A UNIFIED MODEL FOR HAZARDOUS WASTE MANAGEMENT PROBLEM: APPLICATION IN TURKEY

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by

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December 2003

I certify that I have read this thesis and that in my opinion it is fully adequate, in scope and in quality, as a thesis for the degree of Master of Science.

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ABSTRACT

A UNIFIED MODEL FOR HAZARDOUS WASTE MANAGEMENT PROBLEM: APPLICATION IN TURKEY

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M.S. in Industrial Engineering

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December 2003

In real life a number of institutions, typically with conflicting objectives, are affected from the hazardous waste management problem. We investigate all related issues in the hazardous waste management from each institution's perspective. We define the hazardous waste management problem as the combined decisions of selecting the disposal method, siting the selected disposal plant, deciding on the waste flow structure and satisfying any other criteria required by any of the interested institutions. We develop a new unified mathematical model. In order to satisfy law and legislation requirements the incorporation of the Gaussian plume model into our unified model is also accomplished. A large scale implementation into regions of Turkey is provided.

Keywords: Hazardous waste, Facility location, Gaussian plume model

ÖZET

TEHLİKELİ ATIK YÖNETİMİ PROBLEMİ İÇİN KAPSAMLI BİR MODEL VE MODELİN TÜRKİYE'DE UYGULAMASI

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Gerçek hayatta tehlikeli atık problemiyle ilgilenen ve amaçları birbiriyle çelişen birçok kuruluş vardır. Tehlikeli atık yönetimiyle ilgili tüm konuları, ilgili tüm kuruluşların probleme bakış açılarına göre inceledik. Tehlikeli atık yönetimi problemini, bertaraf yönteminin belirlenmesi, bertaraf tesisi yer seçimine karar verilmesi, atık akışının şekillendirilmesi ve ilgili kuruluşların gereksinimlerinden ortaya çıkan kısıtların karşılanması olarak tanımladık. Buna bağlı olarak toplam maliyeti en aza indiren matematiksel bir model geliştirdik. Modele aynı zamanda kanun ve yönetmelik gereksinimlerinden ortaya çıkan hava kirliliği kriterlerinin sağlanması için 'Gaussian plume' formülünü dahil etmeyi başardık. Ortaya çıkan modelin büyük ölçekli uygulaması için Türkiye'nin bölgelerini ele aldık.

Anahtar Kelimeler: Tehlikeli Atık, Tesis Yerleşimi, Gaussian Plume Model

To my parents

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Chapter 1

INTRODUCTION

Hazardous waste generating facilities have been increased in industrialized countries over the years. As generated amount is increased, its potential to adversely impact the environment and to threat the human beings with cancer and other chronic diseases has been realized. Due to these catastrophic consequences of hazardous waste, the management of hazardous waste needs special care. Even though there is an extensive literature on hazardous waste management problem, it is observed that the literature is not quite representative of what exactly happens in real life. Therefore in this thesis we analyze the real life situation and propose a unified mathematical model that includes additional constraints necessitated from real life requirements.

We explain what the hazardous waste is in Chapter 2. We then focus on different properties of hazardous waste since too many types of substances are categorized as hazardous waste. The treatment methods, which only reduce the generated amount of hazardous waste, are explained later in detail. The remaining hazardous waste needs to go through a disposal process which is explained in depth in Chapter 2. We also provide a comparison between the disposal methods. Incineration, during which the wastes are burned, is chosen as the disposal method for this study. The reason for selecting the incineration as a disposal method is also explained in detail. We then state the "*hazardous waste management problem*" in Chapter 2. Lastly we provide the existing literature related to our problem.

The hazardous waste management considers the hazardous waste starting from generation till the final disposal. Throughout this "journey", a number of institutions with different objective functions and different criteria are affected. Since the requirements of the institutions may change from one country to another, we define our problem specific to Turkey. Chapter 3 consists of all the aspects of the hazardous waste management problem in Turkey. The studies showed that, laws and legislations are very important for the hazardous waste management. Therefore the current legislative situation related to the hazardous waste management in Turkey is presented in Chapter 3. In addition to that, Chapter 3 also consists of a detailed analysis of the current project, *Hazardous Waste Management* (HWM), of the Ministry of Environment and Forests.

In Chapter 3 we also present the detailed analysis of laws and legislations for the hazardous waste management problem. By this way the roles, responsibilities and requirements of the affected institutions are specified. Among them the Environmental Impact Assessment (EIA) requirements, the main factor that affects the management of hazardous waste, will be covered in depth.

For the incineration plant, EIA requires the satisfaction of the air pollutant standards at each population center. Therefore in Chapter 4 the incorporation of "the satisfaction of air pollutant standards" into the model is presented.

In Chapter 5, we propose a unified model which also considers the "satisfaction of air pollutants standards". The proposed model aims to decide on the site(s) of the incinerator(s) and the flow of the hazardous waste from the generators to the incinerator(s). The objective of the model is the minimization of total cost. We first provide a combinatorial formulation of the hazardous waste management problem and prove that it is NP-Hard. The proposed model is varied by changing the cost structure of the objective function. By this way two different mixed integer formulations of the hazardous waste management problem are proposed in Chapter 5.

In Chapter 6 we provide a large scale implementation of our proposed models for different regions of Turkey. Firstly our models are applied in the Central Anatolian Region. Then another application area consisting of “four regions” (Marmara, Ege, Akdeniz and Central Anatolian regions) is selected to enlarge the application area. We also make a comparison with the results of the HWM project in Chapter 6.

Lastly we summarize what we have done in this thesis and we give some concluding remarks with the future direction of this research in Chapter 7.

Chapter 2

OVERVIEW OF THE HAZARDOUS WASTE AND RELATED LITERATURE

2.1 Overview of the Hazardous Waste & Disposal Methods

Hazardous waste can be defined as the harmful byproducts of chemical processes produced from either industries or hospitals. From the legal stand point, the Resource Conservation and Recovery Act of United States define the hazardous waste as "a waste, or combination of wastes which because of its quantity, concentration, or physical, chemical or infectious characteristics may cause or significantly contribute to an increase in mortality or an increase in serious irreversible or incapacitating reversible illnesses or pose a substantial present or potential hazard to human health or the environment when improperly treated, stored, transported or disposed of."[16]

Waste is also generated while producing goods and services,. In most cases the generated waste has hazardous properties. Petrochemical industry, metal industry, leather industry, pharmaceutical industry, textile industry are the potential industries which generate hazardous wastes. In addition to the above industries, large amounts of hazardous wastes are also generated in hospitals due to clinical operations.

Since the sources of the hazardous waste include a wide variety of industries, the characterization of the hazardous waste is not a simple matter. For this reason a regulatory agency of United States, Environmental Protection Agency (EPA), has defined special characteristics of hazardous wastes to evaluate whether the waste is hazardous or not. According to EPA, waste can be considered as hazardous if it possesses certain characteristics such as ignitibility, corrosivity, reactivity or toxicity. EPA developed a list that shows each hazardous waste with a special code. According to the above explanations heavy metals, toxic organic substances, asbestos, acids and alkalis, radioactive substances, solvents, oily waste and clinical waste can be given as examples of the hazardous waste.

The philosophy and approach to management of hazardous waste have undergone many changes. These changes reflect the level of industrialization, societal attitudes and population levels [16]. After the 1980's the new philosophy, called conservation and recycling, has been evolved. According to the new philosophy, “at source reduction” and “recycling” should be considered before “disposing” the hazardous waste. At source reduction simply implies the waste minimization during the manufacturing facilities. Recycling can be explained as the reuse of the hazardous waste after the application of some chemical processes. For example, the oily waste generated from the automotive industry can be recycled to a product which is used in the textile industry [8].

Although there are lots of technologies for the reduction of the quantity of hazardous waste, it cannot be eliminated totally. There will be always some quantity of remaining hazardous waste that will need disposal. Hazardous waste disposal methods can be classified into three categories. The first category belongs to thermal methods. Incineration is one of them. Second category is land disposal. Specially designed landfill is the most commonly used alternative among the methods belonging to the land disposal category. Last category contains the usage of new technologies which provides the destruction of the hazardous property of the waste. Solar detoxification is the method that is being currently developed as a new technology.

Incineration uses heat in order to destroy the organic fraction of the hazardous waste. During the incineration process hazardous waste is burned at very high temperature. The actual Celsius depends on the waste type that is being incinerated. This process does turn hazardous waste to municipal waste (the residue is ashes), but during the process the smoke emitting from the stack causes air pollution. The easiest method is the land disposal where specially designed landfills are used to bury the hazardous waste. Since the process is just burying, the hazardous property of the waste does not change and there is no reduction in the volume of the hazardous waste. One of the main concerns of the landfills is the formation of leachate and its migration to the possible water reservoirs. If the landfill is not designed without considering this possibility, hazardous waste can threat the human health and the environment seriously. The nuisance resulting from the blowing of wastes, odors, and attacking of birds may be considered as the disadvantages of the landfills for the hazardous waste disposal method. New technologies are currently being developed in order to treat hazardous waste effectively. However, these technologies are generally very expensive and the treatment process is complex and therefore needs skilled staff for the operational phase.

The usages of the incineration plants as a disposal method are gaining popularity, despite their high capital cost. This is due to the fact that incineration is the only method which offers the detoxification of certain wastes such as all combustible carcinogens, pathological wastes which causes transmission of serious diseases [16]. Incineration is also the method which significantly reduces the volume of the hazardous waste. The major disadvantage of the incineration plant is stated as its high construction cost. However special design of landfills, and controlling leachate problem has also led to increase in the construction cost of landfills. Thus this makes incineration plant as a competitive alternative for the hazardous waste disposal method. However not all of the hazardous waste is incinerated. The hazardous waste such as solvents, plastics, paints, petrochemical wastes, oil waste, chlorinated waste and the clinical waste that come from the hospitals are among the hazardous waste that can be incinerated.

Each disposal method has its own characteristic features and requires different considerations. For this reason the definition of the hazardous waste management problem can change from one disposal method to another method.

Some countries even incinerate their municipal wastes. For example in Japan 74 % of the hazardous waste is incinerated. In France 44 % and in Germany 26 % of the hazardous waste is incinerated. Currently there is one incinerator located in the west side of Turkey, in Kocaeli. We found out from the the Ministry of Environment that three more incineration plants are to be opened in Turkey in the next twenty years. This gives rise to the possibility of selecting of incineration plants as a disposal method throughout this study.

2.2 Hazardous Waste Management Problem

When the whole "journey" of the hazardous waste is considered from the generation to the final disposal, there are many institutions which are affected. These institutions include government, waste producers, disposal plants, transportation companies, public etc. These institutions have different objectives and different criteria. For example, the disposal plant and the transportation companies will mostly be interested in the economical aspects of the process whereas the public will only be interested in the risk exposed to the environment. Government is included in these institutions since the public has no power or authority over the private companies. However the government can put some rules and regulations to protect the public and environment from the risk of hazardous waste. The roles and the responsibilities of these institutions may change from one country to another. In this study the hazardous waste management problem in Turkey is analyzed. The details of the institutions, their responsibilities and the roles will be explained in the following chapter.

Another issue related to hazardous waste management problem is the multidisciplinary nature of the problem. Close coordination of the various disciplines such as environmental engineers, geologists, industrial engineers, etc. must be involved in the management of the hazardous waste [16].

We define the *hazardous waste management problem* as the combined decisions of selecting the disposal method, siting the selected disposal plant, deciding on the waste flow structure and satisfying any other criteria required by any of the interested institutions (like laws and legislations or budgets etc.). In the model development phase, the selected disposal method may result in additional requirements (like land availability for landfill and air pollution protection for incineration). In the literature, the studies show that there is no such model, which combines all the mentioned issues. The related literature is available in the following subsection.

2.3 Related OR Literature

Since there is no differentiation between the disposal methods in the literature, a common synonym "undesirable facility" is used for each type of disposal method. The interest on undesirable facility location has increased magnificently in recent years. This is due to the rapid technological and industrial developments. With increasing technology and industry the problem of locating undesirable facilities comes as a byproduct. For this reason, after the year 1990 there is a steep increase in the undesirable facility location literature.

The earliest works on the undesirable facility location problem aimed to minimize the nuisance and the adverse effects of the undesirable facility on public and environment. Mainly two problem types appear in the literature. The first problem, maximin problem, aims to maximize the minimum distance between the undesirable facility which is to be located and the existing facilities or population centers which are under effect. If the nuisance is taken as the decreasing function of distance, the maximin model can be viewed as the minimization of maximum nuisance. Maximin model is suitable for locating high-risk industry such as explosive manufacturing industry or nuclear power plant since it tries to minimize maximum risk.

For the continuous space maximin facility location problem two solution methods are studied frequently. In the first one the optimal solution is found by enumeration of local maxima. Karush-Kuhn-Tucker conditions are used for this purpose. The second method is developed by using the properties of Voronoi diagrams. Dasarathy and White [6], Drezner and Weselowsky [7], Melachrinoudis and Cullinane [19], Melachrinoudis and Smith [21] studied the maximin problem by using one of the mentioned solution methods.

The second problem type in the undesirable facility location is maxisum problem. It aims to maximize the total distance between the facility to be located and existing facilities. Again by taking the nuisance as a decreasing function of distance, maxisum problem can be viewed as minimization of total nuisance. Maxisum model is suitable for locating a plant that threats continuous risk to the environment. Locating an air pollution causing chemical plant can be modeled by using maxisum model. A drawback of this model is that, it may result in a solution where the optimum solution is in immediate neighborhood of existing facility as it tries to minimize total risk.

A geometrical method based on the branch and bound algorithm and the method based on the Karush-Kuhn-Tucker conditions, like in the maximin problem, are developed solution methods for the maxisum problem. Melachrinoudis and Cullinane [20], Hansen, Peeters and Thisse [15], Fernandez, Fernandez and Pelegrin [11] studied the maxisum problem by using one of the mentioned methods.

In the maxisum literature, Karkazis [17], Karkazis and Papadimitrou [18], developed a model specific to a facility that poses air pollution for the continuous space. By using pollution dispersion model, they minimized the total pollution concentration on existing facilities.

For the undesirable facility location models there is an excellent survey prepared by Erkut and Neuman [9]. The survey contains the models whose objective functions involve distance, like maximin and maxisum model. The paper presents the synthesis of solution procedures of suggested models with emphasis on similarities and differences between the models.

Up to now, the undesirable facility location literature considering the minimization of nuisance is examined. Other than the single objective models one may consider different conflicting aspects of the undesirable facility location problem simultaneously. The minimization of cost, risk and the maximization of equity issues are considered for the location of the undesirable facilities in discrete space.

The first effort to model the location of variable number of undesirable facilities considering the multiple objectives is introduced by Ratick and White [25]. Their objectives are minimization of cost and opposition and maximization of equity. Ratick and White [25] developed a mixed integer programming formulation, which is solved by using the constraint method with cost and equity objectives treated as constraints. Erkut and Neuman [10] also addressed the same problem as in the case of Ratick and White [25]'s model. The main difference is the equity measure. The suggested model contains enumeration procedure for finding all the efficient solutions. Wyman and Kuby [27] also proposed a multiobjective model minimizing risk, cost and disequity. Their model also incorporates treatment technology selection. Wyman and Kuby [27] solved their model first with a weighted objective function and proposed to obtain a tradeoff curve, and secondly by treating risk and disequity objectives as constraints. Melachrinoudis, Min and Wu [22] studied the site selection of landfills. They defined two different risks: population risk and non-human risk. They also considered the changes of the parameters over time. Since their model is specific to landfill location they also consider the leachate problem. They generate efficient set by giving weights to objectives in their model.

Although multiobjective models seem to be appropriate for the undesirable facility location, the selected site may not reflect the right decision due to the uncertainties in the objective function. Thus, especially the risk and the equity measures need to be clearly defined. There is a need for realistic risk and equity impact functions.

Another reason for the inefficiency of the multiobjective models is the fact that the conflicting objectives usually come from different decision makers (cost for companies, risk for public, equity for government). Thus multiobjective modeling does not seem to be appropriate for hazardous waste management problem. A thorough analysis of hazardous waste in real life is needed to develop a realistic model for the problem.

In this thesis the case for Turkey is analyzed. All related issues in the hazardous waste management from each institution's perspective are investigated. A new unified model for the hazardous waste management problem is provided. .

Chapter 3

HAZARDOUS WASTE MANAGEMENT IN TURKEY

In today's world, the removal of hazardous waste is one of the biggest problems of the industry. According to statistical data provided by developed countries the amount of generated hazardous waste is more than 200 million ton per year in the world [30].

Governments have the responsibility for increasing the environmental quality and providing proper management of hazardous waste. The laws and the legislations are the major tools that the government can utilize in order to increase the quality of environment and to provide public safety. The goal of the laws and legislations can be explained as the maximization of protection by minimization of potential risk [16]. Many nations have adopted adequate legislations to regulate all aspects of the hazardous waste management problem. Among them, Germany is the first that recognized the severity of environmental problems and adopted some regulations [28]. In addition to Germany, in 1970's US also developed its own laws and legislations to protect and maintain the quality of environment.

Unfortunately 'Turkish Environmental Law' does not include any definition of hazardous waste. For this reason all responsibilities for the management of hazardous waste are stated in the ' Control Legislation of Hazardous Waste in Turkey' [3]. In Turkey even the distinction of hazardous waste from municipal waste is started with the Basel Convention which is handled by the European countries in 1989 [14]. The content of the convention implies the control of transboundary movements of hazardous waste and the control of their disposals. Based on the convention, 'Control Legislation of Hazardous Waste in Turkey' has been prepared. However the legislation needs a periodic revision according to the developing philosophy of the hazardous waste management.

The laws define a hazardous waste generator as any person whose act or process produces hazardous waste. In Turkey, there are mainly two types of generators for the hazardous waste: industries (factories and recycling centers) and hospitals. According to statistical data obtained from a private disposal plant, the amount of hazardous waste in Turkey is approximately 5 million ton/year and 115.000 ton/year for industries and hospitals respectively.

In 1996, the Ministry of Environment and Forest prepared a report in order to determine the needs of Turkey for the disposal of hazardous waste. World Bank also supports this report as a process of Turkey’s harmonization with the European Union. According to the report, incineration plants are required for at least four regions of Turkey. [32]

In comparison to the above needs there is only one specifically designed 'Clinical and Hazardous Waste Incineration Plant' in Turkey. The plant is owned by a private firm, İzaydaş, and is located in Kocaeli [32]. The incineration plant is actually a part of the waste management facility which contains mainly three plants: solid waste disposal land, clinical and hazardous waste incineration plant, industrial and household wastewater treatment plant. In the plant, the wastes which are not hazardous are disposed of at the solid waste disposal plant. The clinical and hazardous wastes are incinerated in the incineration plant and the wastewaters are treated in the wastewater treatment plant.

The waste management of İzaydaş can be explained by the following figure: [32]

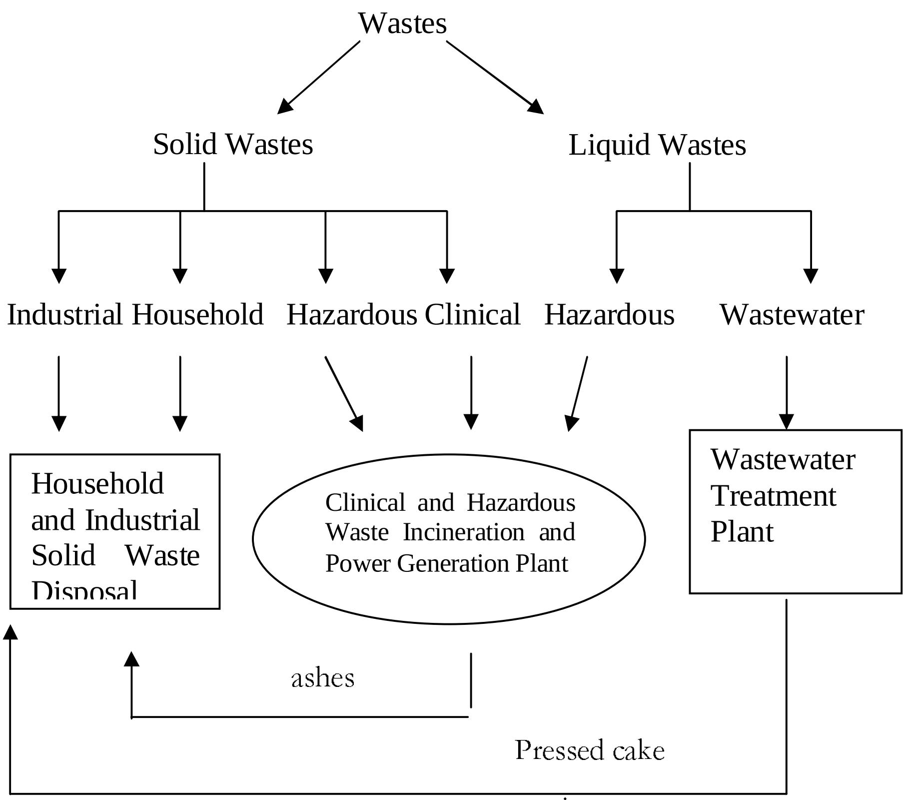

Figure 3.1 The Waste Management Process in İzaydaş

As can be seen from the figure, the hazardous wastes and the clinical wastes are burned in incineration plant and the residue, the ash which is no longer hazardous, is disposed of at the solid waste disposal land. Therefore the incineration plant which is to be located should also consist of disposal land for disposing the residues of incineration plant.

In Chapter 2, the major disadvantage of the incineration plant is stated as its construction cost. However when we look at the construction costs of

İzaydaş we see that the construction cost of the solid waste disposal land, which is designed without considering the hazardous waste, is approximately 120 million Euro and the cost for the incineration plant is approximately 207 million Euro. As it is seen from the cost values the construction cost of incineration plant is not even two times more than the cost of disposal land. If the disposal land were designed for the hazardous waste, this would cause more increase in construction cost of disposal land due to some special precautions. Thus the above results contradict with the common thoughts related to highly expensive construction cost of incineration plants.

In addition to that, the incineration process yields some electrical power. The generated power is used in İzaydaş in order to meet the energy consumption of the plant. However still some amounts remain and it is sold to authorized companies by İzaydaş. By this way the plant is also gaining money for each kg of incinerated waste.

In order to meet the needs of the report of 1996, The Ministry of Environment and Forests prepared a *Hazardous Waste Management Project* (HWM project) in 2001. Although the report stated that the incineration plants should be opened in at least four regions of Turkey, the HWM project only considers three regions of Turkey. The purpose of the project can be summarized as selecting the sites for three incinerators which are to be located in the west side (Marmara, Ege and Akdeniz Regions) of Turkey and deciding the flow structure of hazardous waste from generators of three regions to the incinerators.

The project starts with data analysis to question the necessity of opening incineration plants provided in 1996 report. According to that analysis the amount of incinerable hazardous wastes are calculated as 84600, 22500, 11500 ton/year for Marmara, Ege and Akdeniz regions respectively. The total amount is equal to 118600 ton/year. When the amount is compared with the capacity of the İzaydaş, which is 35000 ton/year, it can be easily seen that, there is a severe need for the incineration plants in Turkey.

Three incinerators (other than İzaydaş) are planned to be opened in the next twenty years by the HWM project. The sites of the incinerators are chosen by the help of the experts by considering the industrialization level of each site. In HWM project, the effecting factor on site selection is the closeness of the sites to the generators. The project only considers the generators of three regions. According to HWM project Tekirdağ, İzmir and Adana are chosen as the sites of incineration plants.

In HWM project, the 'assignment' modeling was applied in order to decide which city sends its waste to which incinerator. The objective of the model is to minimize the total distance between the generators and incinerators.

The above study can be seen as one of the major motivations of this thesis. As it is stated the laws and legislation aim to provide proper management of hazardous waste. Site selection process for incineration plant must take into account various regulatory details. For this reason the proposed site needs to be fully evaluated from the laws and regulatory perspectives. In addition to that the analysis of the laws and legislation provides better understanding of the affected institutions and their roles in the hazardous waste management process.

However, in the HWM project some important features of laws and legislations are not considered for the site selection. Thus in this study it is aimed to create a model which includes the detailed analysis of laws and legislations of hazardous waste from the perspectives of each affected institution and for the site selection of incineration plants.

Before going through the evaluation of laws and legislations, the flow diagram of hazardous waste from generation nodes to disposal plants should be analyzed. In Turkey, there are three different generators for the hazardous waste: factories, recycling centers, and hospitals (Figure 3.2). There are two different types of wastes that are generated from factories: recyclable wastes and unrecyclable wastes. The recyclable waste can go either to a recycling center or directly to the hazardous waste disposal plant. After the recycling process the remaining waste is again sent to the disposal plant. The clinical waste coming from the hospitals are directly sent to the disposal plant. The hazardous waste is transported by the private transportation firms between the pairs of source and destination points.

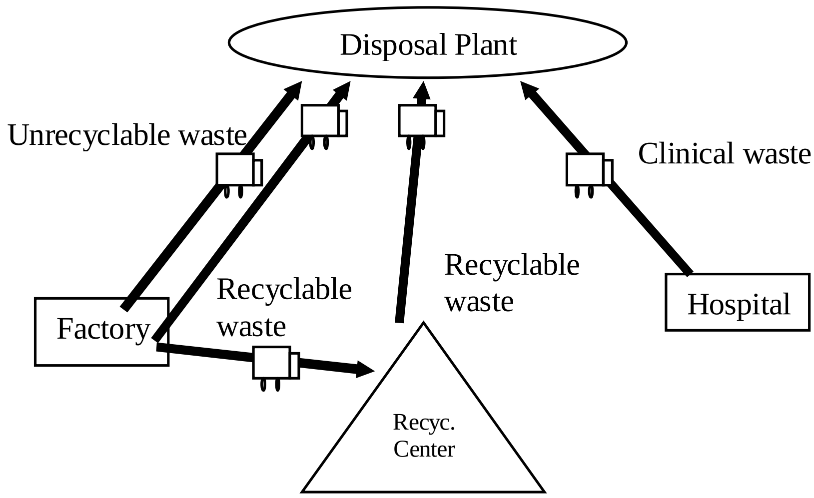

Figure 3.2 Flow Diagram of Hazardous Waste in Turkey

The disposal plant charges a processing fee for each kg of waste that is received regardless of the waste type. On the other hand, generally there is no fee for recycling since after the recycling process the recycling center can get some valuable materials. The transportation fee is charged per truck per km, again independent of the waste type. Apart from these, the incineration process yields electrical power, which is usually sold to authorized institutions. Of course, there is an operational cost for the disposal plant, which is usually cost per kg of hazardous waste.

Via the schematization of the waste flow and the "money" flow, the general picture for the management of hazardous waste in Turkey can now be stated. The 'Control Legislation of Hazardous Waste in Turkey' is the only legislation which has a regulatory power on hazardous waste management [3]. The legislation includes several subsections such as:

Purpose of the Legislation

Definition of Hazardous Wastes

Principles for the Hazardous Waste Management

Roles and Responsibilities

The Decisions on the Transportation of Hazardous Wastes

The Decisions on the Disposal of Hazardous Wastes

Transboundary Movements of Hazardous Wastes

Three of the above subsections can be useful for developing proper management of hazardous waste. These are 'Roles and Responsibilities', 'The Decisions on the Transportation of Hazardous Wastes' and 'The Decisions on the Disposal of Hazardous Wastes'. After the detailed analysis of these subsections, it is seen that there are four institutions responsible for the hazardous waste management: 1.) Transportation Companies 2.) Hazardous Waste Generators 3.) Ministry of Environment and Forests and 4.) Disposal

Plants.

The hazardous waste is transported by the private firms or by the waste generators. The legislation does not contain any restriction related to transportation routes of the hazardous waste. Therefore transportation of hazardous waste occurs much the same as normal movements of goods.

The legislation consists of some regulations to provide safety transportation. For this reason a number of precautions are stated in the legislation. The licensing of the hazardous waste carriers is one of the main precautions to provide safety transportation and to reduce the potential accidental risk. Any carrier of hazardous waste has to be licensed by Ministry of Environment and Forests. Proper identification of hazardous waste is another major concern. According to the legislation each waste type has to be transported separately. The greatest care on the transportation of hazardous waste is given to the container specifications. The container specifications of the hazardous waste carrier need to satisfy the stated standards.

Despite the fact that governments work for high quality of environment, generators are seeking a solution to the problem with minimum cost. For this reason the legislation states some important precautions for the generators to provide high quality standards.

According to the legislation, the hazardous waste generators are responsible from the proper disposal of hazardous waste. They are required to send their waste within the determined time periods. Factories and recycling centers should send their waste within ninety days and hospitals are required to send their waste within two days. The legislation requires keeping a record of the amount of generated waste from each generator. The liability of sending these records to the Ministry of Environment and Forests belongs to the waste generators.

The Ministry of Environment and Forests has a regulatory power on controlling the involved institutions to increase the quality of environment and to provide public safety. The Ministry of Environment and Forests requires an evaluation of the selected disposal site. For this purpose the Ministry requires a complete report prepared for the selected disposal site. The report is referred to as *Environmental Impact Assessment* (EIA) Report.

Disposal plants should receive a positive EIA report for the selected site. The site must fulfill all the stated requirements for the construction and operational phase of the facility. In addition to that the site chosen must be 3000 m. away from any population center.

The requirement for the preparation of the EIA report is mandatory for all types of facilities. The EIA report addresses the environmental impacts of the proposed activity such as unavoidable adverse impact and irretrievable commitments of resources [16]. An EIA forces the disposal site operator to provide full evaluation of the environmental consequences of the proposed facility. In EIA report there are two main restrictions: site restrictions and operational restrictions.

Site restrictions are specific to geographical properties of the selected site. According to the site restrictions, the site which is to be chosen, cannot be on farming land, forest, fault lines or touristic places. The operational restrictions consider the effect of the facility to the environment during its operation.

Since the EIA report is required for any facility, the restrictions are not specific to incinerators. There is one specific requirement for incinerator which considers the air pollution. After the incineration process, some air pollutants such as SO_2, SO_3, NO, NO_2, Cl, HCl, are generated. Although the amount of the air pollutants can be reduced to some extent by using filters and scrubbers, still some air pollutants remain and emit from the stack of the plant. Dispersion of these air pollutants in the atmosphere causes air pollution. The EIA requirement for the incineration plant states that the ambient air concentration of the air pollutants at each population center should be less than some specified values which are provided in 'Control Legislation of Air Pollution in Turkey' [4]. Therefore the siting of incineration plant should not be modeled without considering the satisfaction of air pollutants standards. For this purpose the satisfaction of air pollution standards at each population center is to be incorporated into the proposed model. This achievement is explained in detail in Chapter 4.

Chapter 4

INCORPARATION OF THE AIR POLLUTION CONSTRAINT INTO THE MODEL

In order to observe whether the EIA requirement is satisfied or not, we need to calculate the concentrations of the air pollutants at each population center. The main factor for calculating the concentration of air pollutants on a given point is the meteorological conditions of the atmosphere. In real life, dispersion of the pollutants is not symmetric and the prevalent winds affect the distribution of air pollutant. For example, pollution spreads further in one direction than the others depending on the direction of the prevalent wind.

The dispersion of the air pollutants by the wind is a very complex issue. The main reason is the fact that there are so many factors that affect the dispersion. Besides the meteorological conditions, the geographical condition of the application area is also important. Therefore there is no complete formula that works well for every condition. However based on the empirical data some formulations are developed for calculating the air pollutant concentrations at the population centers. The studies show that actually some of these formulations are useful in estimating the dispersion of air pollutants. Among these formulations Gaussian Dispersion model is the most popular one.[29]

4.1 Gaussian Dispersion Model

EIA uses one of the derived equations, the *Environmental Protection Agency's Gaussian Air Quality Dispersion Model* for checking ambient air concentration of air pollutants. Gaussian Dispersion Model is the most applicable dispersion model in measuring the air pollution concentration on a given point. It is simple enough and it agrees reasonably well with the bulk of field and experimental data [29]. The Gaussian Plume Equation (from Karkazis, Papadimitrou [18]) is given below:

$$C(x,y)=\frac{QK\,exp\left[-0.5\left(y^2/(\sigma_y)^2\right)-0.5\left(h^2/(\sigma_z)^2\right)\right]}{2\Pi u\sigma_y\sigma_z} \qquad (\text{Eqn } 4.1.1)$$

where

C(x,y) = the concentration of the air pollutant at the given point x,y (mg/m^3).
Q = the amount of air pollutant emitting from the stack (kg/h).
K= scaling factor ($10^6/3600$).
u = wind speed in the given region (m/s).
h= stack height (m).
σ_z, σ_y = dispersion factors (m).
(x,y) = the coordinates of the population center according to new coordinate system
x (y) = the x (y) distance between incineration plant and the given population center but in different coordinate system which will be explained at the end of this section(m).

The incinerator plant can only receive a *pass* from the EIA report, if the C(x,y) value of each air pollutant at each population center is less than the standard value of the air pollutant.

Now let us analyze each term in the formula in detail. The amount of the air pollutant emitted from the stack depends on the amount of hazardous waste that is incinerated. The amount of the emitted air pollutants can be changed according to the technological properties of scrubbers used in the incineration plants. Conversion factors for finding the amount of air pollutants from the amount of incinerated hazardous waste depends on the type of the incinerated hazardous waste, the used technological equipment for the scrubber and the type of the air pollutants. Conversion factor can be easily found from the air quality books such as Baumbach [2].

In the formula, the scaling factor, K, is used to convert one unit (kg/h) to another unit (mg/sec).

The wind speed of the given site is not constant throughout the year. The past historical wind speed data can be easily found from the State Meteorological Services.

Dispersion factors (σ_z and σ_y) depend on the atmospheric stability, stack height and the value of x. There are three different types of atmospheric conditions: stable, unstable and neutral. For the air pollutant dispersion, the worst condition is the stable condition. In this atmospheric condition, the air pollutants do not disperse within the air and stay in concentrated amounts which cause more damage to public and environment. The formulas of σ_z and σ_y for the stable atmospheric condition and 150 m. stack height (150 m. is the most common stack height for the incinerator) are given below: [4]

$$\sigma_y = 0.31 \times x^{0.71} \qquad \text{(Eqn 4.1.2)}$$

$$\sigma_z = 0.06 \times x^{0.71} \qquad \text{(Eqn 4.1.3)}$$

The x and y in the formula represent the "relative distance" between the population center under consideration and the incinerator site. For the formula the distance needs to be determined by using the coordinate system based on the incinerator site and specified by the wind direction. The origin of the coordinate system is taken as the base of the incineration plant stack. The x axis is taken as the wind direction and y axis is taken as the cross wind direction (normal to the x axis). Since the axes are defined according to the wind direction, the x and y values of the population center changes for each wind direction. Also, as the coordinate system is based at the incineration site, each population center will have different x and y values for each candidate site.

4.2 Incorporating the Gaussian Plume Equation into the Model

Among the parameters of the Gaussian Plume Equation wind speed and wind direction can be easily found from the meteorological data. Once the wind speed, wind direction, and the atmospheric stability of the candidate sites are known the σ_z and σ_y values can also be calculated. Make a note that σ_z and σ_y also include the x value. The major task seems to be calculating the x and y values since they depend on different wind directions and they require different coordinate systems for each candidate site.

We develop certain formulas to find those x and y values. First of all the coordinate system is formed for each candidate site. The effect of this candidate site to every population center is calculated. There are 8 wind directions. Depending on the wind direction and the position of the population center relative to the candidate site several different formulas are derived. Then this process is automated by writing a simple C code (just to calculate formulas). The code requires the locations of population centers and candidate sites in a unique coordinate system and prevalent wind directions of each candidate sites and outputs the (x,y) values for each candidate site and population center combination. An example for the calculation of x and y is provided next.

Air pollution spreads in the direction of wind. Thus, while some regions are under the effect of pollution some regions are not. These regions can be easily identified if the wind direction of the candidate site is known. For example if the wind blows to the North-East direction, the coordinate system should be formed as in the Figure 4.2.1

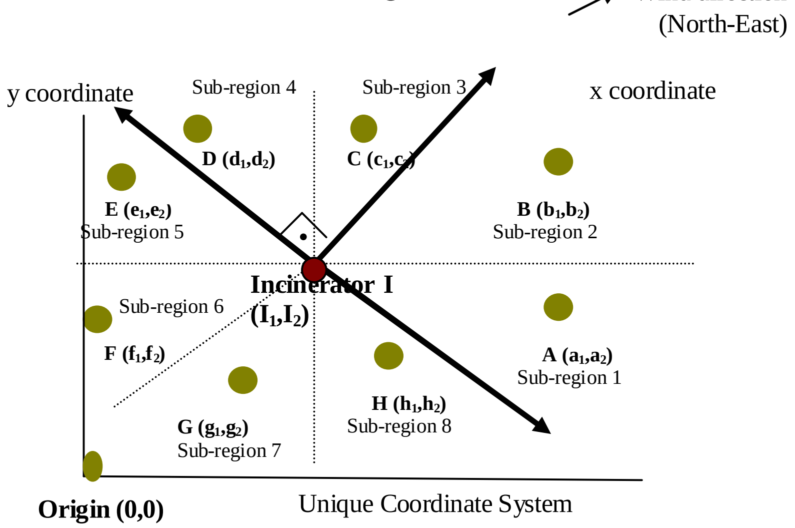

Figure 4.2.1. Coordinate System for Incinerator I

In Figure 4.2.1, the incinerator at site I, and population centers from A to H are located in a unique coordinate system and this coordinate system is originated at (0,0) point. After the wind speed of incinerator is determined (which is North-East for the example), the coordinate system originated from the base of the stack is formed and it is drawn in bold in the figure. From the figure, it is observed that the sub-regions from 1 through 4 are under the effect of pollution. On the contrary, the sub-regions 5 through 8 are not affected from the pollution due to the wind direction.

In order to find x and y "distances" of each population center for incinerator site I, the properties of geometry is used. First of all the region is divided into 8 sub-regions. The main reason for dividing the sub-regions is due to the fact that in each sub-region the calculation of corresponding x and y values differs from each other. The representation of x and y of the population center A for the incinerator I can be seen by the following figure.

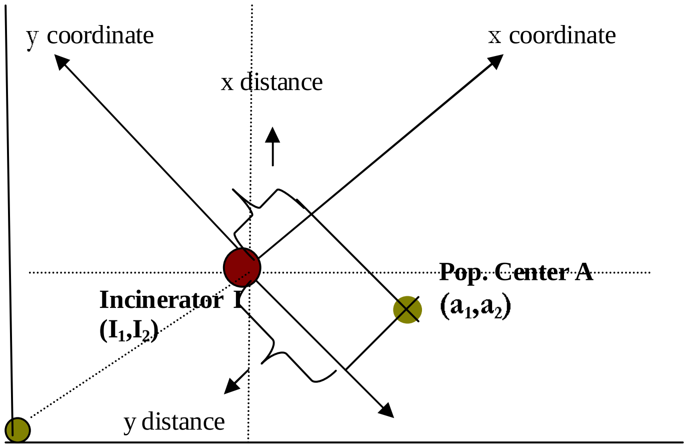

Figure 4.2.2 "Distances" of Population Center A for the Incineration Plant I.

For finding the x value of population center A according to the incinerator I, the geometrical properties are established and they can be seen in the following figure.

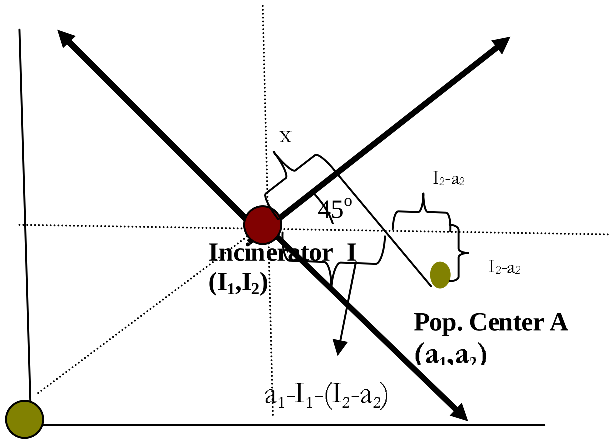

Figure 4.2.3 Derivation of x value from the geometrical properties

The above representation helps for establishing the following equation:

$$2x^2 = [a_1 - I_1 - (I_2 - a_2)]^2 \qquad \text{(Eqn 4.2.1)}$$

Where I_1 and I_2 are the coordinates of the incinerator I and in the same manner a_1 and a_2 are the coordinates of the population center A in the unique coordinate system.

From the equation 4.2.1, x value for population center A and Incinerator I pair can be derived as:

$$x = \sqrt{\frac{[a_1 - I_1 - (I_2 - a_2)]^2}{2}} \qquad \text{(Eqn 4.2.2)}$$

The following table shows the x and y values of the population centers belonging A to G (figure 4.2.1).

Population Centers	**x value**	**y value**
A	$\sqrt{\frac{\left[a_1 - I_1 - \left(I_2 - a_2\right)\right]^2}{2}}$	$x + \sqrt{2\left(I_2 - a_2\right)^2}$
B	$y + \sqrt{2\left(b_2 - I_2\right)^2}$	$\sqrt{\frac{\left[b_1 - I_1 - \left(b_2 - I_2\right)\right]^2}{2}}$
C	$y + \sqrt{2\left(c_1 - I_1\right)^2}$	$\sqrt{\frac{\left[c_2 - I_2 - \left(c_1 - I_1\right)\right]^2}{2}}$
D	$\sqrt{\frac{\left[d_2 - I_2 - \left(I_1 - d_1\right)\right]^2}{2}}$	$x + \sqrt{2\left(I_1 - d_1\right)^2}$
E	0	0
F	0	0
G	0	0
H	0	0

Table 4.2.1 x and y Values for the North-East Wind Direction

If any population center has 0 for x and y values, this means that the population center under consideration is not affected from the air pollution. There are 8 different tables prepared for all wind directions and they are available in appendix part A.

Finally if we know the wind speed, atmospheric stability, and the wind direction of each candidate site, we can calculate x and y values by using our code. Thus the Gaussian Plume equation can now be incorporated into the proposed mathematical model. In the equation the value Q which represents the mass of emitted air pollutant, depending on the mass of hazardous waste that is being incinerated, will be variable and the rest will all be known parameters. For the sake of representation we use a matrix T_{jp} to denote all the known parameters for each candidate site and population center pair. Note that if x and y values are 0 then T_{jp} value will take the value of 0 automatically.

Gaussian dispersion model assumes that the meteorological conditions are constant in the given region and the air pollutants do not react with any other substance throughout its transportation. However, in real life the wind speed and the wind direction are not constant throughout the year. Customarily there are some time periods where the meteorological data of the wind speed and the wind direction can be taken as constants (i.e. month for Turkey). Since the selected site must get a positive EIA report for every possible time periods, it suffices to analyze the worst combination. For the wind speed the smallest is the worst since the air pollutants do not disperse much. For the wind direction the prevalent one is chosen as it is the most encountered.

Chapter 5

PROBLEM DEFINITION AND PROPOSED MODEL

The hazardous waste management problem is highly complex due to the

- strict requirements of legislations,
- multidisciplinary nature of the problem (involves close coordination among various disciplines such as industrial engineers, environmental engineers and geologists etc.)[16],
- unique characteristics of each disposal methods,
- conflicting objectives of each affected institutions (minimization of cost for disposal operator and minimization of risk for government)

Up until now the hazardous waste management problem is examined from different perspectives. It is stated that there are mainly four different institutions which need to be involved in this problem. However, for siting a disposal plant only two of these institutions have the authority. These are the disposal plant and Ministry of Environment and Forest. The waste generators and the transportation companies cannot affect the siting decision. The disposal plant would aim to minimize the operational cost and the transportation fees and maximize the gains. In Turkey, the Ministry of Environment and Forest does not affect the prices (fees) but can force certain restrictions by law and legislation (like satisfaction of ambient air concentration of air pollution).

In this section we propose a unified model for the hazardous waste management problem. The model is to decide on the site(s) of the disposal plant(s) and the flow of the hazardous waste from the generators to the disposal plant(s). In other words, the proposed model selects the sites(s) for the disposal plant(s) among the candidate set **J**={1...j} and decides the flow structure of the generated wastes.

The model includes standard mass balance constraints, capacity constraints, minimum capacity requirements and the Gaussian plume constraint. Since we also include the Gaussian plume constraint, the site selected via our model will automatically receive a positive EIA report. Even though the model seems to be specific to incinerator, due to the Gaussian plume constraint, additional constraints can be incorporated into the model if additional restrictions are defined.

The objective of the model is the minimization of total cost. In addition to that, the structure of the model is applicable to any other linear objectives.

If the amount of hazardous waste in disposal plant j is less than a threshold value, it is not appropriate to operate that disposal plant. We refer that threshold value as Cap^{min}_j. There is also capacity restriction of each disposal plant, which we denote by Cap_j.

Let p denote the number of disposal plants to be opened.

As stated in Chapter 3, there are three main sources of hazardous waste: Factories, recycling centers and hospitals. Let **I**={1....i} denote the set of factories, **R**={1....r} denote the set of recycling centers and **H**={1....h} denote the set of hospitals. There are two types of waste generated from factories: recyclable waste (denoted by **W**={1....w}, where w represents different types of recyclable wastes) or unrecyclable waste (denoted by **U**={1....u}). The clinical waste generated from hospitals is denoted by **C**={1....c} with *c* different types.

In each of these sources some amount of hazardous waste is generated. The amount of recyclable waste type w ϵ **W** (unrecyclable u ϵ **U**) generated from factory i ϵ **I** is denoted by the b_{iw} (b_{iu}). The amount of clinical waste type c ϵ **C** generated from hospital h ϵ **H** can be defined as the b_{hc}. These amounts are needed to be disposed of or sent to a recycling center.

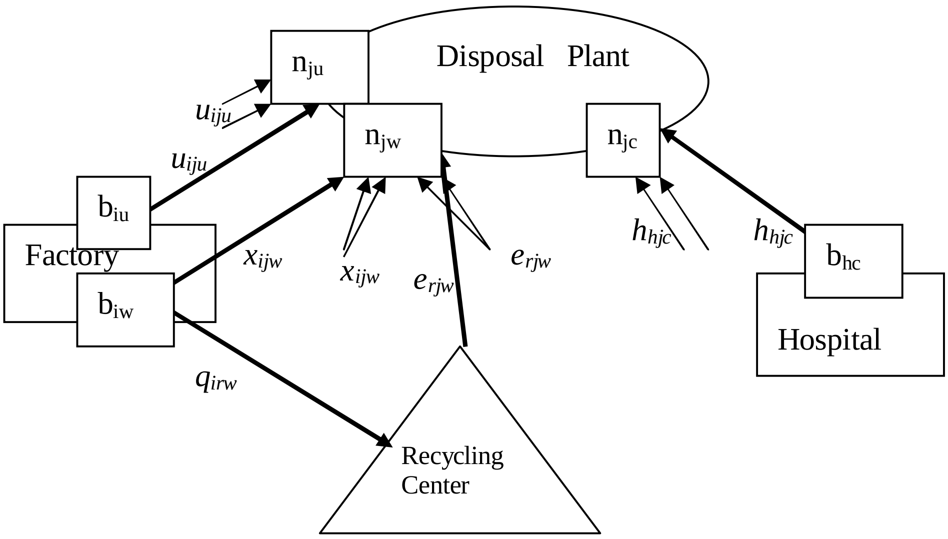

Figure 5.1 Flow Diagram of Hazardous Waste

Now we can define the decision variables of the model. As can be seen from Figure 5.1, the recyclable waste type w generated from factory i can go either to recycling center r or directly to the disposal plant j. The amount of the recyclable waste type w sent to the recycling center r from factory i is denoted by the q_{irw}. In the same manner the amount of waste type w sent from factory i to the disposal plant j is denoted by x_{ijw}. u_{iju} denotes the amount of unrecyclable waste type u from factory i sent to disposal plant j and h_{hjc} represents the amount of clinical waste type c going from hospital h to disposal plant j.

If the recyclable waste is sent to the recycling center r, it undergoes the recycling process. However after the process some amount of hazardous waste still remains. For each recyclable waste type w and for each recycling center r, there is a conversion factor, α_{rw}, which is used to find the amount of remaining hazardous waste w after the recycling process. The amount of recyclable waste type w going to the disposal plant j from the recycling center r is denoted by e_{rjw}.

In the model total amount of recyclable waste w, in disposal plant j is represented by n_{jw}. In the same manner n_{ju} and n_{jc} are used for the total amount of unrecyclable waste type u and clinical waste type c sent to the disposal plant j respectively.

The only binary variable in the model is y_j for j ϵ **J**. If y_j =1, the disposal plant is opened at site j, otherwise the site j is not selected as the disposal plant site by the model.

One main contribution of the proposed model is the incorporation of the Gaussian Plume Equation into the model for the satisfaction of air pollution standards. Let **L**={1....l} denote the type of air pollutants. The concentration of each air pollutant l at any population center must be less than the standard concentration of that air pollutant. Let K_l denote the standard concentration of air pollutant l.

Recall from Chapter 4 that the amount of air pollutants in Eqn 4.1.1 is expressed in terms of the amount of hazardous waste that is incinerated and that amount is the sum of the recyclable, unrecyclable, and hospital wastes. Conversion factors for converting the amount of hazardous waste to the amount of air pollutants is defined as one minus destruction rate (1-DR_{lt}). The destruction rate is specific to waste type t and air pollutant type *l*. The values of conversion factors can be found from air quality books (Baumbach [2]). Thus the amount of air pollutant type *l* emitted from disposal plant j is found by:

$$(Q_j)_l = \sum_w (1 - \mathrm{DR}_{1w})\mathrm{n}_{\mathrm{jw}} + \sum_u (1 - \mathrm{DR}_{1u})\mathrm{n}_{ju} + \sum_c (1 - \mathrm{DR}_{1c})\mathrm{n}_{\mathrm{j}c} \qquad \text{Eqn (5.1)}$$

Recall from Chapter 4 that if the wind speed and wind direction are known, all the parameters in Eqn 4.1.1, except Q, can be calculated. We refer to that fixed part as T_{jp} for disposal plant located at site j and population center p pair.

$$T_{jp} = \frac{K\,exp\left[-0.5\left(y_{(jp)}^{2} \big/ (\sigma_{y(jp)})^2\right) - 0.5\left(h^2 \big/ (\sigma_{z(jp)})^2\right)\right]}{2\Pi u_j \sigma_{y(jp)} \sigma_{z(jp)}} \qquad \text{(Eqn5.2)}$$

The concentration of the air pollutant type *l* at the population center (with x and y coordinates) can now be calculated as:

$[C(x,y)]_l = \Sigma_j Q_j T_{jp}$ (Eqn 5.3)

For the satisfaction of air pollution standards at each population center, C(x,y) (Eqn 5.3) should be less than the K_l value for each air pollutant type *l*.

Now everything is covered except the structure of the objective function. The objective of our model is the minimization of total cost. In this chapter two different Unified Models are proposed: UM1 and UM2. These models differ from each other due to their structure of the objective functions. There are mainly four costs: operational cost of the facility, transportation cost, the power gain and the money charged from the generators. Unified Models proposed in this chapter contains one or more of the stated costs.

Regardless of the waste type, for each ton of hazardous waste to be disposed, there is a unit operational cost o_j of site j.

The incineration process in the disposal plant yields electrical power. The produced electrical power is either used in the plant or sold to the authorized institutions. Therefore the generated electrical power can be thought as one of the gains of disposal plants. The amount of electrical power gain may differ depending on the type of the incinerated waste. Let p_{jt} denote the gain per ton of hazardous waste type t at disposal site j.

Another gain of the disposal plant is the processing fees taken from the sources and we denote f_j as the processing fee charged by the disposal plant j for any type of hazardous waste.

Last term in the objective function is the transportation cost. In Turkey, transportation of the hazardous waste is handled by the private transportation firms. The transportation fee is typically cashed per truck.

In the Unified Models, **UM1** and **UM2**, we assume that per truck fees can be converted to the unit fees for ease of computation. Therefore transportation fee for any combination of source-destination pair is calculated by the multiplication of the three terms: the amount of hazardous waste transported between the source-destination pair, the shortest path distance between the source-destination pair and the unit transportation fee taken per km. per ton of hazardous waste. The unit transportation fee is denoted as ct/dist in the model. UM1 consists of all cost values whereas UM2 contains only the transportation cost.

Even though the transportation cost between factories and recycling centers has nothing to do with the disposal plant we decided to include the transportation fees between the factories and recycling centers to the objective function. This is due to the fact that if there were no such cost, the model will behave as if all recyclable waste from factories would go to recycling centers which is not usually true.

The *literal* definition of the model can now be stated as:

Minimize

Total cost

s.t.

Capacity constraint; (1)

Mass balance constraints; (2-8)

Minimum capacity constraint; (9)

Number of incineration plant constraint; (10)

Gaussian Plume Constraint; (11)

The notation:

Index Set

-Waste generation nodes

I = Factories	**I**={1………i}
H = Hospitals	**H**={1……..h}
R = Recycling Centers	**R**={1……...r}
- J = Candidate Sites	**J**={1……....j}
- P = Population Centers	**P**={1…..….p}

-Waste types

W = Recyclable Waste	**W**={1…….w}
U = Unrecyclable Waste	**U**={..………u}
C = Clinical Waste	**C**={1………c}
- L = Air pollutant type	**L**={1……..*l*}

Let T= **W** U **U** U **C**

Parameters

b_{iw} (b_{iu}) = the total amount of recyclable (unrecyclable) waste type w (u) at i^{th} factory.(ton/90 days)

b_{hc} = the total amount of clinical waste type c at h^{th} hospital. (ton/90 days)

α_{rw} = the reduction rate for waste type w at recycling center r.

T_{jp} = the parameters other than Q in (Eqn 4.1.1) for plant j and population center p pair.

K_l = standard ambient air concentration value of gas type *l*.

(1-DR_{lt}) = conversion factor from hazardous waste type t to air pollutant type *l*,

t = recyclable, unrecyclable, clinical waste type.

o_j = operational cost per ton of hazardous waste at disposal plant j.

ct/dist = unit transportation fee .

d_{ij} = the shortest path distance between i and j. i = factories, recycling centers, hospitals j = disposal plants, recycling centers.

p_{jt}= gains for kilowatt power generated for waste type t at plant j.

f_j = processing fee taken from the sources of hazardous waste from each disposal plant j.

Cap_j = Capacity of j^{th} disposal plant

Cap^{min}_j = Minimum capacity requirement for an disposal plant at site j.

p = number of disposal plants to be located.

5.1. Combinatorial Formulation and Complexity

The hazardous waste management problem is to establish p disposal plants from a set of candidates such that all types of generated wastes are to be disposed of a subset of established disposal plants and the air pollutant standards of each population center, capacity and minimum capacity requirements of each disposal plant are to be satisfied with the minimization of total cost. Data instance of hazardous waste management problem consists of positive integers m, n, k, r, w, u, c, t, l, and z, two m × n cost matrices CREC = $\{crec_{i,j}\}$ and CUNREC = $\{cunrec_{i,j}\}$, a k × n cost matrix CHOSP = $\{ chosp_{h,j}\}$, an m × r cost matrix CRF = $\{crf_{i,r}\}$, an r × n cost matrix CRINC = $\{crinc_{r,j}\}$ four n vectors OPC = $\{o_1....o_n\}$ for operational cost, PC = $\{pc_1...pc_n\}$ for processing fees, Cap = $\{ Cap_1...Cap_n\}$ for capacity of disposal plants, MinCap = $\{ mincap_1...mincap_n\}$ for minimum capacity of disposal plants, an n × t matrix POW = $\{pow_{j,t}\}$ for power gain of each plant for each waste type, three matrices for the amount of waste at sources an m × w matrix BW = $\{b_{i,w}\}$, for waste type w at plant i, an m × u matrix BU = $\{b_{i,u}\}$ for waste type u at plant i, a k × c matrix BC= $\{b_{h,c}\}$ for waste type c at hospital h, an r × w matrix $\alpha = \{\alpha_{r,w}\}$ for reduction rates of recycling centers, the *l* vector K= $\{ K_1 \ldots K_l \}$ for standard concentration of air pollutant type *l*, an n × z matrix T= $\{T_{j,z}\}$ for the fixed part of the Gaussian Plume equation for each pair of candidate site and population center and the integer p for the number of disposal plants which is to be opened.

Theorem 6.1 *The hazardous waste management problem is NP hard.*

Proof: First we need to introduce the P-Median Problem (p-MP). The p-MP problem is to establish p facilities in a set of potential facilities and to supply each client from a subset of established facilities such that the demands of all clients are met and such that the total costs are minimized. The data instance of p-MP problem consists of positive integers m,n and p, the m × n cost matrix COST = $\{cost_{i,j}\}$.The p-MP problem is NP hard. [24]

We now reduce the hazardous waste management problem to the p-MP problem. Let us take a data instance of the hazardous waste management problem as follows: $\|S\| = n$ (the cardinality of candidate sites), $\|F\| = m$ (the cardinality of factories), k = 0 (there is no hospital), r = 0 (there is no recycling center), w = 0 (no recyclable waste), u = 1 (only one type of unrecyclable waste), c = 0 (no clinical waste), z = 0 (there is no population center), *l* = 0 (no any air pollutant), $crec_{i,j} = 0$ for all i and j (no transportation cost for recyclable waste), $chosp_{h,j} = 0$ for all h and j (no transportation cost for clinical waste), $crf_{i,r} = 0$ for all i and r (no transportation cost between recycling center and factory pairs), $cinc_{r,j} = 0$ for all r and j (no transportation cost between recycling center and disposal plant pairs), $o_j = 0$ for all j (no operational cost), $pc_j = 0$ for all j (no processing fees), cap_j is infinity for all j, $mincap_j = 0$ for all j (no minimum capacity restriction), $pow_{j,t} = 0$ for all j and t (no power generation cost), $b_{iw} = 0$ for all i and w (no amount of recyclable waste), $b_{iu} = 1$ for all i (1 unit generation of unrecyclable waste for each factory i), b_{hc} = 0 (no amount of c□nical waste), α_{rw} = 0 for all r and w (no reduction rate of recycling centers), K_l is infinity for all l (no restriction on standard concentrations of air pollutants), T_{jz} = 0 for all j and z (fixed part of Gaussian plume constraint is equal to zero), p is the number of facilities which is to be opened. Then this data instance of hazardous waste management problem is to establish p facilities from a set of candidate set to dispose all unrecyclable waste to the subset of established disposal plant such that the total cost is minimized and data set of this instance consists of p, m, c and m × n cost matrix CUNREC = $\{cunrec_{i,j}\}$. The combinatorial formulation of this instance of hazardous waste management problem is equivalent to the combinatorial formulation of the p-MP problem. This proves that the hazardous waste management problem is NP hard.

5.1 Mixed Integer Formulations

In this part two different Unified Models (UM1 and UM2) are proposed. UM1 model consists of all the cost values whereas UM2 contains only the transportation costs. First of all we define the decision variables.

Decision Variables

y_j = 1 if the disposal plant is opened at j^{th} candidate site; 0 otherwise.

u_{iju} (x_{ijw}) = amount of unrecyclable (recyclable) waste type u (w) that goes from factory i to disposal plant j.

e_{rjw} = amount of recyclable waste w that goes from recyc. center r to plant j

h_{hjc} = amount of clinical waste type c that goes from hospital h to plant j.

q_{irw} = amount of recyclable waste type w that goes from factory i to recycling center j.

n_{jt} = amount of hazardous waste type t to be incinerated at plant j. t = recyclable, unrecyclable, clinical wastes.

The Unified Model (UM1)

min

$$\sum_{j,t} n_{jt} o_j + \sum_{i,j,w} \text{ct/dist } d_{ij} x_{ijw} + \sum_{r,j,w} \text{ct/dist } d_{rj} e_{rjw} + \sum_{i,j,u} \text{ct/dist } d_{ij} u_{iju}$$

$$+ \sum_{h,j,c} \text{ct/dist } d_{hj} h_{hjc} + \sum_{i,r,w} \text{ct/dist } d_{ir} q_{irw} - \sum_{j,t} p_{jt} n_{jt} - \sum_{j,t} f_j n_{jt}$$

s.t.

$$\sum_{i,w} x_{ijw} + \sum_{i,u} u_{iju} + \sum_{r,w} e_{rjw} + \sum_{h,c} h_{hjc} \le Cap_j\, y_j \qquad \forall\ j \in J \qquad (1)$$

$$\sum_{j} x_{ijw} + \sum_{r} q_{irw} = b_{iw} \qquad \forall\ i \in I, w \in W \qquad (2)$$

$$\sum_{j} u_{iju} = b_{iu} \qquad \forall\ i \in I, u \in U \qquad (3)$$

$$n_{jw} = \sum_{i} x_{ijw} + \sum_{r} e_{rjw} \qquad \forall\ j \in J, w \in W \qquad (4)$$

$$n_{ju} = \sum_{i} u_{iju} \qquad \forall\ j \in J, u \in U \qquad (5)$$

$$n_{jc} = \sum_{h} h_{hjc} \qquad \forall\ j \in J, c \in C \qquad (6)$$

$$\sum_{j} h_{hjc} = b_{hc} \qquad \forall\ h \in H, c \in C \qquad (7)$$

$$\alpha_{rw} \sum_{i} q_{irw} = \sum_{j} e_{rjw} \qquad \forall\ r \in R, w \in W \qquad (8)$$

$$\sum_{i,w} x_{ijw} + \sum_{i,u} u_{iju} + \sum_{r,w} e_{rjw} + \sum_{h,c} h_{hjc} \ge Cap_j^{min}\, y_j \qquad \forall\ j \in J \qquad (9)$$

$$\sum_{j} y_j = p \qquad (10)$$

$$\sum_{j} \left[\sum_{w} (1 - DR_{1w}) n_{jw} + \sum_{u} (1 - DR_{1u}) n_{ju} + \sum_{c} (1 - DR_{1c}) n_{jc} \right] T_{jp} \le K_1$$

$$\forall\ p \in P, l \in L \qquad (11)$$

$$y_j \in \{0,1\} \qquad \forall\ j \in J \qquad (12)$$

$$\text{all variables} \ge 0 \qquad (13)$$

The objective function sums up all the related costs. The first term is written for the operational cost. Following five terms represent the total transportation fee. Power gains are included by the seventh term. The last term constitutes the processing fee.

Constraint (1) ensures that a flow to site j is only possible if there is a disposal plant located at that site. The total flow into plant can not exceed its capacity which is again satisfied via constraint (1). Constraints (2)- (7) are the mass balance constraints for factories, disposal plants and hospitals respectively. We need to differentiate between all these waste types since the destruction rates used in constraint (11) may differ. Constraint (8) is the mass balance constraint for the recycling centers. Constraint (9) ensures that the flow into the plant satisfies the minimum threshold value. The limit on the number of disposal plants is satisfied via constraint (10).

Constraint (11) is the Gaussian Plume constraint and it provides the satisfaction of the ambient air concentration of air pollutant standards at each population center.

Unified Model 2 (UM2)

The difference between UM1 and UM2 is their objective functions. Since the parameters for operational cost, power gain and processing fee may affect the optimal solution we wonder what if only the transportation cost is considered as an objective function. For this reason in UM2 the objective function contains only the transportation cost.

$$
\begin{aligned}
&\min \\
&\sum_{i,j,w} \text{ct/dist}\, \text{d}_{\text{ij}}\, x_{ijw} + \sum_{r,j,w} \text{ct/dist}\, \text{d}_{\text{rj}}\, e_{rjw} + \sum_{i,j,u} \text{ct/dist}\, \text{d}_{\text{ij}}\, u_{iju} \\
&\quad + \sum_{h,j,c} \text{ct/dist}\, \text{d}_{\text{hj}}\, h_{hjc} + \sum_{i,r,w} \text{ct/dist}\, \text{d}_{\text{ir}}\, q_{irw}
\end{aligned}
$$

s.t .

(1)-(13)

The objective function contains only the transportation cost, the rest is the same with UM1 model.

The computational analysis of the proposed models is provided in the following chapter.

Chapter 6

COMPUTATIONAL ANALYSIS

For the computational analysis of the proposed models we provide three different applications. In the first one Central Anatolian Region is taken as an application area. In the second one, a larger area consisting of four regions (Marmara, Ege, Akdeniz, and Central Anatolian regions) is chosen in order to see the efficiency of proposed models. As stated in Chapter 3, the Ministry of Environment and Forest prepared a HWM project for the management of hazardous waste in Turkey. Therefore as a last application, we make a comparison between the HWM project and our models.

In order to see the effects of Gaussian plume constraint to the model two different scenarios are developed for proposed models. In the first scenario each model is solved without considering the Gaussian plume constraint and in the second one, our unified model is applied.

As stated in Chapter 3, the candidate sites cannot be the population centers due to the 3000 m. restriction. Therefore we have to make a distinction between the population centers and the candidate sites. We decided to exclude the selected candidate sites from the set of districts and call that new set as the set of population centers. Determination of the candidate sites is also another issue to handle.

In order to find the pollution effect of each candidate site to the population centers we have to know the wind speed and the wind direction data of each candidate site. For some districts these data are available in Turkish State Meteorological Service. Therefore candidate sites are determined according to their availability of meteorological data. However, some districts with available meteorological data are not considered as candidate sites due to the site restrictions of EIA report. As stated in Chapter 3, the sites cannot be sited on the touristic places or on the fault lines. Therefore we eliminate some districts with available meteorological data from the candidate set, if they are on the coast of Turkey.

6.1 Application in Central Anatolian Region

For this application, 14 cities are taken as the cities of Central Anatolian Region. The map of the region can be seen in appendix part B.

There are 183 districts for the region and 37 of these districts are determined as the candidate sites due to the availability of their meteorological data. The remaining 146 districts are considered as population centers. (Figure 6.1.1)

We assume that there exists a factory at each district. For the hospitals; it is assumed that there is a hospital in the district if the population of that district is more than 20000. There are 117 such districts out of 183. In the Central Anatolian region there are 6 districts with recycling centers.

It is assumed that each factory generates both recyclable and unrecyclable wastes. We consider two types of waste from each category. For the clinical waste, again two types are taken. Thus the cardinality of the sets W, U, and C are all two. For every waste type we assume that the amount generated is proportional to the population of the corresponding district.

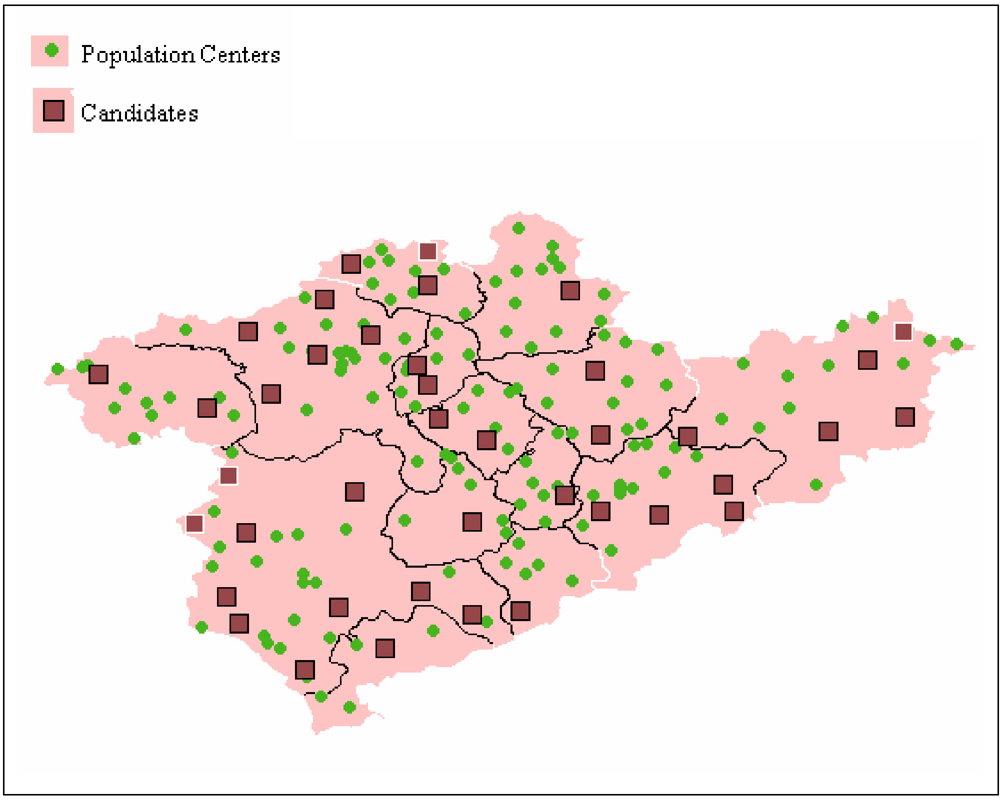

Figure 6.1.1 Candidate Sites and Population Centers of Central Anatolian Region

The conversion factors (α_{rw}) for recycling centers are generated after an interview with one of the recycling center operator in Ankara [8]. We learned that depending on the waste type, the recycling percent can be between 0.35 and 0.95. Then, for each recycling center r and recyclable waste w pair, a random number between these limits is generated as a conversion factor.

For the air pollutant type L, two main pollutants are considered throughout this study: SO_2 and NO_2. According to the "Control Legislation of Air Pollution in Turkey" the standard ambient air concentration of SO_2 (K_{SO2}) at any population center is 150 ($\mu g/m^3$) and that for NO_2 is 100 ($\mu g/m^3$). The conversion factors ($1\text{-}DR_{lw}$) used for converting mass of hazardous waste into the mass of air pollutants are supplied from Baumbach [2] by specifying types of hazardous waste, and types of air pollutants. In our computational analysis we take 0.02 as the conversion factor of SO_2 and 0.13 as that of NO_2 for every waste type (These numbers are actually the conversion factors for oil. One can find the factors for many different types of waste in the stated reference).

The average wind speed data of each candidate for each month between the years 1982 and 1999 are available in Turkish State Meteorological Service [26]. For each candidate site we choose the smallest wind speed among the average wind speeds of each months of that candidate data. However the data of the prevalent wind directions of all candidates is not available in Meteorological Service. For the unknown prevalent wind directions we need to provide educational guesses by considering the nearby districts with available wind direction data.

For the remaining parameters such as operational cost, processing fees, the profit of the power generated process we need to provide "educational guesses".

For the shortest path distances and for getting the unique coordinate system of districts we utilize a Geographical Information System (GIS) software, Arcview 3.2 [12].

We consider three cases: p=1, p=2 and p=3. In fact only one disposal plant is enough to meet the demands of Central Anatolian region. However since we also want to test the efficiency of our models we also apply p=2 and p=3 cases in the region.

The models are solved by using CPLEX 8.1 running on a server type which has 1.133 Ghz speed and 256 MB memory. The results for p=1 are depicted in Table 6.1.1

Unified Models	Without Gaussian Plume Constraints **(Scenario I)**		With Gaussian Plume Constraints **(Scenario II)**	
	Selected Site	CPU (min)	Selected Site	CPU (min)
UM1	KIRŞEHİR	9.01	KULU	6.67
UM2	KIRŞEHİR	9.01	KULU	6.81

Table 6.1.1 Application Results of Proposed Models for p=1

As can be seen from Table 6.1.1, models UM1 and UM2 have the same solutions. The selected sites in two scenarios are completely different from each other. However the sites selected for two scenarios are actually nearby districts (Figure 6.1.2). Even though Kırşehir is the site that minimizes total cost meteorological conditions at that district do not satisfy the EIA requirements. Thus in the second scenario another district, Kulu, is selected.

When p=1, the computational times for each scenario of the models UM1 and UM2 are very close to each other. Therefore we can say that in addition to satisfaction of Gaussian plume constraint, our unified model (Scenario II) also provides a reasonable and compatible computational time for a network similar to Central Anatolian application and p=1.

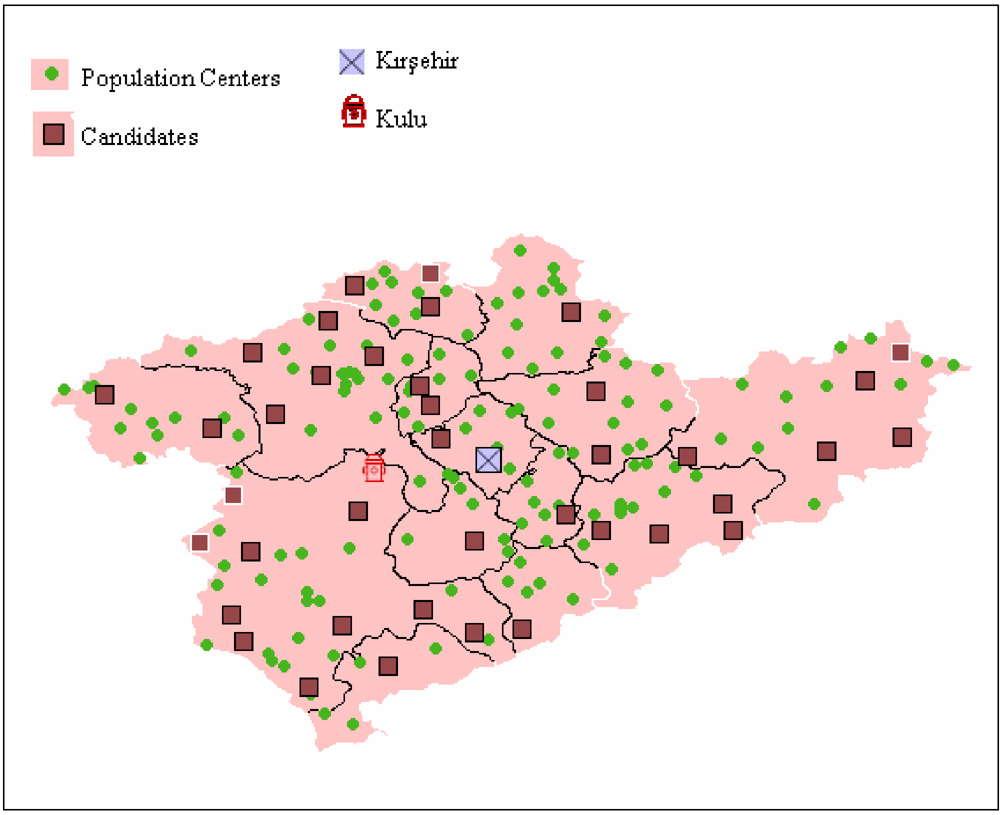

Figure 6.1.2 Selected Sites for p=1

For p=2 case, again CPLEX 8.1 is used and results are summarized in Table 6.1.2

12	Without Gaussian Plume Constraints **(Scenario I)**		With Gaussian Plume Constraints **(Scenario II)**	
Unified Models	Selected Sites	CPU (min)	Selected Sites	CPU (min)
UM1	ETİMESGUT, ÜRGÜP	20.8	ETİMESGUT, KIRŞEHİR	15.87
UM2	ETİMESGUT, ÜRGÜP	22.45	ETİMESGUT, GEMEREK	63

Table 6.1.2 Application Results for p=2

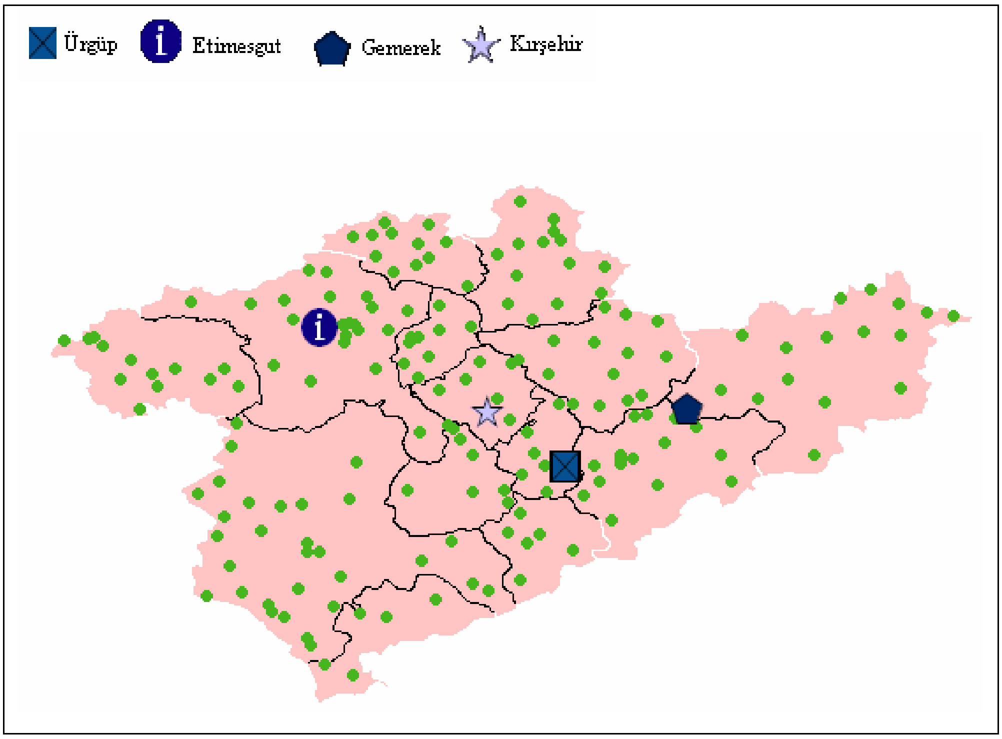

Figure 6.1.3 Selected Sites for p=2

Various observations can be illustrated from the results of the models where the number of disposal plants to be opened is equal to two.

First of all some differences between the models UM1 and UM2 are clearly observed. Recall that the objective function of the UM1 model consists of minimization of all costs (operational cost, transportation cost, power gain, money charged due to processing fees) whereas the objective function of the UM2 model consists of minimization of transportation cost. As stated in Chapter 5, parameters for the operational cost, power gain and processing fee may significantly affect the solution of the models. Due to the effect of parameters into the model, two different results for scenario II are found.

When the objective function is composed of all cost the sites are selected as

Ürgüp and Etimesgut for the first scenario, and for the second scenario the sites are selected as Etimesgut and Kırşehir.

In the case of UM2 model, where the objective function considers only the transportation cost, Ürgüp and Etimesgut are selected for the first scenario, and Etimesgut and Gemerek are selected for the second scenario. While the results of the scenario I are still the same as with the UM1 model, the results of the scenario II differs. This is due to the effects of the parameters. When they are excluded from the objective function, as in the case of UM2, the site chosen is Gemerek instead of Kırşehir. The operational cost, power gain and processing fee of the district Kırşehir cause an improvement in the objective function value of Kırşehir. When the parameters are not considered, Gemerek's objective function value is superior to the objective function value of Kırşehir.

Again the significance of the Gaussian Plume constraint is seen for p=2. The meteorological conditions of Ürgüp do not satisfy the EIA requirements. Thus that district is eliminated by the Gaussian Plume constraint.

Note that for p=1, Kırşehir does not satisfy the Gaussian Plume constraint, however when p=2, Kırşehir is selected as an appropriate site for scenario II. The major factor for such a result is due to the fact that the amount of air pollutant emitted from the plant plays an important role on the Gaussian equation. Since we open two disposal plants the amount disposed of the disposal plant in Kırşehir is reduced. By this way the concentrations of the air pollutants at population centers are changed. Therefore the city of Kırşehir also satisfies Gaussian Plume constraint for p=2 case.

When p=2 the computational time for Scenario II is closer to that of scenario I for UM1 model. However this is not the case for UM2 model where the computational time of Scenario II takes approximately three times more than that of scenario I. These results are again due to the effects of parameters. In any case we can say that, when getting the positive EIA report is considered that additional CPU time for UM2 model will be tolerated. Besides having an optimal solution in 100 minutes over 183 node network is pretty reasonable.

For p=3 case, again CPLEX 8.1 is used and results are summarized in Table 6.1.3

	Without Gaussian Plume Constraints **(Scenario I)**		With Gaussian Plume Constraints **(Scenario II)**	
Unified Models	Selected Sites	CPU (min)	Selected Sites	CPU (min)
UM1	ETİMESGUT, BOĞAZLIYAN, ÇUMRA	21.2	ETİMESGUT, KIRŞEHİR, SEYDİŞEHİR	159 =2.45 hrs
UM2	ETİMESGUT, BOĞAZLIYAN, ÇUMRA	28.5	ETİMESGUT, KIRŞEHİR, KARAMAN	145 =2.41 hrs

Table 6.1.3 Application Results for p=3

As in the case of p=2, while the results of scenario I are the same for both models whereas the results of scenario II differs. This is again due to the effects of parameters to the objective function.

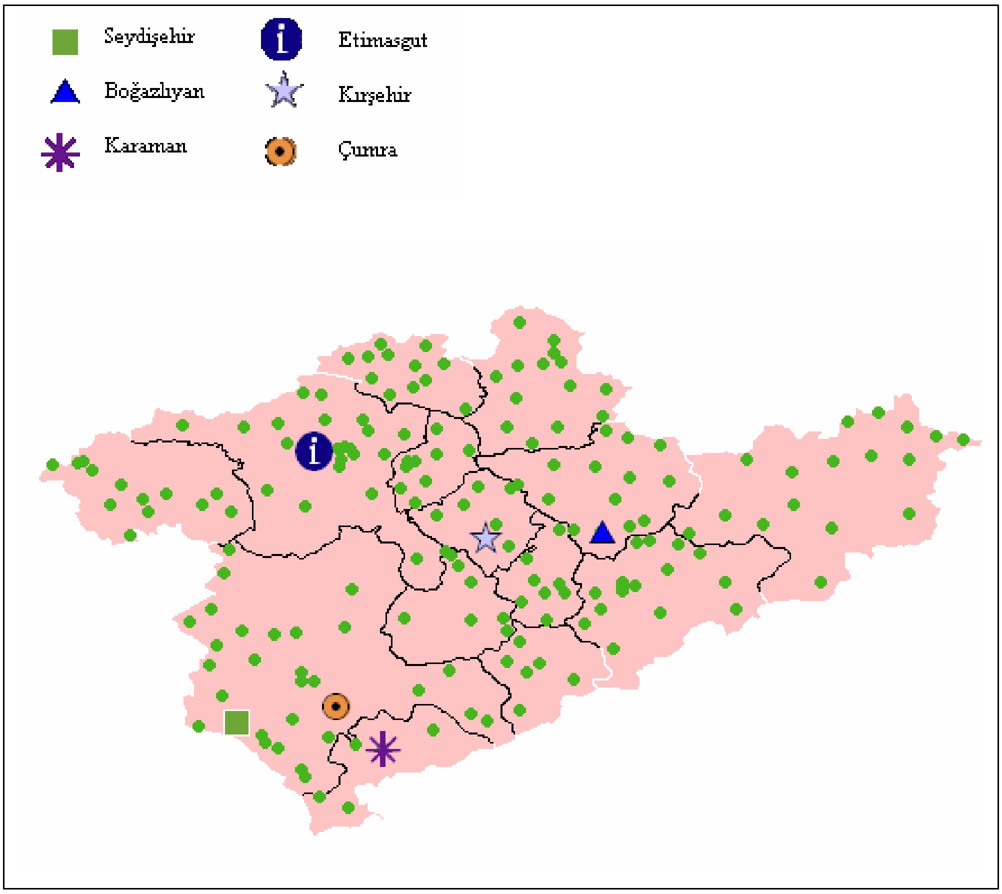

Figure 6.1.4 Selected Sites for p=3

From p=2 case, we know that Etimesgut and Kırşehir are feasible places for scenario II. Again this case is verified in p=3 case. The meteorological conditions of Boğazlıyan and Çumra do not satisfy the Gaussian Plume constraint.

Observe that, even n=183, p=3 case can be solved optimally in less than three hours. This proves that besides being realistic, our models are also very efficient in terms of CPU time requirements.

6.2 Application in Four Regions

For the case of 183-node network, obtaining the optimal solution in a reasonable time lead us to consider the application of our models in a larger network. Therefore we choose a new application area for our proposed models. By this way while we test our models in an area larger than the 183 node network, we will also have a chance to make a comparison between our proposed model and HWM project.

In addition to Marmara, Ege, Akdeniz and Central Anatolian regions, some cities of Karadeniz are also included in the application area due to their geographical locations. We call that area as "four regions" throughout this study. The map of the application area is available in the appendix part B.

In the "four regions" application we generate two different candidate sets. In the first one, we only consider the candidates belonging to three regions. (Marmara, Ege, Akdeniz). By this way we could also make a comparison with the HWM project. However as we also include the cities of Central Anatolian Region as waste generators, it becomes reasonable to add the candidate sites of Central Anatolian region to the first set. Therefore we have two different candidate sets. The first set is composed of 56 districts and the second set is composed of 87 districts. (The maps of the candidate sites are available in appendix part B.)

There are 47 cities and 551 districts in the application area. Out of 551 districts 22 districts have recycling centers (the map of all recycling centers for the application area is available in appendix part B). The locations of these recycling centers are provided from Ministry of Environment and Forests. [32]. Again as in the Central Anatolian application we assume there exists a factory in each district. If the population of the district is more than

10000, it is assumed that there is a hospital at that district. There are 326 such districts.

Other parameters related to waste types, air pollutant types, air pollutant standards, conversion factors, reduction rates are taken as the same as with the Central Anatolian application.

Again for the shortest path distances and for getting the coordinates of districts we utilize Geographical Information System (GIS) software, Arcview 3.2. The road network of the application area is available in appendix part.

Throughout the "four regions" application we only test the UM2 model. Since this part is actually handled to test our model in an area larger than 183 node network, we consider only p=1 case for both candidate sets. We also solve p=4 in a restricted set in the sub-section 6.3.

The two scenarios are again created, one without the Gaussian plume constraint and the other one with the Gaussian plume constraint, as in the Central Anatolian application. The models are solved by using CPLEX 9.1. The results for p=1 and for both candidate sets are depicted in Table 6.2.1

	Without Gaussian Plume Constraints **(Scenario I)**		With Gaussian Plume Constraints **(Scenario II)**	
Candidate Set	Selected Sites	CPU (hrs)	Selected Sites	CPU (hrs)
I	GEYVE	1.84	KOCAELİ	0.5
II	GEYVE	7.08	KOCAELİ	0.2

Table 6.2.1 Application Results for p=1

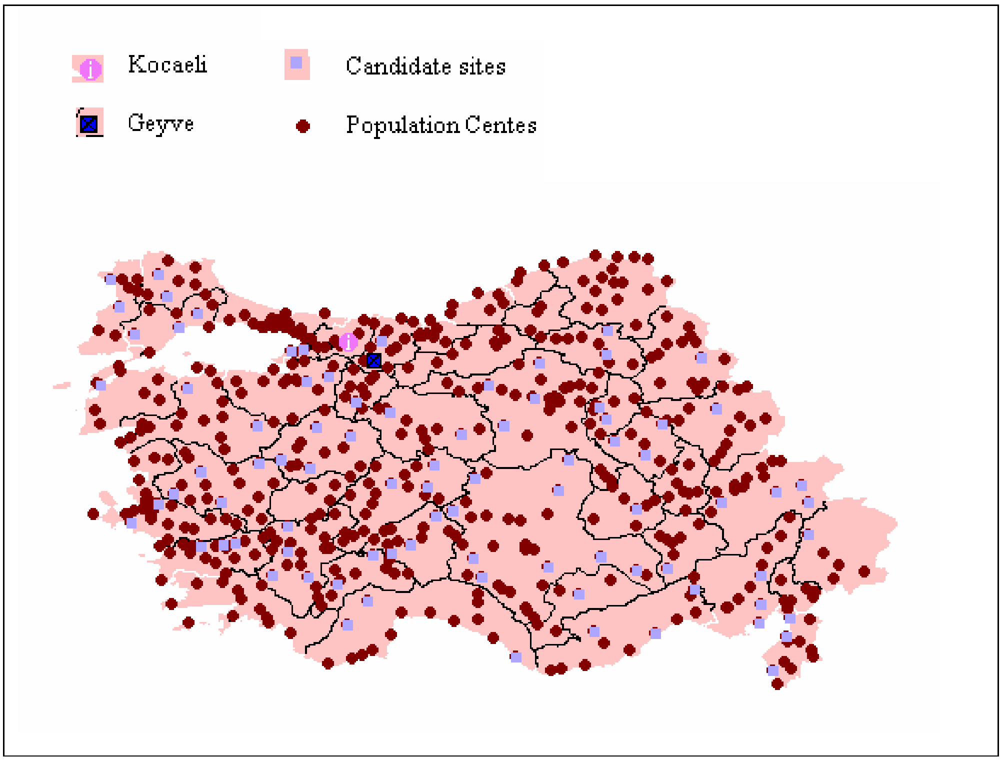

Figure 6.2.1 Selected Sites for p=1

As can be seen from the table for both candidate sets we have the same solutions under each scenario. That is even though we enlarge the candidate set to include Central Anatolian candidate sites, the model still selects the sites from the other three regions. Actually the model selects a site which is closer to İstanbul due to large amount of wastes generated there. The application of UM2 model for the candidate set I and p=1 again results in a solution that shows the significance of the Gaussian Plume constraints. Even though Geyve is the site that minimizes the transportation cost, the meteorological conditions at that district do not satisfy the EIA requirements. Thus in the second scenario another district, Kocaeli, is selected which is actually a nearby district as shown in Figure 6.2.1

In the “four regions” application we use CPLEX 9.1 with strong branching.

Sine we only use strong branching for this application, the CPU times are very effective when 551 node network and such candidate sets are considered. The CPU time differences between the scenarios are not so big.

Another result that can be observed from the application for p=1 is that the site selected via scenario II is Kocaeli. In other words, it is the district where İzaydaş is located. Therefore this application also shows the reliability of our unified model, since İzaydaş did receive a positive EIA report.

6.3 Comparison with HWM Project

In Chapter 3 we gave information related to hazardous waste management project (HWM project), which is prepared by Ministry of Environment and Forest. HWM project aims to select sites for three incinerators located in three different regions: Marmara, Ege and Akdeniz. For this purpose the project experts select the sites by only considering the industrialization level of cities and they pick Tekirdağ, İzmir and Adana as the sites for the new incinerators. By addition of Kocaeli, which already has an incineration plant in Turkey, there will be four incinerators in Turkey for the next 20 years. After the selection of sites, the project also proposes an assignment model for the waste flow with the objective function of minimization of total distance.

Before passing through the comparison part, it should be worthwhile to make a distinction between our model and the HWM project. HWM project does not consider any effects of air pollutants. Besides that, the sites of the incinerators are just determined by the experts of project without developing a mathematical model. In addition to that the waste generators are assumed as the city centers of only the three regions. However, in our study we also include Central Anatolian region and some cities of Karadeniz as generators in addition to three regions. By this way we get our results in a larger area.

Also, to be more realistic, we again work with districts rather than cities which are actually aggregated districts.

Project experts of HWM decided to open one incineration plant for each region: Tekirdağ for Marmara, İzmir for Ege, Adana for Akdeniz. With the addition of Kocaeli to these incinerators they developed a mathematical model in which the assignment of hazardous waste flow is handled.

Therefore we can say that the HWM project is a 2 phase project. In the first phase they choose the sites and in the second phase they decide the flow structure of the hazardous waste. However our model can be considered as 1 phase model in which the selection of sites and the decision on the flow structures of hazardous waste are handled simultaneously. Beside, during the assignment phase the HWM project assigns a city to incinerator. However, it might be better to send the flow of some districts to one incinerator and some districts to other incinerator.

In order to make a comparison with HWM project we add constraints to the UM2 model such that each constraint provides to open one incinerator for each region (constraints 14-16). Also one constraint is also added to ensure that there is an incinerator in Kocaeli (constraint 17). Lastly constraint 18 provides to open 4 incinerators into the region. By this way the model will end up with one site of each region and we can make a comparison with the sites of HWM project.

$$\sum_{j \in M} y_j = 1 \qquad (14)$$

$$\sum_{j \in E} y_j = 1 \qquad (15)$$

$$\sum_{j \in A} y_j = 1 \qquad (16)$$

$$y_{102} = 1 \qquad (17)$$

$$\sum_{j} y_j = 4 \qquad (18)$$

Where the sets M, E, A denote the set of candidates for regions Marmara, Ege and Akdeniz respectively. The cardinality of M is 17, E is 23 and A is 15.

The model is solved by CPLEX 8.1 and the results are depicted in Table 6.2.3.1.

Region	Without Gaussian Plume Constraint (Scenario I)	With Gaussian Plume Constraint (Scenario II)
	Selected Site	Selected Site
Marmara	BOZÜYÜK (BİLECİK)	KELES (BURSA)
Ege	BORNOVA (İZMİR)	BORNOVA (İZMİR)
Akdeniz	KARAİSALI (ADANA)	ERDEMLİ (MERSİN)
CPU (hrs)	**6.08**	**24.7**

Table 6.3.1 The Results of UM2 Model

As in the HWM project, UM2 also selects İzmir as the site of incineration plant for Ege region. If incineration plant is to be opened in İzmir, Bornova is the site that minimizes the transportation cost via UM2 model. Therefore HWM project should consider opening an incinerator plant in Bornova.

When we consider the Marmara region, the site (Bursa) selected via scenario II is completely different than the site (Tekirdağ) suggested by HWM project. The main reason for that is the inclusion of generators from Central Anatolian region. When the Gaussian plume constraint is not considered Bozüyük is the site that minimizes the total cost. When we consider the problem with Gaussian plume constraint, Keles is the site that minimizes total cost. Both are very far from Tekirdağ.

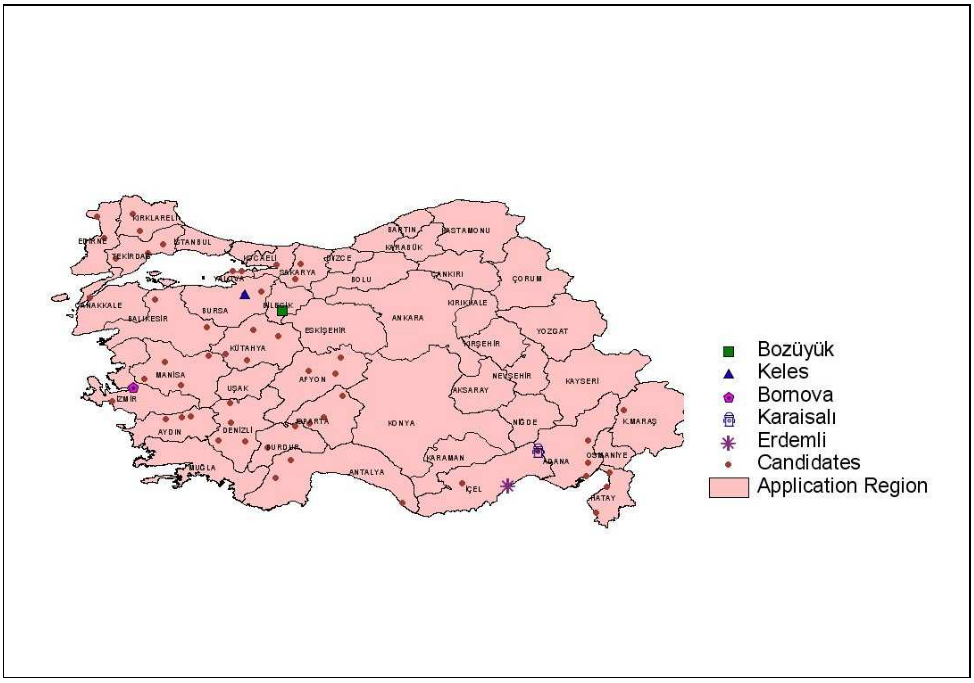

Figure 6.3.1 Selected Sites Via UM2 Model

For Akdeniz, while scenario II selects Erdemli (Mersin) for the location of incineration plant site, scenario I selects Karaisalı (Adana). In HWM project Adana was selected as the site of incineration plant. However our studies show that while Karaisalı (Adana) is the site that minimizes objective function, it does not satisfy the Gaussian Plume constraint and that district will not receive a positive EIA report. Therefore Erdemli should be selected which is a nearby district which also satisfies the Gaussian plume constraint.

From the above results, we can say that except Bursa, sites selected for both projects (HWM and UM2) are very close to each other. However our project is superior to HWM because it also decides the district of the incineration plant. In addition to that the selected site will automatically receive a positive EIA report due to satisfaction of Gaussian Plume constraint.

In Phase 2 part of the HWM project, the mathematical model decides which city should send its waste to which incinerator. According to the results, HWM project states that some cities do not send their waste to the incinerator opened in their region, instead they send their waste to the any other region’s incineration plant. For example according to the results of HWM, Balıkesir (in Marmara region) sends its waste to İzmir (Ege) instead of Kocaeli or Tekirdağ.

When we consider the results of UM2, we see that while some districts of the city send their waste to the incineration plant of their region, some other districts of the same city send their waste to another incineration plants. For example within Balıkesir the districts like Erdek, Manyas and Gönen send their waste to the Keles (Marmara region) whereas the districts such as Ayvalık and Burhaniye send their waste to Bornova (Ege region).

We conclude this chapter by noting that our models UM1 and UM2 can be considered as very applicable methods. They reflect all related real life issues. Besides that, the models can be applied to large instances. We even solved n = 551, p = 4 (in a restricted set) within 24 hours.

Chapter 7

CONCLUSIONS AND FUTURE RESEARCH DIRECTIONS

In this thesis we analyze the hazardous waste management problem from different perspectives. We define the requirements and the criteria specific to different affected institutions of the problem. We first observe that hazardous waste disposal method plays an important role in the model development phase of the hazardous waste management problem. We then focus on incineration and analyze the criteria specific to siting incinerators. We observe that satisfaction of the ambient air concentration of air pollutants is the most important one among these criteria which should be analyzed via Gaussian plume equation.

We develop a methodology to include the Gaussian plume equation into our mathematical model. We then propose a unified model for the hazardous waste management problem which also includes the satisfaction of the ambient air concentrations of the air pollutants at each population center.

We also state the current situation for hazardous waste management problem in Turkey. For this purpose the HWM project is analyzed in detail. The comparison between the project and our proposed model is provided in Chapter 6.

CHAPTER 7 CONCLUSIONS AND FUTURE RESEARCH DIRECTIONS

As it can be seen from our computational analysis provided in Chapter 6, the inclusion of Gaussian plume constraint into the model may change the selected site. If standard approaches were taken (i.e. solve the models which are developed without the Gaussian plume constraint and then apply for the EIA report) the selected site may not receive a positive EIA report. Considering the fact that getting the report is pretty time and money consuming, one would prefer to apply for the report for a site which will "pass" with a high probability. Since our unified model still aims to minimize total cost, the site selected by the model will be the location with the least cost which will get a "pass" from the EIA report.

In addition to its applicability, the proposed unified model is also easily solvable via commercial LP solvers like CPLEX. For example for UM2 model, the problem with 183 node network was solved within 6.81 minutes for p = 1, 1 hour for p = 2 and for 2.41 hours for p = 3 which can be considered as quite fast. Besides these, the instance with n=551 and p=4 is solved within 24 hours which can be considered as acceptable for a long term decision.

Since our proposed model satisfies air pollution standards at population centers via Gaussian plume constraint, our model is also applicable for the location of any air pollution causing facility. For example location of cement plant can also be modeled with our proposed model.

For a future research direction, one may want to model the problem with truck numbers since the actual transportation cost is per truck. A way to deal with this problem can be found by dividing the flow to the capacity of truck (trcap) and requiring the resulting variables to be integers. Dealing with this problem is a subject of future research of this thesis.

In addition to that, in Chapter 4 we stated that the wind direction of a candidate site is not constant throughout the year. Since we aim to get a positive EIA report, it is sufficient to select the wind direction of a candidate site as the prevalent one. However the frequency of each wind direction for each candidate site can be incorporated into the model easily. The main obstacle for this is finding the accurate information related to the frequencies of wind directions for each candidate site. As a future research we plan to supply data for frequencies of wind directions of each candidate site and revise the model such that it also includes the frequencies of wind directions.

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APPENDIX

APPENDIX

A: Tables For Wind Directions

APPENDIX

The locations of the population centers A to H can be seen from Figure 4.2.1.

1. Wind direction (East) ⟶

Population Centers	x value	y value
A	$(a_1 - I_1)$	$(I_2 - a_2)$
B	$(b_1 - I_1)$	$(b_2 - I_2)$
C	$(c_1 - I_1)$	$(c_2 - I_2)$
D	0	0
E	0	0
F	0	0
G	0	0
H	$(b_1 - I_1)$	$(I_2 - h_2)$

Table A.1 x and y Values for the East Wind Direction

APPENDIX

1. Wind direction (North) ↑

Population Centers	x value	y value
A	0	0
B	$(b_2 - I_2)$	$(b_1 - I_1)$
C	$(c_2 - I_2)$	$(c_1 - I_1)$
D	$(d_2 - I_2)$	$(I_1 - d_1)$
E	$(e_2 - I_2)$	$(I_1 - e_1)$
F	0	0
G	0	0
H	0	0

Table A.2 x and y Values for the North Wind Direction

APPENDIX

1. Wind direction (North-West)

Population Centers	x value	y value
A	0	0
B	0	0
C	$\left(\frac{\left[c_2-I_2-(c_1-I_1)\right]^2}{2}\right)^{1/2}$	$x + \left(2(c_1-I_1)^2\right)^{1/2}$
D	$y + \left(2(I_1-d_1)^2\right)^{1/2}$	$\left(\frac{\left[d_2-I_2-(I_1-d_1)\right]^2}{2}\right)^{1/2}$
E	$y + \left(2(e_2-I_2)^2\right)^{1/2}$	$\left(\frac{\left[I_1-e_1-(e_2-I_2)\right]^2}{2}\right)^{1/2}$
F	$\left(\frac{\left[I_1-f_1-(I_2-f_2)\right]^2}{2}\right)^{1/2}$	$x+ \left(2(I_2-f_2)^2\right)^{1/2}$
G	0	0
H	0	0

Table A.3 x and y Values for the North-West Wind Direction

APPENDIX

1. Wind direction (West) ←

Population Centers	**x value**	**y value**
A	0	0
B	0	0
C	0	0
D	$\left(I_1 - d_1\right)$	$\left(d_2 - I_2\right)$
E	$\left(I_1 - e_1\right)$	$\left(e_2 - I_2\right)$
F	$\left(I_1 - f_1\right)$	$\left(I_2 - f_2\right)$
G	$\left(I_1 - g_1\right)$	$\left(I_2 - g_2\right)$
H	0	0

Table A.4 x and y Values for the West Wind Direction

APPENDIX

1. Wind direction (South-West) ↙

Population Centers	x value	y value
A	0	0
B	0	0
C	0	0
D	0	0
E	$\left(\frac{\left[I_1-e_1-(e_2-I_2)\right]^2}{2}\right)^{1/2}$	$x+\left(2(e_2-I_2)^2\right)^{1/2}$
F	$y+\left(2(I_2-f_2)^2\right)^{1/2}$	$\left(\frac{\left[I_1-f_1-(I_2-f_2)\right]^2}{2}\right)^{1/2}$
G	$y+\left(2(I_1-g_1)^2\right)^{1/2}$	$\left(\frac{\left[I_2-g_2-(I_1-g_1)\right]^2}{2}\right)^{1/2}$
H	$\left(\frac{\left[I_2-h_2-(h_1-I_1)\right]^2}{2}\right)^{1/2}$	$x+\left(2(h_1-I_1)^2\right)^{1/2}$

Table A.5 x and y Values for the South-West Wind Direction

1. Wind direction (South) ↓

Population Centers	**x value**	**y value**
A	$(I_2 - a_2)$	$(a_1 - I_1)$
B	0	0
C	0	0
D	0	0
E	0	0
F	$(I_2 - f_2)$	$(I_1 - f_1)$
G	$(I_2 - g_2)$	$(I_1 - g_1)$
H	$(I_2 - h_2)$	$(h_1 - I_1)$

Table A.6 x and y Values for the South Wind Direction

APPENDIX

1. Wind direction (South-East)

Population Centers	x value	y value
A	$y + \left(2(I_2 - a_2)^2\right)^{1/2}$	$\left(\frac{\left[a_1 - I_1 - (a_2 - I_2)\right]^2}{2}\right)^{1/2}$
B	$\left(\frac{\left[b_1 - I_1 - (b_2 - I_2)\right]^2}{2}\right)^{1/2}$	$x + \left(2(b_2 - I_2)^2\right)^{1/2}$
C	0	0
D	0	0
E	0	0
F	0	0
G	$\left(\frac{\left[I_2 - g_2 - (I_1 - g_1)\right]^2}{2}\right)^{1/2}$	$x + \left(2(I_1 - g_1)^2\right)^{1/2}$
H	$y + \left(2(h_1 - I_1)^2\right)^{1/2}$	$\left(\frac{\left[I_2 - h_2 - (h_1 - I_1)\right]^2}{2}\right)^{1/2}$

Table A.7x and y Values for the South-East Wind Direction

B: Figures of Chapter 6

APPENDIX

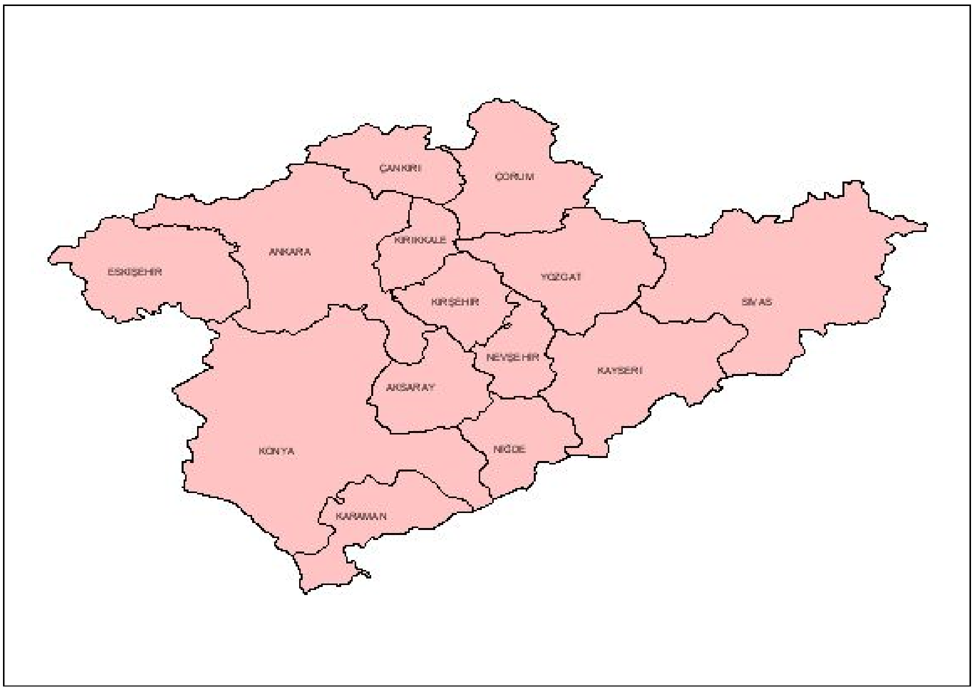

Figure B.1 Cities of Central Anatolian Region

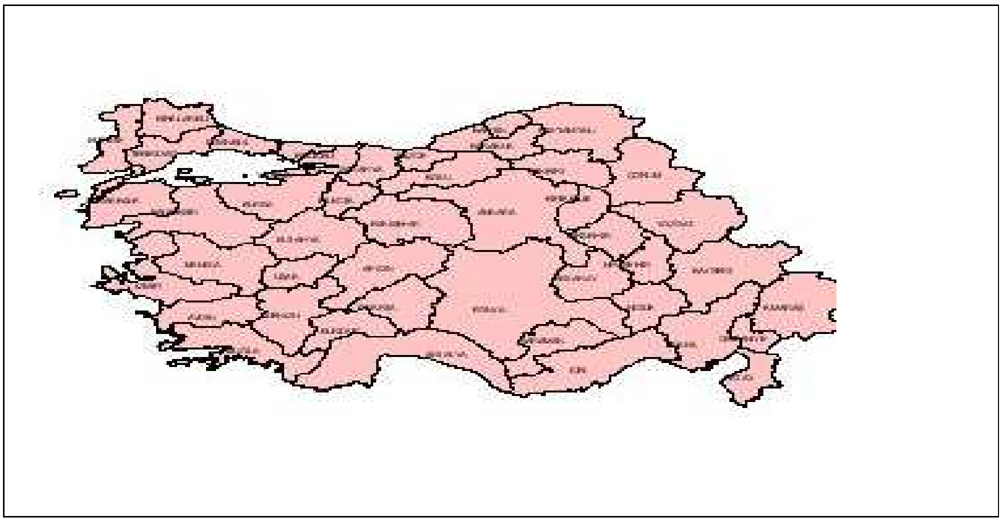

Figure B.2 The Cities of "four regions" Application

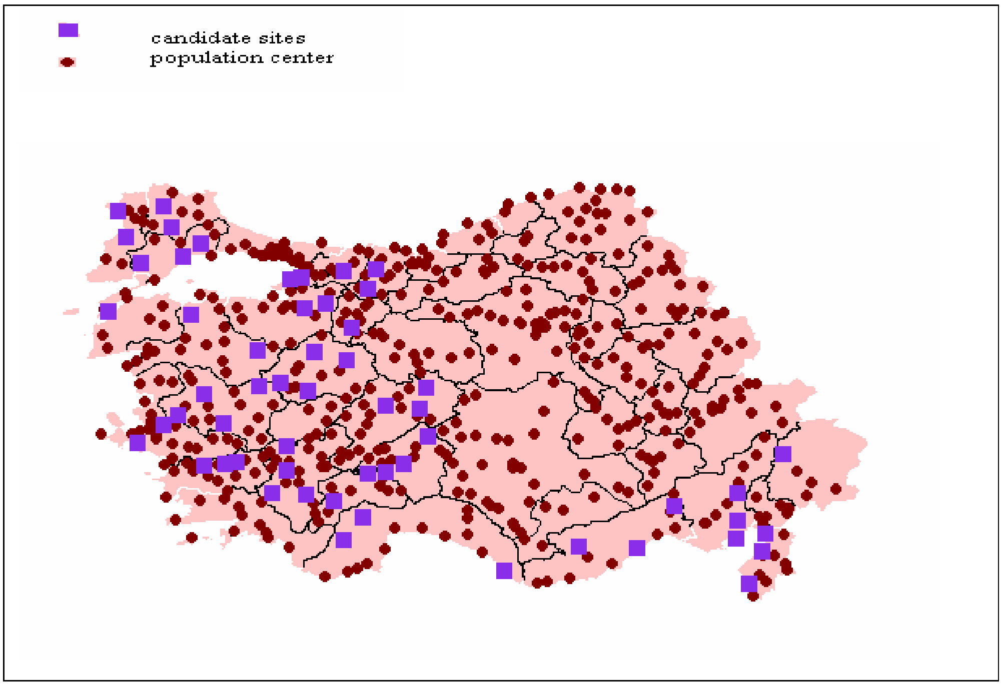

Figure B.3 Candidate Sites and Population Centers For Candidate Set I

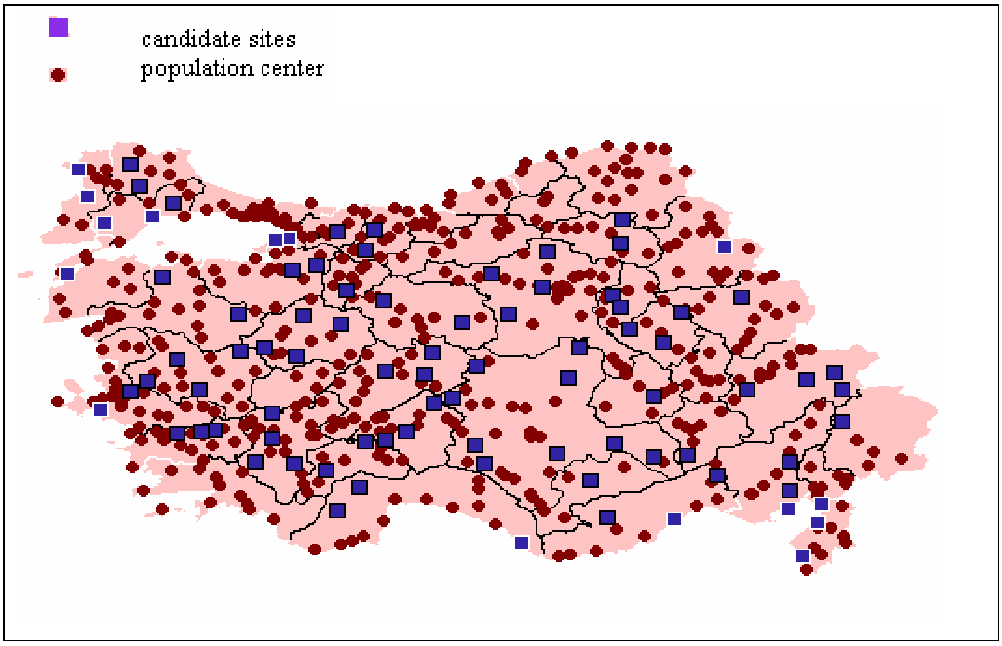

Figure B.4 Candidate Sites and Population Centers for Candidate set II

APPENDIX

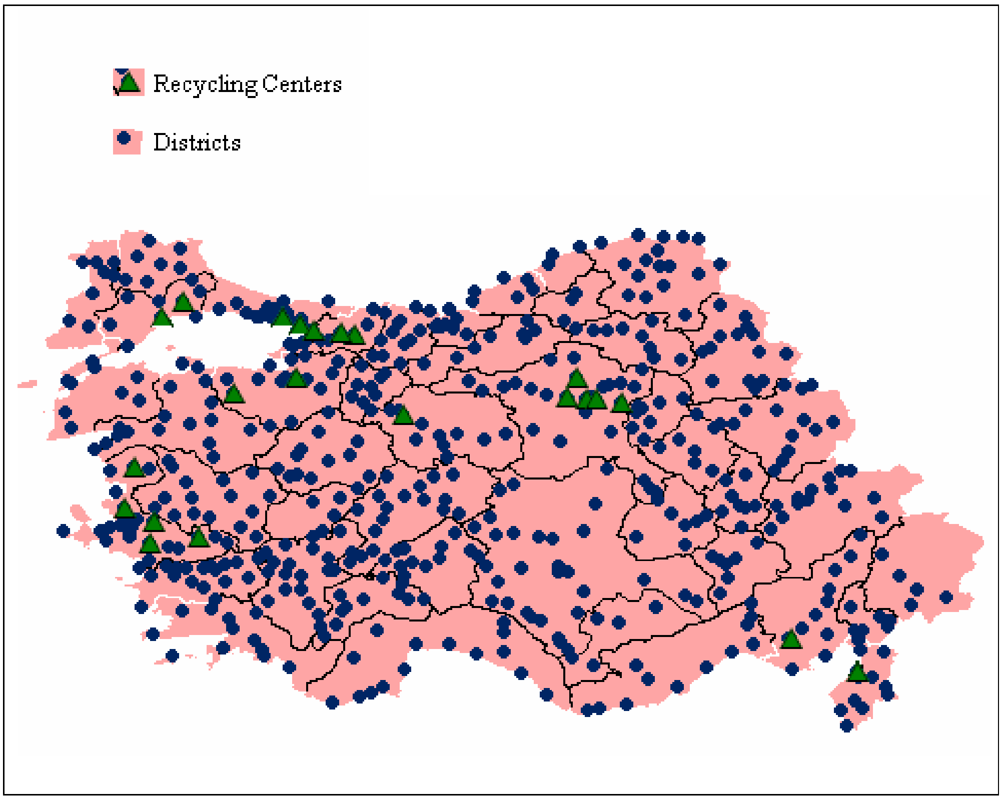

Figure B.5: Districts and Recycling Centers for "four regions" Application

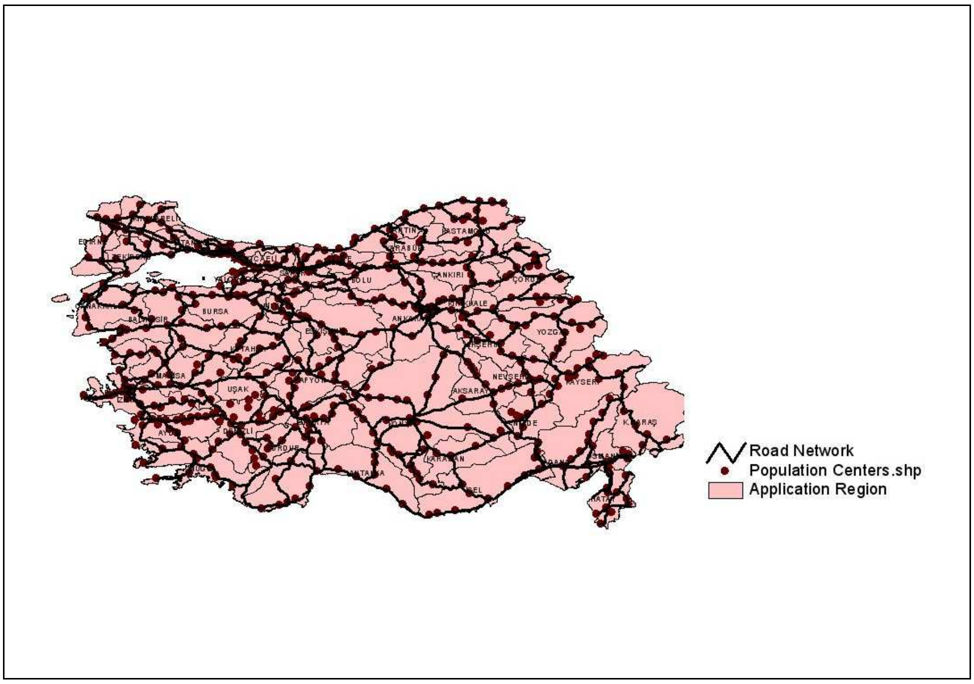

Figure B.6 Road Network for “four regions” Application