	9,285	26	26	82	24,686	810	49,140
Tokat	1,111	250	2	2	66	2,288	174	3,892
Trabzon	2,241	223	2	29	108	3,986	157	6,745
Tunceli	66	15	0	0	9	161	11	262
Şanlıurfa	1,636	387	0	0	168	3,586	265	6,042
Uşak	744	152	2	2	36	1,467	106	2,508
Van	858	204	0	0	107	2,228	154	3,551
Yozgat	1,054	2,025	0	0	52	6,451	122	9,703
Zonguldak	1,678	355	687	764	143	3,753	7,812	15,192
Aksaray	1,648	151	0	0	40	2,299	108	4,245
Bayburt	100	22	0	0	8	213	16	358
Karaman	1,417	100	0	0	25	1,843	72	3,457
Kırıkkale	1,499	98	851	851	30	2,828	6,278	12,435
Batman	614	88	179	179	52	1,287	1,363	3,763
Şırnak	832	128	0	0	46	1,508	93	2,607
Bartın	1,278	63	0	0	20	1,595	44	3,000
Ardahan	108	28	0	0	12	244	20	412
Iğdır	290	46	0	0	20	571	33	959
Yalova	380	61	0	0	21	710	303	1,476
Karabük	1,398	90	0	0	23	1,861	62	3,434
Kilis	167	38	0	0	13	336	28	582
Osmaniye	767	159	17	17	50	1,463	358	2,830
Düzce	834	169	652	798	181	1,724	2,713	7,072

VITA

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EDUCATION

Degree	Institution	Year of Graduation
MS	METU, Environmental Engineering	2006
BS	METU, Environmental Engineering	2003
High School	Özel Aykan Lisesi	1999

WORK EXPERIENCE

Year	Place	Enrollment
2005 – 2010	METU, Environmental Engineering	Teaching assistant

FOREIGN LANGUAGES

English

PUBLICATIONS

- Current Practices in Hazardous Waste Management in Turkey, Yilmaz O. Dogru B. and Yetis U., Desalination and Water Treatment, 26 (2011) 1 – 7
- Waste Oil Generation from Road Vehicles in Turkey, Yilmaz O. and Yetis U.,1st International Conference on Hazardous Waste Management, October 2008, Chania, Greece
- Hazardous Waste Inventory of Turkey, M.S. Thesis submitted to Middle East Technical University, 2006