KADIR HAS UNIVERSITY
GRADUATE SCHOOL OF SCIENCE AND ENGINEERING

MULTI - OBJECTIVE LOCATION ROUTING PROBLEM FOR NUCLEAR POWER PLANTS AND NUCLEAR WASTE DISPOSAL CENTERS

GRADUATE THESIS

GÜL ECEM SEZENLER

December, 2011

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ABSTRACT

MULTI – OBJECTIVE LOCATION ROUTING PROBLEM FOR NUCLEAR POWER PLANTS AND NUCLEAR WASTE DISPOSAL CENTERS

GÜL ECEM SEZENLER

Master of Science in Industrial Engineering

Advisor: Asst.Prof. Dr. Funda Samanlıoğlu

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Nuclear energy is used by many countries and, has already taken its place among the future sources of energy. In Turkey, nuclear energy has recently been accepted by the majority of people as an alternative energy source. As a result, inspections and research have accelerated to establish a nuclear power plant. In this thesis, a new multi-objective location-routing mathematical model is developed and implemented using actual data for Turkey. The model selects best locations for nuclear power plants and disposal centers from respective candidate sets and then identifies the optimal amount of nuclear waste to transport from each nuclear power plant to each disposal center. The problem includes the following objective functions: Minimizing total cost of establishing nuclear power plants and disposal centers, transporting nuclear wastes between them, and holding nuclear wastes, minimizing total social rejection for the establishment of nuclear power plants and disposal centers and transportation of nuclear wastes, minimizing total accident risk of truck, minimizing total risk of earthquake damage to nuclear power plants and disposal centers, and minimizing total risk of terror attacks to the locations of nuclear power plants and disposal centers. The model also includes constraints related to the capacities of disposal centers and temporary nuclear waste holding storages that might be opened inside the nuclear power plants. As the multi – objective decision making method, weighted Tchebycheff method is used and weakly Pareto optimal (weakly non – dominated) solutions are obtained. The mathematical model is formulated and solved by GAMS 23.6. Data required for the thesis is obtained using the ArcGIS Spatial Analyst 10.0.

Keywords: Multi-Objective Location-Routing Problem, Weighted Tchebycheff Method, Nuclear Power Plant, Disposal Center

ÖZET

NÜKLEER SANTRALLER VE NÜKLEER ATIK DEPOLAMA MERKEZLERİ İÇİN ÇOK AMAÇLI YER SEÇİMİ VE ROTALAMA MODELİ

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Endüstri Mühendisliği, Yüksek Lisans

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Birçok ülke tarafından kullanılan nükleer enerji, günümüzde geleceğin enerji kaynakları arasında yerini almıştır. Türkiye'de son yıllarda, nükleer enerji alternatif enerji olarak neredeyse bütün toplum tarafından kabul edilmiştir. Sonuç olarak, Türkiye'de nükleer santral kurulumu için araştırmalar ve incelemeler hızlanmıştır. Bu tezde, Türkiye için çok amaçlı yer seçimi – rotalama matematik modeli geliştirilmiş ve gerçek veriler kullanılarak Türkiye'ye uygulanmıştır. Model, bağlı olduğu aday kümelerinden nükleer santral ve nükleer atık depolama merkezleri için en iyi bölgeleri seçer ve her nükleer santralden, her atık depolama merkezine taşınması için ideal nükleer atık miktarını belirler. Problem beş tane amaç fonksiyonu içerir. Bunlar; toplam maliyetin en küçüklenmesi, nükleer atıkların taşınmasını, nükleer santrallerin ve nükleer atık depolama merkezlerinin kurulmasını toplumun istememesinin en küçüklenmesi ve nükleer atıkları taşıyan kamyonların toplam kaza riskinin en küçüklenmesidir. Ayrıca, nükleer santrallerin ve nükleer atık merkezlerinin depremden zarar görme riskinin en küçüklenmesi ve son olarak nükleer santrallerin ve nükleer atık merkezlerinin terör saldırılarından zarar görme riskinin en küçüklenmesidir. Model ayrıca, nükleer atık depolama merkezlerinin ve nükleer santral içerisinde açılacak geçici depolama merkezlerinin kapasiteleri ile ilgili kısıtlar içermektedir. Modelde desteksiz zayıf Pareto sonuçları bulmak için ağırlıklı Çebişev yöntemi kullanılmıştır. Matematik model GAMS 23.6 kullanılarak formüle edilmiş ve çözülmüştür. Tez için gereken veriler ArcGIS Spatial Analyst 10.0 kullanılarak elde edilmiştir.

Anahtar Kelimeler: Çok amaçlı yer seçimi-rotalama problemi, Ağırlıklı Çebişev yöntemi, Nükleer Santral, Atık depolama merkezi

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To my parents and my sister

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Chapter 1
Introduction

Energy is a force for meeting the basic needs of people and accelerating the technological developments of all countries. Countries have different energy policies in terms of finding and using the energy. Nuclear energy is considered to be one of the best energy alternatives, particularly for the countries with poor natural energy resources. Due to the seasonal demand variation and the risk of future depletion of natural resources, even countries with rich natural energy resources tend to utilize nuclear energy to prevent potential energy bottlenecks. Nowadays Turkey has limited natural energy resources, which are expensive to extract and process. In addition, the demand for energy has increased significantly owing to the high rate of economic development. As a result, Turkey has to import significant amount of energy from abroad to meet its demand (Serteller, 2006).

Over the past two decades, electrical energy consumption in Turkey has increased considerably. While the average annual electrical energy consumption was expected to increase 8% in recent years, the average energy consumption increased 10% annually (Serteller, 2006). In addition, the ratio of electrical energy production to consumption has decreased from 50% to 34% due to the increased electrical energy demand (Kılıç, 2006). Moreover, annual electrical energy demand is expected to increase 7% or 8% until 2020 according to the report which is prepared by Turkey's Energy and Natural Resources Group (Ministry of Turkey Energy and Natural Resources, 2006). This predicted increment shows that it is necessary to meet this resultant energy gap with a constant source. There were two important findings when the reasons of this increase were investigated. The first one was the industrial development and the second one was the high population growth. As a result of this predicted increment, the need to set up new power plants has arisen.

Turkey can meet its energy demand from not only nuclear power plants (NPPs) but also other alternative energy sources such as wind power plants and solar power plants, which are the most popular ones in recent years. However, the electricity generation capacity of these alternative power plants is lower than the electricity generation capacity of NPPs with running on the same power. For instance, a wind power plant (with 1000MW power) produces 3000 GW electrical energy annually and a solar power plant (with 1000 MW power) produces 5000 GW electrical energy annually, but a NPP (with 1000MW power) produces 7000 GW electrical energy annually (Ünalan, 2011). In addition, the production of the electrical energy from wind power plant and the solar power plant depends on the sun and severity of the wind. Therefore, the result cannot always be positive because these conditions always change according to seasons (Taner, 2009). Some resources such as lignite, natural gas, coal and fuel oil are used for electricity generation. In recent years, imported natural gas has played an important role in comparison with fuel oil, lignite and coal; because 50% of the total energy consumption is met by net foreign purchases in Turkey and natural gas constitutes a large share of this percentage but importing natural gas is a very expensive energy resource (Saçlı, 2007). According to Electricity Production Joint-Stock Company (EÜAS), the cost of imported natural gas has reached $5.5 billion since 2000. Taking all these into account, it can be proposed that the establishment of NPP is more logical to meet the energy demand in Turkey. For this reason, investigations about nuclear energy and its locations have started.

In addition to all these necessities, the biggest handicap of nuclear energy is radiation dissemination. As it is known, radiation dissemination affects large masses when any accidents occur. Because of this handicap; all environmentalists, some researchers, some academicians and also some inhabitants oppose to NPPs (Bobat, 2007). They believe that NPPs cause some risks for the population by reason of Chernobyl NPP disaster in 1986 and the explosion at Fukushima in 2011 which affect people's opinions on NPP negatively. It is known that many people, animals and a lot of soil got damaged seriously due to these disasters. However, looking at real life, there are other risks which may harm to people. According to Serteller's research (2007), the number of people who were hurt per year because of the NPP risk is less than the other risks. Table 1.1 shows some results about the number of people who are affected adversely according to the types of risks.

Table 1.1 Types of Risk (from Serteller, 2007)

Types of Risk	**Average number of people who were hurt in a year. (1.000.000 people)**
Natural Disease	10000
All kinds of accidents	500
War	200
Suicide	200
Electrical Handling without credential	200
Power house with fossil-fuel	3
Natural Calamities	1
Nuclear Power Plants	0.09

As a result of this Table 1.1; it can be said that when NPPs are established with respect to proper rules which are explained in the following paragraph, NPPs do not constitute a significant threat.

According to the NPP location rules prepared by Turkey Atomic Energy Authority (Türkiye Atom Enerji Kurumu – TAEK), NPP has some important establishment principles (Resmi Gazete, 2009):

1. NPPs should not be established at locations with very intense earthquake action.
2. NPPs should be established at locations with few population densities and easy evacuation opportunities in terms of impact area, if any accident occurs in the NPPs.
3. NPPs should be established at locations which are away from the effects of anthropogenically (human-induced) events such as terrorist attacks.
4. NPPs should not be established at locations which have often natural events such as snowstorm, fog, hurricanes, lightning, sand storm, avalanches and tsunamis.

5. NPPs should be established at appropriate locations for land and sea transportation of nuclear wastes and also NPPs should be established at locations close to port because of the difficulties of the transportation of the necessary pieces for establishment of NPPs.

6. NPPs should never be established at locations which may be dent.

If NPPs are assessed economically, it can be understood that they have very expensive setup costs. For instance, a NPP with 1000MW power has the second largest setup cost among other power stations whereas natural gas power station with 1000MW power has the lowest setup cost (Deutch *et al.*, 2003). However, the cost of electrical energy generation of NPPs is very low when it is compared with other power plants in terms of electrical energy generation. For instance, the cost of electrical energy generation of natural gas power station is higher than the nuclear, coal hydroelectric and wind power plants (Saçlı, 2007). These costs are shown at Table 1.2.

Table 1.2 Setup and Generation Costs of Different Types of Power Plants

Power Plant Types	**Setup Cost (1000MW)**	**Generation Cost (1KW)**
Nuclear	$1.5 billion	1.1 cent/KW
Coal	$1.4 billion	4.6 cent/KW
Hydroelectric	$1.2 billion	7 cent/KW
Wind	$6 billion	6 cent/KW
Natural Gas	$700 million	8 cent/KW

When NPPs are compared to other power plants in terms of environment and wastes, NPPs emit less harmful gases such as CO_2, NO_x, SO_2 and it is shown at Table 1.3 (Kaya, 2005).

Table 1.3 Harmful Gas Emissions

Power Plant Types	CO_2	NO_x	SO_2
Nuclear	—	—	—
Coal	6 million ton	25 thousand ton	120 thousand ton
Natural Gas	3 million ton	10 thousand ton	60 thousand ton

Except the harmful gas emissions, NPPs have high level radioactive wastes and middle & low level radioactive wastes. High level radioactive nuclear wastes are produced when fission product fragmentation is materialized, low level radioactive wastes are produced at all stages of the fuel cycle and middle level radioactive wastes are produced during reactor operation. The presence of radioactive nuclear wastes causes an opposition for establishing NPPs (World Nuclear Association, 2009). According to International Atomic Energy Agency (IAEA), high level radioactive nuclear wastes should be stored at the repositories until the fall of the level of radioactivity. These repositories are always established in the NPPs; because high-level radioactive nuclear wastes have a lot of radioactive risk, and transportation of these kinds of nuclear wastes is very dangerous. Middle & low level radioactive nuclear wastes should be transported from NPPs to waste disposal centers (Zabunoğlu, 2000). However, the transportation of middle & low level radioactive nuclear wastes is very costly and risky, so it is not done very frequently, not even monthly. Therefore, this type of nuclear wastes can be stored temporarily up to a maximum of six months and these temporary storage centers are in the NPPs. Storage time depends on the amount of wastes which are generated in the NPPs and storage capacity depends on the maximum storage time (Thinkquest, 2002). Temporary storage cost of middle & low level radioactive waste is cheaper than the transportation cost of these wastes every month. Therefore, each NPP allocates a portion of the money which is earned from electricity generation for the temporary storage. The name of this is "fund of waste storage" and it is 0.2cent/Kwh (Belen, 2009).

Middle & low level radioactive nuclear wastes can be conserved in special sealed steel casks. These casks are shipped from NPPs to the storage or are permanently placed in the repository rooms which are excavated in stable rock formations at least 1,000 feet below ground. In addition, the ultimate disposal centers should be located at reverse direction of groundwater flow (Merkhofer and Keeney, 1987). In recent years, USA and Europe have started to develop geological storage technologies by considering earthquake, direction of groundwater flow and the population density. USA plans to store nuclear wastes at Yucca Mountain, Nevada. In Europe, Sweden will store high level nuclear wastes at geological disposal area in Forsmark until 2023. Since 1988, Sweden has had a middle-low level radioactive waste repository.

Also, Finland is building an ultimate disposal area at Olkiluoto (World Nuclear Association, 2009). Since the early 1960s, USA has safely transplanted 3000 shipping of radioactive nuclear wastes to the disposal centers and the average capacity of disposal centers at Yucca Mountain is 100.000 tons (Office of Civilian Radioactive Waste Management, 2006). Based on this data, amount of shipments and total yearly shipments of nuclear wastes from the planned NPP in Turkey can be calculated.

Based on the prediction of Nukte (2000); it can be concluded that Turkey's electricity generation in power plants might not be enough due to the depletion of conventional fuels such as coal and natural gas, and the absence of the location for hydroelectric power plants. For this reason, it is suggested that at least one NPP be established in Turkey.

At first, Turkey considered establishing a NPP between 1968 and 1969. This idea was not actualized due to economic reasons and obstacles of external factors. After that, Turkey again planned to establish a NPP between 1975 and 1976. However, this plan was not achieved because of the difficulties in bargaining with other countries. The plan to establish a NPP was not realized again between 1982-1985 and 1998-2000. It was called off due to economic difficulties and cancellation of tenders. In recent years, the venture of establishing a NPP has progressed more than the past years. The reason of this progress is that Turkey has to meet half of its energy demand from abroad (Temurçin and Aliağaoğlu, 2003).

The Turkey Atomic Energy Authority (TAEK) proposed 7 districts to Turkey's government for establishing NPPs. TAEK said that they decided these districts according to some criteria such as technical details, sea temperature, hydro geological feature, climate wind, society's viewpoints and earthquake reality. These proposed districts are: Sinop – Ayancık (İnceburun), Mersin – Gülnar (Akkuyu), Eskişehir – Sarıyer Barajı, Konya – Beyşehir, Ankara – Nallıhan, Düzce – Akçakoca and Kırklareli – İğneada As a result of negotiations, the government of Turkey has eliminated the alternatives to Sinop – Ayancık (İnceburun) and Mersin – Gülnar (Akkuyu); however has not decided between these two locations for establishing the first NPP (Enerji 2023 Derneği, 2010).

In this thesis, we are taking into consideration some of the establishment principles such as earthquake factors, terrorism and social viewpoints. Other principles such as location (being close to the sea or the port) and hydro geological features (being in the reverse direction of groundwater flow) are also used for determining candidate locations that are considered in the mathematical model solutions.

In light of these issues, the aim of this thesis is to answer the following questions: where to establish NPPs and disposal centers, and how to route low & middle radioactive nuclear wastes from NPPs to disposal centers.

As seen in Figure 1.1, location routing problem starts from the NPPs and ends up at the disposal centers. In the NPP, different types of nuclear wastes are generated and high radioactive ones are stored at the repository which is located in the NPP. However, middle and low radioactive nuclear wastes are to be routed to the ultimate disposal centers. Some of these nuclear wastes may also be temporarily stored at the temporary storage which is also located in the NPP.

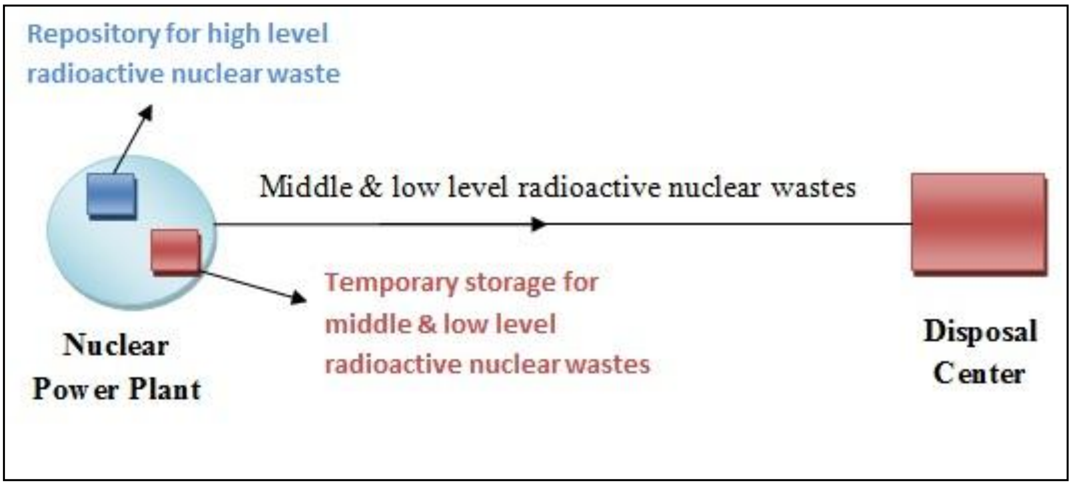

Figure 1.1 NPP and Disposal Center Location-Routing Problem

In this thesis, the aim is to develop a new multi-objective location routing model in order to find weakly efficient solutions to the location routing problem of NPPs and disposal centers.

This thesis consists of five chapters. In the second chapter, related mathematical and ANP models existing in the literature are summarized along with similarities and differences to the proposed model.

In the third chapter, a mathematical model is presented, along with implementation in Turkey in the fourth chapter.

Lastly, in the fifth chapter, some concluding results and suggestions for future research are given.

Chapter 2
Literature Review

In the literature, there are many papers about identification of optimal location of NPPs or obnoxious or undesirable facilities, nuclear waste or hazardous waste transportation, examination of risk factors or safety factors and finally identification of disposal criteria. Studies in the literature can be classified as single-objective, multi-objective and research about the necessity of NPPs, characteristics of NPPs or opinions of societies about the establishment of NPPs.

The earliest single-objective study to find the optimal location of NPP was developed by Dutton *et al.* (1972). This paper's aim was minimizing total cost by taking into consideration the capital construction, operation, and transmission costs to find optimal location of NPP. They used the simplex method and branch and bound process and Vogel's approximation method for solving the location routing problem. Another single objective mathematical model about minimizing total cost was developed by Melkote and Daskin (2001). They developed classical capacitated facility location model on a network in which facilities have constraining capacities on the amount of demand they served. This model was solved by branch-and-bound method and behavior of the model was explored by performing sensitivity analysis. Ghiani *et al*. (2002) introduced another kind of capacitated plant location problem. They developed a single objective mathematical model that minimizes the total cost (the sum of facilities construction cost and transportation cost) for multiple facilities in the same site. This study was motivated by a real world application in Italian municipalities. They developed a Lagrangean heuristic method to solve problem. A different model based on minimizing the total cost (transportation cost and setup cost) was developed by Cappanera *et al*. (2004). They developed a mathematical model about undesirable facilities, activities and materials. An undesirable facility was defined as a facility which has obnoxious interactions with existing facilities.

Some examples are nuclear reactors, equipment which emit pollutants such as particulates, noise and gas or warehouses that contain flammable materials. Their proposed mathematical model was a NP-hard problem. For this reason they solved this problem using Lagrangean heuristic approach. Wu *et al*. (2006) and Chen and Ting (2008) also developed single objective mathematical models which are based on minimizing total cost. Wu *et al.* (2006) presented the capacitated facility location problem, in which the general setup cost (site setup and facility setup cost) and transportation cost are considered. In the problem, multiple facilities were located in several sites that provide services to customers. They developed a Lagrangian heuristic algorithm for solving their problem; because it was a NP-hard problem. Chen and Ting (2008) solved their single source capacitated facility location problem that minimizes total cost (shipping cost and setup cost) using a hybrid algorithm such as Lagrangian heuristic. The characteristic of the single source capacitated facility location problem was that each customer must be supplied from only one facility. Furthermore, there is some research about routing which aim was to minimize total cost in the literature; for instance, the study of Peirce and Davidson (1982) determined the cost effective configuration of transportation routes, transfer stations, processing facilities and secured long term storage impoundments by carrying out the optimal routing strategy. Louberge *et al.* (2002) developed a single objective mathematical model which determines an optimal location for deep geological disposal and surface storage. This mathematical model minimized the expected present value of costs due to nuclear waste, including the random costs of future unanticipated accidents in the case of deep disposal and the random costs of institutional control and hazard management in the case of surface storage.

In the literature, there are many papers about single objective routing problem that aims to minimize total risk. The risk factors and concept of security are really significant if countries have NPPs or obnoxious facilities or if a new NPP or obnoxious facilities are going to be established. The earliest study was developed by Feinstein (1989). He focused on the safety regulations which included violations, inspections, and abnormal occurrences of NPPs. In his study, he developed a statistical model to control the rate of occurrence of violations during each inspection period which persists from one inspection to the next by using Poisson distribution. Another single objective risk model was presented by Erkut and Verter (1998). They determined a method to quantify transportation risk, and suggested different kinds of risk models which selected different optimal roads for transporting hazardous materials between a given origin and destination. They explained their transportation model by three different ways such as unit road segment risk, edge risk and path risk. The next single objective risk model was presented by Reniers *et al*. (2010) and this model analyzed transportation risk for hazardous materials by dividing routes into smaller segments in Flanders, Belgium. An accident risk was the most important risk factor for them. For this reason, they developed their model to consider accident risk. They also compared the resultant risk levels of the segments of routes used in the transportation of hazardous goods.

In the literature, some researchers have developed multi-objective mathematical models for identifying the location of the generation, treatment or disposal facilities and the transportation routes from waste generators to the treatment and disposal facilities. Verter and Kara (2001), Huang *et al.* (2004), Huang *et al*. (2008), Bozkaya and Ak (2008) and Chen *et al*. (2008) developed multi-objective mathematical models for routing decisions. Verter and Kara (2001) proposed a risk assessment methodology which is based on a Geographical Information System (GIS) for hazardous materials transportation. They presented a risk assessment methodology in a multi-commodity and a multiple origins to destination setting. In their model, they minimized the transportation distance, the population exposure, and the expected number of people who evacuated in case of an incident, and the probability of an incident during transportation. Huang *et al*. (2004) developed a mathematical model about hazardous material route planning on urban and suburban road networks. They especially talked about the use of hazardous waste as a weapon of mass destruction. They determined five criteria such as exposure, socio-economic impact, and risks of hijack, traffic conditions and emergency response. They implemented this problem in Singapore and they solved this model using GIS and score system to determine the weights of criteria. After that, Huang *et al*. (2008) improved their model and applied the Tchebycheff function based method to estimate all Pareto front. They developed eight objective functions. These are expected travel time, probability of an accident with release of hazmat materials, expected population at risk, expected population with special needs at risk, expected areas of sensitive environment at risk, expected burden on the economy-industrial, commercial, and transportation facilities at risk, expected additional damage from a delay in emergency response, danger index to account for the risks of hijacking and intentional hazmat released by terrorists. Bozkaya and Ak (2008) studied about hazardous materials transportation using GIS. They developed different kinds of risk models such as population exposure risk model, societal risk model, incident risk model and time-based risk model. This study showed that risk due to transporting hazardous waste can be measurable. Chen *et al*. (2008) developed a multi-objective mathematical model for route selection of nuclear waste transportation. They used geographic information system for solving this developed model. This study took into account three objectives such as minimizing total travel time, minimizing total transportation risk and minimizing the total exposed population. These three objectives also emphasized minimization of the total transportation cost, the cost due to risk and the public resistance along the route. This multi-objective shortest route problem was solved by the weighting method and the weights for each objective were determined by using analytical hierarchy process.

In the literature, there are many multi-objective models about location routing problem. Current *et al.* (1990) discussed and classified the facility location routing problem into four different categories such as cost minimization, profit maximization, environmental concern and demand oriented which means to locate facilities in such a way as to optimize the demand served based upon some measure of proximity or accessibility to a facility. Another multi-objective location routing problem was studied by Jacobs and Warmerdam (1994). They developed a mathematical model about locating storage and disposal sites. In addition, their model routed the single type of hazardous materials to these sites. The aim of this study was minimizing the combination of cost and risk in time. They quantified the risk as the total probability of accident during transportation to storage or disposal. Later, Current and Ratick (1995) presented a multi-objective hazardous location routing problem. They developed a mathematical model which minimizes cost, risk and maximizes equity. In this study, the mathematical model transported a single type of hazardous waste and they analyzed the transportation and facility location components of risk and equity separately. For instance, risk was quantified with population exposure. Nema and Gupta (1999) suggested another multi-objective model for hazardous waste location-routing problem. Their model's aim was to minimize total cost and total risk. They considered transporting different types of hazardous waste. Hence, compatibility of waste to waste and waste to technology has become important constraints. However, they did not implement these constraints in their mathematical model. In addition, they set risk factors with respect to transportation risk, waste treatment and disposal risk. Afterwards, Nema and Gupta (2003) proposed a multi-objective mathematical model to determine location of the treatment and disposal facilities and to route transportation waste from generators to these treatment and disposal facilities. In this model, the compatibility of waste and technology were considered. The objectives were minimization of total cost that included total setup cost of the treatment and disposal facilities, and transportation costs; minimization of total risk that included a probability of an accident resulting in waste dissemination, the estimated result of this accident, amount of waste and finally the number of people who were affected by this accident. Ahluwalia and Nema (2006) worked on computer waste management in India. They developed a multi-objective mathematical model about the location of facilities (allocation, storage, treatment, recycling and disposal) and routing the computer wastes to these facilities. They took into account the total transportation cost, setup cost for all facilities and income of recycled wastes to compute the total cost. In addition, they considered the total transportation risk and total risk of the population due to facilities nearby. This depended on the amount of waste, the probability of accident and affected population. Another multi-objective location routing problem was studied by Caballero *et al.* (2007). The aim of this problem was to determine location of two incineration plants for the disposal of solid animal waste from some pre-established locations in Andalusia, and to design the routes to serve different slaughterhouses in this region. They developed three economic objective functions that are minimizing fixed cost, minimizing maintenance cost, and minimizing transportation cost; and three social objective functions such as minimizing social rejection of each route, equity objectives that minimized maximum social rejection and minimizing the social rejection of being nearby the incineration plant. They used heuristic approach based on Tabu search algorithm for solving this problem. In addition to these papers, Alamur and Kara (2007) developed a multi – objective location routing model for Central Anatolian region of Turkey. Their model determined the location of treatment centers and treatment technologies to be used and the location of disposal facilities and the routing different kinds of hazardous wastes to treatment centers and disposal facilities. They used two objectives functions: Minimize total cost (transportation cost and setup cost) and minimize total risk. In their model, total risk depended on the amount of transported waste and the number of people in the bandwidth of the route of transportation. Their model included some constraints related to hazardous waste and residues' mass and flow balance resulting from treatment. They used weighted sums method to obtain solutions of this problem.

In the literature, there are many papers about applications of Analytic Hierarchy Process (AHP) and Analytic Network Process (ANP) on nuclear waste disposal center, power plants and undesirable facilities location decision. Merkhofer and Keeney (1987) analyzed the alternative sites for disposal of nuclear waste and selected an optimal disposal site using AHP. At first, they determined disposal site criteria which contain health and safety effects, environmental, socioeconomic and economic impacts. Health and safety effects and socioeconomic impacts included radiological and non-radiological health effects to workers and the public and the risk due to repository and transportation waste accidents and its dissemination to people. The impacts to the environment were noise and visual impacts associated with the construction and operation of the repository and damage to historical, cultural properties, animals and plants. Economic objectives were to minimize transportation cost and setup cost of repository. Finally, they evaluated repository site by using sensitivity analysis. In Akash *et al*. (1999) study, they performed a comparison between the different electrical power production options such as fossil fuel, nuclear, solar, wind, and hydro-power plants by AHP. These options were analyzed in terms of economic, social, environmental, efficiency, reliability and safety criteria. As a result of this study, they found that only NPPs have environmental and efficiency advantages. However, they found that NPPs have very expensive setup cost. Tuzkaya *et al*. (2008) clarified the problem of undesirable facility location selection by using the multi-criteria decision-making technique: ANP. This technique considered both qualitative and quantitative criteria such as benefits, opportunities, costs and risks. Also these criteria had some sub-criteria as social opposition, environmental issues, closeness to residential area, distance from the main road, earthquake area, climate, land slope and technical issues, etc. As a result of this analysis, four representative locations were evaluated, and the most convenient one was selected. Chatzimouratidis and Pilavachi (2009) evaluated power plants in terms of technological, economic and sustainability aspects using AHP. In this paper, ten types of power plants were evaluated using nine end node criteria. These power plants are Coal/Lignite, Oil, Natural Gas Turbine, and Natural Gas Combined Cycle, Nuclear, Hydro, Wind, Photo-Voltaic, Biomass and Geo-Thermal. As a result of this study, they found that NPPs are very significant in terms of generation capacity and availability of electricity. With regards to the economic aspect criteria, NPPs were not much more expensive than the other power plants when setup cost, fuel cost, operation and maintenance cost are considered.

In the literature, there are many papers about the necessity of NPPs, characteristics of NPPs, safety and risk managements of the NPPs or opinions of societies to establishment of NPPs. Dien (1998) analyzed conditions currently stipulated for usage of safety procedures in NPPs, and suggested new directions for accident and incident situations. Dien (1998) also talked about the important accidents and the reason of these accidents in the past years such as Three Mile Island in America and the Soviet nuclear plant at Chernobyl. He *et al.* (2007) developed a model of probabilistic safety analysis about maintenance risk management for Daya Bay NPP in China. This study discussed some important issues such as maintenance risk management process, risk monitor tools, risk measures and acceptance criteria, and the role of the regulatory bodies and plant managers. The purpose of the maintenance risk management was to access and manage the plant risk resulted from the unavailability of some important components during maintenance activities. Furthermore, this study developed long term plan for maintenance risk management, monthly plan for maintenance risk management and daily operational risk management. Another paper analyzed safety management by Kettunen *et al*. (2007). Their model provided an analysis of safety management challenges and tensions in the nuclear power industry. They emphasized five challenging areas for nuclear managers that are related to human resource management, organizational climate, culture, public confidence and trust. According to this study, all these challenging areas also depended on each other by economy and safety objectives to meet demands and expectations. As a result of this study, they suggested complex models to nuclear managers about the structure and safety of NPPs. Lastly; another risk analysis model was developed by Kindap *et al.* (2007). Their study analyzed possible threats around the NPP after an accident. This study emphasized especially the risk of earthquake on the NPPs. To determine the possibility of dissemination of radioactive material after an accident was another important point of this study.

There are some studies in the literature about the establishment of NPPs and its reasons for Turkey. Kaya (2005) discussed the establishment of NPPs for Turkey. This study evaluated NPPs economically and environmentally. Kaya talked about types of nuclear reactors and the importance of the NPPs in the world. According to Kaya's evaluations, NPPs have environmentally advantages because NPPs do not emit harmful gases. However, there are economical disadvantages since NPPs have an expensive setup cost around $1-2 billion for 1000 MW power. Serteller (2006) examined the importance of nuclear energy in comparison with existing energy resources. This study was about energy situation and energy gaps of Turkey. This study also investigated potential of the nuclear energy in Turkey and analyzed risk of the NPPs in general form. Another study was developed by Bobat (2007). He analyzed the Akkuyu NPP which was planned to be established in Mersin. This study investigated the reaction of people who are living in that area by exerting survey. As a result of this survey, inhabitants did not want to set up NPP in Akkuyu region because they believed that NPPs might damage their environment and might be harmful to people. Ovalı (2007) investigated radiation accidents and its causes between 1944 and 2001. As a result of this study, the most important effect of nuclear accidents was due to industrial accidents with the rate of %48. Industrial accidents were followed by medical accidents with the rate of %9, fuel accidents with the rate of %5, irradiator accidents with the rate of %4, military accidents with the rate of %1 and waste accidents with the rate of %1 out of all radiation accidents, respectively. Another study was done by Palabıyık *et al*. (2010). This study was about the establishment of the NPPs in Turkey. They analyzed the scientific data for social acceptance or population rejection behavior of local people for the planned NPPs that are going to be set up in the provinces of Mersin, Sinop and Kırklareli. This study analyzed these data by exerting survey to some inhabitants in Mersin, Sinop and Kırklareli. As a result of this study, all inhabitants who attended this survey preferred to set up NPP in other provinces except for their provinces.

In the literature, Rakas *et al*. (2004) proposed the model which is closest to the developed mathematical model in this thesis. Rakas *et al*. (2004) studied the multi objective location routing mathematical model about obnoxious facility and obnoxious materials. Their mathematical model was implemented in Prince George's County of Maryland. In their model, they considered minimizing the total cost, which included transportation cost, land cost and building cost, and minimizing the population opposition if obnoxious facility serves to the landfill area as objective functions. Population opposition depended on the Prince George's County laws. Based on these laws, every landfill shall be located at a certain distance to the population center and obnoxious materials shall be transported at a certain distance to the population center. Their constraints were capacity constraints. They used weighted sums method to obtain solutions of this mixed integer multi – criteria problem.

In this thesis, a new multi-objective location routing problem is developed for locating NPPs and waste disposal centers and routing nuclear materials to these centers. The mathematical model determines where to establish NPPs and waste disposal centers and how to route different types of nuclear waste from NPPs to disposal centers. Different from Rakas *et al*.'s (2004) mathematical model, three different criteria were considered in this thesis. These criteria are total accident risk of trucks, the risk of earthquake damage to NPPs and waste disposal centers, and the risk of terrorist attacks to the locations of NPPs and waste disposal centers. Furthermore, the mathematical model took into account the population opposition to the establishment of NPPs, and waste disposal centers, as well as the population opposition to the transportation of radioactive materials. Rakas *et al*. (2004) used a weighted sum method in their paper. However, all the (weakly) Pareto optimal solutions cannot be found using weighted sum method. In this thesis, weighted Tchebycheff method is used to find supported and non-supported (weakly) Pareto optimal solutions. Detailed description of the developed mathematical model is as follows:

The first objective function of minimizing total cost includes fixed setup cost of NPPs and waste disposal centers, transportation costs of wastes from NPPs to waste disposal centers and storage costs. The second objective function of minimizing total social rejection includes population opposition of opening NPPs and waste disposal centers at the candidate locations and also population opposition of transporting nuclear wastes to these locations. The third objective function minimizes total accident risk by taking into consideration probability of an accident during the transportation of the nuclear waste from NPPs to waste disposal centers. The fourth objective function of minimizing total risk of earthquake damage helps to establish NPPs and waste disposal centers outside of the earthquake regions. The last objective function minimizes total risk of terrorist attacks to the locations of NPPs and waste disposal centers by taking into consideration the number of terrorist attacks since the earliest 1990s.

In addition to these objective functions, the model includes constraints related to the capacity of waste disposal centers and storage centers which is to be located in the NPPs, flow balance constraints and constraints related to regions and the necessity of electricity generation for establishing NPPs. Finally, the application of the mathematical model is presented with the data of Turkey.

Chapter 3
Model Development

In this section, a mathematical model is presented to determine the location of NPPs and disposal centers and to route nuclear wastes from NPPs to disposal centers in a safe and cost effective manner. It is assumed that the candidate sites for NPPs and disposal centers have already been determined in the transportation network, and the high level radioactive nuclear wastes have been stored at repositories in NPPs.

There are costs associated with the establishment of NPPs, disposal centers and storage of different kinds of radioactive nuclear wastes, and the transportation of radioactive nuclear wastes. Furthermore, there is risk to the surrounding population due to transportation of radioactive nuclear wastes and establishment of a NPP and a disposal center. Risk factors can be measured using different risk models such as population exposure risk model, societal risk model, incident risk model and time-based risk model (Bozkaya, 2008). These models can be used to estimate transportation risk. It is known that the radioactive nuclear waste has to be transported using special trucks or special containers. In addition to transportation risk, establishing a NPP and a disposal center causes some risk to the surrounding people. These different risk models can also be used to estimate the risk factors associated with the establishment of a NPP and a disposal center.

A model may use societal risk which is about the probability of the hazardous release event, hazardous or obnoxious materials accident or accident of trucks that are loaded with these kinds of materials. Zografos and Androutsopoulos (2008) computed societal risk using hazardous materials accident probability and the average population exposed to the impacts of an accident. Nema and Gupta (1999) estimated societal risk probability of occurrence of the hazardous release event and population impacted in case of hazardous release event. In addition to these studies, Erkut and Verter (1998) computed societal risk using the probability of the release of hazardous substances, the probability of an accident of trucks and population along the transportation road. Another model may use population exposure which is about the number of people exposed to radioactive nuclear wastes. In the literature, Chen *et al*. (2008) used population exposure in their model. They measured this kind of risk using population along the link from node to node.

In the developed model, there are objective functions related to accident risk for the trucks, the risk of earthquake damage and the risk of terrorist attacks for the NPPs and disposal centers. Another risk related objective function in the model is the social rejection for establishing a NPP and a disposal center, and for transporting radioactive nuclear wastes. The proposed mathematical model for the location-routing problem of a NPP and a disposal center can be stated as follows: Given a transportation network and the set of candidate nodes for NPPs and disposal centers, find the location of NPPs and disposal centers and the amount of radioactive nuclear wastes transported while minimizing total transportation and setup costs, total social rejection, total accident risk, total risk of earthquake damage and total risk of terrorist attacks.

3.1 The Mathematical Model:

The developed model is formulated as a multi - objective mixed integer programming model. The notation and the mathematical model are given below.

Notation:

Let N= (V, A) be a transportation network with V vertexes and A arcs A= {(i, j), i, j$\in$ V}

G={$1, \ldots, g$} Nuclear Power Plant (NPP) nodes, G$\subset$V

D={$1, \ldots, d$} Disposal Center nodes, D$\subset$V

T={$1, \ldots, s$} Time periods

B={$1, \ldots, r$} Regions where $R_1, R_2, \ldots, R_r \subseteq G$ and $\bigcup_{k \in B} R_k = G$

Indices:

i NPP location index $i \in G$

j Disposal Center location index $j \in D$

t Time index $t \in T$

k Region index $k \in B$

Parameters:

$c_{i,j,s}$: Cost of transporting a unit of low & middle radioactive nuclear waste along the link $(i,j) \in A$ at the end of the last period $s \in T$, $i \in G$ and $j \in D$

cc_i : Inventory holding cost of a unit of low & middle radioactive nuclear waste at candidate NPP $i \in G$ per period

Fn_i : Fixed cost of establishing a NPP $i \in G$

Fd_j : Fixed cost of establishing a disposal center $j \in D$

$n_{i,t}$: Amount of low & middle radioactive nuclear waste that will be produced at candidate NPP $i \in G$ (if established) at the end of period $t \in T$

U_i : Total estimated amount of energy that can be generated at candidate NPP $i \in G$

Ic_i : Inventory storage capacity at candidate NPP $i \in G$

dc_j : Disposal capacity of candidate disposal center $j \in D$

On_i : Opposition to the establishment of candidate NPP $i \in G$

Od_j : Opposition to the establishment of candidate disposal center $j \in D$

$Ot_{i,j}$: Opposition to the transportation of low & middle radioactive nuclear waste along the link $(i,j) \in A$, $i \in G$ and $j \in D$

$Acc_{i,j}$: Probability of accident along the link $(i,j) \in A$, $i \in G$ and $j \in D$

E_i : Potential earthquake damage to NPP $i \in G$ based on the corresponding district

Ed_j : Potential earthquake damage to the candidate disposal center $j \in D$ based on the corresponding district

Tr_i : Number of previous terror attacks at the district of NPP $i \in G$

Td_j : Number of previous terror attacks at the district of disposal center $j \in D$

B : Total energy consumption at a total of s time periods

A : Total energy production at a total of s time periods

p : Minimum number of disposal centers to be established

Decision Variables:

$x_{i,j,s}$: Amount of low & middle radioactive nuclear waste transported through along the link $(i,j) \in A$, at the end of the last period $s \in T$, $i \in G$ and $j \in D$

$$l_{i,j} : \begin{Bmatrix} 1, \text{ if the link } (i,j) \in A \text{ is used,} \\ 0, \text{ otherwise} \end{Bmatrix}$$

$$y_i : \begin{Bmatrix} 1, \text{ if the NPP } i \in G \text{ is established,} \\ 0, \text{ otherwise} \end{Bmatrix}$$

$$z_j : \begin{Bmatrix} 1, \text{ if the disposal center } j \in D \text{ is established,} \\ 0, \text{ otherwise} \end{Bmatrix}$$

The mathematical model is as follows:

$$Minimize\ z_1 = \sum_{i\in G}\sum_{j\in D} c_{i,j,s}x_{i,j,s} + \sum_{i\in G} Fn_i y_i + \sum_{j\in D} Fd_j z_j + \sum_{i\in G}\sum_{t\in T} n_{i,t}(s-t) y_i cc_i \qquad (1)$$

$$Minimize\ z_2 = \sum_{i\in G} On_i y_i + \sum_{j\in D} Od_j z_j + \sum_{i\in G}\sum_{j\in D} Ot_{i,j} l_{i,j} \qquad (2)$$

$$Minimize\ z_3 = \sum_{i\in G}\sum_{j\in D} Acc_{i,j} l_{i,j} \qquad (3)$$

$$Minimize\ z_4 = \sum_{i\in G} E_i y_i + \sum_{j\in D} Ed_j z_j \qquad (4)$$

$$Minimize\ z_5 = \sum_{i\in G} Tr_i y_i + \sum_{j\in D} Td_j z_j \qquad (5)$$

Subject to:

$$\sum_{t\in T} n_{i,t} y_i = \sum_{j\in D} x_{i,j,s} \qquad \forall i\in G,\ s\in \mathrm{T} \qquad (6)$$

$$\sum_{t\in T} n_{i,t} y_i \le Ic_i \qquad \forall i\in G \qquad (7)$$

$$\sum_{i\in G} x_{i,j,s} \le dc_j z_j \qquad \forall j\in D,\ s\in T \qquad (8)$$

$$x_{i,j,s} \le Ml_{i,j} \qquad \forall i\in G,\ \forall j\in D,\ s\in T \qquad (9)$$

$$where\ M = \sum_{i\in G}\sum_{t\in T} n_{i,t}$$

$$\sum_{i\in G} U_i y_i \ge B - A \qquad (10)$$

$$\sum_{j\in D} z_j \ge p \qquad (11)$$

$$\sum_{i\in R_k} y_i \le 1 \qquad \forall k\in B \qquad (12)$$

$$x_{i,j,s} \geq 0 \qquad \forall i \in G,\ \forall j \in D,\ s \in T \qquad (13)$$

$$l_{i,j} \in (0,1) \qquad \forall i \in G,\ \forall j \in D \qquad (14)$$

$$y_i \in (0,1) \qquad \forall i \in G \qquad (15)$$

$$z_j \in (0,1) \qquad \forall j \in D \qquad (16)$$

The first objective function (1) minimizes the total cost associated with the transportation cost of radioactive nuclear wastes, the fixed costs associated with the establishment of NPPs and disposal centers, and the storage cost. The cost of transporting one unit of low & middle radioactive nuclear waste is known for each transportation link which is assumed to be directly proportional to the network distance used. The fixed costs of establishing NPPs and disposal centers depend on the size of the facility and the distance to the port. The fixed costs of establishing repositories and storages are assumed to be part of the establishment cost of NPPs. The inventory holding cost depends on the "fund of the waste storage". Details about this concept are given in chapter 1.

The second objective function (2) minimizes the total social rejection due to the establishment of NPPs and disposal centers and transportation of low & middle radioactive nuclear wastes from NPPs to disposal centers. The total social rejection is measured in terms of opposition factors. Opposition factors related to establishment of NPPs and disposal centers are quantified with the population of the districts in which NPPs and disposal centers are to be located, and the opposition factor of transporting nuclear wastes is quantified with population exposure. The population exposure is measured by the amount of people living along a given link that could be affected by a nuclear leakage.

The third objective function (3) minimizes the total accident risk of the trucks or containers carrying the radioactive nuclear wastes on a given link. The total accident risk is measured with the multiplication of accident rate per meter and the road length.

The fourth objective function (4) ensures that the NPPs and disposal centers are established at locations which are less likely to be damaged by an earthquake. This is quantified with the risk degree of earthquake regions. The aim of this factor is to prevent establishing NPPs and disposal centers in potential earthquake areas.

The fifth objective function (5) minimizes the total risk of potential terrorist attacks to the locations of the NPPs and disposal centers. It is assumed that areas with high number of previous terrorist attacks have more potential to have potential future terrorist attacks. This objective function is quantified with the number of terrorist attacks to the candidate locations of NPPs and disposal centers since the early 1990s (Özavcı, 2011), (Bal and Özkan, 2009).

The first constraint (6) is the flow balance constraint for transporting the produced nuclear wastes to the disposal centers. Low & Middle radioactive nuclear wastes produced during at the end of the each period are stored at the inventory until the end of the last period s and then sent to disposal centers.

The second (7) and the third (8) constraints are the inventory holding capacity constraint, and the disposal capacity constraint, respectively.

The fourth constraint (9) is to mark the links that are used. The fifth constraint (10) ensures that sufficient number of NPP is established in order to meet the energy demand.

The sixth constraint (11) ensures that at least a given number disposal centers are established. The seventh constraint (12) limits the number of the establishment of NPPs to at most one at each region.

The eighth constraint (13) is the non-negativity constraint, and constraints (14) – (16) are to determine the binary variables.

3.2 The Weighted Tchebycheff Method:

In this thesis, a new multi-objective location routing problem is formulated in order to simultaneously consider five criteria (objective functions) minimizing the total transportation, setup and inventory holding costs, total social rejection, total accident risk, total risk of earthquake damage and total risk of terrorist attacks. These criteria (objective functions) are potentially conflicting. For instance, the road which has minimum accident risk may not be the most effective road in terms of the cost, or the location which has minimum social rejection may not be the most effective location in terms of the risk of earthquake damage. If there are these kinds of contradictions between objective functions, it is necessary to find compromise solutions using a multi-criteria decision making method based on views and preferences of decision makers.

In the literature, there are many multi – objective solution methods such as weighted sums method, weighted Tchebycheff method, lexicographic weighted Tchebycheff method and modified weighted Tchebycheff method, etc. (Shin *et al.*, 2011). In this research, the weighted Tchebycheff approach is used to obtain (weakly) Pareto optimal solutions (weakly efficient) because regardless of the shape of the feasible region, all non-dominated criterion vectors are computable using weighted Tchebycheff method (Samanlioğlu *et al.*, 2010). With the weighted Tchebycheff method, supported solution as well as non – supported solutions can be found. Supported efficient solutions lie in the convex portions of the Pareto front and non – supported solutions are located in the non – convex portions of the Pareto front (Samanlıoğlu *et al.*, 2008). Since this problem is a mixed integer multi – criteria problem, supported and non – supported solutions exist.

Below are some basic definitions related to these concepts:

A multi - objective program

$$\text{Minimize } f(x) = \{ f_1(x), f_2(x), f_3(x), ..., f_k(x) \} \quad (17)$$

s.t

$x \in S$

Where there are (k $\geq$ 2) objective functions ($x \in R^n, f_i$: $R^n \rightarrow R$) that are to be minimized simultaneously. Here, $z_1 = f_1(x),\ z_2 = f_2(x),\ ...\ , z_k = f_k(x)$.

Definition 3.2.1: A decision vector $x^* \in S$ is efficient (Pareto optimal) for multi-objective program (17) if there does not exist a $x \in S,\ x \neq x^*$ such that

$f_i(x) \le f_i(x^*)$ for $i = 1,...,k$ with strict inequality holding for at least one index i. ($x^* \in S$ is efficient, $f(x^*)$ is non-dominated.)

Definition 3.2.2: A decision vector $x^* \in S$ is weakly efficient (weakly Pareto optimal) for multi-objective program (17) if there does not exist a $x \in S,\ x \ne x^*$ such that $f_i(x) < f_i(x^*)$ for $i = 1,...,k$. ($x^* \in S$ is weakly efficient, $f(x^*)$ is weakly non-dominated.)

Definition 3.2.3: $z_i'' = (z_1'', z_2'',..., z_k'')$ with $z_i'' = \min f_i(x)$ s.t. $x \in S$ is called the ideal point.

The weighted Tchebycheff formulation of this problem is given as:

$$
\begin{aligned}
&\text{Min } \alpha \\
&s.t \\
&\alpha \ge \left\{ w_i \left(z_i - z_i'' \right) \right\} \qquad \forall i \qquad\qquad (18) \\
&\left[(1) - (16) \right] \\
&\textit{where } \ w_i \ge 0 \quad i=1...k, \text{ and } \sum_i w_i = 1 .
\end{aligned}
$$

The solution of problem (18) is weakly non-dominated for positive weights $\left(w_i \succ 0 ,\ \forall i \right)$, and it has at least one non-dominated solution. If the solution of problem (18) is unique then it is non-dominated (Marler and Arora, 2004).

In this thesis, the objectives of the developed multi-objective mathematical model need to be scaled. Therefore, weights of each objective function are multiplied by $\pi_i = 1/R_i$ in the weighted Tchebycheff formulation (18). In this case, the formulation becomes:

$$
\begin{aligned}
&\text{Min } \alpha \\
&s.t \\
&\alpha \geq \left\{ w_i \pi_i \left(z_i - z_i^{''} \right) \right\} \qquad \forall i \qquad (19) \\
&\left[(1) - (16) \right] \\
&\textit{where} \;\; w_i \geq 0 \quad i=1...k, \text{ and } \sum_i w_i = 1 \, .
\end{aligned}
$$

Here, R_i indicates the range of i^{th} objective function over the efficient set and this range is estimated by the difference between the nadir objective vector and the ideal (utopia) vector. The nadir vector z_i^n is defined as the upper bounds of the Pareto optimal set. The weighted Tchebycheff function with scaled objectives (19) is used in this thesis to obtain (weakly) Pareto optimal solutions to the mathematical model [(1) – (16)]. In Chapter 4, detailed solutions are presented along with the data and explanations.

Chapter 4
Application in Turkey

The application of the model is presented with the data related to Turkey. Turkey has 81 administrative provinces and 892 administrative districts. At first, only main roads which covered 81 administrative provinces and 892 administrative districts are considered for the application. The data such as main roads, center of population and population (2002) are acquired from the İşlem Coğrafya firm in İstanbul, Turkey.

Data of Turkey is presented sketchily in Figure 4.1. This figure shows 892 administrative districts and main roads. Since location – routing problem is an NP – hard problem, all of the 892 administrative districts and corresponding roads are not taken into consideration. Data is modified based on establishment principles of NPPs and their disposal centers. Furthermore, earthquake hazard and ground water flow directions are considered while selecting the candidate locations for NPPs and disposal centers.

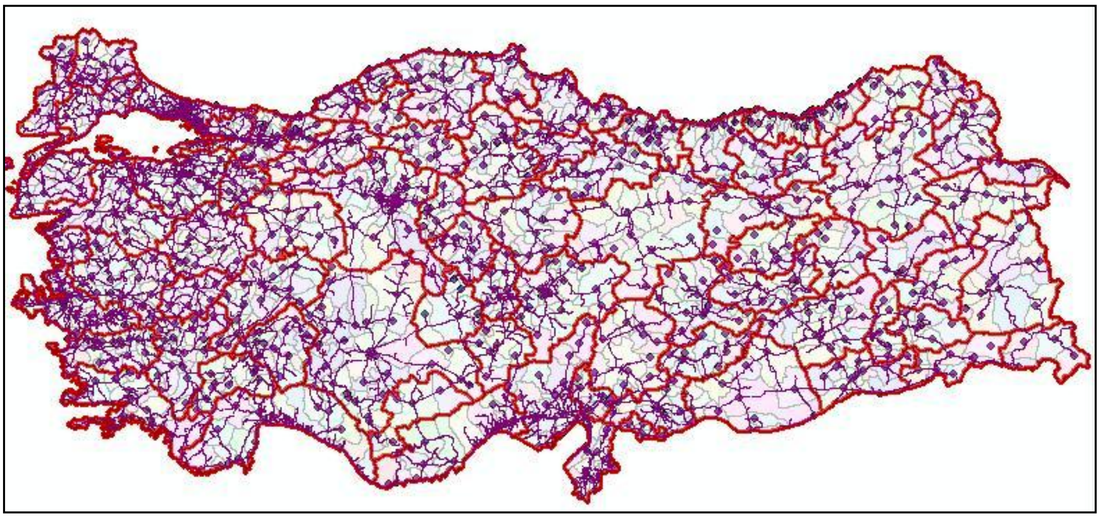

Figure 4.1 Administrative districts and main roads in Turkey

Earthquake hazard is defined as the possibility of a ground motion, which is caused by an earthquake with a magnitude resulting in loss of life and property, in a certain place and time period. Earthquake hazard analysis is made based on calculated maximum ground motion parameters for a defined area, maximum acceleration and intensity (The Ministry of Public Works And Settlement, 2004). According to the acceleration level, seismic zones are defined as follows: 0.4g (g=gravity) accelerated zone is first-degree seismic zone, 0.3g accelerated zone is second-degree seismic zone, 0.2g accelerated zone is third-degree seismic zone, 0.1g accelerated zone is fourth-degree seismic zone. In Turkey, there are some administrative districts even in fifth-degree seismic zone. These earthquake zones of Turkey are shown at Appendix B.

Turkey is located on Mediterranean – Himalayan seismic belt and 42 % of its ground is in first-degree seismic zone. This zone is 328 thousand 995 km^2 wide and includes a major part of Eastern Anatolia Region, a part of Mediterranean Region, northern parts of Central Anatolia Region and all of the central and western Black Sea Region, Marmara and Aegean Regions. 44 % of population lives in the first-degree seismic zone. 26 % of Turkey's population lives in second-degree seismic zone. This zone is 186 thousand 411 km^2 wide. 15 % of the population lives in third-degree seismic zone (139 thousand 594 km^2). 13 % of population lives in fourth-degree seismic zone (97 thousand 737 km^2) and 2 % of population lives in fifth-degree seismic zone which is 37 thousand 57 km^2 wide. Southeastern Anatolia Region is the region with the least earthquake hazard level (Özmen and Nurlu, 2005).

Considering the underground water sources, it is seen that Agean Region, Central Anatolia Region, Marmara Region and a part of Mediterranean Region have the most important sources (Akın and Akın, 2007). Underground water sources and their flow direction are a substantial criterion for storing nuclear waste in underground storage rather than the construction of nuclear power plants. According to nuclear waste storage rules; they must be buried under 305 meters~1000feet deep, on rocky lands without underground water or must be on the reverse side of underground water flow (Merkhofer and Keeney, 1987). Underground water sources and their flow direction of Turkey are shown at Appendix C.

Based on the details about earthquake and underground water resources, the number of administrative districts used in the application of the mathematical model is reduced to 110. Using the main roads, 110 * 110 distance matrix is calculated with the help of ArcGIS 10.0 software and it is shown at Appendix D. Population centers of selected 110 districts are shown in Figure 4.2. 89 of these 110 districts are selected for potential NPP construction and 21 of them are selected for potential disposal centers. Note that, 7 locations suggested by TAEK (also mentioned in chapter 1) are also included in the 89 candidate districts for NPP construction.

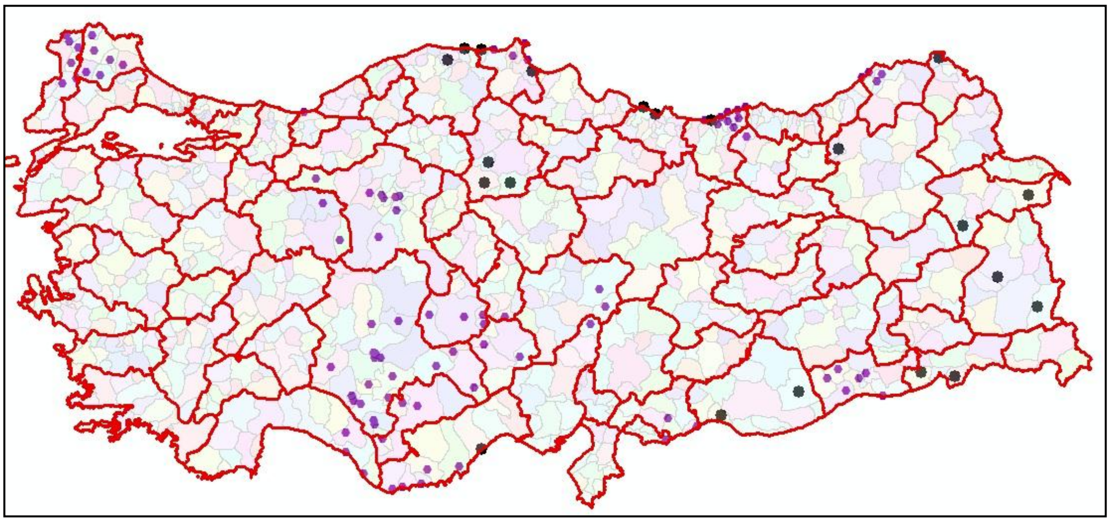

Figure 4.2 Selected 110 districts of Turkey

When NPPs begin production, some radioactive wastes come out. These wastes are categorized in 3 groups as high-level radioactive waste, Middle-level radioactive waste and low-level radioactive waste. High-level radioactive wastes are stored in repositories of NPPs in order to reduce their radioactivity level. On the other hand, other wastes are first stored in storages and then sent directly to their final disposal centers. In this thesis, waste amounts of NPPs are calculated for six months. According to these calculations; a NPP with the capacity of 1000 MW, produces 12.5 tons high-level radioactive waste and 400 tons middle and low-level radioactive waste (İskender, 2007). It is seen that the amount of high-level radioactive waste constitutes 3.04% of total waste amount and it is assumed that 12.5 tons of high level radioactive waste is stored in the repository per six months.

Middle & low level nuclear wastes are assumed to be shipped from NPPs to disposal centers at the end of the sixth months. This time is determined by using the number of shipments since 1960s in USA (also mentioned in chapter 1). Until the end of six months, the middle & low level nuclear wastes are stored in storage which is to be located in a NPP. Because of this, inventory cost should be taken into account in this thesis. This cost depends on “the fund of wastes” (also mentioned in chapter 1) and the amount of the stored middle & low level nuclear wastes. According to calculations, inventory cost of a 1 ton nuclear waste is 60$. In addition, transportation costs of middle & low-level nuclear wastes are assumed to be directly proportional to the amount of waste and distance. There are also fixed costs for establishment of NPPs and disposal centers. As stated in Chapter 3, the society is against the construction of NPPs and their disposal centers, as well as waste transportation. This situation is measured as opposition factor in the thesis. Opposition factor depends on the number of people living in the area selected for establishment of NPPs and disposal centers and, the number of people that might be directly exposed to radioactive wastes in case of a hazard during transportation and amount of waste that is transported. The populations of these candidate locations are shown at Appendix E. In this thesis, the exposure bandwidth of the population is considered as 18 km (Gerger, 1985). By using ArcGIS 10.0, the approximate number of people living in 18 km-wide area along the transportation road and around the NPPs and disposal centers are calculated. During these calculations, it is assumed that the population is uniformly distributed among the districts. The developed model also includes the earthquake hazard during the establishment of NPPs and disposal centers. Earthquake hazard is calculated using damaging factor of earthquake. This factor is based on the maximum acceleration of earthquake which also defines the seismic zones (Appendix B). Furthermore; the accident risk of nuclear waste carrying trucks is calculated by multiplication of the distance and the accident ratio of trucks per kilometer. These data about accident ratio of trucks are taken from Turkey Statistics Office (Türkiye İstatistik Kurumu-TÜİK) and it is shown at Appendix F. Lastly, the risk of terrorist attacks to the locations of NPPs and disposal centers is taken into account in this thesis. The data about the number of terrorist attacks to the candidate districts that are shown at Appendix G are taken from the report about terrorist assessment according to province by Bal and Özkan (2009) and the chronology report about the PKK attacks and battles to the candidate districts between 1990s – 2011 from research by Mefhar Özavcı (2011).

According to the data received from TAEK, the NPP which is planned to be built in Turkey will have 1000 MW power. It'll be closed type (western type) and its reactor type will be pressurized water reactor. In this thesis, it is assumed that the NPP planned for Turkey has all these properties.

The developed mathematical model is solved using GAMS 23.6 software utilizing the mentioned data. The GAMS 23.6 model of the thesis is shown at Appendix H. The Weighted Tchebycheff method is used for finding (weakly) Pareto optimal solutions to the developed mathematical model. First of all, the objective functions (1) – (5) are individually minimized to find the utopia and nadir points using GAMS 23.6 program as see in Table 4.1. Here, z_1 is total cost, z_2 is total opposition, z_3 is total accident risk, z_4 is total risk of earthquake damage, and z_5 is total risk of terrorist attacks objectives.

Table 4.1 Utopia and Nadir Point Calculations

Objective Functions	z_1	z_2	z_3	z_4	z_5
Min z_1	140461000000	3873003.8820	28056.9470	0.6000	16.0000
Min z_2	142916000000	1232171.4580	15179.8950	0.5100	24.0000
Min z_3	141241000000	1536421.0710	7548.4180	0.5000	17.0000
Min z_4	141261000000	3546122.6450	22558.5210	0.3200	60.0000
Min z_5	141671000000	3058763.0710	29416.2570	0.6000	0.0000

Here, utopia point is found as $z_i^{''}$ = (140461000000; 1232171.4580; 7548.4180; 0.3200; 0.0000) and nadir point is found as z_i^{n} = (142916000000; 3873003.8820; 29416.2570; 0.6000; 60).

The objective functions need to be scaled for the Weighted Tchebycheff application thus, ranges are determined as the difference between utopia and nadir points as mentioned in chapter 3, formulation (19). The ranges are found as R_i = (2455000000; 2640832.42; 21867.839; 0.28; 60) and $\pi_i = 1/R_i$ = (0.0000004073;

0.0000379; 0.00457; 3.571429; 0.016667). Here, the scaled weighted Tchybycheff formulation is as follows:

$$
\begin{aligned}
&\text{Min } \alpha \\
&s.t \\
&\alpha \geq \left\{ \mathrm{w}_1 0.0000004073 \ \left(z_1 \text{- } 140461000000 \right) \right\} \\
&\alpha \geq \left\{ \mathrm{w}_2 0.0000379 \ \left(z_2 \text{- } 1232171.458 \right) \right\} \\
&\alpha \geq \left\{ \mathrm{w}_3 0.00457 \ \left(z_3 \text{- } 7548.418 \right) \right\} \\
&\alpha \geq \left\{ \mathrm{w}_4 3.571429 \ \left(z_4 \text{- } 0.32 \right) \right\} \\
&\alpha \geq \left\{ \mathrm{w}_5 0.016667 \ \left(z_5 \text{- } 0.00 \right) \right\} \\
&x \in X \\
&(1) - (16)
\end{aligned}
\tag{20}
$$

By using (20), and equal weights $\mathrm{w}_\mathrm{i} = 0.2$, i=1,…,5, a (weakly) Pareto optimal solution is calculated and details are given in Table 4.2 and Figure 4.3.

Table 4.2 (Weakly) Pareto Optimal Solution Obtained with Equal Weights

GAMS SOLUTION							
z_1	z_2	z_3	z_4	z_5	α	**NPP Nodes**	**Disposal Node**
141236000000	1506204.671	0.41	8874.183	17	0.064	23,34,75,88	13

According to this solution, NPPs should be established in Gaziantep-Kargamış (23), Gümüşhane-Kürtün (34), Niğde-Altunhisar (75) and Kilis-Elbeyli (88) and, a disposal center should be established in Şanlıurfa-Sürüç (13) with the total cost of 141 billion 236 million dollars. Figure 4.3 shows this solution and list of the candidate NPPs nodes and disposal nodes are at Appendix A.

In this thesis, the developed mathematic model was run 100 times with 100 different random weight sets using GAMS 23.6 software. The results of 100 different random weights are obtained in about 40 minutes on HP Pavilion g6 Intel(R) Core (TM) i5 - 2410M CPU 2.30 GHz notebook PC. These sample (weakly) Pareto optimal solutions obtained with these weights are shown in Table 4.3.

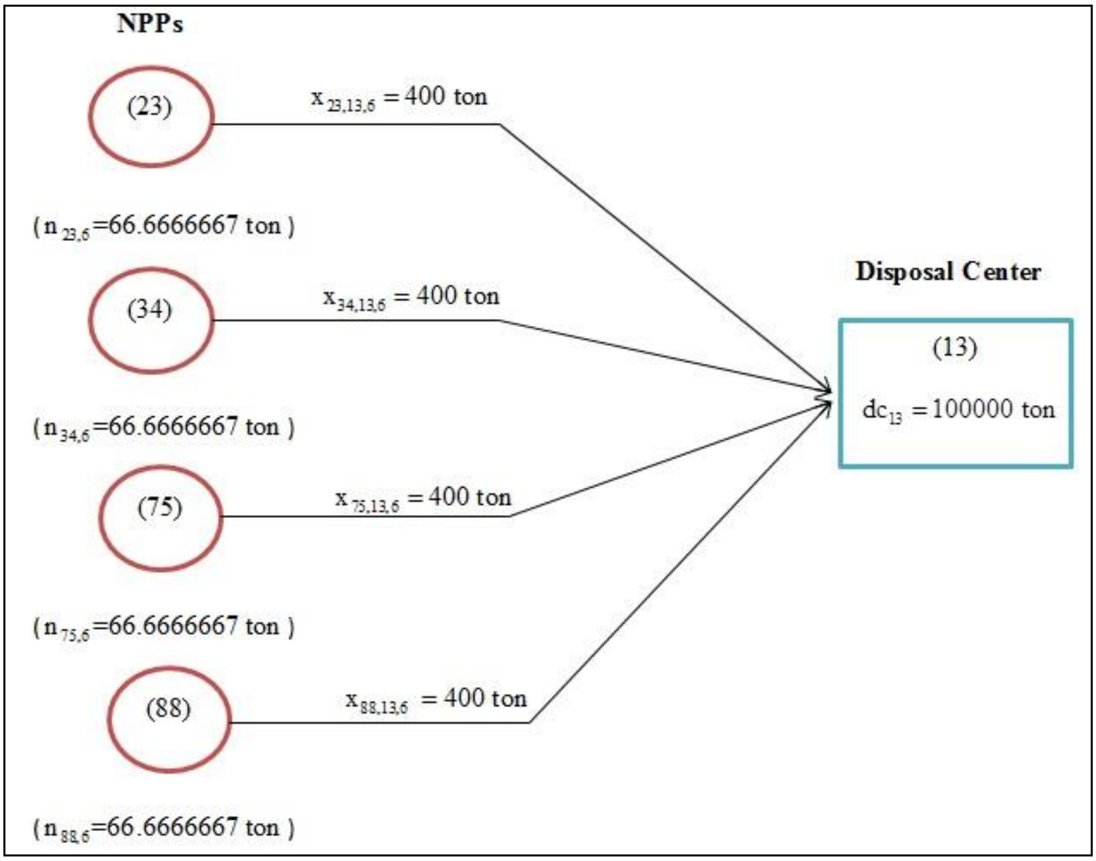

Figure 4.3 (Weakly) Pareto Optimal Solution Obtained with Equal Weights

Table 4.3 Sample (weakly) Pareto Optimal Solutions of the Problem

NO	w_1	w_2	w_3	w_4	w_5	z_1	z_2	z_3	z_4	z_5	α	NPP Nodes	Disposal Center Nodes
1	0.10	0.35	0.24	0.15	0.15	141234500000	1502576.90	0.41	10771.78	17.00	0.05	23, 77, 81, 88	13
2	0.13	0.18	0.38	0.07	0.24	141250600000	1693085.88	0.41	9865.64	15.00	0.06	14, 23, 52, 88	13
3	0.28	0.17	0.28	0.22	0.06	146895600000	2075175.41	0.32	11782.27	24.00	0.05	14, 23, 38, 52	14
4	0.28	0.10	0.13	0.29	0.20	142418000000	2498641.38	0.32	15575.55	15.00	0.05	38, 44, 78, 81	20
5	0.22	0.22	0.11	0.12	0.33	142423300000	1721876.68	0.41	16183.92	4.00	0.04	24, 78, 81, 88	20
6	0.28	0.10	0.23	0.26	0.12	146884000000	2090790.34	0.32	11233.56	24.00	0.05	24, 34, 38, 53	14
7	0.09	0.25	0.11	0.40	0.15	142421300000	1543042.43	0.32	16027.53	15.00	0.04	24, 36, 78, 81	20
8	0.12	0.22	0.26	0.23	0.18	146887100000	2082409.08	0.32	11689.58	24.00	0.07	23, 34, 38, 50	14
9	0.30	0.13	0.24	0.08	0.25	144080700000	2183393.17	0.50	12436.21	9.00	0.05	23, 34, 40, 88	9
10	0.10	0.25	0.22	0.29	0.13	141239900000	1894891.20	0.32	13009.96	28.00	0.06	23, 34, 35, 81	13
11	0.26	0.29	0.25	0.13	0.06	141238600000	1360536.38	0.41	9083.63	22.00	0.04	23, 29, 81, 88	13
12	0.08	0.28	0.25	0.05	0.34	142911700000	1529430.15	0.60	13898.57	13.00	0.07	8, 24, 77, 88	21
13	0.08	0.13	0.28	0.39	0.13	146882800000	2099503.34	0.32	11071.43	24.00	0.05	24, 34, 36, 53	14
14	0.05	0.28	0.29	0.20	0.18	141235500000	1504831.90	0.41	11147.11	17.00	0.06	23, 78, 81, 88	13
15	0.14	0.14	0.09	0.42	0.20	142421300000	1543042.43	0.32	16027.53	15.00	0.05	24, 36, 78, 81	20
16	0.35	0.16	0.09	0.34	0.07	144072800000	1747212.78	0.32	15489.29	25.00	0.03	24, 31, 38, 81	9
17	0.19	0.06	0.23	0.37	0.15	146883200000	2607281.45	0.32	12422.32	22.00	0.06	14, 24, 36, 85	14
18	0.11	0.17	0.16	0.16	0.41	142420700000	2148748.16	0.41	16064.91	6.00	0.06	11, 24, 78, 81	20
19	0.32	0.14	0.14	0.26	0.15	144070800000	1981487.60	0.32	15744.04	20.00	0.05	24, 34, 36, 81	9
20	0.35	0.08	0.29	0.05	0.23	144079500000	2113072.58	0.50	11886.51	14.00	0.06	24, 30, 40, 88	9
21	0.07	0.05	0.24	0.29	0.35	142416800000	2550459.93	0.32	15365.21	15.00	0.09	36, 44, 78, 81	20

Table 4.3 (Continued)

NO	w_1	w_2	w_3	w_4	w_5	z_1	z_2	z_3	z_4	z_5	α	NPP Nodes	Disposal Center Nodes
22	0.13	0.20	0.15	0.10	0.42	142024500000	2009874.21	0.41	16148.30	7.00	0.06	12, 24, 78, 81	19
23	0.25	0.11	0.23	0.23	0.18	146887200000	2653748.45	0.32	12998.00	22.00	0.06	14, 24, 35, 85	14
24	0.43	0.12	0.16	0.07	0.21	144077800000	2193111.67	0.50	12357.22	9.00	0.05	24, 34, 40, 88	9
25	0.12	0.30	0.26	0.18	0.13	141233200000	1568790.50	0.41	11054.92	17.00	0.06	23, 75, 78, 88	13
26	0.21	0.18	0.04	0.26	0.31	142434300000	1966353.94	0.32	22195.62	13.00	0.07	13, 23, 35, 81	20
27	0.21	0.21	0.14	0.21	0.23	142421600000	1488144.88	0.32	16743.85	15.00	0.06	24, 38, 77, 81	20
28	0.25	0.10	0.31	0.25	0.09	146886100000	2294686.28	0.32	10540.12	24.00	0.04	24, 36, 55, 77	14
29	0.27	0.08	0.19	0.21	0.25	142426900000	3044873.76	0.41	15059.82	15.00	0.07	22, 36, 42, 78	20
30	0.14	0.19	0.14	0.17	0.36	142423300000	1721876.68	0.41	16183.92	4.00	0.06	24, 78, 81, 88	20
31	0.40	0.09	0.12	0.26	0.14	142019900000	2481970.36	0.32	15380.53	16.00	0.04	36, 44, 78, 81	19
32	0.25	0.27	0.08	0.15	0.25	142422000000	1711369.67	0.41	16462.90	4.00	0.05	24, 79, 81, 88	20
33	0.30	0.23	0.34	0.04	0.09	141246100000	1514509.50	0.50	8828.57	15.00	0.03	16, 23, 41, 88	13
34	0.09	0.30	0.11	0.40	0.10	142421300000	1543042.43	0.32	16027.53	15.00	0.04	24, 36, 78, 81	20
35	0.21	0.32	0.21	0.22	0.04	141240300000	1812257.25	0.32	13211.28	33.00	0.07	23, 33, 35, 81	13
36	0.23	0.20	0.38	0.10	0.09	141235500000	1506204.67	0.41	8874.18	17.00	0.03	23, 34, 75, 88	13
37	0.08	0.17	0.10	0.07	0.58	142423300000	1721876.67	0.41	16183.92	4.00	0.04	24, 78, 81, 88	20
38	0.27	0.05	0.11	0.40	0.17	142416800000	2550459.93	0.32	15365.21	15.00	0.04	36, 44, 78, 81	20
39	0.27	0.14	0.28	0.10	0.21	141239600000	1711094.40	0.41	11887.43	15.00	0.06	13, 24, 53, 88	13
40	0.15	0.28	0.20	0.15	0.21	141250600000	1693085.88	0.41	9865.64	15.00	0.05	14, 23, 52, 88	13
41	0.31	0.14	0.03	0.32	0.20	142434300000	1966353.94	0.32	22195.62	13.00	0.04	13, 23, 35, 81	20
42	0.12	0.29	0.23	0.06	0.30	142911700000	1529430.15	0.60	13898.57	13.00	0.07	8, 24, 77, 88	21

Table 4.3 (Continued)

NO	w_1	w_2	w_3	w_4	w_5	z_1	z_2	z_3	z_4	z_5	α	NPP Nodes	Disposal CenterNodes
43	0.22	0.08	0.24	0.14	0.32	144072700000	2283271.93	0.41	13862.29	9.00	0.07	24, 34, 81, 88	9
44	0.33	0.04	0.15	0.25	0.23	142419000000	2550056.63	0.32	15554.48	15.00	0.06	36, 42, 78, 81	20
45	0.04	0.30	0.33	0.20	0.13	141232500000	1517251.40	0.41	11536.44	17.00	0.06	24, 78, 81, 88	13
46	0.19	0.05	0.28	0.20	0.27	146879900000	3679580.85	0.41	12296.03	13.00	0.07	24, 78, 85, 88	14
47	0.23	0.20	0.06	0.29	0.22	142034800000	1769494.43	0.32	22367.81	14.00	0.05	16, 23, 36, 81	19
48	0.25	0.22	0.17	0.18	0.18	141233200000	1568790.50	0.41	11054.92	17.00	0.06	23, 75, 78, 88	13
49	0.36	0.28	0.06	0.23	0.06	142024400000	1369338.43	0.32	16427.55	16.00	0.03	24, 36, 78, 81	19
50	0.23	0.09	0.10	0.27	0.32	142429300000	3007404.83	0.32	21383.48	13.00	0.07	24, 37, 44, 81	20
51	0.28	0.27	0.03	0.12	0.30	142425000000	1701988.80	0.41	16775.27	4.00	0.05	23, 79, 81, 88	20
52	0.32	0.33	0.11	0.19	0.05	142421300000	1543042.43	0.32	16027.53	15.00	0.04	24, 36, 78, 81	20
53	0.17	0.21	0.16	0.09	0.36	142898600000	1712292.77	0.51	14760.28	4.00	0.06	24, 77, 81, 88	21
54	0.19	0.09	0.21	0.14	0.37	144072700000	2283271.93	0.41	13862.29	9.00	0.06	24, 24, 81, 88	9
55	0.07	0.21	0.18	0.23	0.31	142419400000	2138241.16	0.41	16343.89	6.00	0.08	11, 24, 79, 81	20
56	0.27	0.16	0.07	0.37	0.12	142421300000	1543042.43	0.32	16027.53	15.00	0.03	24, 36, 78, 81	20
57	0.37	0.20	0.07	0.17	0.19	142029800000	1788439.81	0.32	21829.99	14.00	0.05	14, 24, 36, 81	19
58	0.19	0.08	0.33	0.35	0.05	146879400000	2610157.87	0.32	10409.18	29.00	0.04	24, 32, 36, 85	14
59	0.20	0.13	0.35	0.04	0.27	142113200000	2574190.26	0.60	11438.34	15.00	0.07	16, 23, 40, 88	12
60	0.23	0.22	0.22	0.22	0.11	141237600000	1898482.53	0.32	12931.84	33.00	0.06	23, 31, 37, 75	13
61	0.20	0.30	0.23	0.06	0.22	141248300000	1526695.16	0.50	9203.44	15.00	0.05	15, 23, 40, 88	13
62	0.27	0.30	0.10	0.17	0.16	142421300000	1543042.43	0.32	16027.53	15.00	0.04	24, 36, 78, 81	20
63	0.23	0.17	0.10	0.29	0.22	142421300000	1543042.43	0.32	16027.53	15.00	0.06	24, 36, 78, 81	20

Table 4.3 (Continued)

NO	w_1	w_2	w_3	w_4	w_5	z_1	z_2	z_3	z_4	z_5	α	NPP Nodes	Disposal Center Nodes
64	0.20	0.25	0.23	0.04	0.28	141917200000	1820471.39	0.81	13617.46	5.00	0.07	24, 81, 88, 89	15
65	0.29	0.09	0.25	0.27	0.10	146887000000	2296992.78	0.32	10643.76	24.00	0.04	24, 36, 55, 78	14
66	0.17	0.26	0.30	0.18	0.09	141236300000	1424494.98	0.41	8991.44	22.00	0.06	23, 29, 75, 88	13
67	0.03	0.03	0.31	0.32	0.31	141242100000	1787166.77	0.41	10645.79	17.00	0.10	23, 52, 80, 88	13
68	0.42	0.11	0.07	0.29	0.12	142421300000	1543042.43	0.32	16027.53	15.00	0.03	24, 36, 78, 81	20
69	0.35	0.29	0.13	0.06	0.17	141248300000	1526695.16	0.50	9203.44	15.00	0.04	15, 23, 40, 88	13
70	0.19	0.09	0.28	0.23	0.21	141227100000	1600512.20	0.41	11295.23	17.00	0.07	24, 75, 80, 88	13
71	0.34	0.10	0.11	0.21	0.24	142424800000	2320684.39	0.32	17230.56	15.00	0.06	24, 36, 54, 79	20
72	0.19	0.11	0.46	0.16	0.07	141247600000	1705278.74	0.41	8614.08	17.00	0.05	23, 34, 52, 88	13
73	0.18	0.06	0.40	0.14	0.22	141249700000	1695786.67	0.41	10283.57	15.00	0.06	16, 24, 52, 88	13
74	0.15	0.20	0.30	0.26	0.09	146895600000	2075175.41	0.32	11782.27	24.00	0.06	23, 34, 38, 52	14
75	0.14	0.22	0.36	0.20	0.07	141235500000	1506204.67	0.41	8874.18	17.00	0.06	23, 34, 75, 88	13
76	0.25	0.25	0.14	0.27	0.09	144072800000	1747212.78	0.32	15489.29	25.00	0.05	24, 31, 38, 81	9
77	0.22	0.22	0.27	0.18	0.11	141243900000	1906982.63	0.41	11748.23	33.00	0.06	23, 31, 35, 41	13
78	0.24	0.19	0.06	0.34	0.16	142423000000	1523154.56	0.32	16618.89	15.00	0.04	23, 36, 79, 81	20
79	0.07	0.24	0.04	0.30	0.36	142433500000	1967335.73	0.32	22139.73	13.00	0.08	13, 23, 37, 81	20
80	0.18	0.16	0.22	0.17	0.27	144074500000	2203232.85	0.41	13391.58	14.00	0.06	24, 30, 81, 88	9
81	0.31	0.09	0.13	0.28	0.20	142416800000	2550459.93	0.32	15365.21	15.00	0.05	36, 44, 78, 81	20
82	0.26	0.26	0.24	0.10	0.14	141242900000	1420334.50	0.41	10246.53	15.00	0.03	16, 23, 81, 88	13
83	0.20	0.28	0.08	0.21	0.25	142031900000	1778875.31	0.32	22044.93	14.00	0.06	16, 24, 36, 81	19
84	0.26	0.05	0.35	0.14	0.20	141238500000	1494011.81	0.41	10125.74	15.00	0.05	14, 23, 75, 88	13

Table 4.3 (Continued)

NO	w_1	w_2	w_3	w_4	w_5	z_1	z_2	z_3	z_4	z_5	α	**NPP Nodes**	**Disposal Center Nodes**
85	0.14	0.22	0.22	0.21	0.22	141237800000	1442246.07	0.41	8966.37	17.00	0.07	23, 34, 81, 88	13
86	0.24	0.09	0.19	0.24	0.23	142416800000	2550459.93	0.32	15365.21	15.00	0.07	36, 44, 78, 81	20
87	0.16	0.19	0.14	0.12	0.38	142423300000	1721876.67	0.41	16183.92	4.00	0.06	24, 78, 81, 88	20
88	0.12	0.27	0.23	0.12	0.26	141243000000	1640448.07	0.41	11516.18	15.00	0.07	16, 23, 86, 88	13
89	0.05	0.44	0.05	0.24	0.21	142427000000	1451609.67	0.32	16978.33	15.00	0.05	23, 35, 79, 81	20
90	0.25	0.16	0.20	0.14	0.25	144073500000	2114138.35	0.41	13398.43	14.00	0.06	24, 31, 81, 88	9
91	0.35	0.19	0.10	0.20	0.16	142421300000	1543042.43	0.32	16027.53	15.00	0.04	24, 36, 78, 81	20
92	0.40	0.06	0.23	0.19	0.12	146881000000	2723575.95	0.32	10877.18	24.00	0.05	24, 35, 77, 85	14
93	0.23	0.25	0.16	0.13	0.23	141239100000	1494699.67	0.41	10225.29	15.00	0.06	13, 23, 75, 88	13
94	0.23	0.06	0.17	0.38	0.17	142416800000	2550459.93	0.32	15365.21	15.00	0.06	36, 44, 78, 81	20
95	0.11	0.24	0.21	0.13	0.31	142894400000	1676838.32	0.42	15316.69	15.00	0.08	24, 36, 75, 77	21
96	0.04	0.26	0.04	0.26	0.40	142425000000	1701988.80	0.41	16775.27	4.00	0.08	23, 79, 81, 88	20
97	0.07	0.37	0.17	0.15	0.23	141242900000	1420334.50	0.41	10246.53	15.00	0.06	16, 23, 81, 88	13
98	0.19	0.27	0.07	0.41	0.06	142422500000	1491223.88	0.32	16237.87	15.00	0.03	24, 38, 78, 81	20
99	0.26	0.25	0.21	0.14	0.14	141234800000	1454665.57	0.41	9355.70	17.00	0.04	24, 34, 81, 88	13
100	0.26	0.29	0.18	0.11	0.15	141238500000	1494011.81	0.41	10125.74	15.00	0.04	14, 23, 75, 88	13

Chapter 5
Conclusion and Future Research Directions

In recent years, one of the most important issues which are the most debated is the establishment of NPP in Turkey. In spite of some people who find the establishment of nuclear power plant wrong and unnecessary, it is obvious that Turkey has a major energy gap and need to be met. There are many alternative sources such as solar power and wind power to meet the energy gap however; generating electric energy from these alternatives is more expensive than the NPPs. Actually, NPPs are not dangerous predictably if they are set up in accordance with the establishment principles; nevertheless, the establishment of NPPs has some risks such as earthquakes which will cause a damage and terrorist attacks. As a matter of fact the main reason for Fukushima disaster is an earthquake because; Fukushima is in the first degree earthquake zone. If NPPs are not established in the earthquake zones, they do not have a major risk.

In the literature, there are not any mathematical models about NPP location-routing problem which take into consideration the real life situations. However, various assumptions about obnoxious facilities location and routing problem are made in the presented models and some of these models are applicable in real life.

In this thesis, a new mixed integer programming model is developed. The aim of this mathematical model is to help decision makers decide on the following questions: Where to establish NPP(s), and waste disposal center(s) and how to route middle and low level radioactive nuclear wastes from NPP(s) to waste disposal center(s).

Many real life aspects of this problem are considered and implemented into the model realistically. Some examples are accident rate of trucks, costs (setup and transportation cost), degree of earthquake zones and the number of previous terrorist attacks. However, some assumptions need to be done in the application related to the storage of all high level radioactive nuclear wastes at the repository in the NPPs and related to power of all NPPs (1000 MW).

The developed NPPs and waste disposal center(s) location-routing problem considers five objective functions. The first objective function is minimizing total cost that includes setup costs of NPPs, disposal centers, transportation cost of radioactive nuclear wastes from NPPs to disposal centers and, storage costs. The second objective function is minimizing total social rejection by taking into consideration population opposition to the establishment of NPPs and disposal centers at the candidate locations and also population opposition of transporting nuclear wastes to these locations. The third objective function is related to minimizing total accident risk. This objective function is calculated with the probability of an accident during the transportation of the nuclear waste from NPPs to disposal centers. The fourth one is minimizing total risk of earthquake damage. As a result of this function, NPPs and disposal centers are established outside of the earthquake regions. The last objective function minimizes total risk of terrorist attacks to the locations of NPPs and waste disposal centers by taking into consideration the number of terrorist attacks. This model also includes capacity constraints for disposal centers and storage centers which are to be located in the NPPs, flow balance constraints and constraints related to regions and the necessity of electricity generation for establishing NPPs.

The model is successfully applied in Turkey. 110 nodes have been selected from all 892 administrative districts of Turkey. 89 of these 110 districts have been selected as candidate sites of NPPs and 21 of them as candidate sites of disposal centers based on earthquake zones and underground water flow.

The Weighted Tchebycheff method is used to find sample (weakly) Pareto optimal solutions sets (weakly non – dominated solutions) by running the model 100 times with 100 different weight sets using GAMS 23.6 and this mathematical model is solved for six months.

As a future research direction, different objective functions related to NPPs and waste disposal centers may be considered in the model. For example, traffic can be taken into account. Another criterion can be minimizing number of the special trucks for the transportation of radioactive nuclear wastes. Furthermore, distribution of generated electric energy from the new established NPPs to the customers can be considered. Finally, the results of the mathematical model can be analyzed statistically using cluster analysis in the future research.

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