Healthcare Waste Management in Istanbul;

Improving Decision Making

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Declaration

The candidate confirms that the work submitted is her own and that appropriate credit has been given where reference has been made to the work of others.

This thesis is dedicated to my parents; Aytul Ciplak and M. Haluk Ciplak

I know that letting me go far away from home has not been easy for you...

I would not have made this without your love...

Canim anneme ve babama saygi ve sevgiyle...

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Abstract

Turkey's accession to European Union requires compliance with the EU legislation. Healthcare waste is one waste stream which will be affected by this accession. Currently, in Turkey, especially in large provinces (such as Istanbul) there is an increasing pressure on the government authorities to develop a sustainable approach to healthcare waste management and integrate strategies aiming at pursuing sustainable society. In this respect, the purpose of this research was to develop a framework to support selection and planning of the future healthcare waste treatment systems in Istanbul.

In this study, an Istanbul-scale system dynamics model was developed to estimate future healthcare waste generation to 2040 and it was identified whether any of the assumptions made, because of the data gaps, have any significant influence on the outcomes of the model. The study found that more precise data are required on treatment types (acute or chronic), patient episodes (inpatient and outpatient figures in an age spectrum) and waste generation profiles (e.g. anatomic, genotoxic, sharps, etc.) of healthcare institutions. The model also determined a high potential in decreasing healthcare waste amounts (up to 10,000tpa) through implementing effective segregation along with a significant proportion of the healthcare waste (77%) which being incinerated could, in principle, be treated through alternative technologies.

The data generated by the model was used in the context of Multi-Criteria Decision Analysis (MCDA) by identifying various criteria, measuring them and ranking their relative importance from the point of key stakeholders via a questionnaire within four future scenarios. It was found that autoclave/hydroclave technology option for the treatment of healthcare waste suitable for alternative treatment (HCW SAT) and then their disposal through landfilling with energy recovery has potential to be an optimum option and these alternative treatment methods along with an efficient healthcare waste segregation scheme should be given more attention by the authorities in Istanbul. *The methodology used in this project has been developed based on the primary aim of the project which is to enable the decision makers in Istanbul to gain an improved perception of the decision problem.*

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List of Abbreviations

CDM	Clean Development Mechanism
CHP	Combined Heat Power
GAP	Turkish South Eastern Anatolian Project
GHG	Greenhouse Gas
GWP	Global Warming Potential
HCF	Healthcare Facilities
HCW	Healthcare Waste
HCW SAT	Healthcare Waste Suitable for Alternative Treatment
LCA	Life Cycle Assessment
MCDA	Multi-Criteria Decision Making
MSW	Municipal Solid Waste
MVSS	Multivariate Sensitivity Simulation
OD	Odd Risk
RR	Relative Risk
SARS	Severe Acute Respiratory Syndrome
SAS	Statistical Analysis System
SC	Scenario
SD	System Dynamics
STAAT	US State and Territorial Association on Alternative Treatment Technologies
TMWCR	Turkish Medical Waste Control Regulation
USEPA	United States Environmental Protection Agency
WHO	World Health Organisation

CHAPTER 1: INTRODUCTION

This chapter gives the outlines of this project by providing the aim, objectives, scope and the boundary of this research.

The assessment carried out to evaluate the current healthcare waste management in Istanbul is also covered in this chapter along with the brief information of the project area, Istanbul, Turkey. This assessment contributed to improved understanding of the specific nature of healthcare waste management in the project area, and hence supported the development of the healthcare waste management model as explained in Chapter 4.

1.1 Healthcare Waste Management in Istanbul

The primary objective of managing waste, healthcare waste is no exception, is that the materials should be handled, treated and disposed of safely. Managing the healthcare waste is a complex issue that requires *suitable technologies*, *allocated budget* coupled with *a regulatory system* including comprehensive policies and guidelines.

In Turkey, the early 1990s witnessed the passage of a number of environmental legislations and laws regarding waste management. The most important of which were; regulation on solid wastes (Turkish Ministry of Environment and Forestry 1991), regulation on healthcare wastes (Turkish Ministry of Environment and Forestry 1993) and regulation on hazardous wastes (Turkish Ministry of Environment and Forestry 1995). The healthcare wastes, for the first time, came under the regulation of the Ministry of Environment and Forestry with the Turkish Medical Waste Control Regulation (TMWCR) in 1993. Over the last decade, there has been an increasing pressure on the government authorities to develop a sustainable approach for healthcare waste management; partly to integrate with strategies aimed at pursuing a sustainable society, and also to align Turkish practice to European Union requirements; and hence the TMWCR was upgraded in 2005 by the Turkish Environment and Forestry Ministry (Turkish Ministry of Environment and Forestry 2005).

According to the TMWCR, healthcare institutions are under the duty of care for internal collection and storage of their wastes temporarily on their site. Likewise local district municipalities are legally responsible for collection, transport and disposal of these wastes. All local district municipalities are subordinate to Istanbul Metropolitan Municipality. In practice, transport and disposal of healthcare waste is conducted by Istac Inc, which is an affiliated company of Istanbul Metropolitan Municipality; and the district municipalities are responsible for supervising this service. At the top of the hierarchy the Ministry of Environment and Forestry carries out inspection of the whole service to make sure that healthcare wastes are managed appropriately.

It is stated in the TMWCR that the wastes generated at healthcare institutions are classified under three main groups; municipal, healthcare and hazardous waste. Healthcare waste is further divided into infectious waste, pathological waste and sharps; while hazardous waste includes pressurised containers waste, waste containing heavy metals, pharmaceutical waste, genotoxic waste and hazardous healthcare chemicals.

Although the TMWCR stipulates that hazardous waste must be collected separately and should be regulated under the hazardous waste regulations (Article 14), in practice there are only a few private healthcare institutions (holding accredited quality certificate) which collect their hazardous waste separately from the healthcare waste. The rest of the institutions mix their healthcare wastes and hazardous wastes together in healthcare waste bags with the exception of sharps which are accumulated in rigid containers. As a whole system, majority of the healthcare institutions employ a four-container system; red bag for healthcare and hazardous waste, black bag for municipal waste, blue bag for recyclables and a yellow container for sharps (Figure 1.1). That points out the failure of most waste producers in implementing regulations but also the weakness of the inspection function of the city authorities.

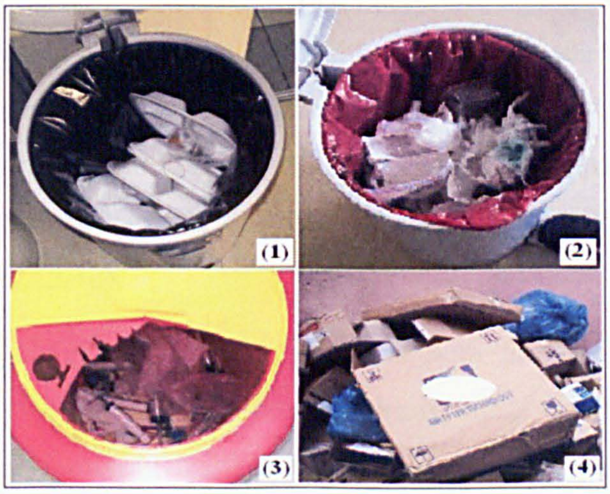

Figure 1.1: Black liner for municipal waste (1), red liner for healthcare and hazardous waste (2), yellow container for sharps (3), blue liner for recyclables (4)

Similar to any waste management, appropriate healthcare waste handling practices includes segregation, collection, storage, transportation, treatment and final disposal. In Istanbul, the waste is stored temporarily at the point of generation before it is collected and treated in a treatment facility. Most hospitals have two different storage rooms; one of which is for municipal waste and recyclables and the other one is assigned for the sharps boxes and red bags (Figure 1.2). At the time of the collection only the waste bags are collected by collection vehicles; and the containers in which the waste bags accumulate are returned to the hospitals to be used again.

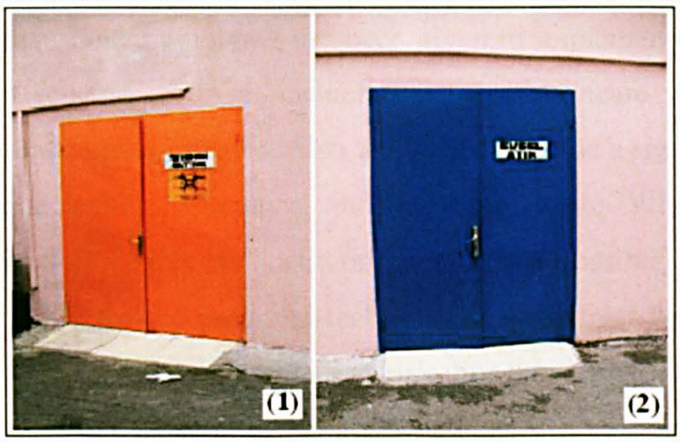

Figure 1.2: Healthcare and hazardous waste storage room (1), municipal waste and recyclables storage room (2)

In Istanbul, the municipality collects the healthcare waste produced on both sides of the city and transports it to the Kemerburgaz Incinerator, which has 1 tonne/ hour capacity and is located on the European Side. Because of the lack of capacity of the plant, excess healthcare waste is disposed of in a landfill site without any pre treatment (Eker *et al.* 2010).

The existence of this improper dump conflicts with the EU Landfill Directive (European Union 1999) which prohibits healthcare waste landfilling without pre-treatment. Besides this, mixing healthcare waste with hazardous waste not only leads to increased quantities of the healthcare waste, but also constrains the options for treatment technology. Therefore, the Ministry of Environment and Forestry still needs to improve the national legislation in a line with the European Union regulations by incorporating both minimisation and segregation schemes during this harmonisation period.

There are a number of studies on healthcare waste management in Turkey. Many of them were particularly conducted in Istanbul and tend to focus on these two objectives; (1) to measure the amount of waste produced in Istanbul by conducting surveys with selected central healthcare institutions (Alagoz and Kocasoy 2008a; Eker and Bilgili 2011); and (2) to examine transportation, treatment and disposal processes in Istanbul (Alagoz and Kocasoy 2007; Alagoz and Kocasoy 2008b; BirpInar *et al.* 2009)

Most of these studies pointed out a need for alternative technologies to be built up. However, so far insufficient emphasis has been given to implementing a healthcare waste segregation scheme to divert incineration-only healthcare wastes from the main red bag healthcare waste stream. Also there appears to be a significant scope to improve segregation between municipal and healthcare waste. Without addressing segregation schemes at healthcare institutions, it is not possible to estimate the quantities of the waste for the proposed technologies or to treat the waste without putting human health and the environment at risk. For this reason, more research is required to establish a database, information and statistics on healthcare waste composition to develop robust models which enable the impact of segregation schemes to be assessed and predict the potential for introducing new technologies. This will form the basis of future planning, design, technology development and implementation of healthcare waste management facilities.

1.2 Description of Project Area

This study focuses on Istanbul which is the Turkey's largest urban centre as well as the cultural, economic, and financial heart of the country. It sits in the north west of Turkey and covers an area of 5,400 km^2 (Istanbul Metropolitan Municipality 2007) with an estimated population of 12.5 million (Turkish Statistical Institution 2007a). It is located on the Bosphorus Strait and extends both on the European (Thrace) and on the Asian (Anatolia) sides of the Bosphorus, and is thereby the only metropolis in the world that is situated on two continents.

Figure 1.3: Map of Istanbul (Google Maps)

The health sector in Istanbul has developed more rapidly than other cities in Turkey. It has 200 central hospitals (administratively state hospitals, private hospitals, research hospitals, university hospitals and social insurance institution hospitals) (Table 1.1) offering acute and chronic care to patients along with almost 7,000 small healthcare facilities, such as healthcare centres, pharmacies, laboratories, dental and veterinary clinics.

Table 1.1: Scale of Hospitals in Istanbul

Number of Beds	Percentages (%)
1,000-2,000	2
500-1,000	6
200-500	8
100-200	25
Less than 100	59

As Istanbul has the most advanced technology in the healthcare sector in the country and as there is no doctor registry system (GP) in place, healthcare institutions not only serve the residents but also patients all across the country. This accelerates the development of the metropolis and attracts migrants seeking employment and education.

As the number of healthcare facilities goes up, the generated healthcare waste from Istanbul rises. The rapid development of Istanbul requires a robust system of healthcare waste management to minimise public health risks as well as occupational hazards among healthcare workers.

1.3 Aims and Objectives of the Study

Aim: The aim of the study is to identify the uncertainties and gaps involved in healthcare waste management in Istanbul and to establish the importance of them in a current decision making system. Following review of past and current information in Istanbul and the relevant research in other countries, this study takes a case study approach based on the healthcare waste management in Istanbul.

Objectives: In order to meet the aim of this study the following objectives have been identified:

- To establish the current status of healthcare waste management in Istanbul.
- To identify the factors and their interactions in healthcare waste generation.
- To evaluate the potential to decrease the amount of healthcare waste by the implementation of efficient segregation schemes at healthcare facilities and the potential of healthcare waste diversion using alternative technologies.
- To identify the criteria in the healthcare decision making process and establish their importance (relative importance) for ultimate decision making.
- To identify, develop and apply suitable modelling tools to support the research investigation.

Original Contribution:

This work is expected to contribute to the decision making process by developing a roadmap to support selection and planning of the future healthcare waste treatment systems. The results of this study should be used as a basis of future planning and anticipation of the needs for investment in the area of healthcare waste management in Istanbul.

This research was undertaken on a case study basis, and hence is subject to the specific nature of Istanbul. However, the developed computer models along with the results of the MCDA can promote improved decision making by providing the criteria, data and an approach that is of generic value to other Turkish cities and beyond.

The first set of results of this research, entitled "A System Dynamics Approach for Healthcare Waste Management: A Case Study in Istanbul Metropolitan City, Turkey", was published as a journal article by the International Solid Waste Association (ISWA), in Waste Management & Research (WM&R) (Appendix 5).

1.4 Scope of the Project

Clinical waste is defined under the Controlled Waste Regulations in the UK (UK DoE 1992) as:

(a) Any waste which consists wholly or partly of human or animal tissue, blood or other body fluids, excretions, drugs or other pharmaceutical products, swabs or dressings, or syringes, needles or other sharp instruments, being waste which unless rendered safe may prove hazardous to any person coming into contact with it; and

(b) Any other waste arising from medical, nursing, dental, veterinary, pharmaceutical or similar practice, investigation, treatment, care, teaching or research, or the collection of blood for transfusion, being waste which may cause infection to any person coming into contact with it.

As mentioned previously, there are four groups of waste generated at healthcare institutions; (1) red bag stream, (2) sharps box -yellow plastic box-, (3) municipal waste -black bag-, (3) recyclables -blue bag-. Within the scope of study only the healthcare waste (red bag stream) along with the sharps is included. The phrase "municipal waste" in the following chapters refers to the municipal waste which is mixed with healthcare waste as a result of the lack of/improper segregation.

Furthermore, within the scope of this study healthcare waste (HCW) was categorised into two groups (as below) to differentiate them according to their suitableness for the alternative technologies. The UK Health Department (UK DoH 2011) states that while anatomical waste, chemically contaminated samples and medicinally contaminated infectious wastes must only be treated by incineration; the others can also be treated by various alternative technologies (Bracketed numbers are from the European Union Waste Catalogue 2000).

(A) Incineration-only HCW, which consists of anatomical waste (18-01-02)[1], healthcare chemicals (18-01-06*), pharmaceuticals (18-01-09 or cytotoxic and cytostatic medicines 18-01-08*) for which incineration is necessary.

(B) HCW such as swabs, soiled dressings and gloves (orange bag 18-01-03*) are suitable for alternative treatment (HCW SAT), for which incineration is not a must, therefore can be treated by alternative treatment plants.

1.5 Limitations of the Study

- As investment costs of various treatment technologies are commercially confidential, the cost analysis of different technologies within the proposed scenarios remained limited with the data provided by some private companies.
- As there is not yet any research on determination of the composition (plastic, glass, paper, and etc content) of the incineration-only HCW and the HCW SAT separately in Turkey, they were assumed to be the same in the calculations of global warming potentials of the scenarios.

[1]: The European Union Waste Catalogue 2000 is divided into 20 chapters. Each chapter is represented by a two-digit code between 01 and 20 and comprises one or more subchapters (Chapter 18 is for healthcare wastes). Individual waste types are detailed in the subchapters and are assigned a six-digit code that comprises two digits for the chapter, two for the subchapter and two specific to the waste type. Hazardous wastes are signified by entries where the EWC code is marked by an asterisk (*).

1.6 Structure of the Thesis

This thesis is divided into six chapters. Chapter 1 introduces key factors of healthcare waste management with a brief overview of Istanbul and also explains the aims, objectives and the limitations of the study.

A review of the literature is presented in Chapter 2. The focus of the review is on the decision making methods and system dynamics modelling; it also presents the issues of the available healthcare waste management technologies and health outcomes due to the treatment of wastes.

Chapter 3 explains the methodology followed to meet the objectives of the study described in this section. The chapter provides the steps of the systems dynamics modelling; it gives the details of multi criteria decision analysis along with the validation of the methodology of the project.

The results and discussion are divided into two; Chapter 4 describes two system dynamics models regarding the healthcare waste generation and an estimation of number of healthcare workers whose health might be affected due to waste treatment activities along with the sourced data. Chapter 5 presents the details used in setting the scenarios to be compared in the context of multi criteria decision making along with the measurement of the identified criteria and assigning relative weights to them.

Lastly, Chapter 6 draws conclusions and provides recommendations for future work in this field.

CHAPTER 2: LITERATURE REVIEW

The purpose of this chapter is to provide an overview of healthcare waste management in developing nations along with currently available technologies for healthcare wastes and related epidemiologic studies. The alternative technologies covered in this project fulfil the best available technique requirements following the international trend.

This chapter also provides the literature survey on the background of system dynamics modelling technique in comparison with generic traditional methods which have been used in the same field for similar purposes. It finally reviews decision making methods in waste management including the techniques of multi criteria decision analysis, life cycle assessment and cost benefit analysis. Their strengths and weaknesses are discussed.

2.1 Healthcare Waste Management in Developing Countries

Sustainable development is development that meets the needs of the present, without compromising the ability of future generations to meet their own needs.

Brundtland (1987)

To improve healthcare standards communities continue to invest in various public and private healthcare facilities which consist of hospitals, veterinary and health-related research facilities, medical laboratories, dental clinics, pharmacies etc. Although all these facilities are the places for the provision of healthcare, they provide environments which could be suitable for the transmission of diseases if these facilities do not manage their waste properly.

Emmerson *et al.* (1995) gave an overview of the studies regarding the management and control of hospitals which indicated that some 8-10% of patients at hospitals develop a hospital acquired infection at any given time. Improperly managed waste is one of the factors which contributes to the spread of infection among patients, healthcare workers and visitors. Some of the problems arising from poor management of healthcare waste may include damage to humans by sharp instruments, disease transmitted to humans by infectious agents, and contamination of the environment by toxic and hazardous chemicals (Blenkharn 2006). There is a particular concern about infection with human immunodeficiency virus and hepatitis viruses B and C, for which there is a high risk of transmission via healthcare waste (WHO 1999; Franka *et al.* 2009).

The importance of proper healthcare waste management has been identified in emerging disease preparedness and infection control. For example in China specific healthcare waste related regulations were adopted after an outbreak of SARS (Severe Acute Respiratory Syndrome) was reported in early 2003 (Ruoyan *et al.* 2010). In 2002, the results of a study of 22 developing countries highlighted the potential problems caused by healthcare wastes by indicating that the proportion of healthcare facilities which do not use proper waste disposal methods, this ranged from 18% to 64% (WHO 2004). All these studies revealed that certain categories of healthcare waste are among the most hazardous and potentially dangerous of the emerging wastes across many communities.

Since the detrimental impacts of inadequate management of healthcare waste were understood by the environmental agencies, adoption of proper healthcare waste service has become a priority for regulatory agencies. This was supported by a great deal of research which has been conducted on healthcare waste management. In many developed countries, specific rules and regulations have been implemented along with the recommendations for handling (collection-transportation-treatment-disposal) of healthcare wastes (Townend *et al.* 2009; Ferreira and Teixeira 2010). On the other side in developing countries, there is some form of guidance already published but not fully implemented for many reasons (Mbongwe *et al.* 2008). In these countries, either healthcare wastes are handled and disposed together with municipal wastes, thus creating a great health risk to the community (Ruoyan *et al.* 2010) or healthcare waste disposal options are limited with open dumping, open burning or in some cases small-scale traditional incinerators (Shinee *et al.* 2008; Abd El-Salam 2010).

There are currently various healthcare waste technologies and accounted segregation practices which have been successfully adopted in developed countries. In order for the adoption of these technologies in developing countries, it is crucial to have an understanding of the composition of healthcare waste. In this respect it is important to make an analysis of the components of healthcare wastes and to handle them differently. This could make it possible to divert a relatively large proportion of healthcare waste from incineration to alternative treatment. Bendjoudi *et al.* (2009) reported that the amount of wastes to be incinerated could be reduced by 80% when only the wastes requiring incineration were rigorously segregated. This has also been supported by Prem-Ananth *et al.* (2010) who stated it is essential to look through the composition of waste and then select appropriate management strategies. On this basis segregation of different healthcare waste categories is critically important to selecting proper treatment methods.

The studies which investigated healthcare waste components indicate that there are considerably large quantities of wastes with a broad range of compositions and characteristics generated at various healthcare institution departments, such as general wards, acute care wards, injury units, theatres, medical laboratories, accident and emergency, admin and support offices. However a large percentage of healthcare waste generated in these institutions could also be classified as 'domestic' in nature. For example, a study conducted by Olko and Winch (2002) in England identified that approximately 50% of the healthcare waste generated annually could be classified as municipal with a possible 35% of this capable of being segregated out for recycling or reuse (cited in Tudor *et al.* (2008)). Such studies led to much more stringent segregation practices to be adopted especially after Hazardous Waste Regulations came into force in the UK (Defra 2005). Surveys in developing countries also confirm the lack of segregation, e.g. Bendjoudi *et al.* (2009) showed that the municipal waste fraction represented 75-90% of the total Algerian healthcare waste. This was also supported by WHO (1999) which concluded that "Between 75% and 90% of the waste produced by health-care is non-risk or general health-care waste that is comparable to domestic waste." In addition, a case study conducted in Istanbul by Alagoz and Kocasoy (2008a) indicated that 64% of healthcare waste generated in Istanbul was municipal, thus only 36% of it needs special attention if it could be successfully segregated and diverted. However there are several shortcomings in current literature regarding setting a proper scope/definition for healthcare waste and a standard on measuring the waste. There is a great deal of research pointing out the need to reach consensus on a worldwide basis on the definitions [different terms are used in the literature to refer to the same type of waste; healthcare waste (Prem Ananth *et al.* 2010), medical waste (Patwary *et al.* 2011), clinical waste (Hossain *et al.* 2011) and hospital waste (Abd El-Salam 2010)]. This issue hinders comparative analyses to be undertaken or the healthcare waste characteristics to be determined appropriately. Furthermore measuring the healthcare waste and estimating future growth in quantities are the most problematic issues especially in the provision of a base of reliable information and the creation of quantity estimating models for the future.

These results have led to an increasing realisation of the potential benefits that could be gained from the segregation of healthcare waste. It has been highlighted by many researchers that the development of a segregation and recycling scheme for healthcare waste which requires special attention can serve to reduce the quantities of healthcare waste and hence treatment costs (Patil and Shekdar 2001; Ozbek and Sahin 2004; Lee *et al.* 2004a; Tsakona *et al.* 2007; Tudor 2007; Cheng *et al.* 2009).

Along with the determination of the healthcare waste characteristics, a comprehensive understanding of the quantities is another basic step in the development of a plan for healthcare waste management. A classical management axiom has been repeatedly proved "You cannot manage what you do not measure". Taghipour and Mosaferi (2009) emphasise that for the successful implementation of any healthcare waste management plan, a fundamental prerequisite is the availability of sufficient and accurate information about the quantities and composition of the waste generated. Tudor (2007) suggested a standardised per capita unit that could be utilised to measure healthcare waste generation patterns across a range of both patient and non-patient departments. He indicated that studies to determine healthcare waste generation patterns either consider the *department type* or the *levels of activity*. He then concluded that most of the department based studies were concerned solely with patients and examine the impact of each determinant separately while other studies sought to combine these two and ended up producing a range of measurement units, such as lb/year, tonnes/bed/year, kg/patient/day and kg/bed/day, which caused ambiguity to some extent.

Since waste generation pattern differs for acute care departments (patient based) and chronic care departments (bed based) and this causes ambiguity in measurement units, in this research, chronic care departments (general surgery ward, intensive care unit, etc) were separated from acute care departments (such as emergency rooms). This allowed the use of two types of units which are tonnes/bed (for chronic care) and tonnes/patient (for acute care). It is explained in detail in Chapter 3: Materials and Methodology.

2.1.1 Available Technologies for Healthcare Wastes

In this section available technologies for healthcare wastes are categorised in two groups: (1) High temperature (incineration) technology and (2) Non-burn/low temperature alternative technologies. The technologies under each group are recognised and well established treatment methods which are employed across Europe, the US and Canada; and currently commercialised by a number of companies across the world. These technology options were selected in proposing scenarios for this research as explained in Chapter 3 and Chapter 5. The required data for economic and environmental analysis and the information regarding the maturity of them were collected from several manufacturers. Within the scope of this section only the technologies which were employed in setting the scenarios were reviewed. Since landfilling of healthcare waste without pre-treatment is forbidden by the EU Landfill Directive (1999), it was not involved as an option by itself in any of the scenarios, but reviewed in this section as it is one of the common methods applied in developing countries including Turkey.

Table 2.1 provides healthcare waste treatment and disposal methods across the world based on the analysis of available literature.

Landfilling

In developing countries, landfills are generally operated like an open dump (Hossain *et al.* 2011). In practice healthcare waste is dumped in the pits mixed with municipal wastes, and later burned (Nemathaga *et al.* 2008). It is the most common method for the disposal of healthcare wastes as it is an easy and low cost waste disposal method (Diaz *et al.* 2005; Hossain *et al.* 2011). Yong *et al.* (2009) reported that in Nanjing Province-China, since a disposal cost mechanism had not been developed based on the market economics, higher disposal costs often encouraged some hospitals to dispose of their healthcare wastes by themselves.

High Temperature (Incineration) Technology

Incineration is a high-temperature dry oxidation process that converts the waste into residual ash and gases. It consists of a primary combustion chamber operating at 800-1000 °C and a secondary chamber operating at 850-1100 °C.

There are often two shortcomings regarding the use of incinerators in developing countries reported in the literature. Firstly these incinerators are poorly designed and run inappropriately. Coad (1994) documented that 57–92% of incinerators were functioning poorly, or not at all in developing nations (cited in Coker at al. (2009)). Nemathaga (2008) investigated an incinerator of Tshilidzini hospital in Limpopo Province and found out that the incinerator was generating high amounts of ash because of incomplete burning of the waste. Secondly they require high investment, operation and maintenance costs along with costly emissions control equipment (Yang *et al.* 2009).

Table 2.1: The Common Treatment Methods for Healthcare Waste across the World

Developed by the Author

Country	**Method**	**Reference**
Bangladesh (Dhaka City)	Dumping Autoclave	Hassan *et al.* (2008)
Brazil (State of Rio Grande do Sul)	Incineration Autoclave	Da Silva *et al.* (2005)
Denmark	Incineration Other Alternative Technologies	Bagge (2009)
Germany	Incineration Autoclave	Hempen (2011)
Greece (Central Macedonia)	Incineration Autoclave	Karagiannidis *et al.* (2010)
India	Open burning Open dumping	Patil and Shekdar (2001)
Iran (Fars Province)	Open dumping Incineration	Askarian *et al.* (2004)
Libya	Open dumping Incineration	Sawalem *et al.* (2009)
		Please see next page

Country	Method	Reference
Nigeria (Ibadan)	Open dumping Incineration	Coker *et al.* (2009)
Palestinian Territory	Open burning Thermal disinfection Incineration	Al-Khatib and Sato (2009)
South Africa (Limpopo Province)	Incineration Autoclave Open dumping Landfill	Nemathaga *et al.* (2008)
Sweden	Incineration Autoclave	Christiansson (2011)
Turkey	Landfilling Incineration Autoclave	Personal Investigation
UK	Incineration Alternative Technologies	Tudor *et al.* (2009)

Despite the fact that developing countries face these difficulties in designing/building and running proper incinerators for particular healthcare waste streams (such as large body parts, animal carcasses, pharmaceutical waste in any form or container, microbiological cultures, cytotoxic and cytostatic contaminated waste, contaminated metal parts, wastes from chemotherapy treatment, mercury, volatile and semi-volatile organic compounds and radioactive wastes), incineration remains the preferred (often mandatory) treatment system in today's world (WHO 1999; Lee *et al.* 2004a; Sawalem *et al.* 2009; Tudor *et al.* 2009; Hossain *et al.* 2011).

(2) Non-burn/Low Temperature Alternative Technologies

Currently available alternative technologies for the treatment of healthcare waste require suitable land disposal facilities (Tudor *et al.* 2009). The main principle of these technologies is to render the waste "safe". "Rendering safe" is defined by the Safe Management of Healthcare Waste Document published by the Department of Health in the UK DoH (2011) to be applied to:

(1) Infectious waste: demonstrates the ability to reduce the number of infectious organisms present in the waste to a level that no additional precautions are needed to protect workers or the public against infection by the waste; (2) Anatomical waste: destroys anatomical waste such that it is no longer generally recognisable; (3) All clinical waste (including any equipment and sharps): renders all clinical waste unusable and unrecognisable; (4) Medicinal waste: destroys the component chemicals of chemical or medicinal and medicinally contaminated waste.

Following the same document, for infectious waste the treatment must demonstrate, as a minimum, Level III criteria. For cultures of pathogenic *microorganisms* (pre-maceration or shredding is not appropriate for such wastes) it should show at least Level IV criteria provided by the US State and Territorial Association on Alternative Treatment Technologies (STAAT) guidelines (USEPA 1994). Level III inactivation indicates the kill of microbial life forms as evidenced by the inactivation of at least $4\log_{10}$ indicator spores which have death curves similar to human pathogenic spores. Thus, B. subtilis spores may be used to indicate Level III microbial inactivation for moist heat treatment, since they also exhibit thermal death data similar to species of the pathogenic spore-forming Clostridium. Level IV indicates the kill of microbial life forms as evidenced by the inactivation of $6\log_{10}$ bacterial indicator spores recognised as most resistant to the treatment process.

Autoclaves

The autoclave consists of a metal cylindrical vessel which is surrounded by a steam jacket. Waste containers are loaded into a vessel on a cycle/batch base and are exposed to elevated temperature/pressure for a set time period [for example, 121°C for 30 minutes (Stidolph 2011)]. Steam is added into the system in order to maintain a prescribed temperature for a given period of time. The steam jacket reduces condensation in the vessel and thus reduces the loss of heat.

In practice, steam is supplied into the system via a boiler. Usually boilers are heated by means of conventional fuels (such as gas, diesel, coal, or biomass) or they use electricity (Emmanuel *et al.* 2004). The selection of a proper boiler for the system is crucial in terms of having a sufficient amount and quality of steam to match the requirements of a system (Diaz *et al.* 2005).

In order for the verification that sufficient steam penetration and exposure time have occurred, biological (spores) or chemical indicators (colour-changing) are placed periodically in waste loads (Emmanuel *et al.* 2004; Diaz *et al.* 2005; Stidolph 2011).

Hydroclaves

The hydroclave is basically a double jacketed vessel with fragmenting paddles inside. After the door is closed, high temperature steam is introduced to the outside jacket to heat the waste via the hot inner surface.

Although the basic principal on which autoclave and hydroclave is based is the same, there is a crucial difference between them in terms of steam recycling. In order for the standard autoclave to function, steam is injected into the sterilizing vessel. This steam is then lost when the cycle ends. On the other side, in hydroclave the steam is injected into the jacket, not into the vessel where the waste is sterilised and therefore the steam is never in contact with waste. This enables the hydroclave to reclaim some amount of steam back to the boiler (Wallis 2010). However one of the disadvantages of the hydroclave over the autoclave is that it takes more steam to heat up initially as it has to transfer the heat from the outer jacket into the vessel chamber through conduction. This initial high energy requirement then diminishes for the continuing cycles. For this reason, an average energy consumption of hydroclave was used in calculations in this research, and explained in Chapter 5 (Table 5.10 Energy Requirement of Alternative Technologies).

Microwaves

Microwaves are electromagnetic waves with frequencies falling below the range for infrared waves and above the ultra-high frequency (Hossain *et al.* 2011). Its working principle is based on converting electrical energy into microwave energy. This microwave energy is used to produce steam from the moisture present in the healthcare waste stream. Some systems apply low frequency radio waves to inactivate microorganisms contained within the waste.

One of the disadvantages of microwave systems is their cost which might not be economically competitive compared to other technologies, especially in developing countries (Alagoz and Kocasoy 2007; Hossain *et al.* 2011).

2.1.2 Epidemiologic Studies Regarding Waste Management

Much of the current understanding of the health impacts of waste disposal is based on the application of epidemiological methodology as stated by Hester and Harrison (2002). In this part of the study, the available epidemiological literature on the health effects among the workers in landfilling sites and incinerators was reviewed systematically in order to provide data and information regarding excess risk estimates for the worker's health system dynamics model which is explained in detail in Chapter 4. Since there is not a significant number of a health effect investigations specifically related to healthcare wastes' treatment and disposal, municipal waste was used as a surrogate for healthcare waste in this section of the study.

Giusti (2009) determined the main pathways of exposure as inhalation, consumption of water, and the food chain. Table 2.2 identifies the source-pathway-receptor relation of waste management methods (landfill and incineration).

Table 2.2: Emission-Pathway-Receptor for Landfill and Incineration. Adapted from DEFRA (2004b) and Rushton (2003)

	Emissions		Pathway	Receptor
Landfill	Air	Landfill Gas (CO_2, CH_4 and numerous trace compounds), exhaust gases from combustion of landfill gas, dust and odour	Emissions of fugitive landfill gas and products of landfill gas combustion.	Nearby sensitive receptors
	Water	Leachate containing salts, heavy metals, biodegradable and persistent and synthetic organic compounds	Leachate run off to water sources	Users of water resources (groundwater or surface water)
	Soil	Metals (Zn, Pb, Cu, As) and various organic compounds	Land contamination during post-operative activities, animal factors (seagulls, vermin, rats) and visual effect	Post operative site users
Incineration	Air	SO_2, NO_x, N_2O, HCl, HF, VOCs, CO, CO_2 emissions, dioxins and furans, metals (Zn, Pb, Cu, As), dust, odour, micro-organisms and PAHs	Emissions of gases and particles from combustion of waste	Nearby sensitive receptors
	Water	From deposition of combustion gases: sulphuric, carbonic and nitric acids, particulate matter, metals (Zn, Pb, Cu, As), dioxins and furans	Deposition of hazardous substances to water resources	Receptors in the vicinity of waste water treatment plants
	Soil	From ash and combustion gases: metals (Zn, Pb, Cu, As), dioxins and furans, sulphuric, carbonic and nitric acids, particulate matter, fluoride and chloride.	Leaching of materials from landfilled ash; and deposition of combustion gases	Receptors exposed to contaminated soil

Although there are a number of studies in the literature which provide information on emissions to air from waste treatment facilities, studies surveying the emissions to land or water are very limited in number. DEFRA (2004a) stated that this does not mean that health effects due to exposure via water or soil are less significant; however, there are controls on food and water quality which make any exposures through these pathways easier to avoid. Therefore inhalation of emissions is the pathway which is mostly assumed by epidemiological studies.

The studies which were evaluated in this research were selected accordingly to the criteria proposed by Hester and Harrison (2002): (1) They have to be conducted in authorised incinerations or landfills; meaning that the ones considering open burning or unregulated disposal sites were disregarded; (2) They must provide some degree of consistency with other different epidemiological studies in terms of the types and significance of the outcomes; (3) They must have a theoretical basis in linking adverse health effects and exposure pathway; and (4) They must have a basis for the effects, as indicated by actual measurements or examinations.

Giusti (2009) categorised these studies into three groups:

(1) Prospective Cohort Studies: Two cohorts of people (exposed and non-exposed) who differ with respect to certain factors under study were followed over a period to determine how these factors affected rates of a certain outcome. This kind of study generally involves the collection and analysis of blood or tissue samples. For example: Unuvar *et al.* (2007) conducted a survey to assess whether pregnant women were at risk of mercury intoxication due to fish consumption by taking blood samples from mothers and their new born babies. Mudge *et al.* (2011) described the prevalence of inadequate energy and protein intake in older inpatients by screening consecutive patients admitted between November 2007 and March 2008 to the Royal Brisbane and Women's Hospital in Australia. Likewise Hoek *et al.* (2002) examined the association between mortality and indicators of traffic related air pollution in the Netherlands by investigating a random sample of five thousand people from 1986 to 1994. A similar study was conducted in China by Cao *et al.* (2011a) to improve understanding of the link between outdoor air pollution and mortality.

On the other side, having too many repeated measurements and the selection of the measurement time points of cohort studies cause these studies to have an ad-hoc basis according to Tekle *et al.* (2011) who pointed out the necessity of optimal design methods with a controlled budget for these studies.

(2) Retrospective Case-Control Studies: A case group of people who have already developed a specific disease, and a control group of healthy people are selected. Information on past exposure is collected retrospectively (generally via interviews with the participants).

These studies are relatively inexpensive compared to prospective cohort studies as (A) they involve smaller groups of people, (B) they do not generally require structured experiments, but are more prone to bias (Giusti 2009). For instance: The study by Burke and Sawchuk (2003) was based on 244 women who died from tuberculosis between 1874 and 1884. Some 12% of them had given birth within the year preceding their death. The study used the records in the local government death registries; and indicated that recent childbirth did not increase the risk of tuberculosis mortality among these women.

(3) Cross-Sectional Studies: They take account a specific group of the exposed population over a short period of time. They are 'cross sectional' because data is collected at one point in time. They can only be useful to generate hypotheses that can be tested later by more comprehensive studies; otherwise they might not be effective at distinguishing whether a particular disease developed before or after the group was exposed to a potential hazard as they do not look at time trends. There are a number of examples of cross-sectional studies in the literature as they are relatively cheap to carry out (Mino *et al.* 2001; Peabody *et al.* 2006; Scheeres *et al.* 2008; Geldart *et al.* 2010).

In order for the definition of the strength of the association between exposure to a potentially toxic substance and specific health effects in epidemiological studies, the ratio of the incidence of a disease in the exposed population to the incidence of the same disease in the non-exposed population is calculated; this is called "Relative Risk" (RR) or "Odd Risk" (OR). For instance, if the RR is 6, the risk is six times higher (or an increase of 500%) in the exposed population than that in the non-exposed population.

The number of the studies satisfying the criteria set by Hester and Harrison (2002) is very limited. Regarding mortality and morbidity among landfill workers there is only one study: Gelberg (1997) carried out a cross-sectional study to examine acute health effects among employees working for the New York City Department of Sanitation. Landfill workers reported a significantly higher prevalence of work-related respiratory (RR=2.14), dermatologic (RR=2.07), neurologic (RR=1.89), gastrointestinal (RR=1.26) and hearing problems (RR=1.73), itching eyes (RR=1.54) and sorethroat (RR=2.26) than the controls.

Regarding the adverse health effects on incineration workers, Gustavsson (1989) investigated mortality among 176 incinerator workers who were employed at least one year or more between 1920 and 1985 at a MSW incinerator in Sweden. Results revealed an excess mortality from cancer (oesophageal cancer RR=2.84; stomach cancer RR=1.27, rectal cancer RR=2.52, lung cancer RR= 3.55, bladder cancer 1.98, malignant cerebral tumors RR= 2.77, hematopoietic cancer RR= 1.35) and nervous disease (RR=1.33), circulatory disease (ischemic heart disease RR=1.38), respiratory disease (asthma, bronchitis, emphysema RR=1.62) and digestive disease (liver cirrhosis RR=4.54). The excess was found to be highest in workers with more than 40 years exposure.

Counter to the above study by Gustavsson (1989), a retrospective study on 532 workers employed at two municipal waste incinerators in Rome did not reveal any excess of lung cancer (Rapiti *et al.* 1997). Mortality from lung cancer was reduced in comparison to the general population and overall cancer mortality did not differ much from that of the general population. However it was noted a 2.79 fold increased risk of mortality from gastric cancer among workers who had more than 10 years latency since first employment.

A similar study was conducted by Hours *et al.* (2003); they carried out a cross-sectional morbidity study for 102 workers employed at three French incinerators during 1996, matched for age with 94 male workers from other industrial activities. The exposed workers were categorised into 3 exposure groups based their workplace: crane and equipment operators, furnace workers, and maintenance and effluent-treatment workers. The maintenance and effluent group encountered elevated relative risks for skin symptoms (RR=4.85). An excess of daily cough was reported for the maintenance and effluent group (RR= 2.55) and for the furnace group (RR=6.58).

Many epidemiologic studies dealing with waste management report limitations regarding a lack of good exposure data and the use of surrogate indirect measures which might lead to exposure misclassification (Rushton 2003; Defra 2004a; Defra 2004b; Porta *et al.* 2009). One of the reasons for that is the unsuitableness of conducting an epidemiologic study based on experiments (not on observations) for ethical reasons (Giusti 2009).

The greatest challenge emphasised in the literature so far is the *"confounding factors"* which might not adequately be controlled in many studies such as ethnicity, gender, socio-economic or deprivation status, age, smoking/alcohol habits, medicinal drug use, occupational history, hazards from other sources, population mobility, long latency period of some diseases, the pre-existing health of the people being studied, the wealth or poverty of the people, the availability of health or social care services and other present or historical sources of pollution.

It is known that adverse health impacts would be difficult to prove or supply with decent figures. The main conclusion of the review of the epidemiology literature is that the evidence of adverse health outcomes is controversial as they are insufficient/inadequate and hence inconclusive in providing entirely convincing, rigorous epidemiological evidence for an association between waste treatment facilities and adverse health outcomes (Hester and Harrison 2002; Giusti 2009). It is clear that future research into the health risks of waste management needs to overcome these current limitations (Porta *et al.* 2009). It is therefore suggested that further collaborative epidemiological studies using a more rigorous approach along with an appropriate methodology which takes account of possible confounding factors are required. It is anticipated that this will benefit in improving a way of shaping public perspective through waste treatment facilities which underlies social values in waste management decision making.

2.1.3 Summary

The risks associated with healthcare waste and its management has gained attention across the world over last decades and this has resulted in the increased recognition of the need for proper healthcare waste management. Despite the realisation of the magnitude of the problem, healthcare waste practices and policies in developing countries are challenging and require stringent measures. To summarise the literature review that is relevant to this research identifies three issues regarding the current healthcare waste management:

(1) Various technologies are available for the treatment of healthcare waste. An understanding of the waste composition and predicting its quantity are essential in adopting a technology and deciding on its scale.

(2) Each healthcare waste treatment technology has its inherent merits and drawbacks. One of the most commonly proclaimed treatment technologies is incineration in epidemiologic studies. There is still an ongoing debate about health outcomes of waste treatment technologies. If adverse health effects due to incineration are proved with robust evidence based studies in the future, then the attempts to divert some of the healthcare waste from incineration to alternative treatment could potentially benefit the environment and wellbeing of people.

(3) There is a strong body of research highlighting a high municipal waste content of healthcare waste. This brings forward a good potential for minimisation and recycling of healthcare waste. Once mixed, this potential cannot be turned to benefit as there is a major concern over the infectious characteristics of the healthcare waste. On this basis a sound understanding of the contents of the non-infectious fraction could also be useful in setting a targeted waste stream to be segregated and then developing appropriate waste recycling programmes. In the absence of a dedicated segregation and collection system, this waste stream is likely to mix with the healthcare waste stream and line up for specialised treatment, resulting in unnecessary costs.

2.2 System Dynamics (SD) Modelling

"We are taught from an early age that every event has a cause, which in turn is an affect of some still earlier cause. Inventory is too high because sales unexpectedly fell. Sales fell because the competitors lowered their price. Such event-level explanations can be extended indefinitely, in an unbroken Aristotelian chain of causes and effects, until we arrive at some first cause, or more likely, lose interest along the way."

- Sterman (2000)

Models represent some aspect of a real system which consists of several interrelated components and interactions among them. This real system could be a living space, a region or a city. Homer and Hirsch (2006) defined a model as an interlocking set of differential algebraic equations developed from a broad spectrum of relevant measured and experiential data. In this regard, System dynamics (SD) is a modelling methodology that allows a system to be constituted as feedback loops. It was developed by J. Forrester and was defined for the first time as *''the investigation of the information-feedback character of industrial systems and the use of models for the design of improved organizational form and guiding policy''* (Forrester 1961).

Since then SD modelling has been used for studying and managing complex feedback systems by visualising, conceptualising, simulating, analysing and documenting such systems in the form of visual models.

2.2.1 Background

"The human mind is not adapted to interpreting how social systems behave. Human evolutionary processes have not given us the mental skill needed to interpret properly the dynamic behaviour of the systems of which we have now become part"

-Meadows D.L. and Meadows D. H. (1973)

SD was originated by J. Forrester at the Massachusetts Institute of Technology with the book-*Industrial Dynamics* in 1961 (Forrester 1961). It was introduced as a modelling and simulation methodology in dynamic industrial management problems (cited in Georgiadis *et al.* (2005)). In 1969, Forrester and his colleagues published another book-*Urban Dynamics* (Forrester (1969), cited in Ford (1999) and Kollikkathara *et al.* (2010)) which presented a computer model describing the relation between population, housing and industry within the urban area. In this book, Forrester built up a model of a city with interacting industries, housing, and people, which could develop under favourable conditions. Since the land area was filled, the model turned into a stagnancy mode by aging housing and declining industry. He then showed with his model that introducing a demolition programme which provided a space for new industries led to improvements for the city. Ford (1999) stated that although Forrester argued that the models were most useful when they lead to *counterintuitive* results as they forced planners to re-examine their intuitive understanding of the system; this proposal did not match with city planners'/designers' thinking.

The number of publications increased in the 1970s. Some of which are: (1) World Dynamics which examined global environmental sustainability (Forrester (1971), cited in Saysel *et al.* (2002)); and (2) "Limits to Growth" which looked at resource usage and unsustainability of the modern way of life and concluded that the sooner the world's people begin working for a sustainable world, the greater would be their chances of success (Meadows at al. (1972), cited in Georgiadis and Besiou (2008) and Ford (1999)).

2.2.2 General Application of SD

SD has been used widely in various areas including business and engineering. It has been used to model topics as diverse as public administration (Bianchi 2010), educational surveys (Munitic *et al.* 1999), library information studies (Heseltine 1982), project management (Stupples 2002; Lee and Miller 2004b; Acharya and Mahanty 2008; Kara and Kayis 2008), economics (Nemeslaki 1990), renewable energy studies (Bala and Satter 1991), architectural management (Mohamed and Chinda 2011) and engineering analysis [civil engineering (Prasertrungruang and Hadikusumo 2008); electrical engineering (Chaturvedi and Satsangi. 1992); mechanical engineering (Wenjie and Jie 2009); computer engineering (Stallinger and Grunbacher 2001)].

The method has also been used in a wide variety of applications for optimisation and policy making. For example, Dyner *et al.* (1995) built a model to simulate the substitution of installed household appliances by more efficient ones and aimed to assist the decision making on energy savings under different scenarios; Shi and Gill (2005) developed a model which provided an experimental platform for the simulation and analysis of alternative policy scenarios in the ecological agricultural sector; Han and Hayashi (2008) looked at the transport system in China and determined the most efficient option with appropriate policies for CO_2 mitigation; Ben Maalla and Kunsch (2008) presented a model based on the replacement of traditional boilers by combined heat power (CHP) which aimed to help regulatory authorities in making policies to meet the sustained growth in energy sector; Xu and Li (2011) studied complex interactions in the coal industry to establish more effective policy; Chyong Chi *et al.* (2009) built a dynamic model of the natural gas industry in the UK by evaluating the effect of low taxation policy on consumption rates; and Rehan *et al.* (2011) proposed a model aiming to provide a new approach for water utilities to plan to meet the requirements of the regulations in Canada.

The application of the method is also growing in health systems. Taylor and Dangerfield (2005) provided a plausible causal framework to present the interaction between bringing health services closer to the community and the improvements in accessing stimulating demand. Evenden *et al.* (2005) examined capturing Chlamydia infection within a population incorporating the behaviour of different risk groups in

Portsmouth. In Canada, McGregor (2010) analysed jurisdictional conflict between a major and a minor healthcare profession by means of system dynamics. Furthermore Mothibi and Prakash (2006) presented an approach for the management of HIV/AIDS in order for the Bostwana government to control the diseases.

Another area of wide application is a supply chain management. Angerhofer and Angelides (2000) provided a research review regarding using SD in supply chain by addressing topics such as inventory decisions, time compression, demand amplification, supply chain design and integration and international supply chain management. This included examples in the literature such as food supply chain modelled by Minegishi and Thiel (2000) and Georgiadis *et al.* (2005); electricity supply industry studied by Dyner *et al.* (1997); and water supply chain researched by Stave (2003).

SD has also been used to model the dynamic nature of the manufacturing and marketing sectors. For instance, modelling costs and value dynamics of activities in manufacturing enterprises (Agyapong-Kodua and Weston 2011), the influence of multiple knowledge transfer mechanisms on organisational performance during crises (Wei-Tsong 2011), allocation of sources to improve quality in organisations (Mandal *et al.* 2002), predicting the performance of companies under different conditions to choose the most favourable manufacturing strategy (Oyarbide-Zubillaga and Baines 2003), forecasting the market size and market share of substituting technology (Kabir *et al.* 1981), demonstrating a comparison of a broadband performance in the market (Lee *et al.* 2009), analysing demand amplification problems for a supermarket chain in the UK (Ge *et al.* 2004), and exploring an effective way to construct an analytical framework of dynamic competitive strategy for the telecommunication industry (Hua *et al.* 2009).

2.2.3 Applications of SD in Environmental Engineering

Analyses using the SD method are also very common in environmental engineering, particularly regarding land reclamation, greenhouse gas assessment, water and waste management. The method was used in assessing the environmental impacts of a government investment which was for one of the most important development projects in the history of Turkey- the South Eastern Anatolian Project (GAP) - in terms of water resources, land degradation, agricultural pollution and demography (Saysel *et al.* 2002). In Taiwan, erosion, sediment yield, nutrient pollution and economic factors of one of the most important rivers-Keelung River- were analysed through the SD approach (Shin-Cheng *et al.* 2006). In New Zealand, the interactions of the principal influences on spring behaviour of rainfall, groundwater, geothermal steam and barometric pressure were identified via SD (Leaver and Unsworth 2007). In Bulgaria, a conceptual system dynamics model was developed to be used for complex water systems when formal analytical models do not exist (Vamvakeridou-Lyroudia *et al.* 2007). There are also a number of generic studies in water management which are flexible and adoptable to lake ecosystems or coastal environments (Vezjak *et al.* 1998; Sahin and Mohamed 2010).

The SD methodology has been used in the waste management field in order to provide a decision support tool to achieve better waste management. Recently there have been a number of studies in waste management using the SD methodology. Karavezyris *et al.* (2002) studied municipal waste to estimate the future quantities through fuzzy logic in conjunction with SD. Inghels and Dullaert (2011) examined how gross domestic product, population and selective collection behaviour have influenced household waste production and collection over time. In the USA, Dyson and Chang (2005) presented a model for the prediction of municipal waste generation in a fast growing urban area, San Antonio, Texas. Likewise Kollikkathara *et al.* (2010) studied municipal waste management in Newark, US and showed that the existing permitted landfill space would be filled by 2012.

Estimating atmospheric emissions from relevant sources is also a growing area of application. For example, Szarka *et al.* (2008) used SD in conjunction with RegAir modelling technique and looked at emissions due to transport, energy consumptions etc. within the system boundary for the EuRegion Austrian-Hungary cross-border area. On the other side, Anand *et al.* (2006) presented a model based on dynamic interactions to estimate CO_2 emissions from the cement industry in India.

Furthermore recycling and recovering activities were covered by researchers. While Georgiadis and Besiou (2008) examined the impact of ecological motivation and technological innovations of recycling activities in Greece, Bala and Sufian (2006) presented an SD model to predict electricity generation from solid wastes in Bangladesh.

2.2.4 Healthcare Waste Modelling

In the literature, in order to estimate the quantity of waste, traditional methods which are based on statistical forecasting analysis have broadly been applied. For example, a curve extension method based on the trend extension in order to verify the inherent systematic features is recognised as related to the observed database. In addition Mohee *et al.* (2005) provided a simple empirical relation ($y=0.0006x-0.19$, where y is the amount of hazardous wastes produced per day per bed and x is the number of occupied beds) to estimate the amount of hazardous waste produced at hospitals with more than 395 occupied beds. Bdour *et al.* (2007) developed models by using a statistical analysis system (SAS) which is capable of handling regular and simple nonlinear and stepwise regression analysis to estimate the quantity of waste produced at different departments in hospitals with more than 100 beds.

As the dynamic properties in the process of healthcare waste generation cannot be fully characterised in those formulations (Dyson and Chang 2005), the application of SD has recently been introduced to the healthcare waste management field by two studies; (1) the research conducted by Chaerul et al. (2008) which analyses the effect of NIMBY (Not In My Back Yard) Syndrome on the healthcare waste generation; and (2) the research carried out by Ciplak and Barton (2012) (Appendix 6).

2.2.5 Summary

Estimating waste generation is a complicated task including many sophisticated interactions with the system components which affect the generation and also change dynamically over time. The SD method helps to conceptualise and rationally analyse the structure, interactions and behaviour of complex systems to explore, assess, and prognosticate their impacts in an integrated, holistic manner (Kollikkathara *et al.* 2010). SD facilitates a more sophisticated, quantitative simulation than simple spreadsheet programs, and is capable of more robust and reliable outcomes (Wolstenholme 2005). It is also flexible enough to accept any adjustment which might be required under different conditions (Jian Li *et al.* 2008). It allows these adjustments to be implemented by fine-tuning the parameters. For all these reasons, in this study, system dynamics was considered to be an appropriate tool to test out the assumptions along with their impact on results in Istanbul healthcare waste management model (details can be found in Chapter 4).

2.3 Decision Making Methods in Waste Management

Decision analysis involves the decomposition of a decision problem into a set of problems. After each smaller problem has been dealt with separately, decision analysis provides a formal mechanism for integrating the results so that the course of action can be provisionally selected. This has been referred to the "divide and conquer orientation" of decision analysis...

-Goodwin and Wright (2004)

It is known that over the years the role of decision analysis has changed and it is no longer seen as a method for producing solutions to decision problems. This perception is supported by Keeney (1982) *"Decision analysis will not solve a decision problem, nor is it intended to; its purpose is to produce insight and promote creativity to help decision makers to make better decisions."*

In decision making process, many factors affect the ultimate decision as a result of an interaction between these factors, as shown in Figure 2.1. The decision makers act within a decision context that can affect them and can be affected by them.

In a complex world, decision analysis has a major role to play in helping decision makers to gain an understanding of the problems they face (Goodwin and Wright 2004). The analysis of the way people make decisions (prescriptive theories) or the way people ought to make decisions (normative theories) is as old as the recorded history of mankind according to Triantaphyllou (2000), although not all of these analyses were scientific approaches as those in literature today.

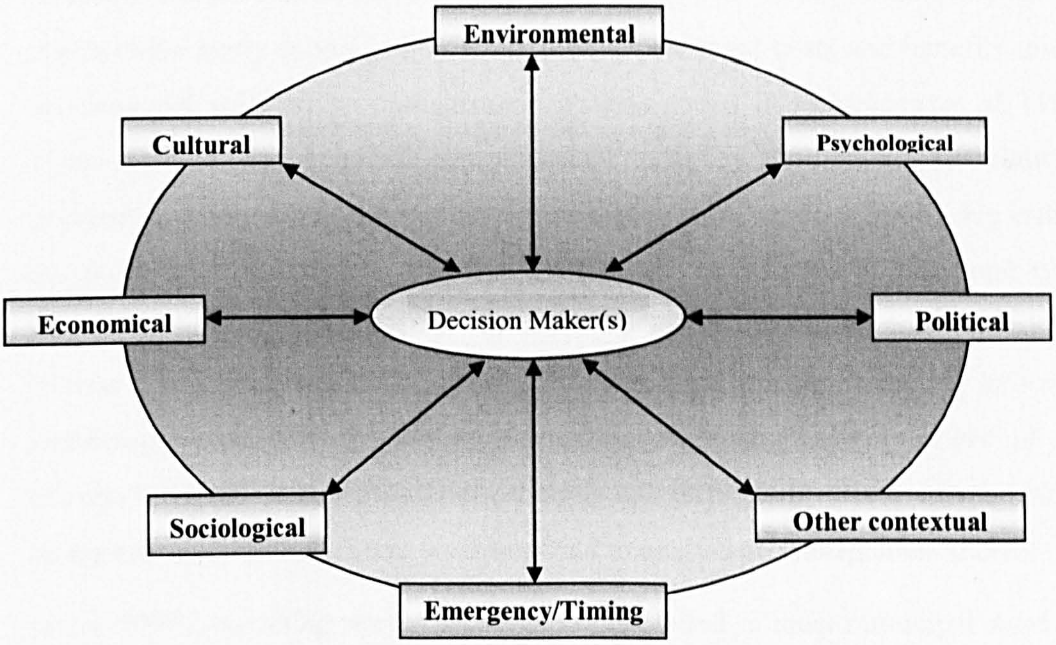

Figure 2.1: Some Factors Inherent in the Decision Making Process
Adapted from Guitouni and Martel (1998)

A Brief History of the Development of Waste Management Models

Modelling of waste management started to be a focus of many researchers in the 1960s, when there was an increased attention to efficiency and effectiveness of waste management operations. MacDonald (1996a), Gottinger (1988) and Tanskanen (2000) gave a comprehensive summary of these early waste management models along with their characteristics and a discussion regarding their details. Their review showed that the models developed during the 1960s and 1970s focused on specific elements of waste management, for instance transporting wastes from transfer stations was a focus of the study conducted by Truitt *et al.* (1969). However, Sudhir *et al.* (1996) stated that this shortcoming of early models make them unsuitable for long-term planning.

In 1980s, the models had a broader scope with a focus of minimising the costs, for example the study conducted by Kaila (1987) presented costs and benefits involved in municipal solid waste management systems (cited in Hokkanen *et al.* (1995)). These models also included computational tools by looking at the relationship between components in the system according to MacDonald (1996b). He criticised the models released in the 80s for utilising the capabilities of only one type of software; and expanded on this; "*in order for the models to be most useful to city planners, who must take a holistic view of a situation, the application of information technology must address the multi-attribute and geographical nature of waste systems*". Up to the 1990s, the concepts of sustainable waste management or integrated waste management were not used in any waste management model.

In the 1990s, *recycling* started to be widely included in most municipal solid waste management models including collection and facility options in the context of *cost* and *energy conversion* in a more holistic manner. For example, Baetz and Neebe (1994) developed a mixed integer programming model for the recycling of various by-product materials within the overall waste system; Chang and Wei (1999) evaluated the tradeoffs between the number of recycling drop-off stations by including the distance travelled by collection vehicles which could be solved by generic algorithms in a geographical information system platform. Furthermore the model developed by Modak and Everett (1996) aimed to determine the volume of waste landfilled, energy content of incinerated wastes and the amount of ash generated at incinerators to provide lowest possible long-term costs for a regional integrated solid waste management system.

Most of the waste management decision support models identified in the literature could be categorised into three groups as stated by Morrissey and Browne (2004): (1) those based on Multi Criteria Decision Analysis, (2) those based on Lifecycle Assessment, and (3) those based on Cost Benefit Analysis. A description of these methods along with a discussion regarding their limitations and benefits is covered in following sections.

2.3.1 Models Based on Multi Criteria Decision Analysis (MCDA)

The introduction of the term *multiple criteria decision making* into management science was made at the University of South Carolina in 1972 with First International Conference on Multiple Criteria Decision Making. In Europe there was a tendency to use "decision analysis", instead of "decision making" to emphasise the difference between the decision maker and the management scientist (Costa *et al.* 1997).

Over the past three decades, MCDA has developed as a major discipline. The principle of the MCDA approach is to take *several individual* and often *conflicting criteria* into account in a multidimensional way. It is a form of integrated sustainability evaluation (Wang *et al.* 2009). Morrissey and Browne (2004) stated that any viable solution has to reflect a compromise between the various objectives, while the discrepancies between the outcomes are traded off against each other by means of preference weights. Each alternative (solution option or scenario) is judged in relation to multiple objectives, so that the desired scenario is the one that performs comparatively well according to the preset scenarios. Mendoza and Martins (2006) defined three dimensions of MCDA, namely: (1) the formal approach, (2) the presence of multiple criteria, and (3) the decisions are made either by individuals or groups of individuals.

Compared to ad hoc decision making, the benefit of using MCDA methods is to employ multi-criteria or attributes to obtain integrated decision making results. This comparison for each step of the decision analysis is summarised in Table 2.3.

Environmental decision making includes multiple interests and multiple actors with long term implications on local or global scale. It requires a trade-off between competing interests and values and is an inherent management conflict characterised by ecological, economic and socio-political value judgements of different stakeholders (Munda *et al.* 1995).

Table 2.3: Comparison of Ad Hoc Decision Making and MCDA

Adapted from (Linkov *et al.* 2006)

Elements of Decision Process	Ad Hoc Decision Making	Multi Criteria Decision Making
Define Problems	Stakeholder input is limited or nonexistent. Therefore, stakeholder concerns may not be addressed by alternatives.	Stakeholder input is incorporated at beginning of problem formulation stage. It often provides higher stakeholder agreement on problem definition. Thus, proposed solutions have a better chance at satisfying all stakeholders.
Generate Alternatives	Alternatives are chosen by decision maker, usually from pre-existing choices with some expert input.	Alternatives are generated through involvement of all stakeholders, including experts. Involvement of all stakeholders increases likelihood of novel alternative generation.
Formulate Criteria by Which to Judge Alternatives	Criteria by which to judge alternatives are often not explicitly considered and defined.	Criteria and sub-criteria hierarchies are developed based on expert and stakeholder judgment.
Gather Value Judgements on Relative Importance of Criteria	Non-quantitative criteria valuation is weighted by decision maker.	Quantitative criteria weights are obtained from decision makers and stakeholders.
Rank/Select Final Alternatives	Alternative is often chosen based on implicit weights in an opaque manner.	Alternative is chosen by systematic, well-defined algorithms using criteria scores and weights.

Dooley *et al.* (2009) considered MCDA as a useful method in environmental decision making to help trade-off the economic, environmental, and social aspects that need to be considered in making strategic decisions. The methodological framework of MCDA is well suited to the complex nature of environmental decision making; more specifically waste management decision analysis in terms of;

(1) It can deal with mixed sets of data, quantitative and qualitative. This aspect is a distinct advantage especially for developing countries where the data are scarce or include uncertainty (Mendoza and Prabhu 2003; Morrissey and Browne 2004; Garfi *et al.* 2009; Wang *et al.* 2009).

(2) It is conveniently structured to enable a collaborative planning and decision making environment. This allows the direct involvement of multiple experts, interest groups and stakeholders. It is transparent to participants and it provides a focus for working through the decision problem by breaking it down (Mendoza and Prabhu 2003; Goodwin and Wright 2004; Garfi *et al.* 2009).

(3) The main benefit is that MCDA provides a better understanding of the decision to be made by accommodating stimulation of discussion and sharing of others' ideas in a structured way. This benefit is particularly significant for group decisions (Bell *et al.* 2003; Vego *et al.* 2008; Dooley *et al.* 2009).

MCDA is one of the disciplines that have found a fertile ground in environmental applications (Beinat 2001). There is considerable literature on various MCDA techniques in waste management. Some of which are given in Table 2.4.

The waste management studies applying MCDA, in the literature, generally focus on the selection of facility locations (Erkut *et al.* 2008; Ersoy and Bulut 2009; Ulukan and Kop 2009; Achillas *et al.* 2010; Banias *et al.* 2010), evaluation of treatment facilities (Dursun *et al.* 2011; Rostirolla and Romano 2011) and development of the strategy (Su *et al.* 2007; El Hanandeh and El-Zein 2010; Su *et al.* 2010). The common ground of all these studies is their attempt to provide sustainability for the waste management system under consideration; and one of the requirements of this is the identification of the set of evaluation criteria.

The criteria identified in the waste management literature mainly focus on these four aspects: technical, economic, environmental and social as provided in Table 2.5.

Table 2.4: Studies in the Waste Management Literature Applying MCDA Techniques

Developed by the Author

MCDA Techniques	**Applications**
Single Synthesising Criterion	
AHP (Analytic Hierarchy Process)	Garfi *et al.* (2009), Karagiannidis (2010) and Brent *et al.* (2007)
Fuzzy	Dursun *et al.* (2011) and Xi *et al.* (2010)
TOPSIS (Technique for Order by Similarity to Ideal Solution)	Jun-Pin *et al.* (2010)
Outranking Methods	
ELECTRE (Elimination and Choice Expressing Reality)	Perkoulidis *et al.* (2010), Banias *et al.* (2010), El Hanandeh and El-Zein (2010), Karagiannidis and Perkoulidis (2009), Achillas *et al.* (2010)
Mixed MCDA Methods	
fuzzy TOPSIS and AHP	Ekmekcioglu *et al.* (2010), Onut and Soner (2008) and Gumus (2009)
TOPSIS and ELECTRE	Cheng *et al.* (2003)
EV (Evamix), WS (Weighted Summation), Electre and REG (Regime)	Coronado *et al.* (2011)
PROMETHEE (Preference Ranking Organisation Method for Enrichment Evaluation) and GAIA (Geometrical Analysis for Interactive Aid)	Vego *et al.* (2008)
Other Mixed Methods	
NSGA (non-dominated sorting generic algorithm) and TOPSIS	Cao and Zhang (2011b)
MCDA and GIS (Geographical Information Systems)	Sharifi *et al.* (2009) and Sumathi *et al.* (2008)
AHP and GIS	Siddiqui *et al.* (1996), Charnpratheep *et al.* (1997) and Ersoy and Bulut (2009)

Table 2.5: The Evaluation Criteria of Waste Management Systems

Developed by the Author

Aspects	**Literature**	**Total Number**
Economic	Rushbrook and Finnecy 1988; Hung *et al.* 2007; Gumus 2009; Tseng 2009; Ekmekcioglu *et al.* 2010; El Hanandeh and El-Zein 2010; Karagiannidis *et al.* 2010; Perkoulidis *et al.* 2010; Su *et al.* 2010; Tuzkaya *et al.* 2010; Dursun *et al.* 2011; Generowicz *et al.* 2011; Rostirolla and Romano 2011	13
Environmental	Rushbrook and Finnecy 1988; Hung *et al.* 2007; Ramjeawon and Beerachee 2008; Gumus 2009; Tseng 2009; El Hanandeh and El-Zein 2010; Karagiannidis *et al.* 2010; Perkoulidis *et al.* 2010; Su *et al.* 2010; Dursun *et al.* 2011; Rostirolla and Romano 2011	10
Technical	Rushbrook and Finnecy 1988; Hung *et al.* 2007; Ramjeawon and Beerachee 2008; Tseng 2009; Tuzkaya *et al.* 2010; Dursun *et al.* 2011; Generowicz *et al.* 2011	7
Social (Public Acceptance)	Rushbrook and Finnecy 1988; Joos *et al.* 1999; Hung *et al.* 2007; Tseng 2009; Karagiannidis *et al.* 2010; Su *et al.* 2010; Dursun *et al.* 2011	7

2.3.2 Models Based on Cost-Benefit Analysis

This method enables decision-makers to examine the performance of a set of scenarios by converting all factors into a common measurement, usually monetary. This means the estimation of monetary values for environmental changes, for example how much individuals are willing to pay for an environmental improvement due to pollution caused by incineration. However results and interpretations of the ecologic/environmental studies in the literature point out two important limitations; (1) measuring the compensation for deterioration of the environment in monetary terms is not a sustainable approach in waste management (Morrissey and Browne

2004); and (2) attributing a monetary value to, for example social factors, might not be appropriate or ideal all the time (Simpson and Walker 1987).

In practice, the decision problem is further complicated by several uncertainties and there are always some objectives which cannot simply be traded off against each other by means of monetary units according to Loken (2007). Using a single dimensional objective method for this type of problem would probably lead to deadlock as it imposes conditions too rigid to reach a compromise between stakeholders (Haastrup *et al.* 1998). Nijkamp and Delft (1977) supported the opinions against this method by stating "*When making decisions, decision makers always try to choose the optimal solution. Unfortunately, a true optimal solution only exists if you are considering a single criterion. In most real decision situations, basing on decision solely on one criterion is insufficient.*"

It is known that environmental decisions usually involve conflicting objectives and various types of information and several individuals. Therefore environmental decision making using a multi-dimensional way leads to more rational decision-making than the optimisation of a single dimensional function (Vego *et al.* 2008). For this reason, Weng and Fujiwara (2011) argued that cost-benefit analysis is not a suitable method for this kind of process unless it is coupled with a workable integrated framework.

2.3.3 Models based on Life Cycle Assessment

A life cycle assessment (LCA) is a quantitative methodology consisting of the compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle -"cradle to grave" (ISO 14044 2006). In the definition of LCA, the term 'product' not only refers to analysing material products, but also includes service systems such as waste management. It allows decision makers to analyse the direct impacts (such as emissions to air, water or soil) and indirect outcomes (such as consumption of resources or the emissions generated to make available the energy or the infrastructure needed by the production process) of these systems. The technique of LCA consists of four phases each of which is subject to International Standards (ISO 14044 2006): (1) definition of the goal and scope (definition), (2) compiling an inventory of relevant inputs and outputs of a system (inventory analysis), (3) evaluating the potential impacts of those inputs and outputs (impact assessment), (4) interpreting the results (interpretation) in relation to the objectives of the study.

Environmental LCAs developed rapidly during the 1990s and had reached a certain level of harmonisation and standardisation (Finnveden 1999). They have been commonly undertaken in the governmental, non-governmental, industrial and consulting sectors in the waste management field. LCA applications in the literature are generally in one of two groups in terms of their scope; the first (A) are those which have a particular focus on one of the waste management system elements (such as the selection of an appropriate recycling scheme or deciding on which ash treatment system would be appropriate for the incineration in place); and secondly (B) the ones considering different waste management strategies ranging from local planning to strategic decision making at national and international levels. They aim to determine the optimal scenario from an environmental point of view by making a comparison of several alternatives. The examples of these two groups along with their details are provided in Table 2.6.

The benefits and limitations of the technique have been identified by various researchers in the LCA literature. McDougall *et al.* (2001) emphasised that LCA takes a holistic approach as it provides a system map and attempts to address a broad range of environmental issues. Cherubini *et al.* (2009) stated that a broader perspective of the LCA allowed users to take into account significant environmental benefits that could be obtained through different waste management processes, for instance, waste incineration with energy recovery reduced the need for other energy sources. Likewise Ekvall *et al.* (2007) emphasised that LCA helps to expand the perspective beyond the waste management system as it covers not only direct impacts but also indirect impacts of the system. They found this important since the indirect environmental impacts caused by surrounding systems, such as energy production, often override the direct impact of the waste management system itself.

Table 2.6: Group A and B Applications in the Literature

Developed by the Author

A		
Focus	**Study Area**	**Reference**
Waste Treatment Facilities	Pudong-Shangai, China	Hong *et al.* (2006)
	Indonesia	Aye and Widjaya (2006)
Incineration Ash Treatment Systems	Sao Paulo City, Brazil	Mendes *et al.* (2004)
Waste to Energy Plants	Hypothetical Italian Cities with population of 200,000-1.2 million	Consonni *et al.* (2005)
Waste Collection Methods	Rural communities in two districts in the province of Salzburg, Austria	Beigl and Salhofer (2004)

B	
Study Area	**Reference**
Hangzhou City, China	Yan *et al.* (2009)
Umbria Region, Italy	Di Maria and Fantozzi (2004)
Ankara City, Turkey	Ozeler *et al.* (2006)
Sweden	Finnveden *et al.* (2005)
Bologna District, Italy	Buttol *et al.* (2007)

Recently there have been a number of LCA software tools developed by researchers. The initial aim of developing LCA computer models was defined by Winkler and Bilitewski (2007) as making sure that the results of LCAs which are conducted by different researchers are within an acceptable range and not leading to different or even contradictory conclusions. These models, some of which are shown below, have recently extended beyond the scientific world to a widespread practical application.

- EPIC/CSR (Integrated Waste Management Model / Canada) (Early *et al.* 2009)
- DST (Decision Support Tool / United States EPA) (Thorneloe *et al.* 2007)
- IWM2 (Life Cycle Inventory Model for Integrated Waste Management / UK) (Biswas *et al.* 2012)

- WRATE (Waste and Resources Assessment Tool for the Environment/ UK Environment Agency) (Tunesi 2011)
- ORWARE (Organic Waste Research Model / Sweden) (Eriksson *et al.* 2002)
- EASEWASTE (Environment Assessment of Solid Waste System and Technologies / Denmark) (Bhander *et al.* 2010)

Some of these tools, for example IWM-2 and WRATE, are based on integrated waste management aiming to deliver both environmental and economic sustainability. In order for the LCA technique to be improved further the scope and the level of detail needed at the life cycle inventory stage should always be reviewed in the light of the practical results obtained according to Barton *et al.* (1996). Winkler and Bilitewski (2007) believed that this improvement can only be achieved by sharing more of the data and modelling methodology.

LCA has also been used in conjunction with other environmental information and assessment tools. Harrison *et al.* (2001) and Craighill and Powell (1996) extended lifecycle assessment methodology to incorporate an economic evaluation of the environmental impacts in their studies. Additionally Reich (2005) conducted an economic analysis (namely life cycle costing –LCC-) including the same system boundaries as his LCA. However he reported some theoretical discrepancies which stemmed from different perspectives in dealing with the timing of effects.

Regarding the LCA method there are some issues needed to be considered by strategic decision makers. Firstly LCA does not predict actual impacts or assess risks, or whether thresholds are exceeded (McDougall *et al.* 2001). The actual environmental effects of emissions and wastes will depend on when, where and how they are released into the environment (McDougall *et al.* 2001). Secondly, LCA, itself does not typically address the economic or social aspects within the system. However these aspects are essential in sustainable waste management decision making which has a combinatorial nature with multiple objectives. LCA requires risk assessment or environmental impact assessment or both, to address these issues according to Morrissey and Browne (2004).

Petts (2000) mentioned that LCA has traditionally not been subject to public involvement, being a specific and highly technocratic environmental loading accounting tool. She further commented that at the current stage of development of LCA is incapable of dealing with health effect predictions; it can only have partial relevance to public deliberation. For all these reasons, it is highlighted in the literature that (1) decision making on the basis of LCA results should be made by open public debate as part of the democratic process (McDougall *et al.* 2001); and (2) LCA should only be used for identifying opportunities for improvement and not used as the sole basis for a final decision on a waste strategy (Emery *et al.* 2007).

In conclusion, while LCA can be a powerful tool for estimating cradle to grave environmental impacts, these outputs still need to be weighted against socio-economic factors. Thus LCA is one of the best pre-assessment tools to generate inputs for decision tools such as MCDA.

2.3.4 Summary

Three main categories of decision making models have been identified with their benefits and limitations: multi criteria decision models, cost-benefit analysis models and life cycle analysis models. Since the models are the representatives of the real world with respect to the scope of the study, none of them could encompass all the aspects of waste management cycle. At this point, for decisions to be effective it is necessary to set a balance between the environmental sustainability, economically viability, technically soundness and the social acceptability of the system.

Waste management decision making in developing countries has moved towards being more pragmatic, transparent, sustainable and comprehensive. On the other side it has been recognised that a fully quantitative approach in decision making is difficult to apply in the context of developing countries due to lack of information and variety of data. Likewise, the comprehensiveness of the method to be adopted is also restricted by the nature of local specific environmental and social issues.

Recently MCDA has become a more widely used technique in decision making. A broad range of decision analysts emphasised that the most important advantage of MCDA over other methods is its capability of dealing with social criteria which is a necessity for sustainability. Petts (2000) encouraged MCDA techniques to be used by concluding that "*Such approaches incorporating multi criteria analysis are more consistent with the objectives of resolving problems as they force values and problem framing to be made transparent*". Therefore the MCDA technique was employed in this study to improve Istanbul healthcare waste management decision making mechanism to make it environmentally, economically and technically sound, and socially viable.

CHAPTER 3: MATERIALS AND METHODOLOGY

In this chapter, the *multi-criteria approach* is discussed along with the scenarios which were built up to be assessed against multiple criteria. Each of these criteria was identified in a decision tree and then ranked by the stakeholders via a questionnaire. In order to measure the relative importance of these criteria, a system boundary was drawn and relative importance of each of the criteria was measured within this boundary.

To quantify the criteria in the decision tree required data and information. These data were generated by using the technique, called *system dynamics.* The system dynamics modelling technique was basically implemented to;

(1) Assess the amount of healthcare waste from healthcare facilities (HCFs) and to test out which factors this generation is sensitive to. The results of this model (HCW SD model) were used in determination of the required capacities of technologies while setting the scenarios.

(2) Estimate the number of employees whose health could be adversely affected by emissions from waste treatment plants. The results of this model (Employees' Health SD Model) were used to measure the criteria of safety of different scenarios in MCDA.

3.1 System Dynamics Modelling

"All decisions are based on models, usually mental models. In system dynamics, the term mental model includes our beliefs about the networks of causes and effects that describe how a system operates, along with the boundary of the model and the time horizon we consider relevant our framing or articulation of a problem."

-Forrester, (1961)

As people have limited capacity in predicting how complex, interdependent systems will behave, computer tools have been developed to improve the quality of thinking and decision making. System dynamics (SD) models help to enhance understanding of the problem through analysing its elements interacting with each other. A significant aspect is that they are helpful in terms of integrating partial models of the problem in order to reveal the dynamics of its holistic behaviour (Shi and Gill 2005).

3.1.1 System Dynamics Modelling Software

In general, system dynamics models rely on the use of the software such as Stella, Dynamo, Vensim, i-Think and Powersim. Some of them are specialised for particular applications such as for business (e.g. Powersim). Vensim is one of the visual softwares, which provides user-friendly iconographic interface to facilitate building of dynamic systems and has elements that are created to simulate the dynamic systems. Once the model is built, it can be used to simulate the effect of proposed actions on the problem and the system as a whole.

In the project, both of the models were built by using a graphical programming language, called Vensim. System dynamics software like Vensim provides a tool to assist the problem solving mechanism by;

(1) Building a shared mental model of systems;

(2) Keeping track of complex interrelationships and feedback loops among variables;

(3) Allowing decision makers to employ what-if questions.

3.1.2 Reasons for Using System Dynamics

The purpose is improved understanding, NOT point prediction;

The system dynamics (SD) models, regardless of where they are used, are designed for general understanding, not point prediction (Ford 1999). As distinct from the SD models, there are "predictive models" which are constructed for a single task to provide the best possible forecast of future state of the system, for example, a weather forecast model developed by Sathye *et al.* (1997).

There are three justified reasons for choosing the SD methodology in this project;

1) Dealing with Data Shortcoming

It is now well-established that both the availability and quality of input data is limited in waste management. This is an important challenge in producing waste projections and to build reliance on them. One of the crucial advantages of SD over a deterministic approach is its capability of enabling assumptions to be made and testing the impact of these assumptions on the results where data are scarce. In this way SD enables users to identify which sort of data is essential *in the first place* to bridge the data gap as pointed out in the waste management literature.

2) Dealing with Complexity

SD, as a method, is particularly suited to analysing *complex systems* such as waste management (Sahin 1980; Chaerul *et al.* 2008). Traditional methods used to estimate waste generation generally rely on demographic factors on a per-capita basis. However the estimation of waste arisings by providing insight on model behaviours is a complex task and requires a broader perspective using an appropriate technique.

The first SD model (HCW SD Model) developed in this project incorporated the complexity of the process to some extent which was achieved through a combination of simpler sub-processes (inpatient episode, outpatient episode, bed inventory, etc) that are linked together to form a whole.

3) Capability of analysing the interaction of sub-processes

The sub-processes were individual dynamic models exhibiting specific system behaviours such as exponential growth or decline, S-shaped growth, overshoot or collapse, and oscillation (Saysel *et al.* 2002). The SD models were aimed at helping in understanding why these patterns occur by particularly monitoring the effects of changes in sub-processes and their relationships (Shi and Gill 2005). In this regard, dynamic models differ from the static models, which examine systems at rest. Dynamic models help thinking regarding how a system changes over time and understanding why some systems oscillate.

3.1.3 Structure of the System Dynamics Model

We shape our buildings; thereafter our buildings shape us.

-W. Churchill (cited by Sterman 2000)

The structure of the SD model is presented by *causal loop (influence) diagrams* which inherit the major feedback mechanisms (Figure 3.1). Causal loop diagrams are important as (1) they can simply give an overview of a model; and (2) they represent preliminary sketches of causal hypotheses during model development.

3.1.3.1 Causal Loop Notation

The word *causal* refers to *cause-and-effect* relationship. The word *loop* refers to a closed chain of *cause and effect*. The words represent the *variables (parameters or elements)* in the system; and the *arrows* represent *causal connections*.

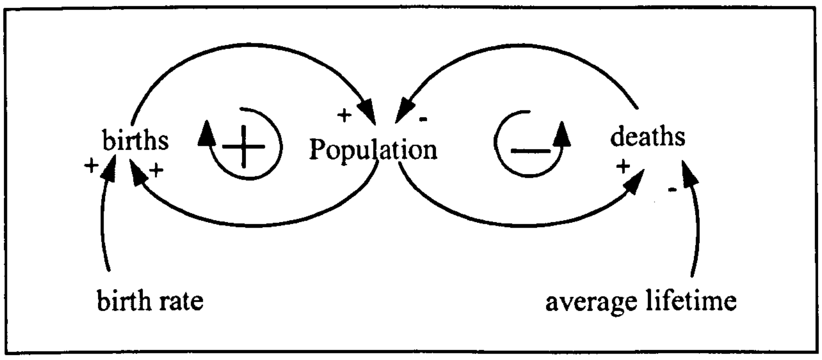

Figure 3.1: Causal Loop Diagram Notation portrayed with Vensim

Adopted from (Sterman 2000)

Figure 3.1 shows the population stock example, which is fed by the flow of births and drained by the flow of deaths. The diagram includes arrows linking the elements together and signing either (+) or (-) on each link. These signs have the following meanings:

1. A causal link from one element to the other element has positive polarity (+); if the two variables in a cause-and-effect relationship change in the same direction. For example in Figure 3.1, the positive polarity on the arrow from *population* to *births* could mean that *a larger population* will tend to have *a greater number of deaths.* It could also mean that *a decrease in population* causes *decrease in births*.

2. A causal link from one element to another element has negative polarity (-); if two variables change in opposite directions. In Figure 3.1 the negative polarity on the arrow between *deaths* and *population* could mean that *an increase in deaths* causes *a decrease in population* or that *a decrease in deaths* causes *an increase in population.*

In addition to the signs on each link, a complete loop is given a sign. All dynamics arise from the interaction of just two types of feedback loops, positive (or self-reinforcing) and negative (or self-correcting) loops. The direction of sign of a feedback loop is determined according to the direction of arrows which link the parameters within the feedback loop. Specifically:

1. Positive loops tend to reinforce or amplify whatever is happening in the system. In positive feedback loops an initial disturbance leads to further change, suggesting the presence of an unstable equilibrium (for example, population and births feedback loop in Figure 3.1)

2. Negative loops counteract and oppose the change. These loops describe processes that tend to be self-limiting, processes that seek balance and equilibrium. They exhibit a goal-seeking behaviour. After a disturbance, the system seeks to return to an equilibrium situation (for instance, population and deaths feedback loop in Figure 3.1)

3.1.3.2 Dynamics of Stocks and Flows

"Much of the art system dynamics modelling is discovering and representing the feedback processes, which, along with stock and flow structures, time delays, and nonlinearities, determine the dynamics of a system. You might imagine that there is an immense range of different feedback processes and other structures to be mastered before one can understand the dynamics of complex systems. In fact, the most complex behaviours usually arise from the interactions (feedbacks) among the components of the system, not from the complexity of the components themselves."

-Sterman (2000)

The SD models are constructed by building variables categorised as stocks, flows, auxiliary variables, and connectors (shown in Figure 3.2).

(1) Stock variables (symbolised by a rectangle) are the state variables and they represent the major accumulations in the system;

(2) Flow variables (valves) are the rate of the change in stock variables and they represent those activities that fill in or drain the stocks,

(3) Auxiliary/constant variables are intermediate variables used for miscellaneous calculations.

(4) Finally the connectors (arrows) are the information links representing the cause and effects within the model structure.

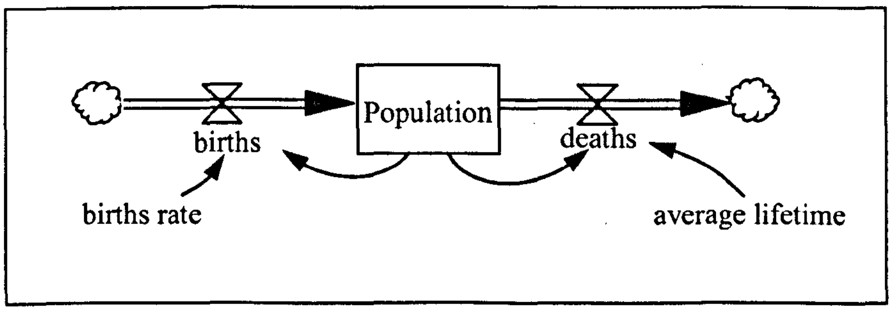

Figure 3.2: Stock and Flow Diagram. Adopted from (Ford 1999)

Mathematical Representation

Integral Equation: Population (t) = $\int_{t_0}^{t}$ [births (s) – deaths (s)] d_s + Population (t_o)

Eq.3.1: Integral Equation

Differential Equation: d(Population)/dt = Net Change in Population = births(t) – deaths(t)

Eq.3.2: Differential Equation

Notation Used in the Model: Population = INTEGRAL(births - deaths, Population $_{to}$)

Eq.3.3: Notation of SD Model

The Integral () function is exactly equivalent to Eq 3.1 and represents the concept that the stock (population) accumulates its inflows (births) and drains its outflows (deaths), beginning with an initial value of stock (population). The mathematical mapping of a system occurs via a system of differential equations, which are solved numerically via simulation.

3.1.4 Development of HCW SD Model

Parameter selection and model form have been based on the authors' observations in Istanbul and a review of the literature regarding the factors affecting origin, definition, composition and weight flows of healthcare waste. The detailed breakdown of parameters in the sub-models also reflects the availability of data for Istanbul (published and additionally gathered by the author via information petition). For example, three age ranges of population were selected on the basis of clear differences in incidence rate in Turkey (Chapter 4, Section 4.1.1.1 Population Sub-System).

The HCW SD model was designed to obtain insights into the long-term interactions and dynamics of elements that play a role in healthcare waste generation in Istanbul. The purpose of this model is to identify critical variables for their impact on waste generation. In order to set up a proper hospital waste management system, many factors including regulations, welfare of residents, social aspects, etc. need to be in interaction and the relationships between them have to be determined.

Hospitals, as a main source of healthcare wastes, undertake various activities in a range of different departments such as cardiology, gastroenterology, maternity, microbiology, neurology, orthopaedics, pharmacy, physiotherapy, radiotherapy, etc. In these departments, waste generation could either be based on the number of beds or the number of patients depending on the characteristics of treatment. To better estimate the dynamics of this waste generation, in this model, it was assumed that while the waste generation from small healthcare institutions is dependent on their numbers; at general hospitals, it is based on the type of treatment; acute care or chronic care (Tudor 2007; Diaz *et al.* 2008). In this project "Category-1"is defined as chronic care treatment at hospitals which represents the type of the treatment that requires patients to stay at hospital over an extended period of time and so the waste generation is based on per bed; "Category-2" is for acute care in which a disease is treated for a short period of time and "out-patient" is for treatment only and assumes no overnight stay, so the waste generation for the latter is based only on patient numbers. While Category-1 and 2 represent the waste generation patterns based on treatment types at hospitals, Category-3 stands for the healthcare waste generation from small healthcare institutions.

The system being modelled also includes the relationship between supply and demand. The supply side of the system comprises healthcare facilities, basically general hospitals. Development of these healthcare facilities is directed by healthcare targets. Investments in healthcare are made by government in order to meet these targets. Demand side focuses on the number of patients and their needs. Demand rises as population goes up. When the number and capacity of healthcare facilities increases, healthcare waste increases. However the demand increases faster than supply, demand eventually equals, and then exceeds supply.

The conceptual model presented in Figure 3.3 simplifies many elements of healthcare waste management but embraces important links. This structure represents the dynamic hypothesis, or preliminary explanation of the structural relationships that lead to changes over time in the system. The aim of Figure 3.3 is to make explicit the multifaceted nature of the problem under review.

Time Period;

The time period for this project was taken as starting in 2015 as it was anticipated that 2015 is the year for the healthcare facilities (HCFs) to initiate further segregation of their HCW as incineration-only HCW and HCW SAT (details can be found in Chapter 4); and it extended to 2040 in order to include expected service lives of proposed technologies in scenarios as required for civil engineering projects. The starting time of the HCW SD Model was set as 2007 in order to carry out historical behaviour test (3.1.6 Building Confidence in the HCW SD Model) to compare statistical data with the results of the simulation for the years 2007 and 2008.

3.1.5 Development of Employees' Health SD Model

The potential for a causal link between waste treatment facilities (landfill and incineration) and certain adverse health outcomes in workers employed in these facilities is a matter of concern. The process encompasses epidemiological studies that examine incidence rates of adverse health outcomes. The employees' health SD model was built up in order to estimate the number of workers whose health might be affected badly due to released emissions from the waste treatment. The results of this model were used to measure the criteria of safety in the decision tree (Chapter 5).

The required data for the model were gathered from both epidemiological studies providing relative risks (RR) and exposure time for a number of diseases (Chapter 2 Literature Review); and Turkish Statistics Databases which provided frequency of each specific disease in the non-exposed population.

The model (details are included in Chapter 4) was kept as simple as possible while capturing all necessary elements for the analysis of the system under study. The emphasis of the model was on structural and functional simplicity. An effort was made to find the minimal model that could represent the dynamic behaviour of health outcomes of the employees who had been working at an incinerator or landfill for a considerable time period.

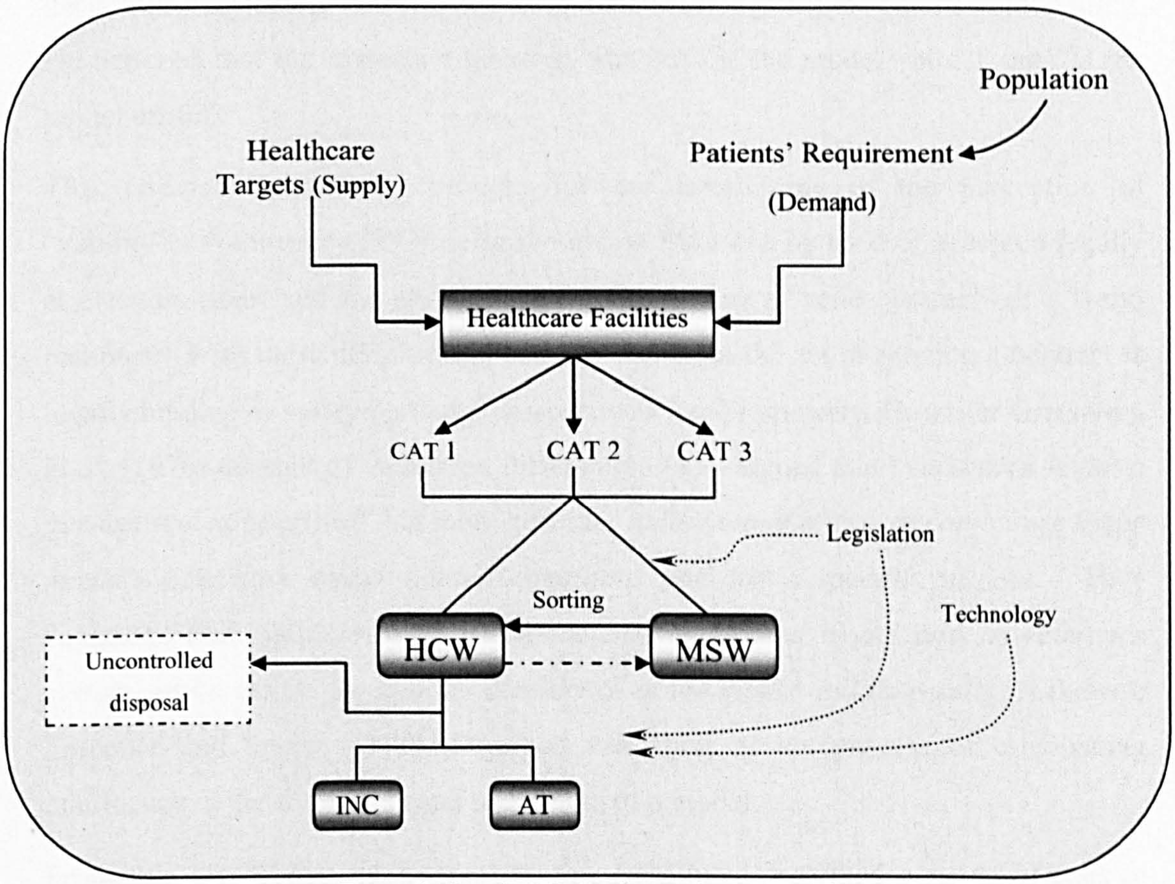

Figure 3.3: System Boundaries (INC: Incineration AT: Alternative Treatment) Developed by the Author

3.1.6 Building Confidence in the HCW SD Model

A model represents a real system only with respect to the specific purpose for which the study is made (Mohapatra *et al.* 1994). Therefore unimportant factors, which are considered as not contributing to the mode of the real system behaviour, are left out. Once a factor is left out, the model is subject to the criticism that it is *invalid*.

Greenberger *et al.* (1976) argued that such criticism was unhelpful by concluding that *"There is no uniform procedure for validation. No model has ever been or ever will be thoroughly validated. Since, by design, models are simplifications of the reference system, they are never entirely valid in the sense of being fully supported by objective truth. Useful, illuminating, convincing or inspiring confidence are more apt descriptors applying to models than valid"*. Ford (1999) supported this view in his book by indicating this criticism as pointless and against the nature of modelling. He believed that the important question was not "Is the model valid?" but "Is the model useful?"

This criticism importantly brought forward questioning of the perception of "validity". Wehmeier (1993) defined valid as "that can be used or accepted legally at a certain time" and she also gave examples such as a "valid contract" or a "valid passport". With these definitions, "validate" refers to the act of proving a contract is legally binding or verifying that a passport was issued properly. However Greenberg *et al.* (1976) thought of validation differently. They argued that "*validation is not a general seal of approval*" but more general *"indication of a level of confidence in the model's behaviour under limited conditions and for a specific purpose"*. They suggested that "*data provide a tangible link between a model and its reference system, and a means for gaining confidence in the model and its results*." Likewise Forrester and Senge (1980) described validation as the process of establishing confidence in the soundness and usefulness of a model.

From this perspective, researchers in this field have described a range of tests to build confidence in their models on the basis of the data utilized (Karavezyris *et al.* 2002; Saysel *et al.* 2002; Shi and Gill 2005; Anand *et al.* 2006; Georgiadis and Besiou 2008). These are specifically; historical behaviour, dimensional consistency, integration-error and extreme-condition tests.

(1) Historical Behaviour

This is one of the most common and important tests, which sets the inputs to the model at their historical values to see if the outputs match history. In order to examine whether the model can replicate the observed behaviour, the *population* and the *total HCW waste generated* variables were selected. The full model worked under historical conditions driven by the statistical data series belonging to 2007 and 2008, as the statistical data are known for these variables in these years. The model results (Chapter 4, Figure 4.9 and Figure 4.10) give agreement with the actual values which were gathered from the Istanbul Metropolitan Municipality Waste Management Department through petitions.

(2) Dimensional Consistency

This was checked out to see whether there is any inconsistency in the units of the parameters (The units of the parameters and details are included in Chapter 4).

(3) Integration error tests:

As an integration type, Euler was used in the model as it is an acceptable integration method in the cases where a variable time step method is used (Sterman 2000). Since the shortest time constant in the model was set to 1 year and standard practice in SD suggests that the integrating time step (DT) should not be more than 1/4 of the shortest time constant in the model, the DT was initially set at 1/4 year and the model was run. Afterwards the DT was cut to 1/16 of a year and the model was run again. This made a change in one fifth of the resultant values. Therefore DT was used as 1/16 year for the rest of the analysis.

(4) Extreme-Condition Test

"Nature reveals herself in extremes."

-Sterman (2000)

One of the most revealing tests is to make a major change in the model parameters and see if the models' response is plausible. Extreme condition testing can be facilitated by the software, in this case by use of the "reality checks" feature in the Vensim software. Each reality check test consists of a test input coupled to an expected behaviour. They take the form, "If test input A is temporarily replaced with a given extreme input, then behaviour B will result".

In the model, for example, "births per mature female per year" was set as decaying over the 5 years between 2017 and 2022, after a considerable time, new values of "Young Population" start to be smaller than they were before. Another example was used: If there is no hospital implementing further segregation, then no HCW for alternative treatment appears, in response to this the amount of incineration-only HCW peaks over the period of time. Thirdly, if the government increases its targets on the number of beds per capita, then there will be enough bed capacity to accommodate all the inpatients, so Category-1 waste generation starts to be patient based rather than bed-based.

The reality check test of Vensim only refers to behaviour; this feature matches the requirement of a validity test as explained by Barlas (1996); "*In behaviour validity tests, emphasis should be on pattern prediction rather than point prediction because of the long-term orientation of the model*". In other words, the emphasis in validity tests is placed on trends rather than on the precision of the simulated outcomes.

Even though the validity tests were important in terms of building trust in the model, it is worth emphasising that it is impossible to correctly predict the behaviour of a chaotic system based on observation of the system's past (Hannon and Ruth 1996). This means that the output of the model should be taken as indicative under specified scenarios only rather than as a definitive statement of real future events.

3.2 Setting of Scenarios

In developing scenarios to test, the main aim was to ensure a range of candidate technologies were represented and the service offered was logistically feasible. Four scenarios were considered;

(a) Test the impact of changing segregation practices on the cost and performance of healthcare waste management in Istanbul,

(b) Generate the input data needed to evaluate the use of MCDA as a potential decision making and support tool.

Whilst the four scenarios developed were considered technically realistic and robust, it is not suggested that these are optimal or fully cover the potential future options available.

A range of alternative treatment processes have been developed over the years for the treatment of healthcare wastes and many of them could be applied for the amounts produced in the Istanbul Metropolitan. The processes and technologies were selected within the scenarios by taking these factors into account;

(1) The technologies were chosen based on whether their operational requirements suited the HCW management system in Turkey in terms of waste definition, categorisation and segregation.

(2) The Turkish private sector was consulted to select the most appropriate technologies for Istanbul in terms of cost and environment.

(3) Technologies being promoted in Europe were also taken into account. It was observed that small scale decentralised technologies had more recognition in many European countries rather than large scale central waste treatment plants.

(4) The technologies proposed within the scenarios were the best available technologies, which are proven internationally. They suit the definition of BAT- *"most effective and advanced stage in the development of an activity and its methods of operation, which indicate the practical suitability of particular techniques for providing, in principle, the basis for emission limit values designated to prevent or eliminate or, where that is not practicable, generally to reduce an emission and its impact on the environment as a whole"* (European Union 1996).

The details of the selected scenarios are explained in detail in Chapter 5.

3.3 Multi Criteria Decision Analysis (MCDA)

The MCDA process quantifies value judgments (and the sensitivity of outcomes to those judgments), scores different project alternatives on the criteria of interest, and facilitates selection of a preferred course of action (Linkov *et al.* 2006). Within the scope of MCDA in this project, four scenarios, each of which involved different combinations of technologies nationally and/or internationally available in markets were developed. The capacities of these technologies were assigned according to the estimated amount of healthcare waste by the HCW SD model. These scenarios were then assessed against multiple criteria in the context of the MCDA.

3.3.1 Decision Making Software

The analysis of the results was made by using a computer tool, Right Choice Software, which was designed for the situations where multiple choices exist and an optimum solution is required. The software is able to process data and translate them into relevant information for the use of decision makers. It allows decision makers to rapidly narrow down the selection of available options to a few appropriate for the type of problem which they are interested in by conducting frontier analysis and sensitivity analysis. The aim of using decision making software (i.e. Right Choice) is to show its potential to be useful to stakeholders in making robust decisions.

The steps which were followed in the context of MCDA in this project are as follows:

(1) The identification of criteria in the decision tree was made through a literature review (Chapter 2) and judged against the completeness, operational soundness, decomposability, absence of redundancy, and minimum size which were proposed by Keeney and Raiffa (1976), cited in Goodwin and Wright (2004). This is explained further in Chapter 5 (Figure 5.5: Healthcare Waste Management Decision Tree in Istanbul).

(2) The scenarios developed were measured on each criterion and scored in a [0-100] range [100% was given for the scenario(s) which performed the best on that criterion and 0% was for the least, others were ranged between the scale] (3.3.1.1: Measurement of Criteria).

(3) Having scored the scenarios on each of the criteria, relative weightings were used to bring the criteria to comparable scales, before they were combined at the next level up the tree. This stage required assessing the relative importance of each criterion (3.3.1.2: Assigning Relative Weights to Criteria).

(4) On completion of the analysis, the scenario with the greatest benefit was assigned as a conditionally preferred scenario.

3.3.1.1 Measurement of Criteria

For each of the scenario, optimum transportation routes were investigated and the most feasible routes from the point of view of efficiency and economy were scheduled. Operating costs and investment costs of the proposed plants were sourced from private companies (Turkey and Europe) and they were estimated in present values (2010), by taking into account interest rates (where applicable) and staffing costs in Turkey (Chapter 5, 5.4.1.1 Treatment Cost).

In order to estimate greenhouse gas (GHG) emissions that are produced by each treatment option, a spreadsheet model was developed in Excel. The model took into account CO_2 equivalents generated by the transportation of wastes, the consumption of fossil fuels and electricity for the treatment of wastes and the direct emissions of GHG emissions from wastes due to combustion and/or disposal operations. Standard methods from the literature (e.g. IPCC) were used to calculate values; and Turkish data sources (e.g. CO_2 emissions from Turkish power industry) were selected where possible (Chapter 5, 5.4.1.2 Global Warming Potential).

The number of employees whose health could be adversely affected due to emissions was used as an indicator in the measurement of safety of treatment options (Chapter 4.2 Employee's Health Model Development).

Most of the data were collected from the private sector based in Turkey and Europe. Chapter 5.4 Measurement of Criteria provides all further details.

One of the concerns regarding the comparison of different processes is the time aspect. Within the scenarios some amount of healthcare waste is treated by alternative treatment methods and then disposed of in landfills whereas some healthcare wastes are incinerated. A significant difference between landfilling and incineration is the time frame over which the comparison is to be made. As emissions from landfills may prevail for a very long time, often thousands of years or more, there are no possibilities for measuring actual landfill emissions- they have to be "predicted" (Camobreco *et al.* 1999; Finnveden 1999). It is therefore necessary to make integration over a certain time period in order to make the potential emissions from landfill comparable to the potential emissions from incineration (Finnveden 1999). This raises a question concerning what time period should be applied. Although this question has no concrete answer, it was suggested by Finnveden *et al.* (1995) that the time frame should be assumed by considering the goal and scope of the LCA to be undertaken. Various time frames have been implemented so far. However these time periods have been subject to criticism due to the short period of time over which the emissions occur, for example heavy metals or leachate. This could cause the overall emissions to be seriously underestimated according to Finnveden *et al.* (1995).

As a response to these concerns Finnveden *et al.* (2005) brought forward the use of "surveyable time period" and "hypothetical-infinite time period". The surveyable time period is defined by them as the time to reach a pseudo-steady state, after which the changes are slower than during the initial phases. It was suggested by them that this period should be approximately a century in order to be able to compare different waste management options. However they warn that it should be re-defined for any specific waste material as the kinetics of landfills are dependent on site-specific characteristics. Hence the assumption of timeframe as a century has a relation to a human life-time and close future generation. This time horizon is now used by many researchers and regulatory agencies (i.e. IPCC).

In addition, they define the hypothetical-infinite time period as the time needed for a complete degradation and emission of the landfill materials. This time period is split into the surveyable time period and the remaining time period in order to facilitate the inventory analysis (Finnveden *et al.* 2005; Moberg *et al.* 2005). This might be a useful method in a case where significant environmental burdens are expected to occur after the surveyable time period.

3.3.1.2 Assigning Relative Weights to Criteria

A weight can be defined as a value assigned to a criterion which indicates its relative importance with respect to other criteria under consideration (Garfì *et al.* 2009). In MCDA, the relative weight of criteria plays an important role (Tiwari *et al.* 1999). In selection of the criteria and assigning relative weightings to them, one of the ideal ways is holding decision making conference with the participation of all identified stakeholders in the field (McCartt and Rohrbaugh 1989). This kind of decision making process provides not only the agreement of most participants but also the resolution of minority objections through group cohesion and interpersonal connection.

Schuman and Rohrbaugh (1991) stated that decision conferences are designed for groups that need to reach consensus about a complex, unstructured problem for which there is no "formula" or objective solution, a need increasingly common in the information society. Obviously, several individuals who are involved in decision making bring together a broader experience, knowledge, skills and insights. Therefore the fundamental objective behind decision conferencing is to provide a synthesis of decision analysis techniques and the positive characteristics and dynamics of small-group decision making (Goodwin and Wright 2004). Shared understandings of a problem and gained sense of common purpose by decision makers bring a commitment to ultimate action.

However, due to the limited budget and time of this project, the decision tree was constructed based on the literature review (Chapter 2); and in order to assign relative weights to the criteria, a structured questionnaire was prepared (Appendix 1) and sent to the stakeholders in Turkey (Chapter 5.5 Assigning Relative Weights to Criteria).

The questions in questionnaire were designed on a cost basis. This means that issues, such as environmental impacts, were estimated in monetary terms by the stakeholder. This sort of measurement enabled a commonly shared and understood quantitative scale on monetary value to be produced in order to judge how well the scenarios performed on each criterion.

In this research, a relative weighting procedure was used by assigning monetary values (through questionnaire-Appendix 1) to the savings which appear by preferring the best scenario (the scenario which performs best on that criterion) to the worst scenario. The steps of this procedure are as follows;

(1st Step) Stakeholder's value, as a nominal unit of each criterion in terms of monetary value, was gathered via the questionnaire, e.g. Stakeholder's value on 1 tonne of CO_2-e is £10. (Represented as f_i)

(2nd Step) An average of stakeholder's value was calculated;

$$1 \text{ tonne of } CO_2\text{-e} = \sum_{i=1}^{n} (f_i + \cdots + f_n)/\text{n}$$

(3rd Step) The performance of the four scenarios on each criterion was measured as explained in 3.3.1.1 Measurement of Criteria;

For example; CO_2-e emissions of the four scenarios (SC1, SC2, SC3 and SC4) were 200 tonnes, 100 tonnes, 400 tonnes and 600 tonnes respectively.

(4rd Step) In order to assign relative weightings to each criterion, the scenario which performed best on this criterion and the scenario which performed worst were chosen. The differences between these performances were converted to monetary values;

For example; Value of 1 tonne of CO_2-e is £10 (average f_i) and;

The difference between the best and worst scenario's performance on Global Warming Potential (GWP) was 600 tonne- 100 tonne = 500 tonne CO_2-e.

The monetary weight of the criterion of "Global Warming Potential" was; £10 x 500 tonne = £5,000

(5th Step) Once the monetary weighting procedure was completed for all the criteria in one branch (for example GWP, water usage and landfill requirement), monetary values were normalised to percentages;

For instance; if monetary value of Landfill Requirement, Water Usage and GWP were calculated as £1,000, £4,000 and £5,000 respectively; the relative weightings of them would be 10%, 40% and 50% respectively.

These steps present how monetary values were converted into the relative importance of each branch node (here for Environment). It should be noted that the figures given above are illustrative as the actual values, with the details of the calculations on each branch node, are covered in Chapter 5.

3.4 Validation of Methodology of the Project

Validation testing was carried out to analyse how sound and understandable the methods of the project were to stakeholders and how much it was contributing to the waste management field. This test was structured in a form of the questionnaire which was based on a likert scale, and sent to the stakeholders in the UK (Dr Tudor, Dr Woolridge and Dr Townend) and in Turkey (Ministry of Environment and Forestry, Provincial Directorate of Environment and Forestry of Istanbul and Turkish Academia [Gebze Technology Institution]) (Appendix 2). While none of the Turkish stakeholders responded back, all the UK responders sent their feedbacks; Dr Tudor and Dr Woolridge provided their comments to the questions (as below) but did not explicitly indicate their rates to the questions; Dr Townend stated that he agrees to the questions 1,2,3,5 and strongly agrees to the question 4, and he sent his comments regarding the questions 6, 7 and 8 as below. All of the comments/feedback received were very useful in terms of obtaining various ideas for the project and also for the further research topics.

The main feedbacks/returns are grouped and outlined below.

Comments regarding system dynamics modelling techniques;

(1) Usefulness of SD Models and Availability of Data

"I think the idea of using systems design to measure and predict is good, but there are two fundamental issues that need to be discussed: (1) Who will use the model(s)? (2) How will you ensure that the data are available, valid and reliable to be inputted into the model? Often a key problem is that the data tend to be patchy at best and not very reliable, particularly for a waste stream such as this, thus the outputs from any model will not be valid or reliable."

- Tudor (2011)

The targeted beneficiaries of this project are Istanbul city authorities on behalf of any city development agencies or governments, who are seeking to improve their decision making mechanisms. However using tools and techniques and analysing the output diagrams requires professional vision and experience. For city authorities to make the best use of SD modelling technique, they would need expert help (such as environmental consultant agencies) in terms of receiving advice and interpretation on how to make practical use of resultant model outcomes.

The second issue of the comment points out availability and reliability of the data. Making the best possible estimation on the waste generation by using any model is dependent on first availability and then quality of input data. It is therefore essential for healthcare institutions to record and report their treatment types, patient episodes and waste generation profiles regularly as well as for the Turkish Health Ministry to develop a database, which keeps this information on a standard basis. This kind of auditing could greatly aid in dealing with uncertainties of waste management systems by reducing the data gap and also by improving the quality of data. One of the key benefits of developing a model is to highlight and define the data that needs collecting in the first place. The importance of interpreting SD models and accuracy of data was also raised by another responder as below;

"SD Models are too complicated. They may be useful at a strategic level, but needs to be interpreted by strategic decision makers conversant with SD methods. If you were a strategic decision maker presented with all this information, how would it help you to make a decision? Whilst theoretically this is good, will it be used in reality? If one section is populated with inaccurate data or an estimate, can the effect be amplified? Is there contingency capacity in such models? If so, very hard to interpret from a diagram."

- Woolridge (2011)

(2) Averaging the Input Values

"Regarding the classification of Category 1, 2 and 3; there might be some long term conditions that can generate very large quantities of waste while some short-term conditions very little. Regarding healthcare waste segregation success at hospitals, a lot depends on whether segregation is in place as some hospitals may have 64% whilst others very little inappropriate mixing"

- Woolridge (2011)

The more sensitive data results in more precise outputs. In other words, the preciseness of outputs is determined by the sensitiveness of the input data. The aim of the project was never to make a point prediction of future waste arisings, but to make a best possible estimation by using limited data and information currently available in databases and literature. This "problem" was one of the main reasons for adopting an SD approach rather than a deterministic approach (Chapter 3, Section 3.1.2 Reasons for Using System Dynamics).

<u>(3) Important Factors of the HCW SD Model</u>

"Using the number of beds to predict future waste arisings is fine, but it's not just about quantities, you also need to consider waste types/steams as well. Levels of segregation between municipal and infectious are only theoretical, and there are often logistical issues that limit/prevent complete segregation (e.g. lack of bins, sources of the waste, where for example, waste from a barrier ward would be classified differently than that from a kitchen). Appropriate segregation also requires training and retraining of staff, and the provision of correct containment systems."

- Tudor (2011)

There are two HCW streams (incineration-only HCW and the HCW SAT) involved in the HCW SD model as each of them has its own dynamics in the system. A range of factors limit the segregation of wastes to some extent. There are various reasons behind the lack of complete segregation as some of them were given by Dr Tudor, above. From the point of modelling, whatever the reason, the level of this segregation can be represented as a parameter and how sensitive model results are to any change in this parameter can be tested via sensitivity analysis (Chapter 4, Section 4.1.3.1 Sensitivity Analysis).

Comments regarding multi-criteria decision making analysis;

(1) Global Point of View Rather Than Local

"There should be an opportunity to measure perceived risk by the population at large. Whilst I appreciate this is difficult it does have a significant impact on decision making as to the type of treatment equipment to be used"

"There should be an additional criterion for environment pollution other than global warming and an effect on the flora and fauna and habitats"

"If you are using a monetary scale then a full cost benefit analysis should be included"

- Townend (2011)

The feedback above focuses on importance and necessity of baseline assessments (e.g. environmental impact assessment) for the research area- Istanbul. However it should be emphasised that the primary aim of the project was to provide a "general picture" of healthcare waste management of the city in the light of "available data/information". It could be then further analysed, for example, where exactly to locate waste facilities in the city by conducting location-specific assessments and risk assessment including the relation between source, pathway and reception.

Analysing a decision making process at a practical level requires a specific location and detailed data for this location. Currently there is very limited literature regarding the adverse health effects of emissions on employees who are working at waste treatment plants in Istanbul; and there is no evidence of public participation in decision making regarding waste facilities in Turkey so far. It is therefore inevitable that the set of criteria in the waste management decision tree for Istanbul will restructure as time passes. However in order to initiate the decision making mechanism with appropriate tools and techniques in Istanbul, the scope and the viewpoint of this project is determined on a strategic level rather than a practical level. Any further research which presents detailed data with less uncertainty could benefit the results of this project in the future.

CHAPTER 4: RESULTS AND DISCUSSION ON THE DEVELOPMENT OF SYSTEM DYNAMICS MODELS

The required data for this project were generated by building two system dynamics models. The first model was designed to reflect the complexity of the healthcare waste management process for Istanbul and was achieved through a combination of simpler sub processes (sub models) that were linked together. The second model was built to address health issues of workers employed in waste management sector by taking into account the nature of the systems and the outcomes of previous studies. There were two objectives in discussing how these models were built;

(1) To show how the sub-models were structured and linked together; and document which sources of data were used to simulate the models. To illustrate the effect of factors, such as waste segregation efficiency and implementation of regulations and estimate health outcomes of waste treatment processes.

(2) To generate the data required for setting the scenarios and ranking them in a decision tree for the Multi Criteria Decision Analysis. This further step is analysed and discussed in the following chapter (Chapter 5).

4.1 Healthcare Waste Management Model Development

The dynamics of the healthcare waste management model were determined by the causal loop diagram as shown in Figure 4.1. Each arrow represents an influence of one parameter on another as explained in Chapter 3.

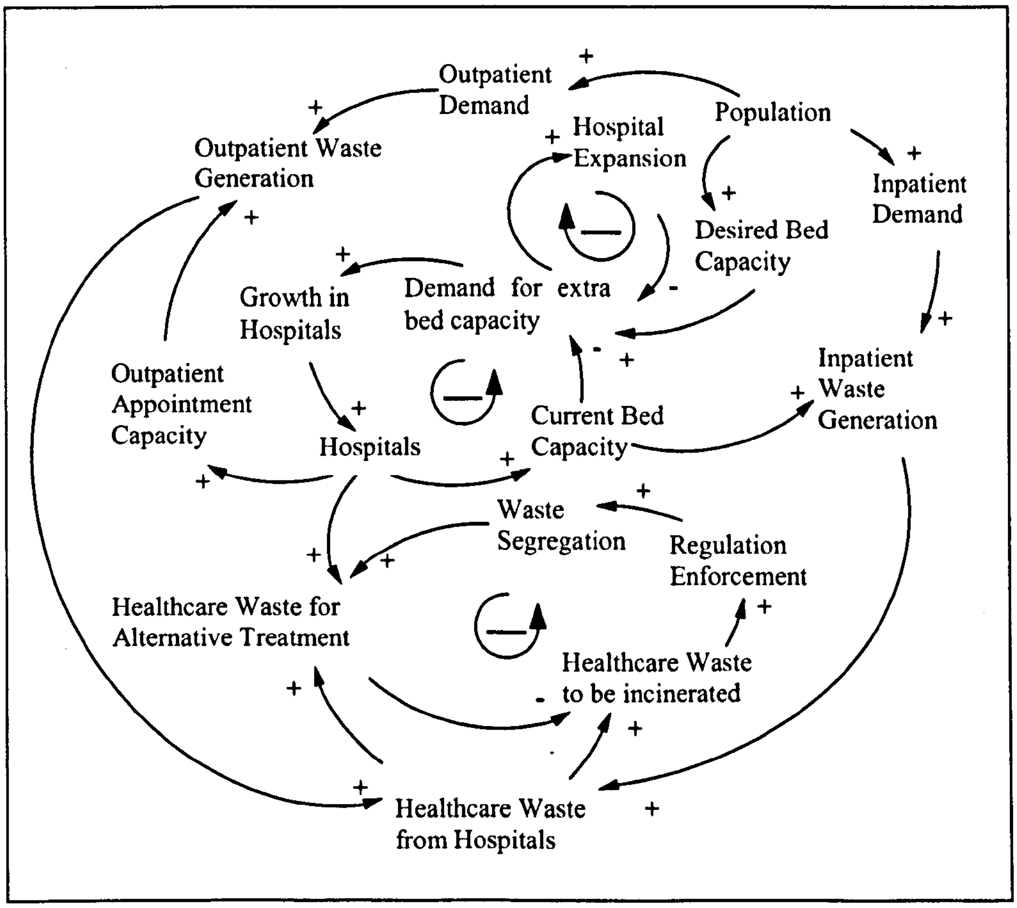

Figure 4.1: Causal Loop Diagram of the HCW SD Model

Healthcare waste generation from HCFs should be proportional to the population, number of beds available for inpatients and outpatient appointment capacity of hospitals. Segregation is required to separate healthcare waste from municipal waste; but further segregation of incineration-only-HCW from the general HCW stream is essential in terms of allocation of appropriate treatment facilities. The performance of the waste segregation process depends on the knowledge of the hospital's staff and visitors at the points of generation. The collected waste is treated either at incinerators (incineration only HCW) or alternative treatment plants (HCW SAT), depending on its hazardous nature, and then disposed of in a final disposal site.

After definition of key parameters, they have to be quantified and their influences have to be formulated mathematically. The HCW SD model is definitely determined when the parameters and the initial values for the stock variables have been specified.

4.1.1 Structure of the Model

Complexity of system dynamics models is achieved through combinations of simpler sub-models linked to simulate the system in question. The sub-models are again system dynamics models exhibiting specific systems behaviours. The totality of the relationships between these sub-models constitutes the "structure" of the system and operating over time, the structure produces "dynamic behaviour".

4.1.1.1 Population Sub-System

The population was divided into three age cohorts; young population who are below 20, mature between 20 and 60 and elderly population who are above 60s. Migration in and out rates and mortality rates of each of the cohorts affect the population stocks. The "births" should be proportional to the average rate of births per female gives per year as well as the population of females in the mature population (Figure 4.2 and Figure 4.3).

The time boundary of the model was set between 2007 and 2040 and the resultant outcomes for the years 2007 and 2008 were used to carry out an historical behaviour test (Chapter 3.1.6 Building Confidence in the HCW SD Model). The HCW SD model (with all its sub-systems) was simulated twice; once with a set of data belonging to the Asian Side and once with a set of data for the European Side (more details can be found in Chapter 4.1.2 Data Sources). Mathematical formulations and units of the parameters are presented in Tables A.1, A2, A3, A4, A5 and A6 in Appendix 3.

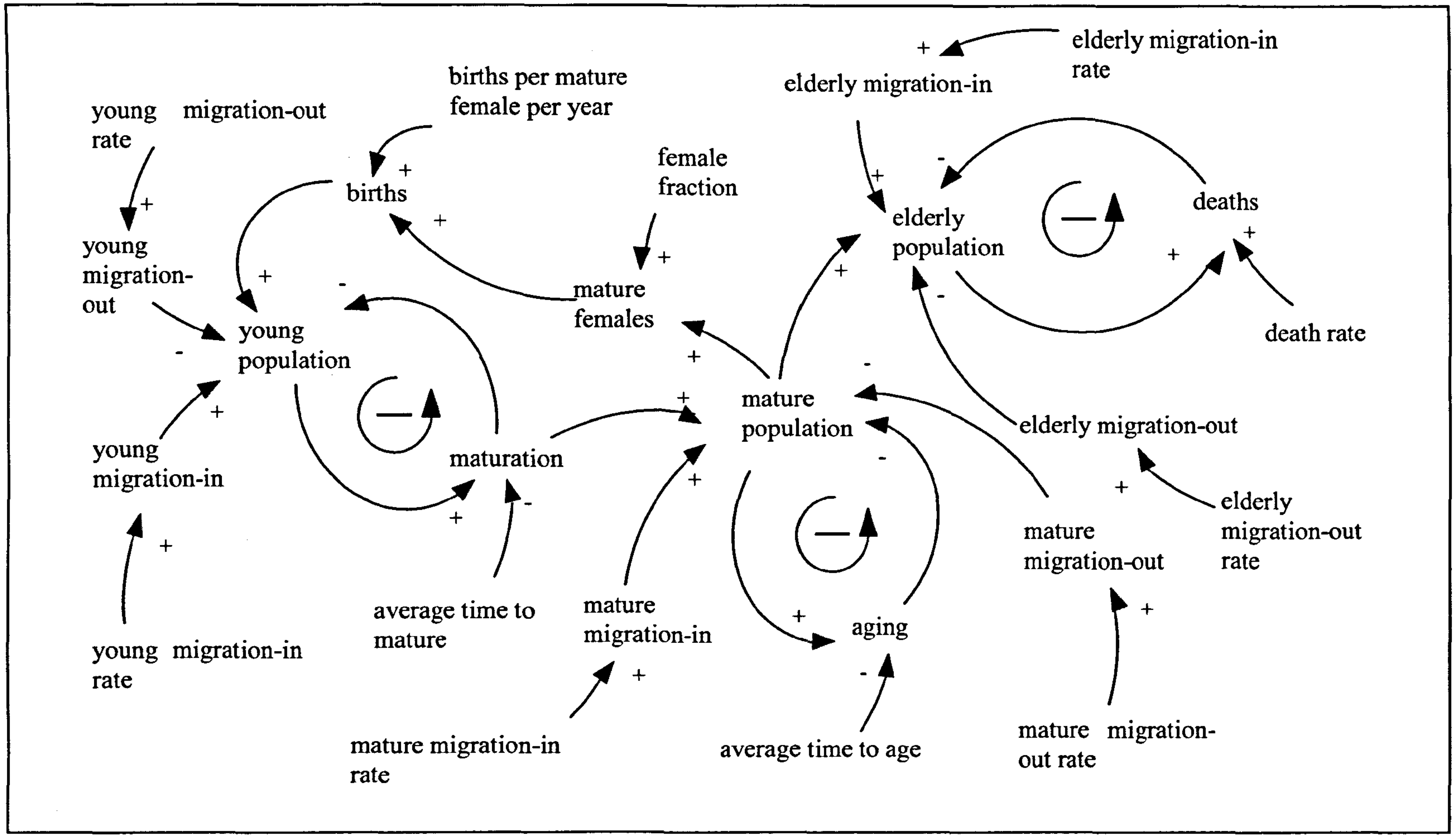

Figure 4.2: Population Causal Loop Diagram of the HCW SD Model

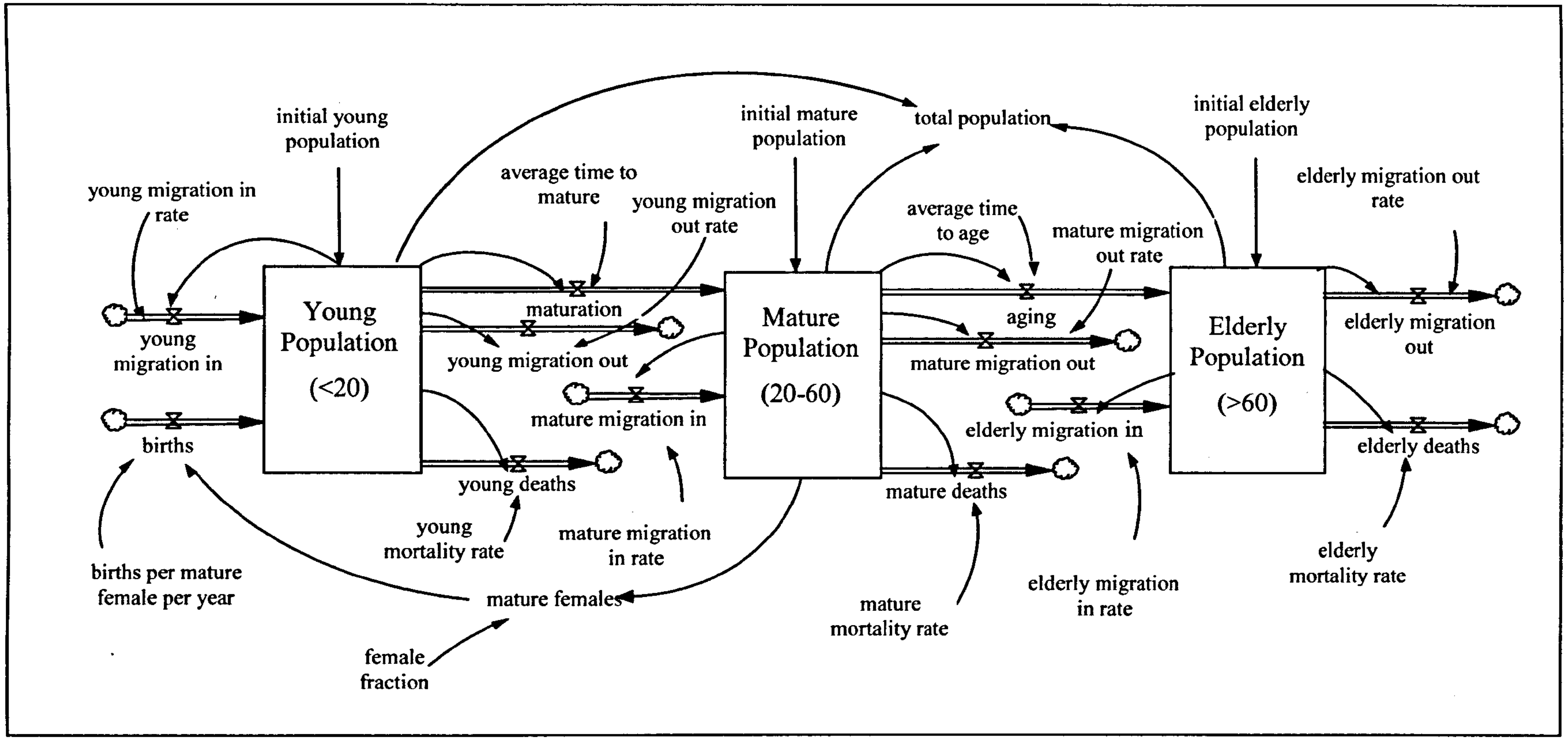

Figure 4.3: Population Sub-System of the HCW SD Model. Mathematical formulations and units of the parameters are presented in the Table A.1 in Appendix 3

4.1.1.2 Waste Generation Sub-System

Figure 4.4 displays the bed-inventory feedback loop, which was built up to determine the demand for extra bed capacity depending on the gap that occurs between a current bed capacity and a desired bed capacity. The desired bed capacity is based on a number of beds per capita, which was set by the State Planning Organisation of Turkish Government and released as the 9th Development Plan (Turkish Ministry of Development 2006).

The demand of Category-1 patients, in the feedback loop, could either be met by building new hospitals or by expanding current bed capacity at existing hospitals. Both options encounter an average delay time, which stands for the time difference between when the demand occurs and the government responds to this.

Waste generation from Category-1 type of treatment is led by two factors; (1) in-patient demand, (2) available bed capacity. In the case, where the demand of in-patients exceeds the bed capacity, the waste generation is based on in-patient demand. Otherwise, the waste generation is limited by the bed capacity and if this is the case, the waste production is oriented by the bed occupancy rate.

Figure 4.5 represents the Category-1 sub-system. In order to estimate the number of in-patients (annual in-patient demand), "Incidence Rate" parameters for each cohort were linked to the *"population sub-system"*. These incidence rates represent the proportion of *the number of hospital admissions of each cohort population* to *the total cohort population* on an annual basis as the number of elderly in-patients hospital admission, for example, would not be the same as the number of young in-patients hospital admissions.

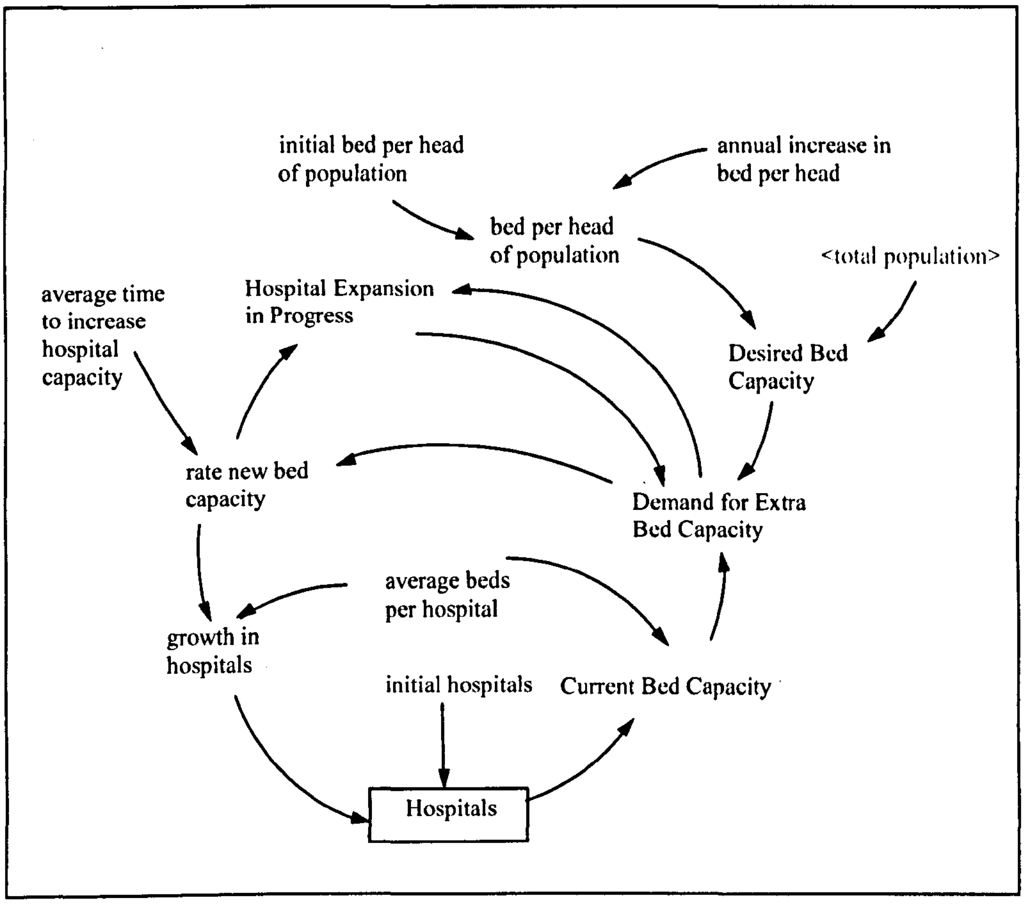

Figure 4.4: Hospital Bed Inventory Sub-System of the HCW SD Model

*Shadow variables (< >) represent the variables taken from previous sub-systems

Mathematical formulations and units of the parameters are presented in Table A.2 in Appendix 3.

Figure 4.6 represents the sub-system showing the estimation of healthcare waste generation from Category-2 type of treatment at general hospitals. As previously stated, Category-2 type of treatment, and hence the waste arisings from this, is based on per patient and this should be restricted by hospital appointment capacity. While the waste generation from Categoty-2 type of treatment is simply led by the two factors (1) waste generation rate per out-patient appointment and (2) number of appointments; the number of appointments is determined whether the outpatient demand is higher than the appointment capacity. If the demand is higher than the capacity, then available appointment capacity turns out to be a determinative factor in waste generation, but if not, then the demand determines the waste generation.

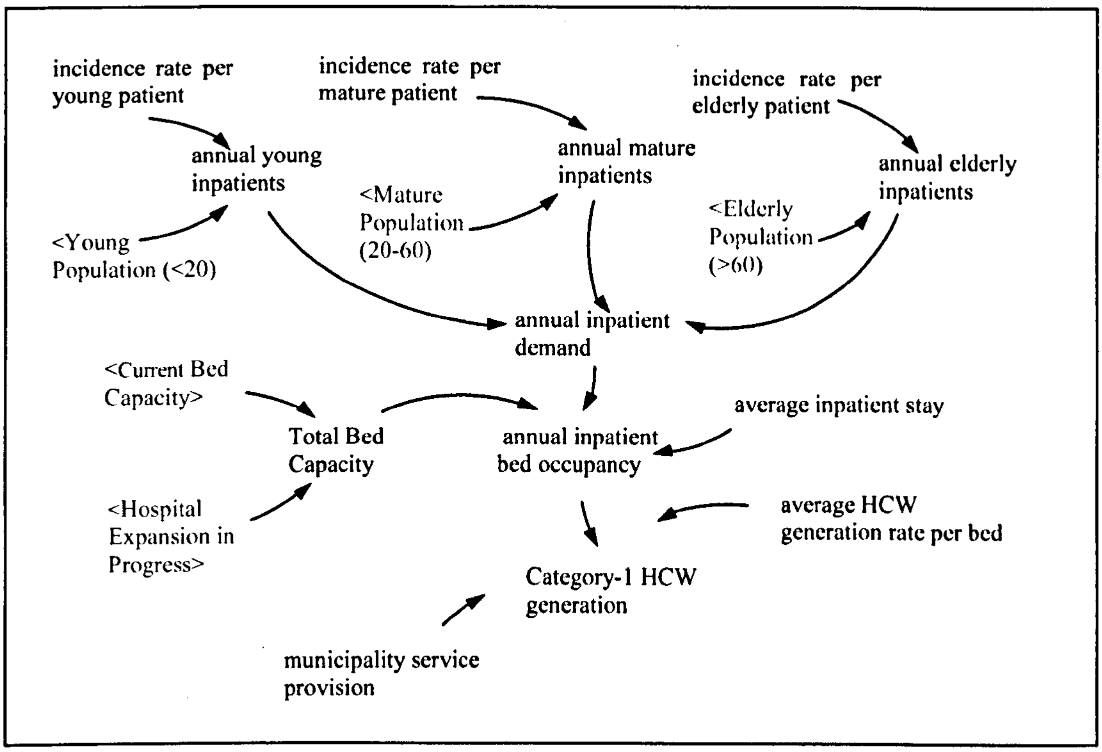

Figure 4.5: Category-1 Sub-System of the HCW SD Model

*Shadow variables (< >) represent the variables taken from previous sub-systems.

Mathematical formulations and units of the parameters are presented in Table A.3 in Appendix 3

The "average number of appointments" for each of the cohort determines "out-patient demand" (as shown in Figure 4.6). Since each hospital has certain appointment capacity, Category-2 sub-system recalls the parameter of number of hospitals (shown as <Hospitals>) from the hospital bed inventory sub-system. While the government invests in building up new hospitals in the city, this leads to an increase in bed capacity as well as the total appointment capacity. In bridging the gap between the appointment demand and the capacity, a delay for the feedback loop is included. Mathematical formulations and units of the parameters are presented in Table A.4 in Appendix 3.

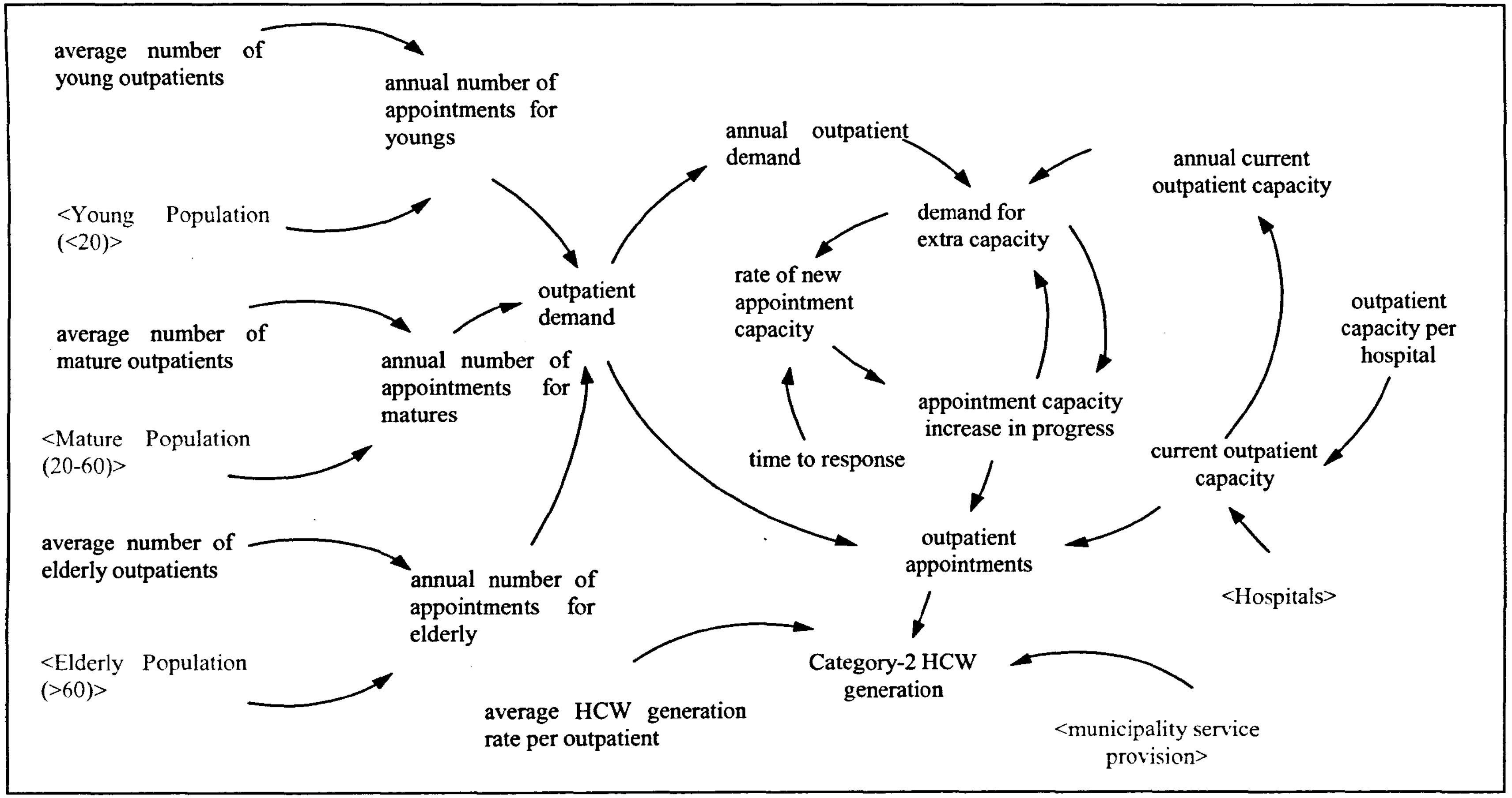

Figure 4.6: Category-2 Sub-System of the HCW SD Model

Mathematical formulations and units of the parameters are presented in Table A.4 in Appendix 3

The last pattern of waste generation (Category-3) is displayed by Figure 4.7. Category-3 waste generation is based directly on the waste generation rate and the number of small healthcare facilities (HCFs), whose number is re-valued over time.

4.1.1.3 Waste Segregation Sub-System

As discussed in the Introduction Chapter 1 - Scope of Project Section, there are essentially two main healthcare waste streams generated at HCFs:

(A) Incineration-only HCW, which consists of anatomical waste (18-01-02), healthcare chemicals (18-01-06*), pharmaceuticals (18-01-09 or cytotoxic and cytostatic medicines 18-01-08*) for which incineration is necessary.

(B) HCW such as swabs, soiled dressings, and gloves (orange bag 18-01-03*) are suitable for alternative treatment (HCW SAT), for which incineration is not a must, therefore it can be treated by alternative treatment plants.

According to the Health Technical Memorandum-Safe Management of Healthcare Waste (UK DoH 2011) the key treatment types of these streams along with their specific codes under the European Union Waste Catalogue 2000 are illustrated in Table 4.1.

Having these two main streams segregated (this is called "further segregation") depends on how successfully the further segregation scheme is introduced to the hospitals in Istanbul. This factor was included in the waste segregation sub-system (Figure 4.8) by using a Lookup Function, which allows customised relationships between a variable and its causes to be defined. Lookup Functions have the same logic as an equation of y=f(x), in which the output variable y is changed by input variable x. For this sub-system, the x variable was used as the ratio of the number of hospitals implementing further segregation to a total number of hospitals, and the y as the effect of implementing further segregation on the generation of the HCW SAT. By doing so, the output variable y was changed by input variable x through the Lookup function.

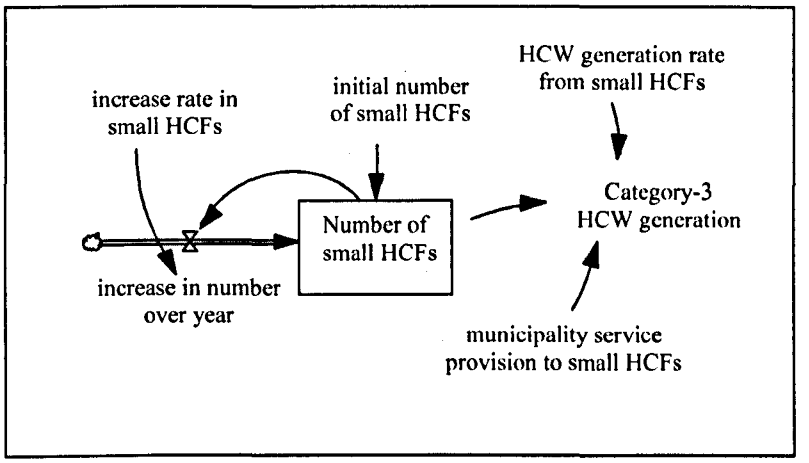

Figure 4.7: Category-3 Sub-System of the HCW SD Model

Mathematical formulations and units of the parameters are presented in Table A.5 in Appendix 3.

Table 4.1: Types of HCW Arising from Hospitals in the UK

Stream	Waste Type	EWC Codes	Examples of the waste
(A) incineration-only HCW	Chemicals	18-01-06*	
	Sharps	18-01-01	
	Anatomical	18-01-02	Body parts and organs (included blood bags)
	Cytotoxic and Cytostatic	18-01-08* 20-01-31*	
	Pharmaceutical	18-01-09 20-01-32	
(B) HCW SAT	Infectious	18-01-03*	Swabs, soiled dressings, gloves
	Offensive	18-01-04 20-01-99	Diapers, sanpro

There were essentially two points to validate the function; first, when there was no hospital implementing this segregation, there would not be any designated alternatively treatable HCW arising, in other words, all HCW produced would be collected together to be sent to incineration (x=0 and y=0). The second point is when "all" hospitals implement further segregation, which makes x equal to 1 and so y reaches the maximum value at which *almost* all generated HCW SAT in the HCW stream is separated (details can be found in Chapter 4.1.2 Data Source). Employing a Lookup function basically allowed predicting the waste generations over the period during which the number of hospitals is changing over time as well as the proportion of the hospitals which implement further segregation.

Regardless of how successfully the waste segregation is conducted at hospitals it is inevitable to have some municipal solid waste (MSW) mixed with HCW due to the logistical issues that limit/prevent the complete segregation (e.g. lack of bins, sources of the waste, locating waste bins). A number of studies have shown that a large percentage of HCW generated in these institutions could be classified as 'domestic' in nature; a case study conducted by Olko and Winch (2002) in England showed that approximately 50% of the HCW generated at HCFs annually could be classified as MSW (cited in Tudor *et al.* (2008)). Surveys of the waste by Sawalem (2009) showed that the HCW generated at HCFs consisted of 28% hazardous waste and 72% municipal waste. Also in Algeria, Bendjoudi *et al.* (2009) showed that the municipal waste fraction represented 75-90% of the total Algerian HCW. This was shown in Figure 4.8 by labelling the MSW mixing stream as (2), unmixed HCW stream from hospitals as (1); and HCW from small HCFs as (3).

4.1.2 Data Sources

In order to simulate the sub-systems the required data were gathered from different sources as represented in Table 4.2, Table 4.3, Table 4.5, Table 4.6 and Table 4.7.

Table 4.2: Data Sources for Population Sub-System

Parameters	Source
initial cohort populations	Turkish Statistical Institution (2007a)
migration in and out rates for each of the cohort population	
mortality rates for each of the cohort population	
births per mature female per year	

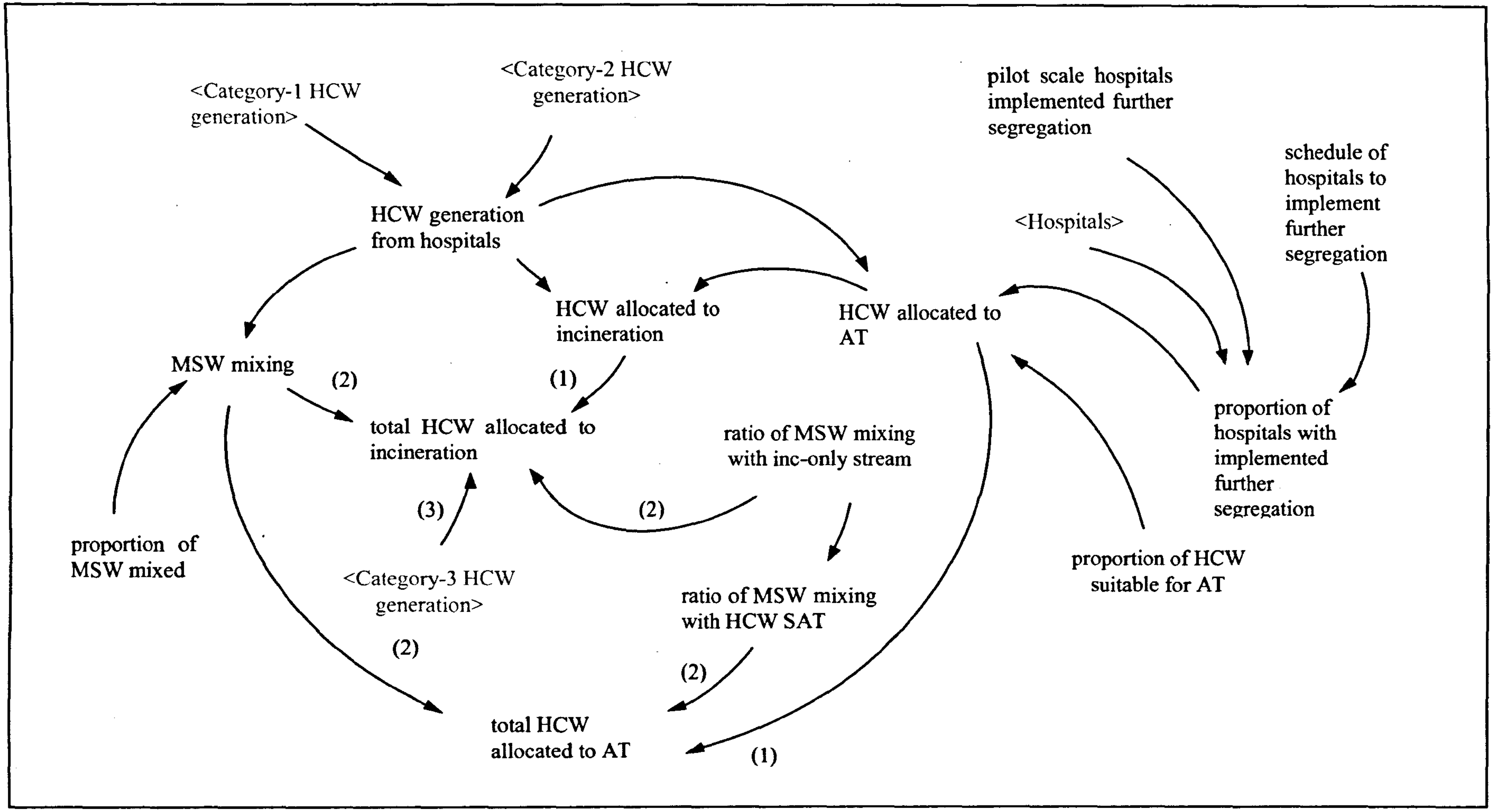

Figure 4.8: Waste Segregation Sub-System of the HCW SD Model.

Mathematical formulations and units of the parameters are presented in the Table A.6 in Appendix 3

Table 4.3: Data Sources for Waste Generation (Category-1) Sub-System

Parameters	**Source**	**Explanation**
initial hospitals	Turkish Ministry of Health (2007a)	-
average beds per hospital		-
average inpatient stay		-
initial bed per head of population	Turkish Ministry of Health (2007a) and Turkish Statistical Institution (2007a)	sources were used in conjunction
annual increase in bed per head	Turkish Ministry of Development (2006)	-
average HCW generation rate per bed	Turkish Ministry of Health (2007a), Alagoz and Kocasoy (2008a) and Mohamed *et al.* (2009)	sources were used in conjunction *
incidence rates for each cohort population	Turkish Ministry of Health (2007a) and UK National Health Service (2007)	sources were used in conjunction to normalise total annual incidence rates to cohort incidence rate

* A case study conducted in Istanbul (Alagoz and Kocasoy 2008a) provided a composition and daily production rate of HCW generated from hospitals on the Asian and the European Sides separately (Table 4.4). Furthermore the research carried out by Mohamed, et al (2009) indicated that at hospitals 88% of HCW was generated from Category-1 type treatment (kg/(bed*day)), while the out-patient based fraction (Category-2) was only 12% (kg/(patient*day)). The outcomes of these two studies were used in conjunction with Turkish Health Ministry Statistics and the resultant outcomes were used as data for the parameters called "average HCW generation rate per bed" and "average HCW generation rate per outpatient".

Table 4.4: Daily Production of HCW from Hospitals in Istanbul. Adopted from: Alagoz and Kocasoy (2008a)

Type of Waste	European Side		Asian Side	
	kg/day/bed	%	kg/day/bed	%
municipal	1.198	64.74	1.369	63.06
anatomical	0.110	5.94	0.159	7.34
radioactive	0.011	0.01	0.005	0.21
chemical	0.035	1.89	0.116	5.36
infectious	0.320	17.92	0.392	18.05
sharps	0.110	5.94	0.069	3.19
pharmaceutical	0.024	1.29	0.046	2.14
pressurised containers	0.042	2.27	0.014	0.65
Total	1.850	100	2.171	100

Table 4.5: Data Sources for Waste Generation (Category-2) Sub-System

Parameters	Source	Explanation
average number of outpatients for each cohort population	Turkish Ministry of Health (2007a) and UK National Health Service (2007)	sources were used in conjunction to normalise total annual number of appointment rates to cohort number of appointment rates
outpatient capacity per hospital	Turkish Ministry of Health (2007a)	-
average HCW generation rate per outpatient	Turkish Ministry of Health (2007a), Alagoz and Kocasoy (2008a) and Mohamed *et al.* (2009)	sources were used in conjunction*
*As explained previously		

Table 4.6: Data Sources for Waste Generation (Category-3) Sub-System

Parameters	Source
initial number of small HCFs	Turkish Ministry of Health (2007b)
increase rate in small HCFs	
HCW generation rate from small HCFs	Karaca (2009)

Table 4.7: Data Sources for Waste Segregation Sub-System

Parameters	Source	Explanation
proportion of MSW mixed	Alagoz and Kocasoy (2008a) *	-
pilot scale hospitals implemented further segregation	Sonmez (2008)	-
proportion of HCW suitable for AT	UK DoH (2011), Alagoz and Kocasoy (2008a)	sources were used in conjunction**
ratio of MSW mixing with incineration-only stream	assumed***	-
schedule of hospitals to implement further segregation	assumed****	-

*The case study conducted in Istanbul (Alagoz and Kocasoy 2008a) indicated that 64% of HCW generated in Istanbul was municipal waste, thus only 36% of it needed special attention if it could be successfully segregated and diverted. By entering a range of values for the auxiliary variable called "proportion of MSW mixed" (primarily set as 64%) in the model it was determined how effective the improvement of MSW segregation was on ultimate healthcare waste arisings by sensitivity analysis (4.1.3 Results and Analysis of the Model).

** Out of this 36% healthcare waste fraction, almost 18% of it was suitable for alternative treatment; the rest of it was pharmaceuticals, pressurised containers, chemicals, anatomical and sharps waste streams (18%) which required to be treated in an incinerator (Table 4.1 and Table 4.4).

*** The MSW mixed with HCW either entered to the incineration-only HCW stream or the HCW-suitable-for-alternative-treatment stream. The locations of where pharmaceutical, chemical, pressurised containers, etc waste (incineration-only HCW) arise were mostly hospital wards, theatres, laboratories and intensive care units. Therefore disposal of this type of HCW was under control of reasonably well trained hospital staff. However a range of alternatively treatable HCW arises from out-patient departments, waiting rooms where the waste is mostly disposed by patients and/or visitors. For this reason, out of the 64% MSW mixing fraction, 5% of it was assumed to be mixing with incineration-only HCW (and hence the remaining mixing with HCW SAT). It was then determined how sensitive this assumption was to any change by sensitivity analysis (4.1.3 Results and Analysis of the Model).

**** The parameter called "Schedule of hospitals to implement further segregation" was mathematically defined by the Lookup function as explained in Chapter 4.1.1.3-Waste Segregation Sub-System. In order to estimate how efficiently the hospitals started to implement the further segregation scheme, it was assumed the 5 year transition period, during which the proportion of the hospitals implemented further segregation to the total number of hospitals increases by 20% starting from 2015 to 2020. After this period is completed in 2020, it is assumed that all hospitals implement the further segregation.

4.1.3 Results and Analysis of the Model

The HCW SD model (with all its sub-systems) was simulated twice; once with a set of data belonging to the Asian Side and once with a set of data for the European Side (Chapter 4.1.2 Data Sources and Appendix 3 include the data and formulations). A set of results of the simulation of the previous sub models for the population, total bed capacity at hospitals and healthcare waste generation by 2040 is represented in Figure 4.9 (for the Asian Side) and Figure 4.10 (for the European Side). The population of Istanbul increases from nearly 12 million in the base year to almost 17 million at the end of the simulation. The HCW arisings (tonne/year) goes up with time mainly due to the increase in population and the investments in bed capacity, which is led by the increase in the number of hospitals.

The healthcare waste generation is affected by the level of waste segregation performed at hospitals. As long as the municipal waste fraction in the healthcare waste stream is 64% in Istanbul, the amount of healthcare waste reaches up to 15,500 tpa on European Side and 7,400 tpa on Asian Side by 2040. The total HCW produced in Istanbul reaches almost 23,000tpa, which is more than twice the annual capacity of the Kemerburgaz Incinerator.

MSW segregation; The amount of the healthcare waste can be reduced, as the level of MSW segregation is improved at hospitals in Istanbul. To analyse how sensitive healthcare waste generation is to any improvement in the MSW segregation efficiency, the model was run several times with different MSW segregation fractions. Figure 4.11 shows the output values of the simulation which was set to run for four times; run4, run3, run2 and run1. Run4 represents current segregation practices, which is the case of 64% MSW fraction in the healthcare waste stream in Istanbul; while run3, run2, run1 are the runs for 30%, 15% and 5% of the MSW fractions in HCW stream respectively.

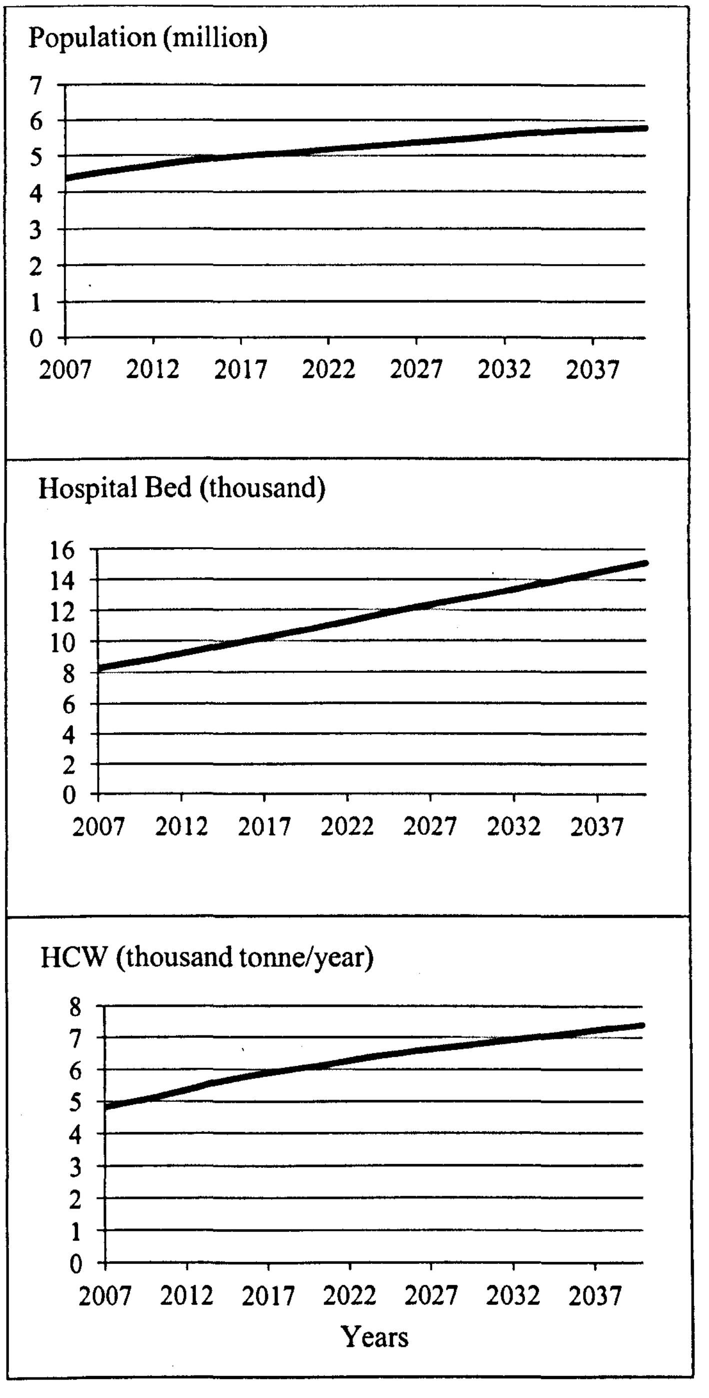

Figure 4.9: Simulation of Population, Bed Capacity and HCW generation between 2007 and 2040 for the Asian Side of Istanbul

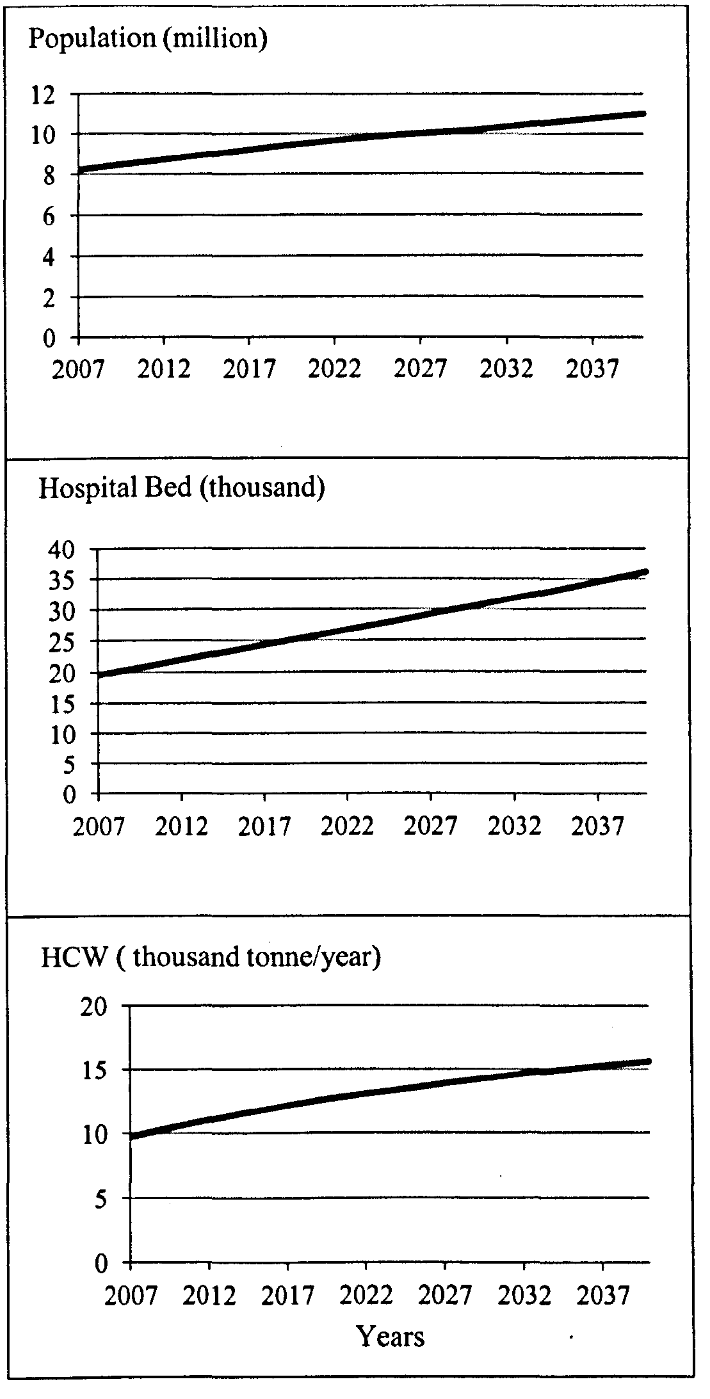

Figure 4.10: Simulation of Population, Bed Capacity and HCW generation between 2007 and 2040 for the European Side of Istanbul

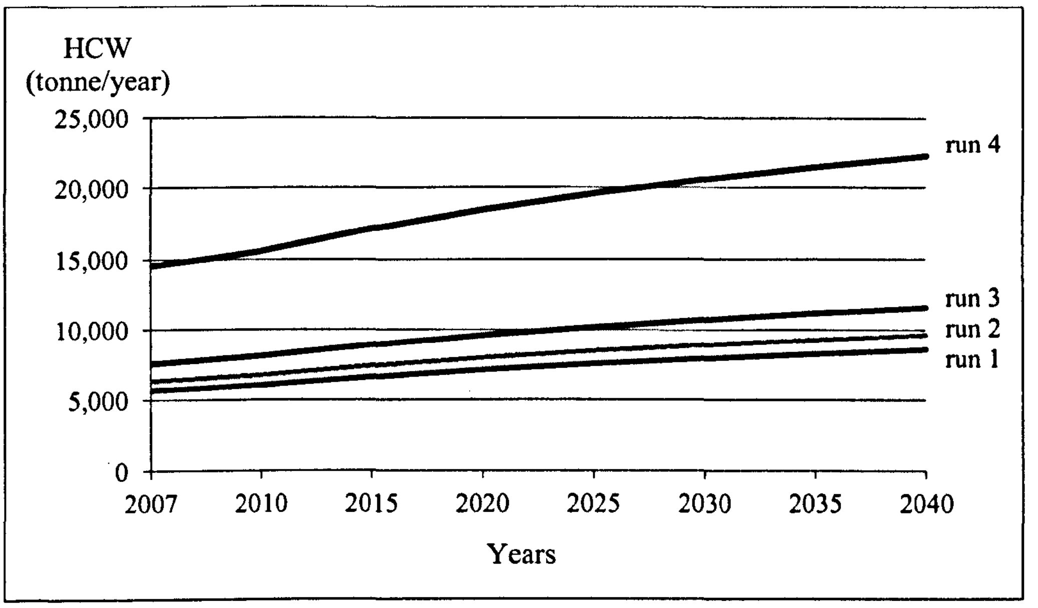

Figure 4.11: HCW Generation Based on Simulations (run 4-64% MSW in HCW; run3-30% MSW in HCW; run 2-15% MSW in HCW and run 1-5% MSW in HCW)

Table 4.8 takes a closer look at Figure 4.11 for particular years, 2015, 2025 and 2035. If the fraction of municipal waste in the healthcare waste stream is reduced from 64% to 30%, there is the potential to avoid some 8,000tpa of healthcare waste by 2025 and almost 10,000tpa by 2035. Furthermore a decrease from 64% to 5% results in more than 50% drop in the amounts of HCW annually. This is a very important shortfall, if one considers that a saving of 8,000 tpa is equivalent to the annual capacity of the current incinerator. Further improvements in segregation, such as reducing the MSW from 30% to 15% (difference between run3 and run2) and from 15% to 5% (difference between run2 and run1) also results in almost 1,000tpa less HCW produced.

Table 4.8: HCW Projections with Different MSW Segregation Levels

Years	**Run4** (tonne/year)	**Run3** (tonne/year)	**Run2** (tonne/year)	**Run1** (tonne/year)
	MSW fraction: 64%	MSW fraction: 30%	MSW fraction: 15%	MSW fraction: 5%
2015	17,200	8,800	7,600	6,700
2025	19,600	9,990	8,650	7,600
2035	21,500	11,000	9,500	8,400

On the other side, the segregated MSW stream inevitably causes an increase in the amount of MSW stream at HCFs. However, as long as the treatment of HCW requires more specialised techniques and processes, efficient segregation reduces the treatment cost in a long term (Sawalem *et al.* 2009) and provides a powerful incentive to increase the motivation of the hospital staff, patients and the visitors in terms of disposing of their waste in the right bin.

In determining capacities of treatment facilities for each of the scenarios (Chapter 5), HCW amounts were projected based on Run 4 which takes the current MSW fraction in Istanbul, 64 %. This rate might be pessimistic if it is considered that the awareness regarding the importance of segregation and efforts have recently risen in Turkey. However it is not unrealistic if it is compared to European figures reported as, for example, 75.4% and 82.4% in surgery departments and infection therapy departments respectively in Xanthi, Greece (Graikos *et al.* 2010); 67.8% and 50% in the UK in years 2001 (Barrett *et al.* 2004) and 2002 (Olko and Winch 2002 cited in Tudor *et al.* 2008); and also 70.5% overall in Europe (HCWH 2005).

Further Segregation; further segregation represents the segregation of HCW SAT from inc-only HCW under the assumption of that out of the 64% MSW mixing fraction 5% of it is mixing with incineration-only HCW (and hence the remaining is mixing with HCW SAT). This analysis aims to present the potential of healthcare waste diversion. Although there are currently a few private hospitals already implementing the further segregation, it is assumed that it will take some time (transitional period was assumed as 5 years (2015-2020) in this project) for all hospitals in Istanbul to employ this practice. Figure 4.12 represents the proportion of HCW SAT in the HCW stream for the selected years after the transitional period 2020, 2025, 2030, 2035 and 2040.

Figure 4.12 indicates that once the transitional period is completed, almost 77% of healthcare waste does not have to be incinerated if only the healthcare waste requiring incineration is rigorously segregated. In developing four scenarios alternative treatment plants were designed to treat this segregated waste stream. It could be treated at alternative treatment plants, which could be built as modular units to treat yearly increasing arisings on a more flexible basis (Chapter 5).

4.1.3.1 Sensitivity Analysis

Sensitivity testing is the process of changing the value of constants in the model and examining the resulting output. Monte Carlo simulation, also known as multivariate sensitivity simulation (MVSS), makes this procedure automatic. This analysis helps to explain the effect of change in assumption(s) on the outputs of some other pre-specified parameter(s).

In this research, sensitivity analysis was conducted in order to present the capability of system dynamics under foreseeable future conditions. In sensitivity testing firstly the parameters whose minimum and maximum values are known are chosen. The model is simulated once with the existing parameter values; and then additional simulations (200 in number as default) are performed while the selected parameters are varied automatically within the range of these minimum and maximum values. This variation is called distribution.

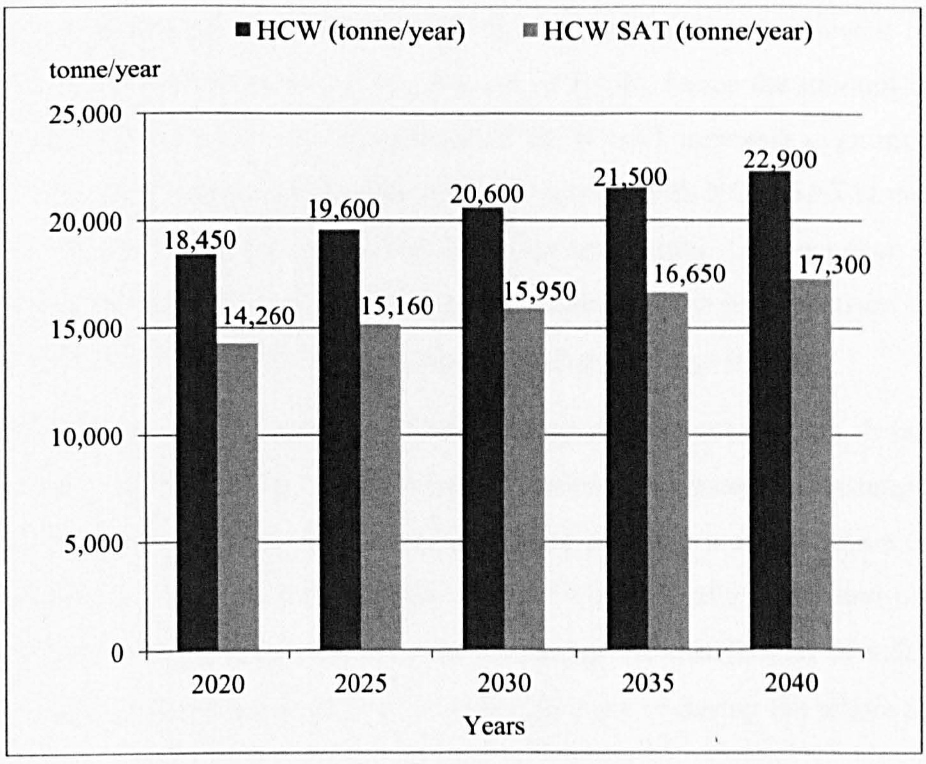

Figure 4.12: Amount of HCW SAT in HCW Stream

There are two commonly used distribution types in sensitivity testing; random uniform distribution and random normal distribution. In random uniform distribution any value of the parameter between minimum and maximum are equally likely to occur (i.e. probability within the range is the same everywhere and zero outside), whereas in random normal distribution the values ranges in a form of Bell Curve with mean and standard deviation which are required to be set by the software user (Figure 4.13).

The HCW SD model contains two uncertain constants (assumptions), the proportion of MSW in HCW stream (64%) and the ratio of MSW mixing with HCW SAT stream (95%). As previously mentioned in England approximately 50% of the HCW could be classified as MSW. By sensitivity analysis it was shown how the HCW SAT stream was affected whether this proportion in Istanbul improves from its current rate-64% (maximum) to the rate in England-50% (minimum); and "at the same time" the ratio of MSW mixing with HCW SAT stream ranges between 80% (minimum) (means that remaining 20% mixing with inc-only HCW stream) and 100% (maximum).

Setting the proportion of MSW in HCW stream smaller than its current rate-64% should have a reducing effect on the amount of HCW, hence the amount of HCW SAT stream. This reduction in the amount of HCW SAT increases even more when the spectrum of the values of the ratio of MSW mixing with HCW SAT stream range between 80% (lower range limit) and 95% (current value). On the other side this reduction in the amount of HCW SAT is counteracted when this spectrum turns out to range between 95% (current value) and 100% (upper range limit).

The results of sensitivity testing can be displayed in different formats. It is either a graph of the variable whose value is tested against the change in assumptions by showing uncertainty bounds, or a histogram which provides a cross section of values for that variable in a given range at the specific time (usually at the end of project period). They both provide a mechanism for seeing the distribution of values for a variable over all the simulations done at a specific time or during the whole time.

Figure 4.14 shows confidence bounds (50%, 75%, 95%, and 100%) for the values of HCW SAT parameter which were generated when two parameters were varied about their distribution. The type of distribution was set as random uniform for both of the parameters as it was assumed that any value within the range had an equal probability to occur. The simulation, with the original constant values contained in the model, is shown by a black line.

The confidence bounds are computed at each point of time by ordering and sampling all the simulation runs. Thus, for example, for a confidence bound at 50%, ¼ of the runs will have a bigger value than the top of the confidence bound and ¼ will have a lower than the bottom. The outer bounds of uncertainty (100%) show maximum values of approximately 17,700 tpa and minimum 10,100 tpa at the end of the simulation.

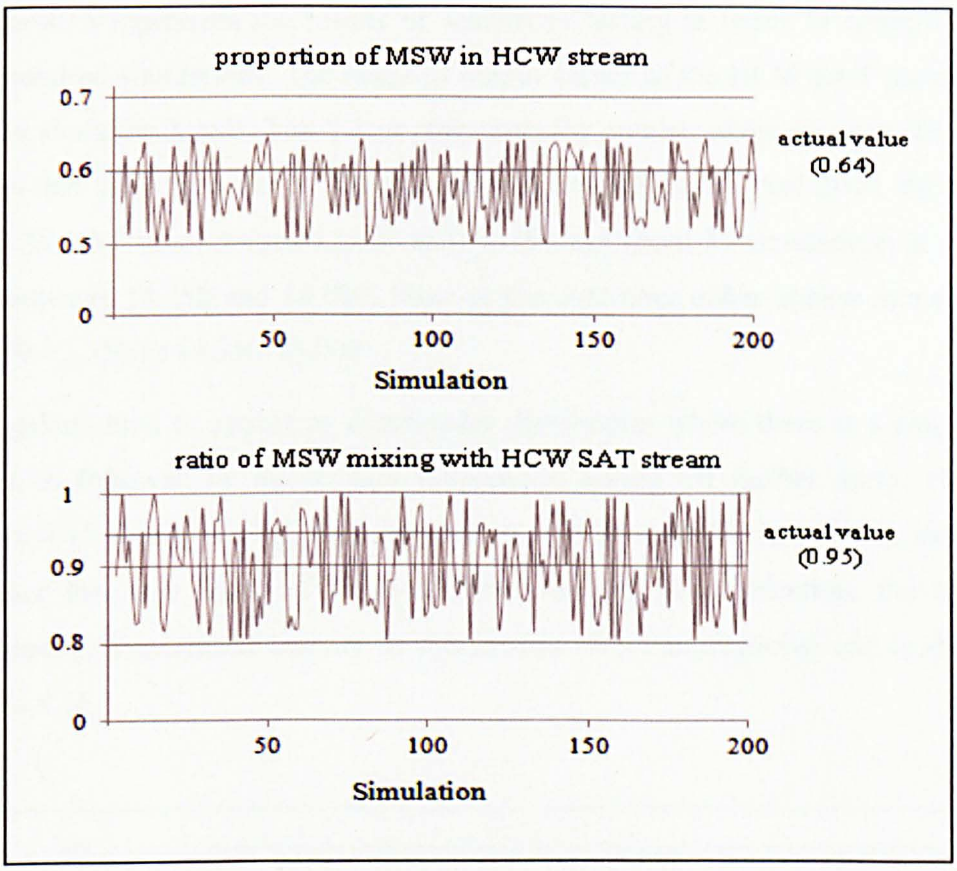

Figure 4.13: Random Uniform Distribution of Selected Parameters

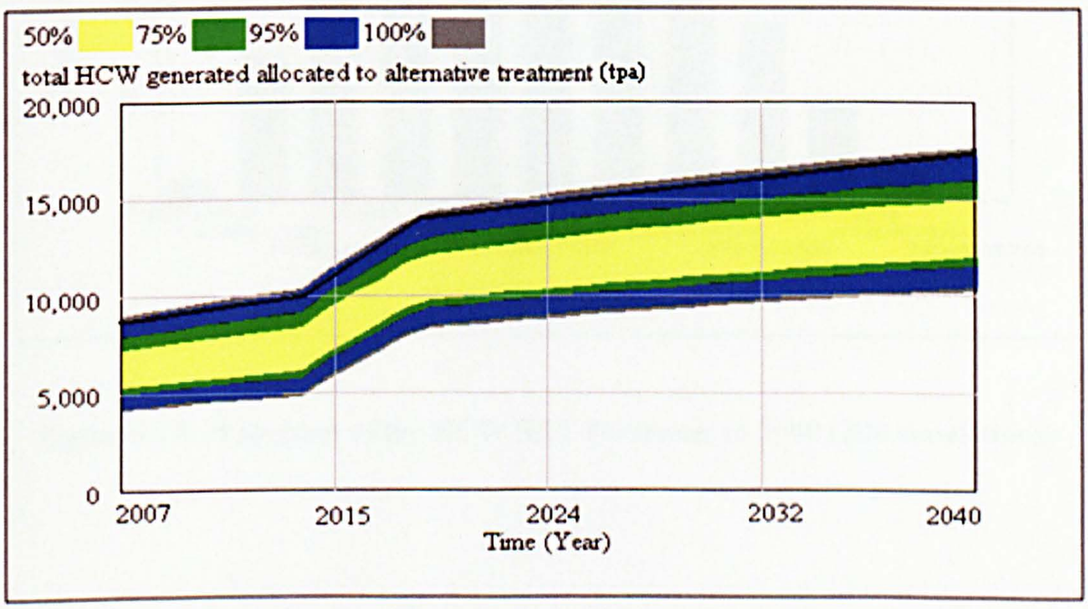

Figure 4.14: Sensitivity Graph of the HCW SAT Parameter

Figure 4.15 represents the results of sensitivity testing in terms of histogram with two hundred simulations. The range of output values of the HCW SAT parameter is shown along the X axis. The Y axis represents the number of simulations. The figure shows that there were about 32 simulations for which, in the year 2040, the amount of HCW SAT was between 12,000 and 12,750 and about 31 simulations in which it was between 14,250 and 15,000. Most of the outcomes either appear in a range of 12,000-12,750 or 14,250-15,000.

Histograms tend to appear as a unimodal distribution where there is a single peak which is followed by the smaller frequencies tailing off further away. However Figure 4.15 displays a bimodal distribution with two peaks. In order to determine whether this is a result of artefact of the random value selection, the test was repeated with increased number of simulations (5000 simulations) and is shown in Figure 4.16.

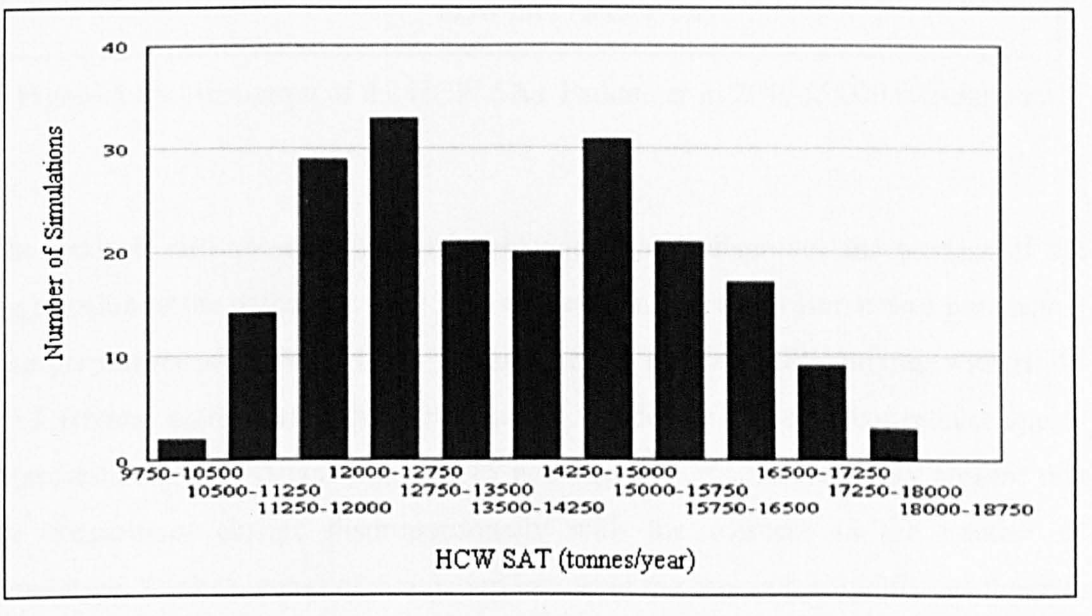

Figure 4.15: Histogram of the HCW SAT Parameter in 2040 (200 simulations)

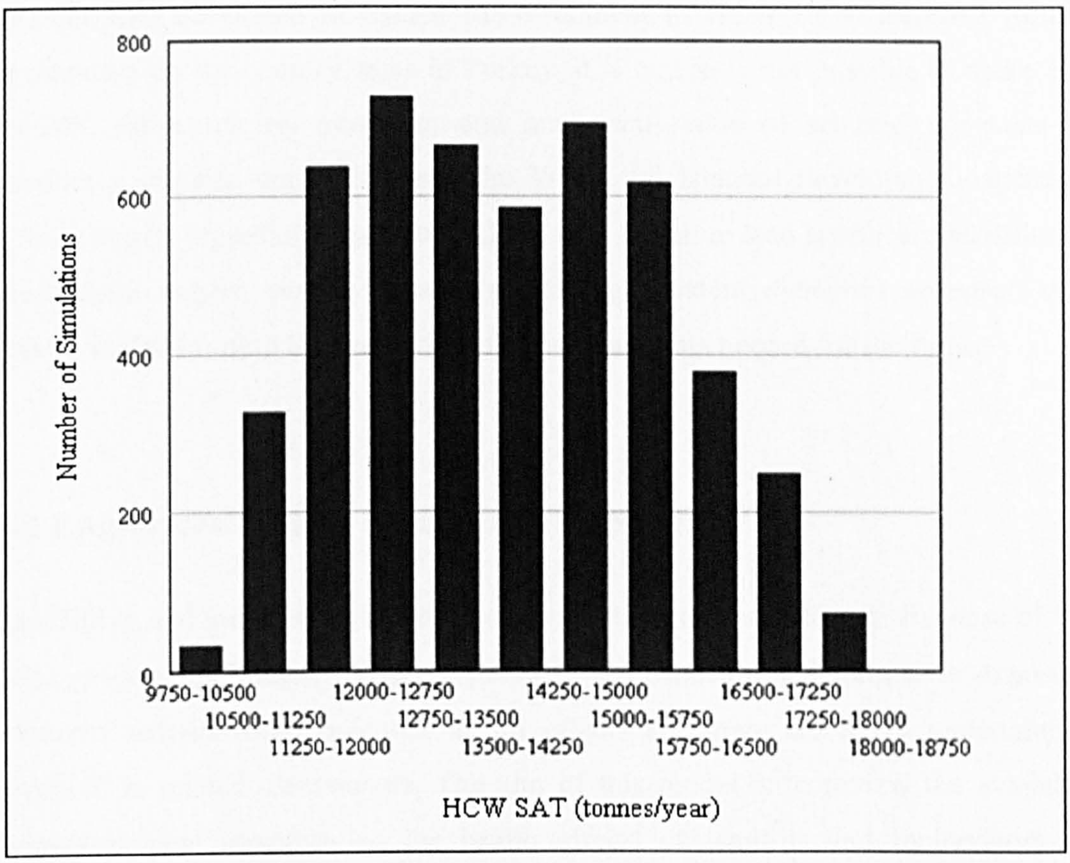

Figure 4.16: Histogram of the HCW SAT Parameter in 2040 (5,000 simulations)

The analysis still shows a bimodal behaviour which disproves the artefact of the aggregation of the outcomes. This is an expected model behaviour as two parameters (the proportion of MSW in HCW stream and the ratio of MSW mixing with HCW SAT stream) could easily cause two noises (randomly highest frequencies) due to interactions in the system. Figure 4.15 and Figure 4.16 comparatively present that the frequencies change disproportionally with the increase in the number of simulation. As the number of simulation increases the bars in the middle get closer to the peaks.

The sensitivity analysis facilitates the best possible future predictions to be made under foreseeable future conditions where minimum and maximum values for the constant variable/variables are "reasonably predictable". This could imply at countries where the strategy regarding improving healthcare waste segregation (MSW segregation and/or further segregation) has already been developed, and then the targets will have been set to be met in forthcoming years. As yet there is not any strategy/plan developed to reduce MSW content in HCW or to improve further segregation on the country basis in Turkey, it is currently not possible to make any realistic estimation on minimum and maximum value of selected constants to conduct a reliable sensitivity analysis. When the Istanbul development agencies release targets regarding segregation along with a plan to lead healthcare facilities to meet these targets, sensitivity analysis through system dynamics approach will benefit in determining the capacities of treatment plants needed for the future.

4.2 Employees' Health Model Development

Landfilling and incineration of solid waste releases toxic substances. Because of the wide range of pollutants, different pathways of exposure and long term exposure concerns remain about potential health effects but there are many uncertainties involved in related assessments. The aim of this model is to review the available epidemiological literature on the health effects of landfills and incinerators on workers at waste processing plants to derive usable excess incidence estimates for health impact assessment.

4.2.1 Structure of the Model

The Literature Review (Chapter 2) indicated that the frequency of a number of incidences is higher among landfill/incinerator workers due to their exposure to hazardous emissions in their workplace compared to non-exposed societies. The models (Exposed Workers SD Model and Non-Exposed workers SD Model) aim to estimate the number of "additional cases" which is expected to appear in 30-year-employment-time based on the data gathered from the literature survey.

The Exposed Workers SD Model (Figure 4.17: Causal Loop Diagram and Figure 4.18: Exposed Workers SD Model) starts with the initial workers who have completed their exposure time period to develop the disease specified by the epidemiologic studies. When the model is run, depending on the "average time to get infected" exposed-workers move to infected-workers stock. Based on average time for mortality, infected workers either die or recover and enter the susceptible-workers stock. Exposure time introduces a delay for susceptible workers to reach to the certain level at which they start to develop symptoms of a disease.

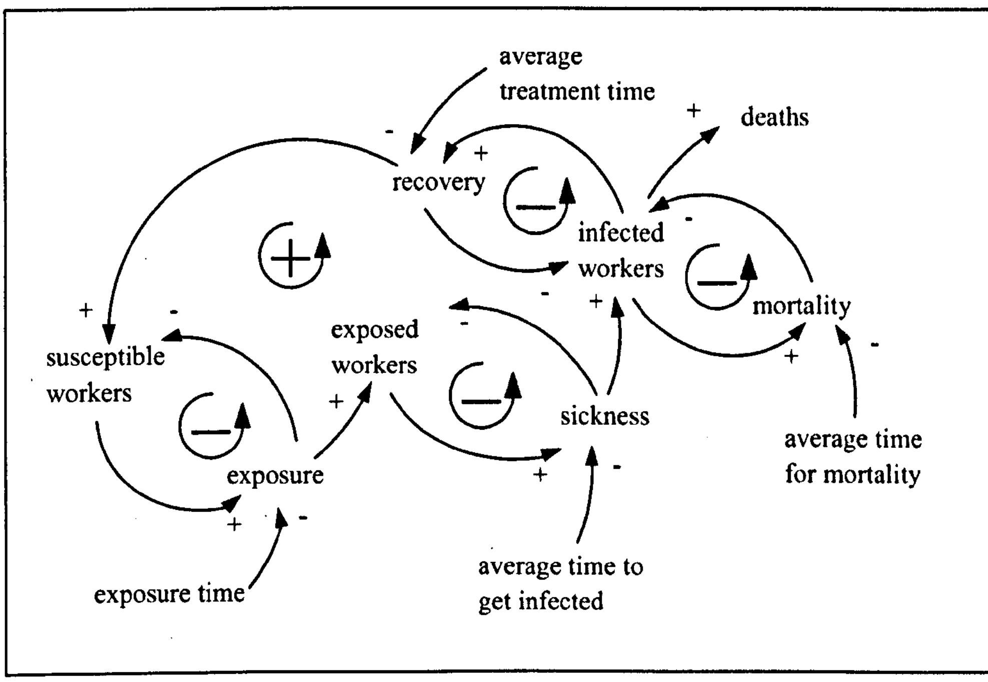

Figure 4.17: Causal Loop Diagram for the Exposed Workers SD Model

The Non-Exposed Workers Model (Figure 4.19) aims to estimate the number of cases for the selected diseases that would appear in the same number of individuals (workers) in the same time period as Exposed Workers SD Model. This facilitates determining *additional cases* (additional hospital admissions and/or additional deaths) by subtracting the number of cases in exposed population from the number of cases in non-exposed population within the same amount of time. The number of additional cases refers to the number of workers whose poor health is due to the emissions from the waste treatment facility where they work.

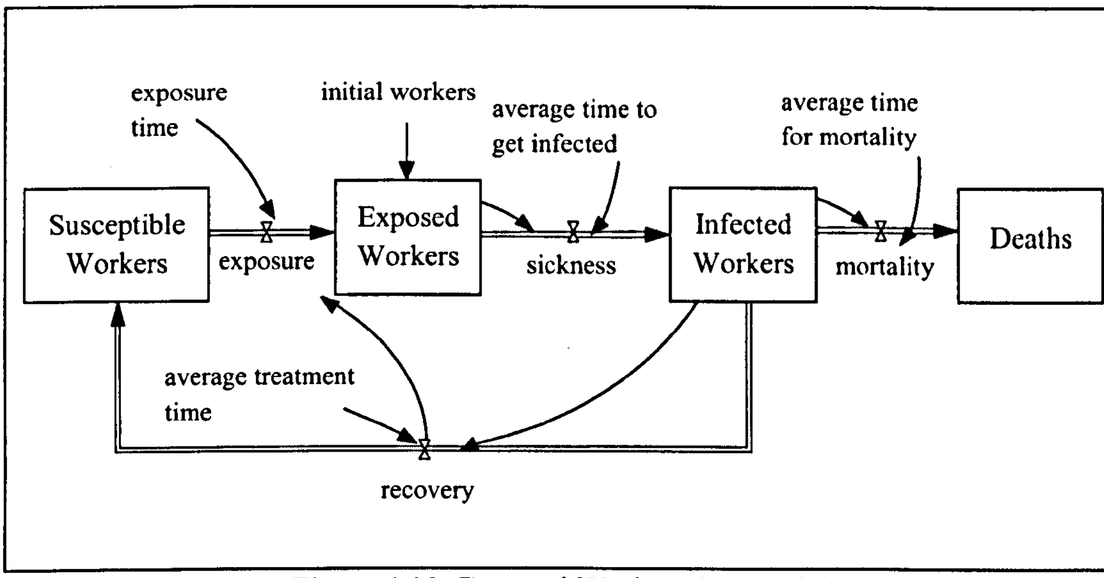

Figure 4.18: Exposed Workers SD Model

Mathematical formulations and units for the parameters are presented in Table A.7 in Appendix 4

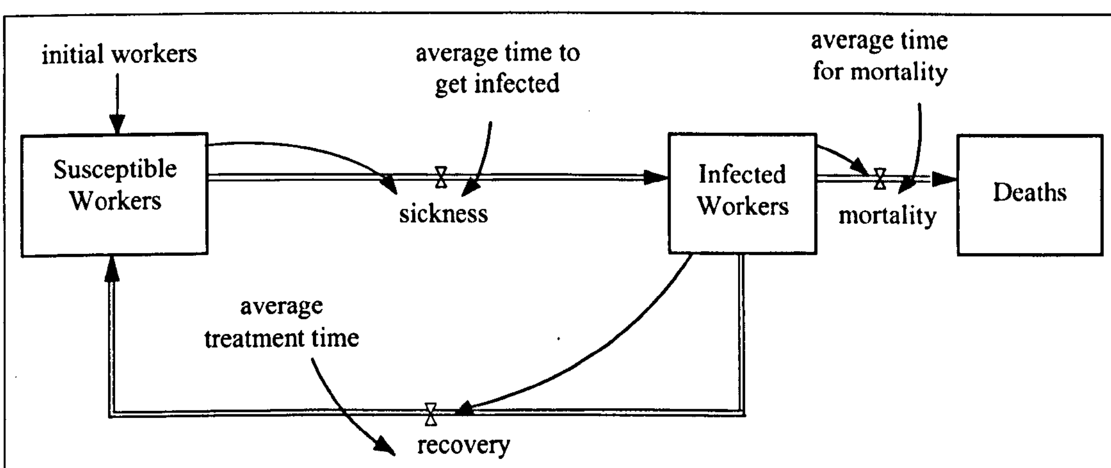

Figure 4.19: Non-Exposed Workers SD Model

Mathematical formulations and units of the parameters are presented in Table A.8 in Appendix 4.

Since initial workers are introduced to Exposed Workers SD Model as the exposed workers who have already completed an exposure time period, time period of both of the models was adjusted by subtracting the number of exposed years from 30-year-employment time (Figure 4.20).

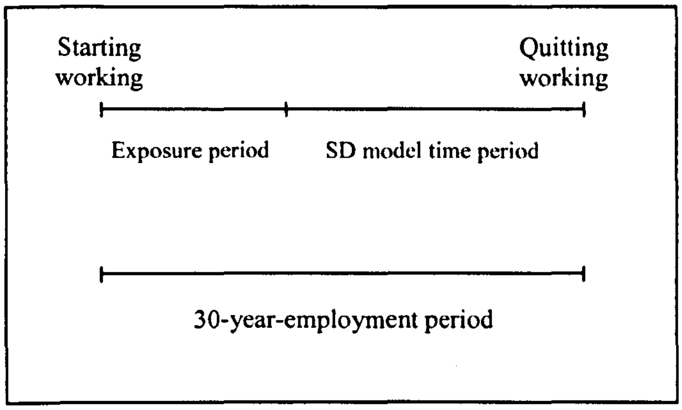

Figure 4.20: Time Frame for the Employees' Health Models

4.2.2 Data Sources

The data required for Exposed Workers SD model were gathered from epidemiologic studies (Chapter 2). Table 4.9 presents the relative risk values of certain diseases in the measured exposure period given by these studies.

4.2.3 Model Parameters

The latency periods (exposure time) provided in Table 4.9 were used to define the parameter called exposure time in Exposed Workers SD Model.

The parameter called "average time to get infected" in Exposed Workers SD Model was derived from the frequency of each specific disease in non-exposed population and the relative risk of each disease by following these steps;

(1) The frequency of each specific disease in non-exposed population ($f_{non\text{-}exposed}$) was gathered from nationwide records of annual hospital admissions in Turkish Health Statistics Database (Turkish Statistical Institution 2007b)

(2) The frequency of each specific disease in exposed population ($f_{exposed}$) was calculated from the equation (Eq.4.1) (RRs are as provided in Table 4.9)

$$RR = f_{exposed} / f_{non\text{-}exposed}$$

Eq.4.1: Relative Risk (Giusti 2009)

(3) The exposed frequencies were converted into time constants corresponding to the average time it takes for someone to be infected. This facilitates computing the output rate (namely "sickness") by dividing the stock (namely "Exposed Workers" by the rate (namely "average time to get infected") and not multiplying it by a frequency.

$$\text{Average time to get infected} = 1/\, f_{exposed}$$

Eq.4.2: Conversion of Frequency to Time Constant in Exposed Workers SD Model

In converting frequencies to a time constant in Non-Exposed Workers SD Model, the parameter called "average time to get infected" was derived from the non-exposed frequency of each disease;

$$\text{Average time to get infected} = 1/\, f_{non\text{-}exposed}$$

Eq.4 3: Conversion of Frequency to Time Constant in Non-Exposed Workers SD Model

(4) The parameter called "Average time for mortality" was derived from a mortality rate of each specific disease by using the same correlation as above. Whereas the exposure of hazardous emissions was reported to increase mortality (Table 4.9 incineration mortality), "average time for mortality" of each disease was derived from the exposed mortality rates which is equal to multiplication of non-exposed mortality rate (Turkish Statistical Institution 2007b) and $RR_{mortality}$ (Table 4.9).

Table 4.9: Data Sources for the Employees' Health SD Models

Landfill (Morbidity)			**Incineration (Morbidity)**		
	RR	exposure time (years)		RR	exposure time (years)
Respiratory Problems [1]	2.14	1	Skin Symptoms [2]	4.85	12.6
Dermatologic Problems [1]	2.07	1	Daily Cough [2]	6.58	12.6
Neurologic Problems [1]	1.89	1	**Incineration (Mortality)**		
Gastrointestinal Problems [1]	1.26	1	Oesophageal Cancer [3]	2.84	18.7
Hearing Problems [1]	1.73	.1	Stomach Cancer [3]	1.27	18.7
Itching Eyes [1]	1.54	1	Rectal Cancer [3]	2.52	18.7
Sorethroat [1]	2.26	1	Lung Cancer [3]	3.55	18.7
-	-	-	Bladder Cancer [3]	1.98	18.7
-	-	-	Malignant Cerebral Tumors [3]	2.77	18.7
-	-	-	Hematopoietic Cancer [3]	1.35	18.7
-	-	-	Nervous Disease [3]	1.33	18.7
-	-	-	Ischemic Heart Disease[3]	1.38	18.7
-	-	-	Respiratory Problems [3]	1.62	18.7
-	-	-	Liver Cirrhosis [3]	4.54	18.7
-	-	-	Gastric Cancer [4]	2.79	10

[1] Gelberg (1997) [2] Hours *et al.* (2003)
[3] Gustavsson (1989) [4] Rapiti *et al.* (1997)

Tables 4.10, 4.11 and 4.12 present the preparation of data to input to the models by following the steps above.

Table 4.10: Data Preparation for Landfill Workers

MORBIDITY	1st STEP		2nd STEP	3rd STEP		4th STEP	
Disease	$f_{non\text{-}exposed}$	RR	$f_{exposed}$	average time to get infected (Non-Exposed Workers SD Model)	average time to get infected (Exposed Workers SD Model)	mortality rate	average time for mortality
	dimensionless	dimensionless	dimensionless	1/ dimensionless	1/ dimensionless	dimensionless	1/dimensionless
Respiratory Problems	7.68×10^{-3}	2.14	16.44×10^{-3}	130	61	1.50×10^{-2}	67
Dermatologic Problems	1.63×10^{-3}	2.07	3.37×10^{-3}	613	297	0.10×10^{-2}	1,000
Neurologic Problems	2.12×10^{-3}	1.89	4.01×10^{-3}	472	249	1.30×10^{-2}	77
Gastrointestinal Problems	5.52×10^{-3}	1.26	6.96×10^{-3}	181	144	0.90×10^{-2}	111
Hearing Problems	0.43×10^{-3}	1.73	0.74×10^{-3}	2,326	1,351	0.02×10^{-2}	5,000
Itching Eyes	0.64×10^{-3}	1.54	0.99×10^{-3}	1,563	1,010	0.00×10^{-2}	-
Sorethroat	0.02×10^{-3}	2.26	0.05×10^{-3}	50,000	20,000	0.10×10^{-2}	1,000

Average treatment time was assumed 1 year and

Number of workers in a landfill site (initial workers) was assumed to be 10 (Samat 2009)

Time period of model is 29 years (by taking into account a 1 year exposure in 30-year-employment time)

Table 4.11: Data Preparation for Incineration Workers' Morbidity

MORBIDITY	1st STEP		2nd STEP	3rd STEP		4th STEP	
Disease	$f_{non\text{-}exposed}$	RR	$f_{exposed}$	average time to get infected (Non-Exposed Workers SD Model)	average time to get infected (Exposed Workers SD Model)	mortality rate	average time for mortality
	dimensionless	dimensionless	dimensionless	1/dimensionless	1/dimensionless	dimensionless	1/dimensionless
Daily Cough	$1.24x10^{-5}$	6.58	$8.16x10^{-5}$	80,645	12,255	$3.36x10^{-3}$	298
Skin symptoms	$1.63x10^{-3}$	4.85	$7.91x10^{-3}$	613	126	$1.11 x10^{-3}$	901
Average treatment time was assumed 3months (0.25 year) Number of workers in one incinerator (initial workers) was assumed to be 14 (Chapter 5.4.2.3 Employment) Time period of model is 17.4 years (by taking into account a 12.6 year exposure in 30-year-employment time)							

Table 4.12: Data Preparation for Incineration Workers' Mortality

MORTALITY	1st STEP	3rd STEP	4th STEP				
Disease	$f_{non\text{-}exposed}$	average time to get infected	non-exposed mortality rate	average time for mortality (Non-Exposed Workers Model)	$RR_{mortality}$	exposed mortality rate	average time for mortality (Exposed Workers Model)
	dimensionless	dimensionless	dimensionless	1/dimensionless	dimensionless	dimensionless	1/dimensionless
Oesophageal Cancer	5.38×10^{-5}	18,587	48×10^{-3}	20.8	2.84	136.0×10^{-3}	7.35
Gastric (stomach) Cancer	9.92×10^{-5}	10,081	50×10^{-3}	20.0	1.27	63.5×10^{-3}	15.75
Rectal Cancer	7.51×10^{-5}	13,316	30×10^{-3}	33.3	2.52	75.6×10^{-3}	13.23
Lung Cancer	30.13×10^{-5}	3,319	60×10^{-3}	16.7	3.55	213.0×10^{-3}	4.70
Bladder Cancer	9.59×10^{-5}	10,428	30×10^{-3}	33.3	1.98	59.4×10^{-3}	16.84
Hematopoietic Cancer	23.00×10^{-5}	4,348	42×10^{-3}	23.8	1.35	56.7×10^{-3}	17.64
Nervous Diseases	2.15×10^{-3}	465	13×10^{-3}	77.6	1.33	17.1×10^{-3}	58.48
Ischemic Heart Disease	2.90×10^{-3}	345	36×10^{-3}	27.8	1.38	49.7×10^{-3}	20.00
Respiratory Problems	8.00×10^{-3}	125	15×10^{-3}	66.7	1.62	24.3×10^{-3}	41.15
Malignant Tumours	5.52×10^{-3}	181	6×10^{-3}	117.4	2.77	16.6×10^{-3}	60.24
Liver Cirrhosis	2.66×10^{-4}	3,759	58×10^{-3}	17.2	4.54	263.3×10^{-3}	3.80
Gastric Cancer *	9.92×10^{-5}	10,081	50×10^{-3}	20.0	2.79	139.5×10^{-3}	7.17

Average treatment time was assumed 5years; Time period of model is 11.3 years (by taking into account a 18.7 year exposure in 30-year-employment)

* 10 year of exposure was taken into account as reported by Rapiti *et al.* (1997)

4.2.4 Results and Analysis of the Model

Simulation runs were carried out for each specific disease to predict health impacts on employees working at landfill sites and incineration plants separately (Table 4.13, Table 4.14 and Table 4.15) by assuming that;

(1) There was no immunity so that after the recovery period is completed, recovered workers enter susceptible workers stock.

(2) Employees' population is closed; once a worker is recruited, he keeps working in the same workplace for 30 years without changing his job or work environment.

$$S(t) + I(t) = N$$

Eq.4.4: Boundary for Population

Where S (t) and I (t) are the numbers of susceptible and infected individuals (including deaths after infection) at time t, and N is the constant population size

(3) Each reported case is a non-transmissible disease; hence it does not spread over other members of the society.

Table 4.16 presents total additional cases (mortality and morbidity) based on each reported case sourced in Table 4.9. It is stated by Defra (2004a) that on a national scale, taking into account the amount of waste managed by each process at present, emissions to air from waste management are estimated to result in approximately five hospital admissions for respiratory disease per year, and one death brought forward due to air emission per year in the UK as a whole.

The uncertainties surrounding the resultant outcomes of these variables should be considered carefully when health effects are to be estimated. Although there are concerns regarding the outcomes of epidemiologic studies, this research does not ignore the health issues reported previously since wellbeing of humans is a priority of any healthcare waste management to be developed. It is clear that future research into the health risks of waste management needs to overcome current limitations.

Table 4.13: Additional Cases for Landfill Workers

	Results of Exposed Workers SD Model		Results of Non-Exposed Workers SD Model		Additional Cases (30 year)	
Disease	Number of Recoveries	Number of Deaths	Number of Recoveries	Number of Deaths	Number of Recoveries	Number of Deaths
Respiratory Problems	4.48	0.0607	2.24	0.0303	2.24	0.0304
Dermatologic Problems	0.84	0.0009	0.45	0.0004	0.39	0.0005
Neurologic Problems	1.12	0.0133	0.56	0.0073	0.56	0.0060
Gastrointestinal Problems	1.96	0.0159	1.40	0.0133	0.56	0.0026
Hearing Problems	0.20	0.0000	0.11	0.0000	0.09	0.0000
Itching Eyes	0.28	0.0000	0.17	0.0000	0.11	0.0000
Sorethroat	0.01	0.0000	0.01	0.0000	0.00	0.0000
				TOTAL	3.95	0.0395

Figures in the table are out of 10 people as the number of workers in a landfill site (initial workers) was assumed to be 10 (Samat 2009)

The values on this table were used to evaluate the additional cases due to alternative treatment technologies proposed in the scenarios (Chapter 5) as alternatively treated HCW requires landfilling.

Table 4.14: Additional Cases for Incineration Workers' Morbidity

	Results of Exposed Workers SD Model		Results of Non-Exposed Workers SD Model		Additional Cases (30 year)	
Diseases	Number of Recoveries	Number of Deaths	Number of Recoveries	Number of Deaths	Number of Recoveries	Number of Deaths
Daily Cough	0.02	0.0001	0.00	0.0000	0.02	0.0001
Skin symptoms	1.60	0.0017	0.32	0.0004	1.28	0.0013
				TOTAL	1.30	0.0014

Figures in the table are out of 14 as the number of workers in one incinerator (initial workers) was assumed to be 14 (Chapter 5.4.2.3 Employment)

Table 4.15: Additional Cases for Incineration Workers' Mortality

	Results of Exposed Workers SD Model	Results of Non-Exposed Workers SD Model	Additional Cases (30 year)
	Number of Deaths	Number of Deaths	Number of Deaths
Oesophageal Cancer	0.0022	0.0009	0.0013
Gastric (stomach) Cancer *	0.0021	0.0017	0.0004
Rectal Cancer	0.0019	0.0008	0.0011
Lung Cancer	0.0165	0.0062	0.0103
Bladder Cancer	0.0019	0.0010	0.0009
Hematopoietic Cancer	0.0045	0.0034	0.0011
Nervous Diseases	0.0136	0.0104	0.0032
Ischemic Heart Disease	0.0501	0.0372	0.0129
Respiratory Problems	0.0697	0.0442	0.0255
Malignant Tumours	0.0337	0.0177	0.0160
Liver Cirrhosis	0.0166	0.0053	0.0113
Gastric Cancer*	0.0092	0.0042	0.0050
		TOTAL	0.0886

Figures in the table are out of 14 as the number of workers in one incinerator (initial workers) was assumed to be 14 (Chapter 5.4.2.3 Employment)

*When the set of data documented by Rapiti *et al.* 1997 was taken into account, more additional cases for gastric cancer mortality were gathered (0.0050>0.0004), hence 0.0050 was taken into account as it was the worst case scenario.

Table 4.16: Total Additional Cases

	Total Additional Cases in **30 year Employment Period**		Total Additional Cases on **Annual Basis**	
	Incineration	Landfill	Incineration	Landfill
Morbidity	1.30	3.95	0.04	0.13
Mortality	0.0900	0.0395	0.0030	0.0013

CHAPTER 5: RESULTS AND DISCUSSION ON MULTI-CRITERIA DECISION MAKING

This chapter describes how Multi Criteria Decision Analysis (MCDA) was used to analyse the decision problem. Four scenarios (alternatives) were proposed and each scenario was assessed against a number of criteria which were selected based on the literature review. Each criterion was then allocated a weighting relative to the others based on its importance by using a questionnaire. This analysis was conducted in five steps as below;

(1) Stakeholders were identified in healthcare waste management in Turkey.

(2) A decision tree and scenarios were built up according to interviews with the stakeholders and a literature review.

(3) A number of analyses were conducted to measure how well each scenario performed on each criterion.

(4) A questionnaire was prepared and sent to the stakeholders in order to assign relative weights to the identified criteria. This enabled comparison of the values allocated to one criterion with the values contributed to others.

(5) Resulting outcomes were inputted in the Right Choice Decision Analysis Software Tool to test how well each scenario performed overall and how sensitive the healthcare waste management system was to any change in the score of the identified criteria.

It is expected that once merits and drawbacks of the scenarios are evaluated in terms of multiple attributes; the outcomes will provide decision makers with an insight to improve their understanding of the decision problem; and to make the optimum decision based on past and present information and future predictions.

5.1 Identification of Stakeholders

The definition of stakeholder was firstly made by Freeman (1984) as *"Any group or individual who can affect or is affected by the achievement of the firm's objective"* (cited in Heidrich *et al.* (2009)). Later it was extended to include the actions, decisions, policies, practices, or goals of the organisation (Carroll and Buchholtz (2000) cited in Heidrich *et al.* (2009)) Furthermore in the waste management field, Joseph (2006) defined stakeholders as people and organisations having an interest in good waste management, and participating in activities that make it possible. They include enterprises, organisations and all others who are engaged in waste management activities.

The research brought forward the names and the roles of stakeholders involved in healthcare waste management in Turkey;

(1) "Turkish Ministry of Environment and Forestry" sets environmental regulations and standards; integrates environment in developmental planning and supporting environmentally sound developments with a long term view in allocating resources.

(2) "Provincial Directorate of Environment and Forestry of Istanbul Metropolitan" represents the Ministry of Environment and Forestry; and monitors and enforces the implementation of regulations.

(3) "Istanbul Metropolitan Municipality and ISTAC Company (affiliated company of the Municipality)" provides infrastructural inputs and services with trained staff implementing legislation and penalties for violators; and promotes sector participation.

(4) "Healthcare Institutions" practice source reduction and source segregation by providing training courses for hospital staff; and prepare waste management plans and monitor their implementation.

(5) "Private Sector" searches and implements appropriate actions.

(6) "Consulting Agencies" provide advice in the implementation of waste management schemes and targets.

(7) "Public/Patients/Visitors" participate in decision making and implementation; and cooperate with civic bodies in the identification of sites for waste management facilities and their operation.

(8) "Non-Governmental Organisations" mobilise community participation, voicing a local concern; and take a lead in forming community participation; and network with other organisations working in the same field. They are in cooperation with the municipality and other influential bodies to ensure maximum support.

(9) "Media" promotes environmental awareness by considering local priorities; and highlights environmental issues.

(10) "Academia" carries out relevant research and development in corporation with the needs identified by the governmental organisations.

The environmental problems are addressed by the interaction of these stakeholders who are concerned with certain aspects of the waste management. It might be assumed that many other actors are involved in the system. However the identified ones above are self evident actors, who play a direct role in healthcare waste management in Istanbul.

5.2 Determination of Scenarios

By considering these factors, four static scenarios were set to be judged in the MCDA. Different healthcare waste alternative treatment technologies were selected for each of the scenarios along with the Kemerburgaz Incinerator as it is the only plant in Istanbul, which treats the healthcare waste generated in the metropolitan in accordance with the EU directives.

5.2.1 Criteria for Determining Plant Design and Capacities

Although manufacturers provide national plant design capacities available for their various models, in practice operational experience and/or design methods that take account of for the specific densities, volumes and compositional characteristics will be used to make a final selection suited to local conditions. For example; in the initial stage of selecting a technology unit, a commissioning test is carried out on the system to find the most desirable capacity level to make sure the effective destruction of any bacteria. This capacity level, for instance, was determined as 70% of the actual processing ability of the Newcastle Autoclave SRCL Plant (Stidolph 2011). For the utilisation, the companies set targets to meet the optimum operating level (90% for the Newcastle Autoclave SRCL Plant (Stidolph 2011)).

Alternatively, the optimum operating level is based on the density of the inputted waste. The technology manufacturers size their machines by assuming the waste density (Diaz *et al.* 2008 determined that the average bulk density of healthcare waste varied between 151-262 kg/m^3); and then with the calculated average waste volume per hour, and the discussions with their customers regarding the overtime/downtime of the machine working hours, an operating throughput is estimated. The operating level of alternative technologies is assumed to be 85-95% by most of the manufacturers in the industry (McCoy 2010; Wallis 2010).

When determining the number of treatment units to deliver the four scenarios in this research, these axioms were assumed according to the information gathered from the manufacturers (Table 5.1);

1. Where multiple limits were shown, the capacity was set to be the largest in the manufacturer range.
2. A range of maximum throughput for the proposed plants was assumed as 85-95% of the design capacity.
3. Final unit capacity was selected based on it being utilised in a range of 50-75% of capacity to give a small supply margin.

5.2.2 Plant Design and Capacities of Scenarios

For each of the scenario, Table 5.2, Table 5.3, Table 5.4 and Table 5.5 represent briefly the type of plants, their capacities and their usage rates according to the estimated amounts of HCW from previous chapter (Chapter 4).

The main characteristics of the four scenarios considered in the research can be described as follows;

Table 5.1: Manufacturers of Alternative Technologies

Treatment Option	Manufacturer Reference	Model	Capacity (kg/cycle)	Time (minutes/cycle)	Capacity (tonne/hour)	Capacity * (tonne/annum)
Incinerator	Incinco Inc (Moynihan 2010) and Istac Inc. (Samat 2009)	-	*	-	1.000	8,760
Autoclave	Metan Inc. (Kaldirimci 2010)	Oil Fired Autoclave MWS 4000	*	-	0.450	3,942
Autoclave	Turanlar Inc. (Esen 2010)	Oil Fired Autoclave NYIR CLAVE LAJTOS 1000	*	-	0.200	1,752
Autoclave	Sanipak Inc. (McCoy 2010)	Electrical Autoclave 240-3P Sterilizer	75	70	0.065	569
Microwave	AMB-Ecosteryl Inc. (Jasmin 2010)	Ecosteryl 250	*	-	0.250	2,190
Hydroclave	Hydroclave Inc. (Wallis 2010)	Hydroclave H-25	90	60	0.090	788

* These systems are designed to work in continuous process (no cycles or batches)

** Treatment systems were assumed to work 365 days and 24 hours

Scenario-1:

It includes centralised treatment for both inc-only HCW and HCW SAT based at Kemerburgaz on the European Side.

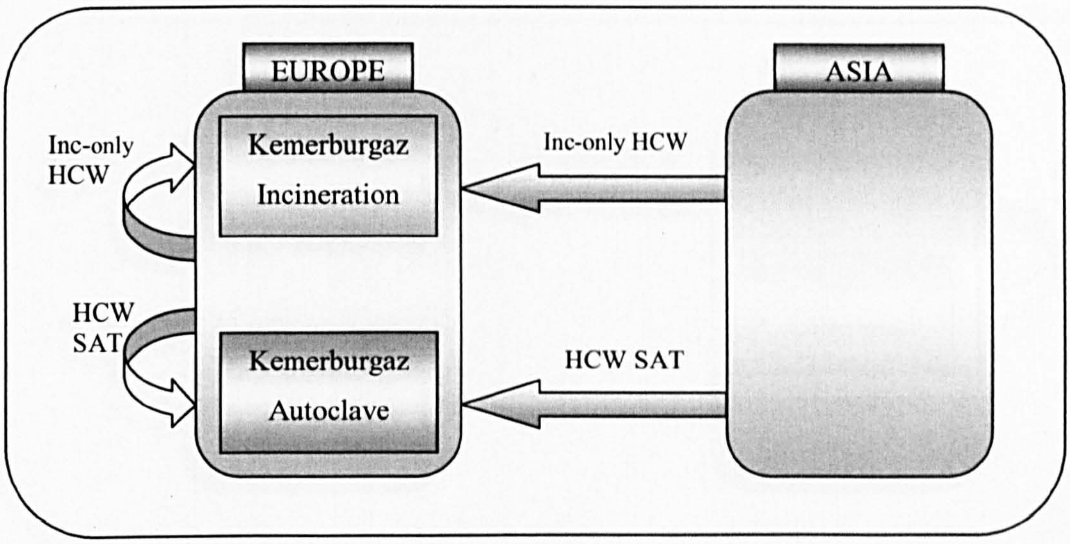

Figure 5.1: Schematic View of Scenario-1

Table 5.2: Facilities in Scenario-1

European Side Facilities	Manufacturer	Capacity (tonne/hour)	Average Capacity Utilisation (%)
Kemerburgaz Autoclave Unit 1 (Proposed)	Metan Inc.	0.450	85
Kemerburgaz Autoclave Unit 2 (Proposed)	Metan Inc.	0.450	85
Kemerburgaz Autoclave Unit 3 (Proposed)	Metan Inc.	0.450	85
Kemerburgaz Autoclave Unit 4 (Proposed)	Metan Inc.	0.450	85
Kemerburgaz Autoclave Unit 5 (Proposed)	Metan Inc.	0.450	85
Kemerburgaz Incinerator (Present)	-	1.000	54

Scenario-2:

It consists of centralised treatment for inc-only HCW at Kemerburgaz and regional centralised treatments for HCW SAT on both European and Asian sides.

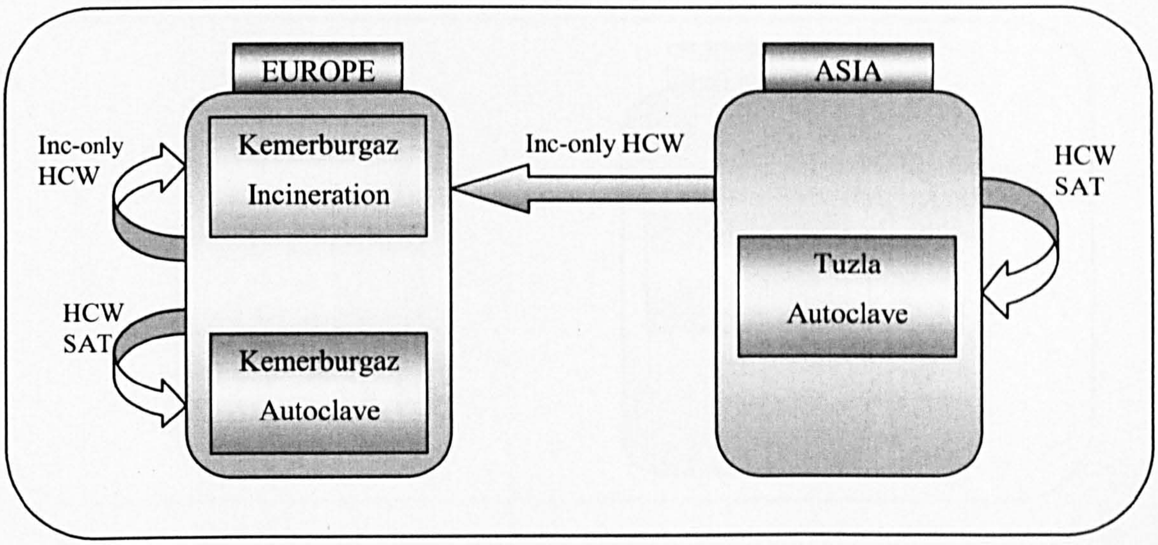

Figure 5.2: Schematic View of Scenario-2

Table 5.3: Facilities in Scenario-2

Asian Side Facilities	**Manufacturer**	**Capacity (tonne/hour)**	**Average Capacity Utilisation (%)**
Tuzla Autoclave Unit 1 (Proposed)	Metan Inc.	0.450	85
Tuzla Autoclave Unit 2 (Proposed)	Turanlar Inc.	0.200	85
European Side Facilities			
Kemerburgaz Autoclave Unit 1 (Proposed)	Metan Inc.	0.450	85
Kemerburgaz Autoclave Unit 2 (Proposed)	Metan Inc.	0.450	85
Kemerburgaz Autoclave Unit 3 (Proposed)	Metan Inc.	0.450	85
Kemerburgaz Autoclave Unit 4 (Proposed)	Sanipak Inc.	0.065	85
Kemerburgaz Incinerator (Present)	-	1.000	54

Scenario-3:

It comprises independent centralised treatment in both regions (incinerator and microwave on the European side and incinerator on the Asian Side)

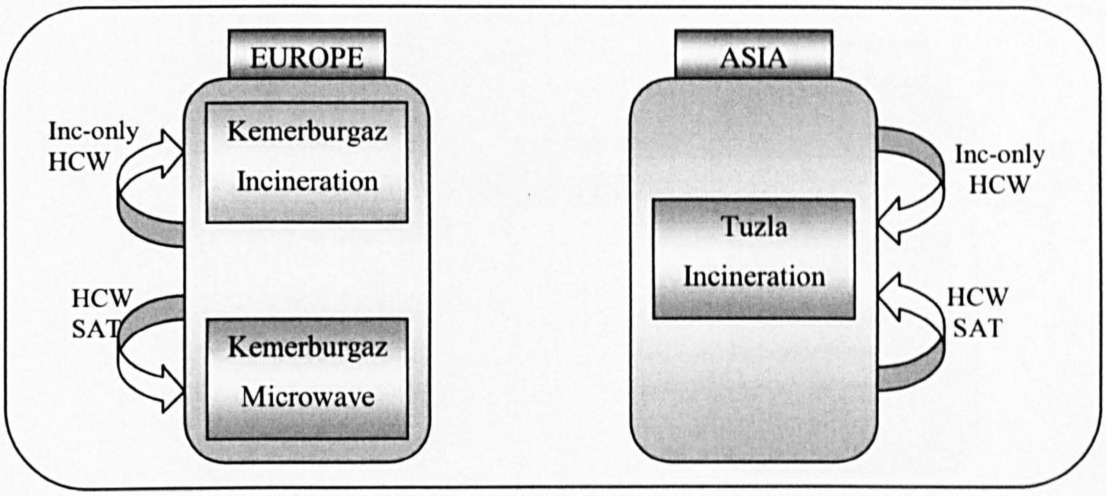

Figure 5.3: Schematic View of Scenario-3

Table 5.4: Facilities in Scenario-3

Asian Side Facilities	**Manufacturer**	**Capacity (tonne/hour)**	**Average Capacity Utilisation (%)**
Tuzla Incinerator Unit 1 (Proposed)	-	1.000	76
European Side Facilities			
Kemerburgaz Microwave Unit 1 (Proposed)	AMB-Ecosteryl Inc.	0.250	80
Kemerburgaz Microwave Unit 2 (Proposed)	AMB-Ecosteryl Inc.	0.250	80
Kemerburgaz Microwave Unit 3 (Proposed)	AMB-Ecosteryl Inc.	0.250	80
Kemerburgaz Microwave Unit 4 (Proposed)	AMB-Ecosteryl Inc.	0.250	80
Kemerburgaz Microwave Unit 5 (Proposed)	AMB-Ecosteryl Inc.	0.250	80
Kemerburgaz Microwave Unit 6 (Proposed)	AMB-Ecosteryl Inc.	0.250	80
Kemerburgaz Incinerator (Present)	-	1.000	36

Scenario-4:

It consists of centralised treatment for inc-only HCW at Kemerburgaz from both regions, decentralised facilities (hydroclaves) for HCW SAT based at hospitals.

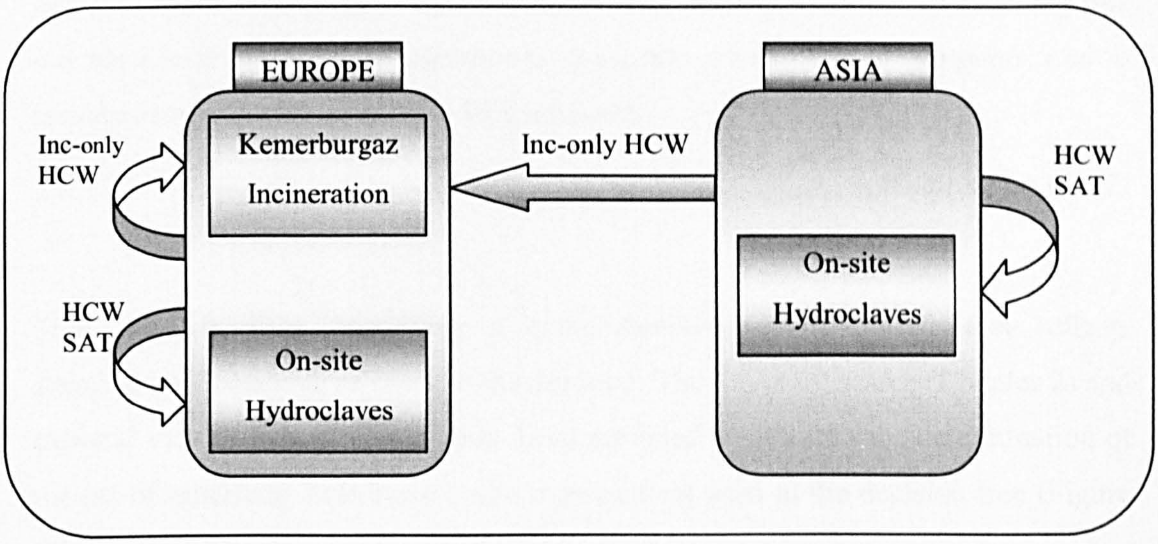

Figure 5.4: Schematic View of Scenario-4

Table 5.5: Facilities in Scenario-4

Asian Side Facilities	Manufacturer	Each Capacity (tonne/hour)	Average Capacity Utilisation (%)
8 Hydroclave Units (Proposed)	Hydroclave Inc.	0.090	90
European Side Facilities			
16 Hydroclave Units (Proposed)	Hydroclave Inc.	0.090	90
Kemerburgaz Incinerator (Present)	-	1.000	54

5.3 Building a Decision Tree

In the world as it is, we are nearly always operating in situations in which we would like to achieve several quite different goals. The conventional way of handling this has been to break our total aspirations down into a collection of sub-goals, and to concentrate on each one of these independently.

- Waddington (1977)

This stage involves specifying a comprehensive set of criteria that reflects stakeholders' concerns relevant to the decision. The literature search (Chapter 2) and experts' view (Chapter 3 Validation Test) provided insight into the determination of the set of criteria in healthcare waste management used in the decision tree (Figure 5.5).

The proper management of waste, according to Rushbrook and Finnecy (1988), has several aspects; political, social, environmental, economic and technical; other objectives of waste management policy differ from country to country. In particular public perception/participation is considered an important pillar of the robust decision making mechanism in developing countries. However in developing countries such as Turkey, this is underemphasised and very limited and thus excluded as a criterion in the decision tree. It is, therefore, inevitable that in the future, this decision tree will need to be restructured in a way to include this criterion more effectively as stakeholder participation widens and planning authorities in Turkey become more inclusive/sensitive to public opinion.

5.4 Measurement of Criteria

The criteria should be measurable as quantitative values if possible but also a qualitatively expressed valuation method can be used.

5.4.1 Quantitative Criteria

The quantitative criteria such as cost, global warming potential, water usage etc. are the criteria which could be measured and expressed as a numerical value.

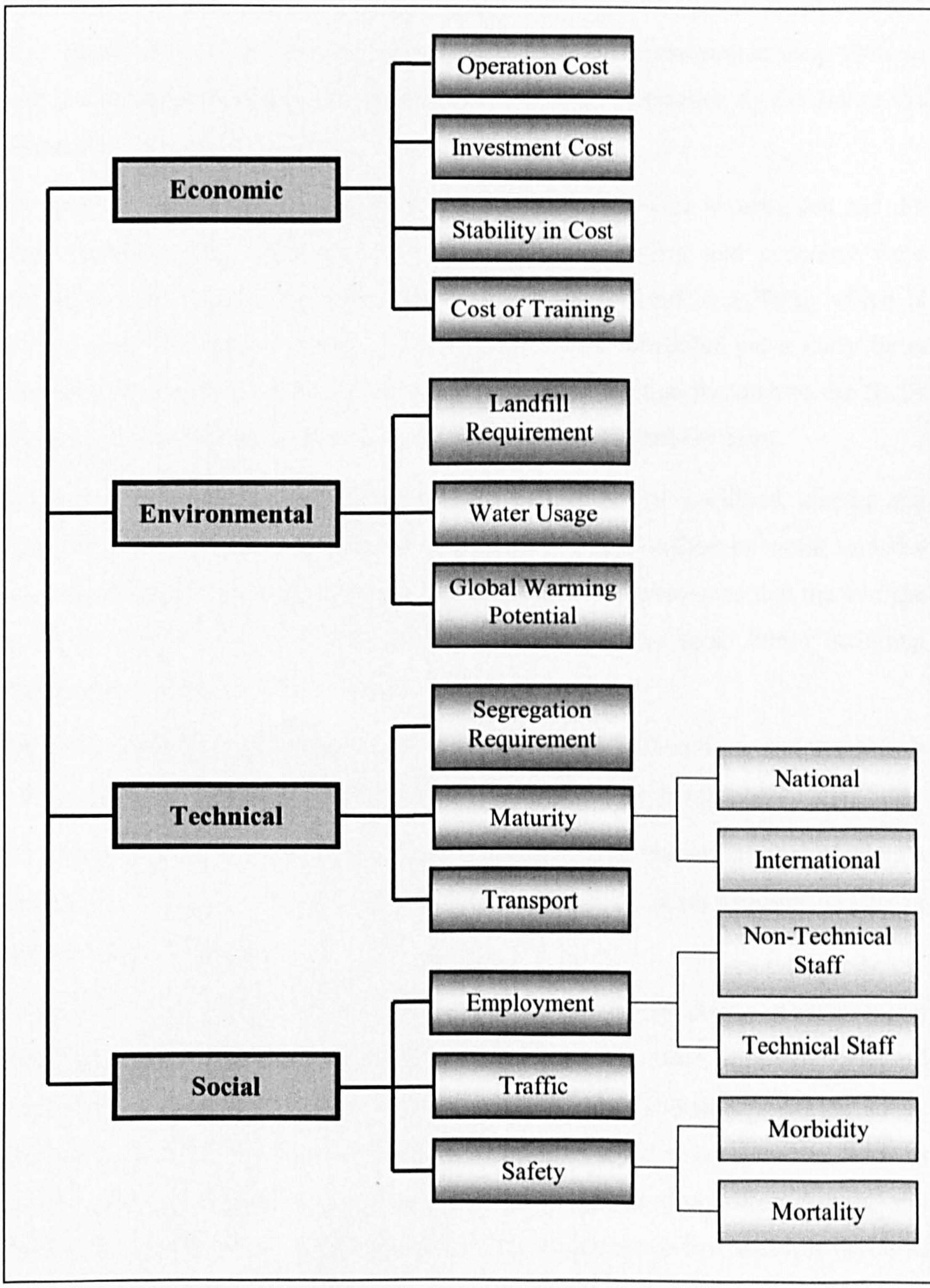

Figure 5.5: Healthcare Waste Management Decision Tree in Istanbul

5.4.1.1 Treatment Cost

The treatment cost (£/tonnes) was estimated based on the following assumptions;

Transportation of the HCW from hospitals to the treatment plants is conducted by collection vehicles owned by the Municipality. The cost of transport consists of fuel cost, salary of workers, cost of transport vehicles and maintenance cost of these vehicles (Turkish databases and additionally gathered information by the author via petitions).

For each of the scenarios, optimum transportation routes were investigated and the most feasible routes from the point of view of efficiency and economy were scheduled. The capacity of collection vehicles was selected as 2,500kg which is mostly used and sold in Turkey. The vehicles were scheduled on a daily basis including weekends. It was planned to have weekly collection for each of the HCFs starting from the treatment plant and ending at the same treatment plant.

According to the location and distance, carrying weight and workload, loading and unloading process times, the transit time between each collection point and the number of vehicles were determined. This was based on estimations that the average speed of vehicle was 35-40km/h and the loading process took 20min including picking up, loading and other required procedures.

The daily collection periods were planned as 12am-6am, 10am-4pm, and 9pm-12am for the weekdays in order to avoid traffic congestion in rush hours.

For each vehicle a driver and helper were allocated based on the maximum employees' working hours not exceeding 45hour/week (Turkish Ministry of Labour and Social Security 2004).

Investment costs consist of the costs relating to the purchase of mechanical equipments (and boilers if required), construction of a plant, infrastructure, and technological installations (e.g. temporary containers, container washing units, cooling units). *Operation costs* consist of three parts; (A) the consumables, such as electricity, water and fuel costs to run the facility; (B) the salary of employees, any replacement cost for the equipment; and (C) the maintenance cost which is involved in a cash flow after the equipment completes its service life as the technology requires additional maintenance and renovation after its service life completed. The service life for alternative treatment plants was assumed as 10 years and for the incinerator as 25 years.

Operating costs and investment costs of the proposed plants were sourced from the private companies (Turkey and Europe) as referenced by Table 5.1. They were then estimated as present values (base year 2010) by taking into account staffing costs in Turkey, shown in Table 5.6.

The resultant outcomes for each of the scenario are presented in Table 5.7. It should be noted that these values are indicative to be used for the comparative evaluation between the scenarios in terms of economics in the MCDA.

Table 5.6: Investment and Annual Operating Costs of the Plants

Treatment Option	**Capacity**	**Operating Cost**	**Operating Cost**	**Operating Cost**	**Investment Cost**
		(A)	**(B)**	**(C)**	
	tonne/hour	**£/annum**	**£/annum**	**£/annum**	**£**
Incinerator	1.000	313,500	1,140,400	-	2,000,000
Autoclave-1	0.450	59,100	161,200	10,125	980,000
Autoclave-2	0.200	26,300	130,800	10,125	360,000
Autoclave-3	0.065	15,400	48,400	1,300	170,000
Microwave	0.250	44,400	162,500	81,300	550,000
Hydroclave	0.090	20,700	42,600	4,250	130,000

The 2010 based operating cost (C) and investment cost values in Table 5.6 were provided by the Technology Manufacturers (referenced in Table 5.1). As the service life of the incinerator was assumed to be 25 years, the operating cost (C) was not included in the cash flow which covers the period of the project (2015-2040). Where it was needed to discount values from 2009 to 2010, the value was calculated by Eq.5.1

$$R_{2010}=R_{2009}\,(1+i)^t$$

Eq.5.1: Discounting Values

Where;

t: time of the cash flow (1 year)

i: interest rate

[6.5% for Turkey (Fikirkoca 2011)]

R_{2009}: cash flow at time 2009

R_{2010}: cash flow at time 2010

In calculating the operating cost (A), the cost of electricity, water and fuel was assumed to be £0.062kWh, £1.370/m^3 and £0.660/L respectively. For operating cost (B) the monthly salary of workers, engineers and managers were estimated at £615, £1,025 and £1,500 respectively. More details regarding the number of employees are included in Section 5.4.2.3 Employment.

Table 5.7: Cost Values of the Scenarios

Scena-rios	Proposed Facilities	Total Amount of HCW between 2015 and 2040 (project period)	2010 Based Investment Cost	**Performance of Scenarios in terms of Investment Cost***	Average Annual Operating Cost	**Performance of Scenarios in terms of Operating Cost***	Average Annual Transport Cost	Average Treatment Cost **
		tonne	£	%	£/annum	%	£/annum	£/annum
SC1	5 Autoclave-1 units	531,185	4.9 M	**17%**	2.46 M	**100%**	0.50 M	3.14 M
SC2	4 Autoclave-1 units 1 Autoclave-2 unit 1 Autoclave-3 unit		4.5 M	**35%**	2.64 M	**89%**	0.47 M	3.31 M
SC3	6 Microwave units 1 Incinerator		5.3 M	**0%**	4.04 M	**0%**	0.45 M	4.68 M
SC4	24 Hydroclave units		3.0 M	**100%**	2.73 M	**83%**	0.32 M	3.16 M

* Cost values were normalised in the [0-100] range for the ease of comparison of scenarios' performances in MCDA.

** Average Treatment Cost includes "Average Annual Operating Cost" and "Average Annual Transport Cost" and also annualised investment cost which was introduced in the cash flow as a 10-year payback period.

5.4.1.2 Global Warming Potential

A lifecycle approach was taken to produce estimates of the impact of each scenario on atmospheric GHG emissions over a 25 year design life. In order to compare performances of the four scenarios on the basis of functional equivalence, the *functional unit* was defined as one tonne of collected HCW. All emissions and energy uses were expressed as *"per tonne of HCW"*.

The lifecycle of the HCW, in this project, begins when materials become waste and are disposed of. It focuses on environment impacts in terms of GHG emissions, and energy recovery from incineration and landfill. These emissions were assumed basically to be based on the emissions of transportation, the consumption of fossil fuels and electricity for the treatment of wastes and the combustions of wastes for each of the scenario.

The system boundary includes collection processes until disposal in the incineration or alternative treatment plant. Emissions produced from the construction of facilities, nitrous oxide (N_2O) released from landfills and the fuel consumption for on-site operations, such as spreading and compaction of the waste and energy requirements for leachate treatment were not included as it was considered that these emissions are small in comparison to those released during the use of the facilities.

In *inventory analysis* of the assessment, GHG emissions from several sources were evaluated as follows;

Transport Emissions: The transportation of the HCW to the plants was calculated based on the distances travelled by each truck and illustrated by Table 5.8.

Process Emissions: These are the GHG emissions from the processing of the waste. They occur through combustion in the incineration and through the escape of methane from wastes degrading in landfill sites. In addition, this category includes any energy consumed in the process, such as auxiliary electricity and/or fuels.

Regarding GHG emissions due to landfilling the waste after alternative treatment process, the following approximations were assumed;

Table 5.8: Emissions due to Transport

Scenarios	Distance (km/annum)	CO_2 emissions due to transport * (tonnes/annum)	CO_2 emissions due to refining diesel** (tonnes/annum)	Total CO_2 Emissions due to Transport (tonnes/annum)
1	614,900	276.70	14.32	291.02
2	591,217	266.05	13.77	279.35
3	571,011	256.95	13.30	270.25
4	293,976	132.29	6.85	139.14

* Small Lorry (L1) 3.5-7.5 tonne capacity rigid vehicle emits 0.45 kg CO_2/km (Smith *et al.* 2001)

** Emission factor (tonne CO_2 per tonne of petrol refined) is 0.14 (Turkish Ministry of Energy and Natural Resources 2008)

- Intergovernmental Panel on Climate Change (2006) on greenhouse gas assessment reports that biogenic emissions of carbon should not be included in the assessment of emissions from waste. Biogenic emissions are considered to be from biomass sourced and are therefore treated, like biomass renewables, as having a zero carbon emission factor. The CO_2 component of landfill gas is considered carbon neutral. For GHG emissions from landfill sites in this study, it was assumed that only the contributing component was the methane that was not recovered by the landfill gas system.

- Where a gas collection system was in place, the landfill was fitted with a system to prevent the release of gas in combination with a system of wells and pumps used to extract the gas for combustion in a gas engine. The results of the study conducted by Spokas *et al.* (2006) showed 35% gas recovery for an operating cell with an active gas recovery system; 65% for a temporary covered cell with an active recovery system and 85% for a cell with clay final cover.

- Landfill gas (50% CH_4 and 50% CO_2) was generated during the waste acceptance lifetime of the landfill and for some considerable time after waste has ceased being accepted (Manfredi *et al.* 2010). While in this project an operational lifetime of 25 years was used, landfill gas production will continue even after the landfill stops accepting waste. In order to accommodate this, the landfill gas, which is emitted over a hundred year period, was taken into account in the context of life cycle analysis.

- The emissions from landfilled waste were estimated using first order decay method (FOD) as recommended by the IPCC methodology (IPCC 2000) and frequently applied to estimate landfill gas production (Ritzkowski and Stegmann 2010). The FOD also meets the requirement of a "conservative approach", which is adopted in technical assumptions underpinning the Clean Development Mechanism (CDM) (Couth *et al.* 2011; Maciel and Juca 2011). The CDM is one of the "flexibility" mechanisms along with emissions trading (ET) and joint implementation (JI) as defined in the Kyoto Protocol (UNFCCC 1998) in order to promote sustainable development.

According to the FOD method, the generation rate of the landfill gas depends on a number of factors, including gas generation rate as a function of the available waste in a landfill site, gas generation potential (L_o), gas generation rate constant (k), and age of the waste. The rate k is a function of the moisture content (precipitation, leachate circulation), while L_o is a function of waste composition. Eq.5.2, Eq.5.3 and Eq 5.4 give the FOD equations and default values used in the calculation of landfill gas emissions and Table 5.9 provides the composition of HCW for Istanbul.

$$CH_4 \text{ generated in year } t = \Sigma_x [(A \cdot k \cdot MSW_T(x) \cdot MSW_F(x) \cdot L_0(x)) \cdot e\hat{}(-k(t-x))]$$

Eq.5.2: Amount of Methane Generated. Adopted from IPCC 2000

Where;

t = year of inventory

x = years for which input data should be added

A = (1 – e^ (–k)) / k; normalisation factor which corrects the summation

k = Methane generation rate constant [k=0.05 default (IPCC 2000)]

MSW_T (x) = Total municipal solid waste (MSW) generated in year x

MSW_F (x) = Fraction of MSW disposed of in year x

L_0 (x) = Methane generation potential [MCF (x) • DOC (x) • DOC_F • F • 16 / 12]

Eq.5.3: Methane Generation Potential. Adopted from (IPCC 2000)

[L_0(x) was calculated as 0.0633t CH_4/tonne of waste]

Where;

MCF (x) = Methane correction factor in year x [MCF (x) =1 default (IPCC 2000)]

DOC (x) = Degradable organic carbon (DOC) in year x

DOC_F = Fraction of DOC dissimilated [DOC_F = 0.55 default (IPCC 2000)]

F = Fraction by volume of CH4 in landfill gas [F=0.5 default (IPCC 2000)]

16 / 12 = Conversion from C to CH4

$$DOC (x) = (0.4 \cdot A) + (0.17 \cdot B) + (0.15 \cdot C) + (0.3 \cdot D)$$

Eq.5.4: Degradable Organic Carbon. Adopted from IPCC 2000

[DOC(x) was calculated as 0.1725]

Where;

A = Fraction of MSW that is paper and textiles (A=0.25 from Table 5.9)

B = Fraction of MSW that is garden waste, park waste or other non-food organic putrescibles (B=0.25 from Table 5.9)

C = Fraction of MSW that is food waste (C=0.20 from Table 5.9)

D = Fraction of MSW that is wood or straw (D=0 from Table 5.9)

Table 5.9: Composition of HCW in Istanbul. Adopted from Demir *et al.* (2002)

Material	**Mass (%)**
Paper, Cardboard	15
Glass	15
Metals	1
Plastics	14
Blood and blood products	25
Food waste	20
Textile	10

The methane production profile from landfill sites in the scenarios are shown in Figure 5.6. The graph shows the methane generation (tonnes) from landfill with time. The generation peaks 35 years after the start of landfill and drops sharply after the landfill stops accepting the waste. However, the methane gas is still generated for almost 80 years after the landfill has closed.

The emissions due to landfilling of HCW after alternative treatment are shown by Table 5.10. *The electricity generation* from landfill sites was calculated based on the amount of methane collected by taking into consideration the electricity production rate of methane [1MWh=570m^3/h (Couth *et al.* 2011)]. The engine selection was done based on the methane generation profile. Since the methane generation varies with time, the engine may sometimes run below capacity.

The avoided emissions displace the need to draw equivalent electricity from the national grid by producing electricity from the HCW. In other words, the produced electricity from the waste was assumed to displace electricity drawn from the national grid, which is comprised of coal, oil and renewable origins. The CO_2-e emissions are not generated at the point of electricity used, but they are emitted in the process of power generation.

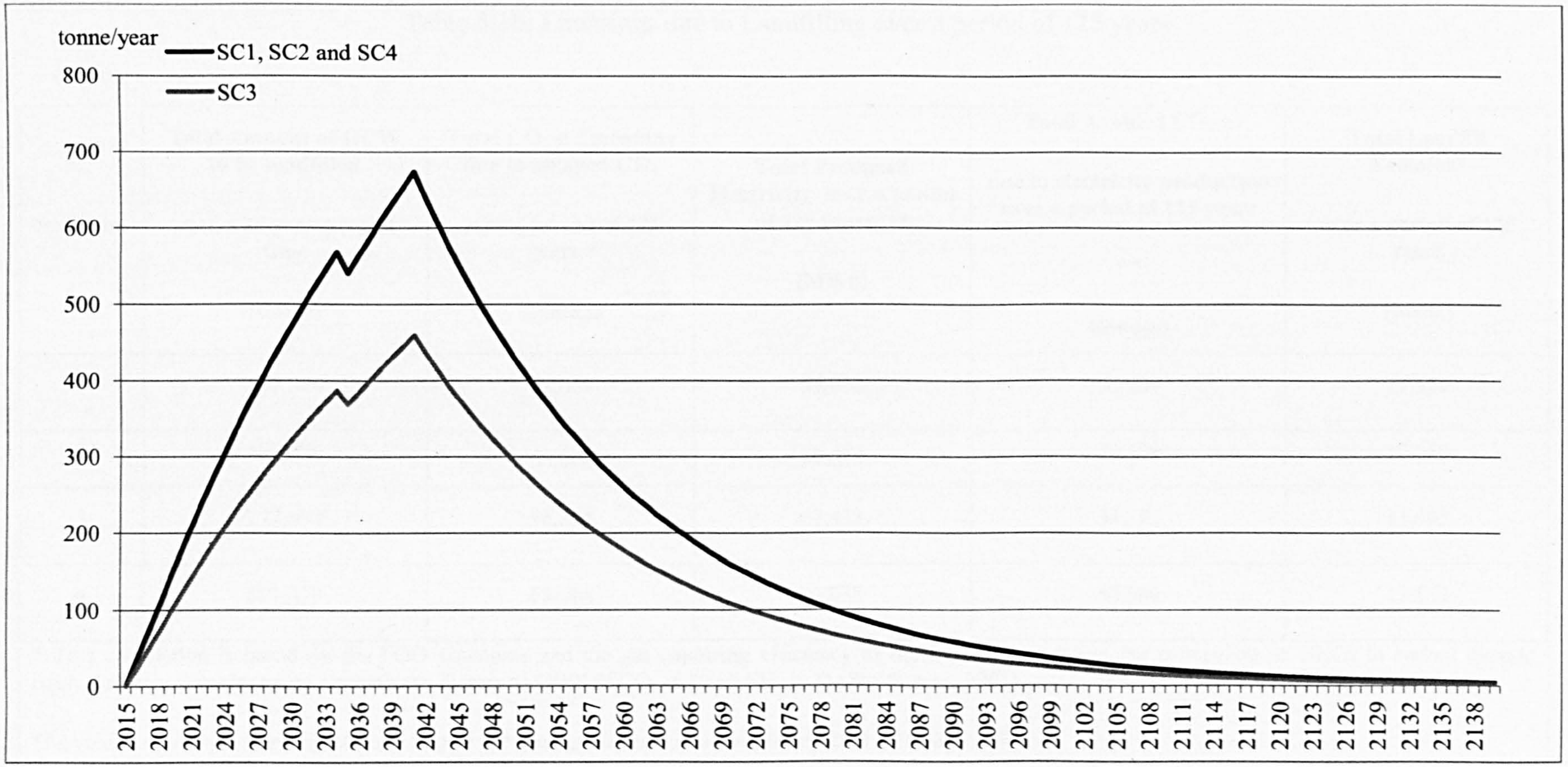

Figure 5.6: Methane Emission Profile of Landfill Sites based on IPCC 2000

Table 5.10: Emissions due to Landfilling over a period of 125 years

Scenarios	Total Amount of HCW to be landfilled over a 25 year project time (tonne)	Total CO_2-e Emissions due to escaped CH_4 over a period of 125 years * (tonnes)	Total Produced Electricity over a period of 125 years*** (MWh)	Total Avoided CO_2-e due to electricity production over a period of 125 years ** (tonnes)	Total Landfill Emissions over a period of 125 years (tonne)
1	407,379	68,068	99,038	50,509	17,559
2	407,379	68,068	99,038	50,509	17,559
3	277,397	46,334	67,438	34,392	11,942
4	407,379	68,068	99,038	50,509	17,559

* This calculation is based on the FOD equations and the gas capturing efficiency of the landfill cover; and the conversion of GHGs to carbon dioxide equivalent was done by using equivalence factors as GWP of CO_2 is 1 and CH_4 is 21 (Smith *et al.* 2001).

**Avoided emissions were offset according to the average national emission factor (0.51 CO2-e kg/ kWh).

***125 years was used in the model even though cost effective energy generation is probably not possible 25 years after landfill completion.

While some of these power plants operate as a base-load supply, such as fossil fuelled power plants; the others are intermediate and peaking plants, whose operation can be altered to meet the desired load at a given time of day, such as natural gas plants. As each of the plants have a different level of emissions rate, it is necessary to account for all these sources in the emission factors. There are mainly two approaches: (1) The average emission rate, which equals the total carbon equivalent emissions over total electricity consumption of the grid; and (2) the marginal emission factor, which excludes the base-load electricity sources and compares incremental changes that occur in the margin by a project that reduces the demand for electricity from existing plants (operating margin) or provides new generation from lower carbon sources than would otherwise be used (build margin).

However the grid operation is extremely complex, determining the sources of electricity offset by a given project poses a major challenge (Sathaye *et al.* 2004). Therefore several methods and models have been developed to simulate the emission offsets. One approach to estimating average and marginal emission rates for a grid is to use generation planning models, e.g., Ader, that simulate future grid operation in order to meet a forecasted hourly load (Rau *et al.* 2000; Kerr *et al.* 2002). In the international scale, the CDM proposes the marginal emission factor to be used in calculating the contribution of reducing CO_2 emissions from the grid power (Sharma and Shrestha 2006).

Nevertheless in the complex nature of the sources in the grid power, specifying the marginal emission factor is subject to considerable uncertainty in the long-term, particularly in the electricity sector where it is unclear what type/mix of generation will constitute the marginal source of electricity supply (Lelyveld and Woods 2010). For a reasonable assessment of emission reductions, the proper emission factor must be employed. It is therefore noteworthy to state that the average emission factor was used in offsetting electricity generation in this project.

The Turkish Statistical Institution (2008) provided the data for the total electricity generated and supplied in Turkey as 198,418GWh. Furthermore annual GHG emissions (CO_2 and CH_4) due to electricity production were reported by the Turkish Ministry of Energy and Natural Resources (2008) as 100,694Gg. By using these data, a national emission factor for Turkey was calculated as 0.51CO_2-e kg/ kWh.

The national emission factor was used where it was necessary to convert electricity requirement to CO_2-e emissions.

The HCW SAT is treated by alternative treatment plants (autoclave, hydroclave or microwave) prior to landfill. Currently there is no evidence in the literature reporting the formation of hazardous emissions due to treatment of waste by alternative treatments. However the electricity and the fuel oil required to run these plants indirectly cause emissions to be released.

Table 5.11 illustrates the electricity and fuel oil requirements of the proposed plants in the scenarios. The data in Table 5.11 were sourced from the private companies which were referenced in Table 5.1. These data were used in determination of the emissions due to alternative treatment and shown by Table 5.12.

Table 5.11: Energy Requirement of Alternative Technologies

Technology	**Capacity (tonne/hour)**	**Electricity Requirement (kW)**	**Fuel-Oil Requirement (Litre/tonne)**
Fuel Oil Fired Autoclave	0.450	27.5	15.6
Electrical Autoclave	0.065	29.4*	-
Microwave	0.250	80	-
Hydroclave	0.090	364**	-

*Requires external boiler and the values includes the electricity requirement of the external boiler.

** "The Hydroclave takes more electricity than the autoclave to heat up initially as it has to transfer the heat from the outer jacket into the vessel chamber through conduction. Once the Hydroclave is hot, it will require considerably less energy. The high energy requirement is only for the first run, and then diminishes. This value represents the worst case scenario, a very cold Monday morning after the machine been off all weekend. Most of the time, the boiler will be idle except for the beginning of the day. " (Wallis 2010).

Table 5.12: Emissions due to Alternative Treatment over a 25 year project time

Scenarios	Alternative Technology	Total amount of HCW to be alternatively treated over a 25 year project time (tonne)	CO_2-e Emissions due to electricity requirement to run the facility * (tonne)	CO_2-e Emissions due to fuel refining ** (tonne)	CO_2-e Emissions due to fuel burning *** (tonne)	Total Emissions due to Alternative Treatment over a 25 year project time (tonne)
1	Oil Fired Autoclave	407,379	12,674	763	17,396	30,833
2	Oil Fired Autoclave	399,261	12,327	742	16,918	29,987
	Electrical Autoclave	8,118	2,577	-	-	2,577
3	Microwave	277,397	45,271	-	-	45,271
4	Hydroclave	407,379	75,626	-	-	75,626

* Based on the average national emission factor (0.51 CO2-e kg/ kWh).

** As explained in Transport Emissions

*** The CO_2 emission due to burning of fuel was calculated as 3.2 kg CO_2 / kg of fuel oil based on the chemical reaction of

$$2\ C_{12}H_{23} + 71/2\ O_2 \rightarrow 23\ H_2O + 24\ CO_2$$

Regarding the emissions due to incineration, the method provided by the Intergovernmental Panel on Climate Change (IPCC 2006) was implemented. In this method, only CO_2 emissions from the incineration of carbon of fossil origin (i.e. plastics, certain textiles, rubber, liquid solvents and waste oil) needs to be reported, biogenic CO_2 emissions from the combustion of wastes are not taken into account.

The calculations of the emissions due to burning of wastes and producing electricity depending on the calorific value of the HCW are shown in Eq.5.5 and Eq.5.6. Default values of healthcare waste components and Calorific Values of HCW Components are shown in Table 5.13 and 5.14 respectively. The data regarding to the electricity requirement to run the incinerator were sourced from Moynihan (2010) as 55 kWh/tonne; and the fuel input per tonne of material throughput was determined as 1.2 kg fuel by Fisher *et al.* (2006). The emissions due to incineration were documented in Table 5.15.

$$CO_2 \text{ Emissions} = MSW * \Sigma_j (WF_j * dm_j * CF_j * FCF_j * Of_j * 44/12)$$

Eq.5.5: CO_2 Emissions from Incinerators. Adopted from IPCC 2006

Where;

CO_2 Emissions = CO_2 emissions in inventory year,

MSW = total amount of waste as wet weight incinerated (HCW),

WF_j = fraction of waste type/material of component j in the MSW

dm_j = dry matter content in the component j of the MSW incinerated

CF_j = fraction of carbon in the dry matter (i.e., carbon content) of component j

FCF_j = fraction of fossil carbon in the total carbon of component j

OF_j = oxidation factor (100% assumed)

44/12 = conversion factor from C to CO_2

Table 5.13: Default Values of HCW Components. Adopted from IPCC 2006

Material	% WF_j	dmj in % of wet weight *	CF_j %	FCF_j (%)	WFj *dmj* CFj* FCFj *Ofj*44/12
Paper, Cardboard	0.15	0.9	0.46	0.01	0.0023
Glass***	0.15	1.0	NA	NA	–
Metals***	0.01	1.0	NA	NA	–
Plastics	0.14	1.0	0.75	1	0.3850
Blood and blood products	0.25	–	–	NA	–
Food waste	0.20	0.4	0.38	NA	–
Textile**	0.10	0.8	0.50	0.2	0.0293
					0.4166

* The moisture content given here applies to the specific waste types before they enter the collection and treatment.

**40 percent of textile is assumed to be synthetic (default).

*** Metal and glass contain some carbon of fossil origin. Combustion of significant amounts of glass or metal is not common.

$$DE = CV \times ECE \times EF \times 277.8$$

Eq.5.6: Incineration Displaced Emissions (Green 2005)

Where;

DE = displaced emissions (kg CO_2/tonne of waste)

CV = calorific Value of Waste (GJ/tonne of waste)

ECE = energy conversion efficiency (%) [Assumed to be 20% as stated by Fisher *et al.* (2006)]

EF = national energy emission factor (kg CO_2/kWh) (0.51 CO_2-e kg/ kWh)

Table 5.14: Calorific Values of HCW Components

Components	**Calorific Values (CV)***	**Contribution weight to incinerator**	**Net Calorific Values Contribution**
	GJ/tonne of waste component	%	GJ/tonne waste
Paper, Cardboard	11.5	0.15	1.725
Glass	0	0.15	0
Metals	0	0.01	0
Plastics	31.5	0.14	4.41
Blood and blood products	0	0.25	0
Food waste	3.98	0.2	0.796
Textile	14.6	0.1	1.46
Total			8.391
*Net calorific values of the components were sourced from European Commission Waste Management Options and Climate Change Report [Smith *et al.* (2001)].			

The GHG emission per tonne of healthcare waste was calculated for each of the scenarios and displayed by Table 5.16. The produced electricity on the landfill sites and incinerators were assumed to be used in running these facilities. Therefore the avoided emissions by using the HCW to produce electricity (via landfill gas engines and incinerators) were subtracted from the sum of the process emissions.

In this section, an overview of the GHG assessment has been provided. For reference some calculations of GHG emissions from proposed plants were provided, although it should be noted that these are indicative estimates only.

Table 5.15: Emissions due to Incineration over a 25 year project time

Scenarios	Total amount of HCW to be incinerated over a 25 year project time (tonne)	CO_2 Emissions due to waste burning (tonne)	CO_2 Emissions due to fuel burning* (tonne)	CO_2 Emissions due to fuel refining** (tonne)	Avoided CO_2-e Emissions due to electricity production (tonne)	CO_2-e Emissions due to electricity requirement to run the facility (tonne)	Total Incineration Emissions over a 25 year project time (tonne)
1	123,806	51,579	470	21	29,436	3,473	26,107
2	123,806	51,579	470	21	29,436	3,473	26,107
3	253,788	105,731	963	43	60,341	7,119	53,515
4	123,806	51,579	470	21	29,436	3,473	26,107

*As explained in the Alternative Technology Emissions Section

** As explained in Transport Emissions Section

Table 5.16: CO2-e Emissions of the Scenarios

	Emissions CO_2-e (kg) /tonne of HCW						
Scenarios	Transport	Incineration	Landfill	Alternative Treatment	Total Emissions CO_2-e (kg) /tonne of HCW	Total Emissions* CO_2-e (tonne)	**Performance of Scenarios in terms of GWP (%) ****
1	13.7	49.1	33.1	58.0	153.9	81,749	**100%**
2	13.2	49.1	33.1	61.3	156.7	83,237	**97%**
3	12.7	100.7	22.5	85.2	221.1	117,445	**13%**
4	6.5	49.1	33.1	142.3	231.0	122,704	**0%**

* Based on 531,185 tonne HCW is processed between 2015 and 2040.

** GWP (Global Warming Potential) values were normalised in the [0-100] range for the ease of comparison of scenarios' performances in MCDA.

5.4.1.3 Water Usage

The data on water usage for each treatment technology option was supplied by the companies, which were referenced in Table 5.1, and how much water is required to operate each treatment technology was illustrated in Table 5.17. The water usage for each of the scenario was then calculated by using the amount of waste treated in each treatment technology proposed in the four scenarios were presented in Table 5.18.

5.4.1.4 Landfill Requirement

This is the criterion based on the amount of the HCW (Chapter 4) which requires to be landfilled after alternative treatment. Since all the HCW which was produced from the Asian Side is proposed to be incinerated in the Tuzla Incinerator in the Scenario-3, the landfill requirement in this scenario is less than that of the other scenarios (Table 5.19).

Table 5.17: Water Consumption of the Treatment Options

Treatment Options	**Water Consumption Litre/hour**	**Source of Reference**	**Reference**
Incineration	2,500	Literature	Yufit (2010)
Autoclave	200	Manufacturer: Metan Inc.	Kaldirimci (2010)
Microwave	*	Manufacturer: AMB Ecosteryl Inc.	Jasmin (2010)
Hydroclave	228 **	Manufacturer: Hydroclave Inc.	Wallis (2010)

* Dry heat processes do not use water or steam.

** On average, the steam used per batch is 91kg. However, as noted previously, 97% of this steam is returned to the boiler. Therefore, water loss per cycle is 2.7kg. This is not included in the 228L used for the condenser bottle (Wallis 2010).

Table 5.18: Water Consumption of the Scenarios

Scenarios	Total Water Consumption over a 25 year project life (m^3)	**Performance of Scenarios in terms of Water Consumption (%) ***
SC1	484,686	**100%**
SC2	488,761	**100%**
SC3	634,469	**71%**
SC4	1,238,338	**0%**

* Water Consumption values were normalised in the [0-100] range for the ease of comparison of scenarios' performances in MCDA.

Table 5.19: Landfill Requirement of the Scenarios

Scenarios	Inc-only HCW estimated to be produced between 2015-2040	HCW SAT estimated to be produced between 2015-2040	**Performance of Scenarios in terms of Landfill Requirement** *
	(tonne)	(tonne)	%
SC1	123,806	407,376	**0%**
SC2	123,806	407,376	**0%**
SC3	253,788	277,397	**100%**
SC4	123,806	407,376	**0%**

* Landfill Requirement values were normalised in the [0-100] range for the ease of comparison of scenarios' performances in MCDA.

5.4.1.5 Segregation Requirement

Alternative technologies can only treat the HCW SAT stream. Therefore further segregation is necessary to separate HCW SAT from inc-only HCW if the HCW management system includes any alternative technology in place. If all the HCW is planned to be treated in the incinerator, this further segregation is not required to be undertaken (as it is the case on Asian Side in Scenario-3).

When the dynamics of building new hospitals according to the demand of Category-1 (chronic) and Category-2 (acute) patients over the projected period is considered, the number of hospitals is expected to increase on both the European and Asian Sides (Chapter 4: HCW SD Model). Moreover the number of hospitals which undertake further segregation is also dependent on the transition period during which the proportion of the hospitals implementing further segregation relative to the total number of hospitals increases by 20% starting from 2015 to 2020 (as explained in Chapter 4). According to the outcomes of HCW SD Model it is estimated that in Scenario 1,2 and 4 there will be 192 and 81 hospitals undertaking this segregation on the European and Asian Side respectively on a yearly average basis between 2015 and 2040.

Further segregation is not required on the Asian Side in Scenario 3 as the proposed plant is an incinerator (Figure 5.3: Schematic View of Scenario 3). If it is considered that not stipulating further segregation brings forward more practicality to the hospitals where healthcare waste occurs in the first place, Scenario 3 has the advantage of having no further segregation scheme in these 81 hospitals on the Asian Side compared to other scenarios. The practicality of having less segregation is represented by the criterion of segregation requirement under the branch node of "Technical" in the decision tree {for which SC3's performance in a [0-100] range is 100%, while others are 0% as they are equally lower than SC3}, whereas the criterion of "training cost" under the branch node of "Economic" stands for the cost due to training medical staff on how to conduct further segregation {SC3's performance on the cost of training in a [0-100] range is 100%, while others are 0% as they require equally higher cost than SC3}.

It is essential to deliver training courses for the medical personnel who work at the hospitals which are obliged to conduct further segregation. Providing these training courses aims to improve quality standards at hospitals along with training the staff on how to carry out further segregation in their working environment. Bekci and Toraman (2011) conducted research in order to identify a range of cost components in one of the Turkish hospitals, namely Suleyman Demirel Research Hospital. They determined that delivering training courses required a conference room with a laptop computer, an air-conditioner and a projector. The study found that the electricity requirement for lighting the room along with the operating cost of the equipments was £444 annually based on the assumption that 50 training sessions, 2 hours/each, were undertaken annually (base year 2010).

They also identified that consultancy service was required from one of the consultant agencies which costs £566 on an annual basis (base year 2010). As the instructor(s) who give presentations is/are already medical staff working at hospitals, there is no additional payment made to them, however it should be noted that this training is undertaken during staff working hours; hence 100 working hours (50 training sessions, 2 hours/each) of each personnel is allocated to these courses per year (allocated hours).

The cost of training was calculated as £8,666/hospital on average (base year 2010) of which £1,010 (444+566) was the operating cost of conference equipment and £7,656 was annual personnel cost (allocated hours cost) based on the assumptions: (1) The number of medical personnel in Istanbul (physicians –including general practitioners and specialist physicians-, nurses and midwives) per hospital is 25 (Turkish Ministry of Health 2010); (2) Maximum working hours per week is 45hour/week (Turkish Ministry of Labour and Social Security 2004); and (3) The average salary of health practitioners in Turkey is £7,500 per year.

In comparison to other criteria under the branch node of "Economic", training cost is not a serious burden in the healthcare waste management system. It is also because this cost is paid periodically by hospitals (from hospital budgets) as a part of their other mandatory payments; it is an *absorbed* cost and its' relative weight is not expected to be high compared to, for example, investment cost.

5.4.1.6 Transport

This criterion was tested by measuring the distances (km/annum) each collection vehicle was required to travel in each of the scenarios. The results of the transport schedule (the length of the routes of proposed collection vehicles for each scenario and the time required for the collection) can be found in Table 5.20 and the assumptions of this calculation can be found in the Section on Treatment Costs.

5.4.2 Qualitative Criteria

For these criteria to be expressed either a scale could be used or the criteria could be broken into quantitative sub criteria. For instance, the criterion of social cannot be expressed as a measureable figure, so it was quantified in terms of "traffic", "safety" and "employment".

5.4.2.1 Traffic

This criterion was assessed by measuring the time which was spent by each of the collection vehicles in traffic according to the transport schedule (Table 5.20).

Table 5.20: Transport Schedule

	European Side	Asian Side	Total	% Normalised Values in the [0-100] range
Scenario 1				**For the node criteria of "Traffic" and Transport" in MCDA**
Number of vehicles	5	3	8	
Number of collection points	314	162	476	
Number of routes in week	88	56	144	
Distance (km/week)	6,570	5,223	11,793	**0%**
Total time (h/week)	361	263	624	**0%**
Number of workers	18	12	30	
(¾) Vehicle Capacity usage (%)	81%	82%	82%	
Scenario 2				
Number of vehicles	5	3	8	
Number of collection points	314	162	476	
Number of routes in week	88	56	144	
Distance (km/week)	6,570	4,769	11,339	**7%**
Total time (h/week)	361	228	589	**13%**
Number of workers	18	10	28	
(¾)Vehicle Capacity usage (%)	81%	82%	82%	

Please see next page

	European Side	Asian Side	Total	% Normalised Values in [0-100] range
Scenario 3				
Number of vehicles	5	3	8	
Number of collection points	314	97	411	
Number of routes in week	88	48	136	
Distance (km/week)	6,569	4,381	10,950	**14%**
Total time (h/week)	361	165	526	**36%**
Number of worker	18	8	26	
(¾)Vehicle Capacity usage (%)	81%	97%	87%	
Scenario 4				
Number of vehicles	15	9	24	
Number of collection points	261	134	395	
Number of routes in week	50	37	87	
Distance (km/week)	3,550	2,088	5,638	**100%**
Total time (h/week)	216	137	353	**100%**
Number of worker	10	8	18	
(¾)Vehicle Capacity usage (%)	61%	70%	65%	

5.4.2.2 Safety

The safety of waste treatment technologies is vital to society. The basic safety for workers on the site has to be guaranteed first. The results of the Employees' Health SD Model (Chapter 4) were used in assessing this criterion and are displayed in Table 5.21.

Table 5.21: Estimated Increase in Morbidity and Mortality

Scenarios	Facilities*	Morbidity**			Mortality**		
				% Normalised Values			**% Normalised Values**
SC1	1 Incinerator	0.04	0.17	**100%**	0.0030	0.0043	**100%**
	1 Landfill	0.13			0.0013		
SC2	1 Incinerator	0.04	0.30	**0%**	0.0030	0.0056	**57%**
	2 Landfill	0.13x2			0.0013x2		
SC3	2 Incinerator	0.04x2	0.21	**69%**	0.0030x2	0.0073	**0%**
	1 Landfill	0.13			0.0013		
SC4	1 Incinerator	0.04	0.30	**0%**	0.0030	0.0056	**57%**
	2 Landfill	0.13x2			0.0013x2		

Unit is people (cases)

* Number of Facilities is based on schematic views of the four scenarios show in Figure 5.1, Figure 5.2, Figure 5.3 and Figure 5.4. It was assumed that the treated waste via alternative treatment was disposed of at the landfill site which is on the same side as the alternative treatment, i.e., if HCW SAT was treated in the autoclave located on the European Side, treated waste is disposed of the landfill on the European Side.

** Mortality and Morbidity values are taken from Chapter 4-Table: 4.16

5.4.2.3 Employment

Waste management facilities create jobs which are beneficial to improve the living quality of local people. In this criterion, contribution of waste treatment facilities to job creation was examined (Table 5.22).

Table 5.22: Number of New Work Positions in Scenarios

T: Technical Personnel	NT: Non-Technical Personnel										
Scenarios	Alternative Treatment		Incineration		Transport		Total Technical Personnel*		Total Non-Technical Personnel**	
	T	NT	T	NT	T	NT	Total	% Normalised Values	Total	% Normalised Values
SC1	10	60	2	12	-	30	12	0%	102	14%
SC 2	11	60	2	12	-	28	13	25%	100	7%
SC 3	12	48	4	24	-	26	16	100%	98	0%
SC 4	12	96	2	12	-	18	14	50%	126	100%

*Technical staff consists of plant managers, engineers and general managers.

**Non-Technical Staff includes collection vehicle drivers and their helpers; and also employees who work at the waste plants.

5.4.2.4 Maturity

Measuring the degree of maturity of technologies could refer to how widespread the technology is at both national and international level. This factor could be related to the resistance of a technology to failure or the ability of "fail well" (fail without catastrophic consequences) (Wang *et al.* 2009). In order to measure this criterion, the scale which was proposed by Beccali *et al.* (2003) was used;

1. Not present on the market at least in an experimental stage
2. Pilot plants
3. Start of market availability
4. Market availability of the technology for less than 10 years
5. Market availability of the technology for more than 10 years

On a national scale, the experience of Turkey on alternative technologies is very limited. There are only a few autoclaves, which have been used mostly to treat MSW for less than 10 years. On the other hand, in the UK (Tudor *et al.* 2009; McIntyre 2011), Germany (Hempen 2011), Luxembourg (Thyes 2011), Sweden (Christiansson 2011), Latvia (Gusca 2011) steam based technologies, such as hydroclave and autoclave, have been used for more than 10 years ago and have recently become widely used technologies. However the same trend has not been observed for microwave technology and its usage remains limited within a few European countries. According to the references above, the scenarios were ranked as below (Table 5.23);

Table 5.23: Maturity of Scenarios

Scenarios	Alternative Technology	National		International	
		In Scale Above	**% Normalised Values**	In Scale Above	**% Normalised Values**
SC1	Autoclave	4	**100%**	5	**100%**
SC2	Autoclave	4	**100%**	5	**100%**
SC3	Microwave	1	**0%**	4	**0%**
SC4	Hydroclave	4	**100%**	5	**100%**

5.4.2.5 Stability in Cost

This criterion represents the flexibility of technologies in the scenarios to any unpredictable change in the amount of HCW in the future. For instance, Scenario 4, which consists of a number of on-site hydroclaves, is the most flexible scenario compared to other scenarios in responding to any increase in capacity which might be required in the future.

In order to measure this criterion, the number of treatment units was used in scoring each scenario; i.e. 6 treatment units in Scenario 1 (Table 5.2: Facilities in Scenario 1), 7 treatment units in Scenario 2 (Table 5.3: Facilities in Scenario 2), 8 treatment units in Scenario 3 (Table 5.4: Facilities in Scenario 3) and 25 treatment units in

Scenario 4 (Table 5.5: Facilities in Scenario 4). The normalised values in a [0-100] range are; 0% for SC1, 6% for SC2, 12% for SC3 and 100% for SC4.

5.5 Assigning Relative Weights to Criteria

The investigation of relative weights according to the stakeholders was conducted by a questionnaire (Appendix 1). The questionnaire required about 15 minutes to complete, and primarily consisted of questions which had multiple options. In designing the questions, a multiple options style was employed in order to specifically measure how important one criterion was compared to the others.

This sort of design enabled collecting the required type of data in a limited time. The stakeholders in Turkey were either sent the questionnaire or interviewed if they were prepared to commit time to do this; and they expressed their judgements by choosing an option which they thought best represented their own ranking.

The questionnaire was sent to the identified Turkish stakeholders (Chapter 5.1); namely the Ministry of Environment of Forestry, Provincial Directorate of Environment and Forestry of Istanbul, Acibadem Private Hospital, Optimet Company, Turanlar Inc. Company, Istanbul Metropolitan Municipality, Istac Company, Eracevre Inc. Company and Gebze Technology Institution. The response came from only; (1) Government Authority; Mrs N. Ozkovalak on behalf of Provincial Directorate of Environment and Forestry of Istanbul, (2) Academia; Dr S. Bayar and Assoc. Prof. Dr. G. Engin on behalf of Gebze High Technology Institute and; (3) Private Sector; Mr C. Esmen (Eracevre Inc.). Although the number of responders to the questionnaire was limited in number, the received rankings were valuable in conducting this analysis.

Following the procedure on how monetary values were converted into relative weights, the weights of each criteria were determined by following the steps of procedure described in Chapter: 3.3.1.2 Assigning Relative Weights to Criteria, Table 5.24, Table 5.25, Table 5.26 and Table 5.27 present how this procedure has been applied to the criteria of Environment, Social, Technical and Economy respectively.

Table 5.24: Relative Weighting of Environment

Procedure Step		GWP			Water Usage			Landfill Requirement		
		Gov.	Aca.	Pri.Se.	Gov.	Aca.	Pri.Se.	Gov.	Aca.	Pri.Se.
1	f_i (£)	£10	£10	£50	10p	50p	50p	£2	£2	£4
2	Average of f_i	£23.3/tonne			37p/m^3			£2.7/tonne		
3	Best v Worst	SC1 and SC4 Chapter 5: Table 5.16			SC1 and SC4 Chapter 5: Table 5.18			SC3 and SC1 (or SC2/SC4) Reference: Table 5.19		
		40,955 CO_2-e (tonne)			753,652 m^3			129,982 tonne		
4	Monetary Value (£)	954,187			278,851			350,951		
5	Relative Weight	60%			18%			22%		

Table 5.25: Relative Weighting of Social

Procedure Step		Social														
		Employment						Traffic			Safety					
		Technical Staff			Non-Technical Staff						Morbidity			Mortality		
		Gov.	Aca.	Pri.Se.	Gov.	Aca	Pri.Se.	Gov.	Aca.	Pri.Se.	Gov.	Aca.	Pri.Se.	Gov.	Aca.	Pri.Se.
1	f_i (£)	2,000	2,000	20,000	1,000	1,000	20,000	2	25	50	£20,000	10,000	50,000	100,000	250,000	500,000
2	Average of f_i	£8,000/person			£7,333/person			£26/hour/year			£26,666/hospital admission/year			£283,333/death/year		
3	Best v Worst	SC3 and SC1 Chapter 5: Table 5.22			SC4 and SC3 Chapter 5: Table 5.22			SC4 and SC1 Chapter 5: Table 5.20			SC1 and SC2 (or SC4) Chapter 5: Table 5.21			SC1 and SC3 Chapter 5: Table 5.21		
		4 people			28 people			14,092 hour/year			0.13			0.0030		
4	Monetary Value (£)	32,000			205,324			366,392			3,467			850		
		237,324									4,317					
5	Relative Weight	14%			86%						80%			20%		
		39%						60%			1%					

Table 5.26: Relative Weighting of Technical

Procedure Step		Technical											
		Segregation Requirement			Transport			Maturity					
								Nationally			Internationally		
		Gov.	Aca.	Pri.Se.	Gov.	Aca.	Pri.Se.	Gov.	Aca.	Pri.Se.	Gov.	Aca.	Pri.Se.
1	f_i (£)	£4,000	£400	£0	£10	50p	£10	£10,000	£20,000	£100,000	£10,000	£20,000	£100,000
2	Average of f_i	£1,467/hospital			£6.8/km/year			£43,333/one step movement			£43,333/one step movement		
3	Best v Worst	SC1 (SC2/SC4) and SC3 Chapter 5: Section 5.4.1.5			SC4 and SC1 Chapter 5: Table 5.20			SC1 (SC2/SC4) and SC3 Chapter 5: Table 5.23			SC1 (SC2/SC4) and SC3 Chapter 5: Table 5.23		
		81 hospital			320,060km/year			3 unit			1 unit		
4	Monetary Value (£)	118,746			2,176,408			129,999			43,333		
								173,332					
5	Relative Weight	5%			88%			75%			25%		
								7%					

Table 5.27: Relative Weighting of Economy

<table>
<tr><th rowspan="2">Procedure
Step</th><th colspan="4">Economy</th></tr>
<tr><th>Investment Cost</th><th>Operating Cost</th><th>Stability in Cost</th><th>Cost of Training</th></tr>
<tr><td></td><td colspan="4">Stakeholder's response to Question 9th is; To save £400,000 investment cost, they accept paying £200,000/year more on operating costs (Gov.: £400,000, Aca.:£100,000, Pri Se.:£100,000). Best v Worst on investment cost is £2.3 million (SC3:£5.3 million, SC4: £3 million, Chapter 5: Table 5.7) which means that to save £2.3 million on investment cost, they think it is worth paying £1.15million/year more on operating costs. It results that if relative importance of operating costs is assumed 1 unit, then the relative importance of investment cost results in 1.3 units from the proportion of 1.5 million to 1.15million.(Best v Worst on Operating cost is £1.5 million/year from Table 5.7)

Stakeholder's response Question 5th is; £11,333/year (Gov.:£2,000/year, Academia: £16,000/year and Private Sector: £16,000/year). The annual cost difference between the most flexible scenario (SC4) and the least one (SC1) is £20,000 year (Chapter 5: Table 5.7). The proportion of £11,333/year to £20,000/year results in 0.57 unit relative importance on stability in cost.

Stakeholder's response Question 8th is; £6,667/hospital/year (Gov.:£8,000, Academia: £4,000, Private Sector: £2,000). The annual cost difference between the best (SC1/SC2/SC4) and worst (SC3) is £8,666/hospital/year (Chapter 5.4.1.5 Segregation Requirement). The proportion of £6,667/year to £8,666/year results in 0.77 unit relative importance on stability in cost.

When they are normalised;</td></tr>
<tr><td>5</td><td>35%</td><td>28%</td><td>15%</td><td>22%</td></tr>
</table>

5.5.1 Weighted Average or Simple Average of Monetary Values?

Fulop (2005) states that in a correct method for synthesising decisions of multiple stakeholders, the competence of the different actors to the different professional fields has also to be taken into account. Because of the fact that not all the stakeholders, in healthcare waste management system, have the equal power in decision making; the rankings received from the stakeholders should be analysed by taking a simple average and also by taking a weighted average of these judgements of stakeholders as recommended by Goodwin and Wright (2004). In order to conduct analysis by taking a weighted average of their judgements, the questionnaire included an open ended question (Question 14) which asks the stakeholders to rank their own influence on the ultimate decision (scale:0 to 10).

The results of the questionnaire showed that the decisions which are made in healthcare waste management are determined 50% by the government agencies, 21% by the private sector and 29% by the academia in Istanbul. However when the relative weights were normalised according to the simple average and the weighted average in the best versus worst scale, it was observed that there is not a considerable difference between these two set of results (Table 5.28). More importantly when they were inputted in decision tree models for the analysis, the resultant outcomes do not differ to any measured extent.

It was emphasised by Goodwin and Wright (2004) that in the case of small groups, even if we are fortunate enough to identify the best individual estimate, its accuracy is unlikely to be much better than that of the simple average of the entire group's judgements. This claim was also supported by Ashton A.H and Ashton R.H. (1985) who stated that simple averages produce estimates which are either as good as, or only slightly inferior to weighted averages. For these reasons, it was assumed in this project that the stakeholders' judgements can be regarded as equally influential; hence in MCDA of this project, simple average of relative weights were used, normalised and then inputted as data in the decision analysis software model.

Table 5.28: Simple Average and Weighted Average of Relative Weights

Branch Node		Simple Average	Weighted Average	Criteria Node	Simple Average	Weighted Average
Environmental	Water Usage	18%	18%	-	-	-
	GWP	60%	60%	-	-	-
	Landfill Requirement	22%	22%	-	-	-
		100%	**100%**	-	-	-
Economic	Investment Cost	35%	33%	-	-	-
	Operation Cost	28%	31%	-	-	-
	Stability in Cost	15%	14%	-	-	-
	Training Cost	22%	22%	-	-	-
		100%	**100%**	-	-	-
Technical	Segregation Requirement	5%	7%	-	-	-
	Maturity	7%	5%	National	75%	75%
				International	25%	25%
				-	**100%**	**100%**
	Transport	88%	88%	-	-	-
		100%	**100%**	-	-	-
Social	Employment	39%	38%	Technical	14%	14%
				Non-Technical	86%	86%
				-	**100%**	**100%**
	Traffic	60%	61%			
	Safety	1%	1%	Morbidity	80%	82%
				Mortality	20%	18%
				-	**100%**	**100%**
		100%	**100%**	-	-	-

5.6 Analysing the Results

From an analytical point of view, a central characteristic of sustainable development is economic-ecological integration (Munda *et al.* 1995). Environmental systems provide resources for economic development; in return, economic development has an impact on the environment, which provides the economic foundation for environmental protection (Tao 2010). Since the models aimed at structuring decision making systems generally have far reaching economic and ecological consequences, there is a strong body of research focusing particularly on the mechanism of environment-economy systems, e.g. Sugiyama *et al.* (2009) presented an investigation on how economic and environmental assessment results change when different process options or evaluation settings are considered. In this project, two phases were used; the first phase includes a decision tree with the criteria of economy and environment (Figure 5.7); and the second phase consists of a tree including all criteria identified previously (economic, environmental, social and technical) (Figure 5.8).

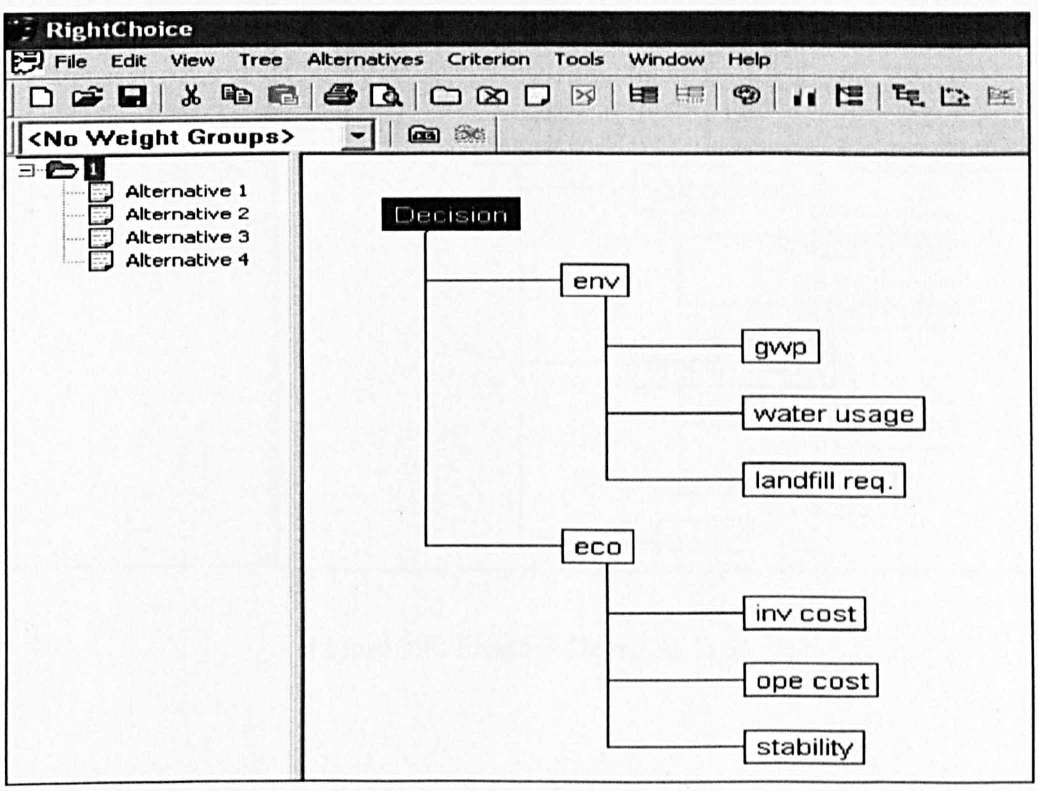

Figure 5.7: Phase 1-Decision Tree

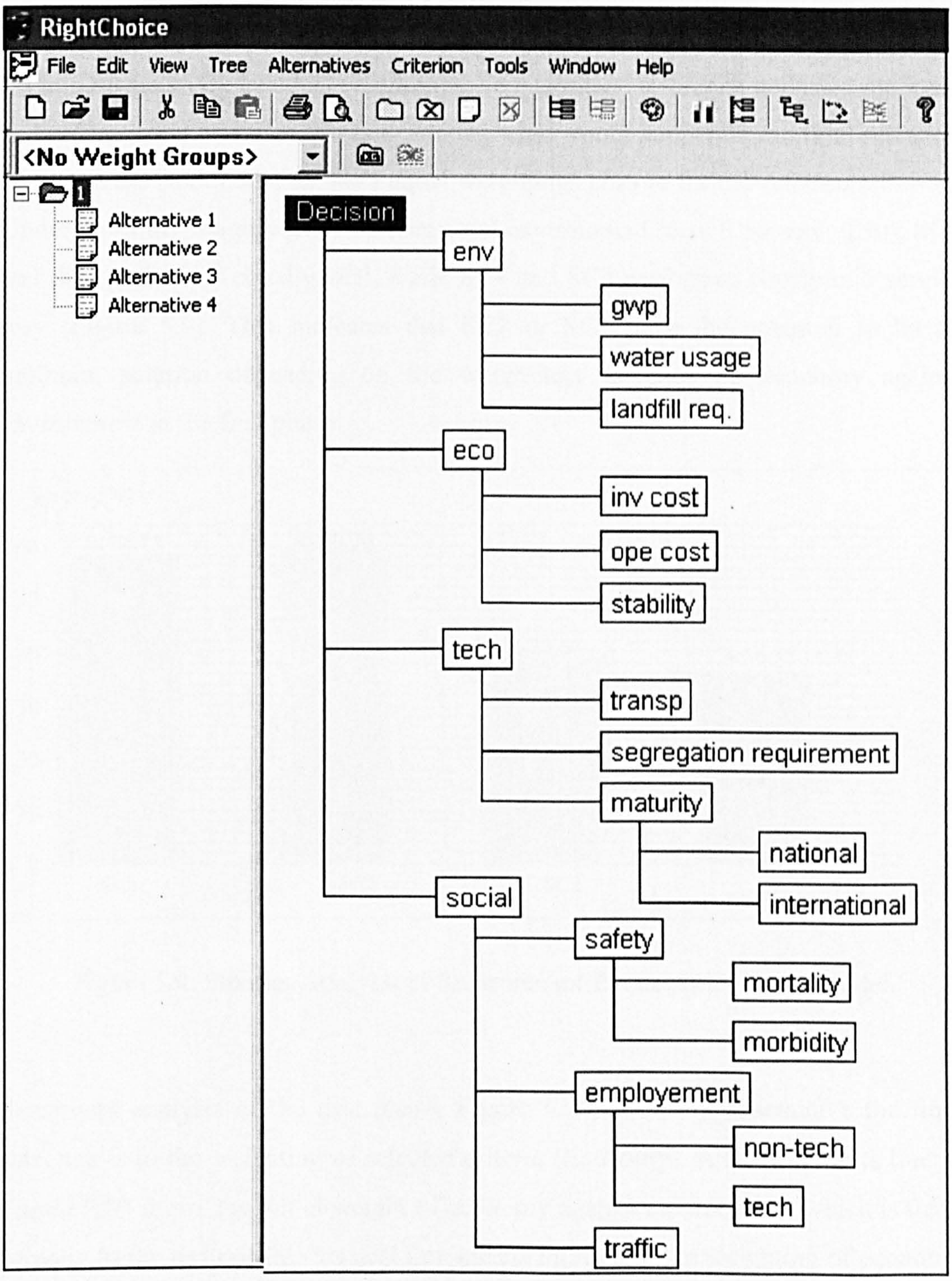

Figure 5.8: Phase 2-Decision Tree

First Phase

To initiate the analysis, equal weightings were assigned to branch nodes of economy and environment and then it was examined what would happen to the final selection of first phase (root node) as these equal weightings change for the selected criterion. Under the equal weightings of economy and environment (eco: 0.50; env: 0.50), SC2 and SC1 performed equally well, while SC4 and SC3 performed poorly in a similar way (Figure 5.9). This indicates that SC2 or SC1 have the potential to be an optimum solution depending on the weightings assigned on economy against environment in the first phase.

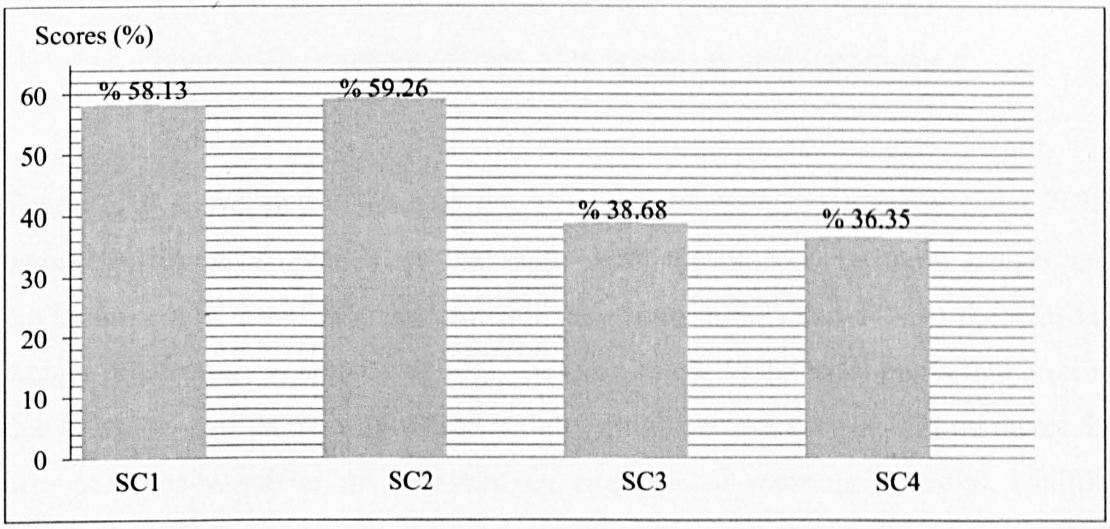

Figure 5.9: Frontier Analysis of Environment-Economy Decision Model

Sensitivity analysis of the first phase, Figure 5.10, shows how sensitive the final selection is to the weighting of selected criteria (Economy). A vertical white line in Figure 5.10 shows the initial weight of economy against environment, which is 0.50. Moving to the right of this vertical line means increasing the weighting of economy against environment (i.e. economy is more important than environment).

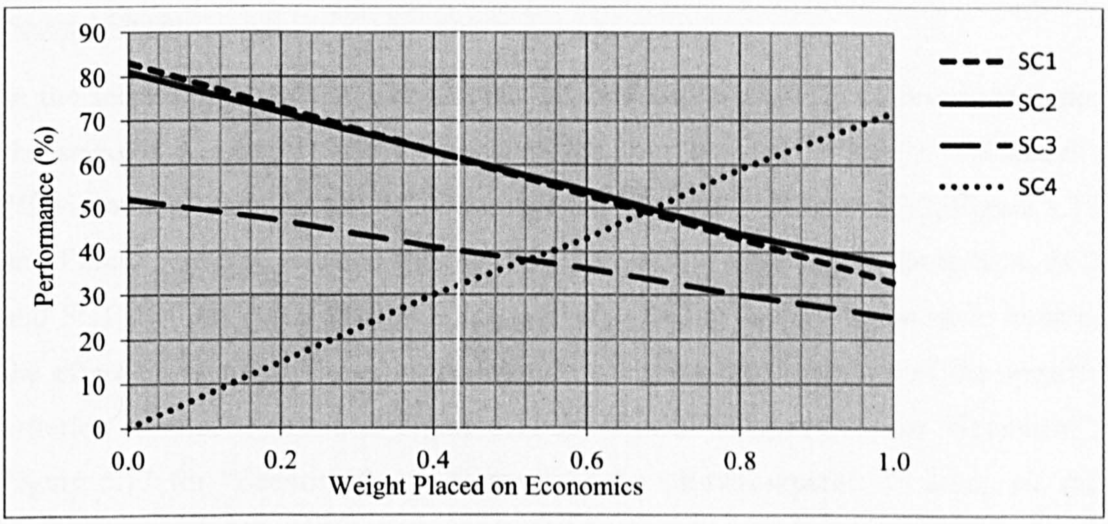

Figure 5.10: Sensitivity Graph of Economy against Environment

Figure 5.10 shows that as long as the weighting of economy remains under 70% against environment (which, at the same time, means 30% or more weight on environment), SC2 and SC1 perform well compared to SC3 and SC4. If the relative weight of economy is more than 70%, SC4 comes out as the most preferable option due to its low cost on investment and stability (high performance of SC4 on them). It also performs worst on environment, i.e. high global warming potential, landfill requirement and water usage. This large difference in relative performance of SC4 for the two criteria is also evident from the sharpness of the slope. It should also be noted that SC3 is never the optimal solution as it is outweighed by other scenarios whatever the relative performance of economy against environment (or vice versa) is.

Since decision making concerns the future, the weighting of each criteria which enters the evaluation of any proposed waste management system is necessarily uncertain. In order for a decision maker to distinguish which judgemental evaluations create determinative behaviours in obtaining the optimum solution, sensitivity analysis plays a significant role.

Second Phase

In the second phase of the analysis, the whole decision model was examined under the selected weight of 0.25 for each of the four criteria, "Social", "Technical", "Environment" and "Economy". On reviewing Figure 5.11, Figure 5.12, Figure 5.13 and Figure 5.14, the selected weight of 0.25 gives the same result where SC4, SC2 and SC1 perform better than SC3 respectively. Taking each criterion node in turn, the effect on scenario scores in response to changing the weighting of the specific criterion selected is shown in Figure 5.11 for "Social", Figure 5.12 for "Technical", Figure 5.13 for "Economy" and Figure 5.14 for "Environment". In doing so, the relative weight of the other three criteria (i.e. the ones apart from selected one) is maintained in this process, i.e. they remain of equal importance to each other but less or more in overall influence, for instance, if the weighting of social criterion (Figure 5.11) increases to 40%, economic, environment and technical reduce to 20% each.

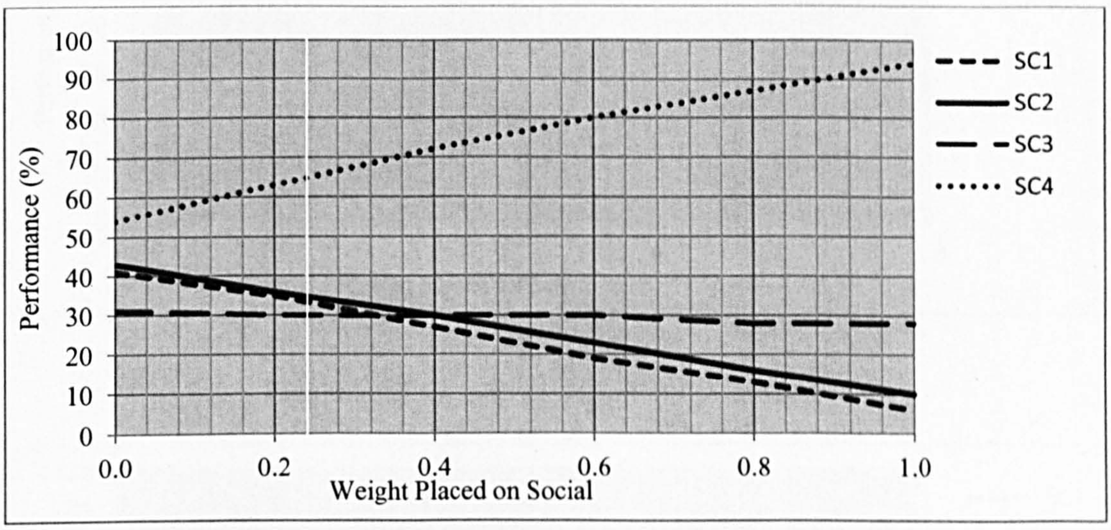

Figure 5.11: Sensitivity Graph of "Social"

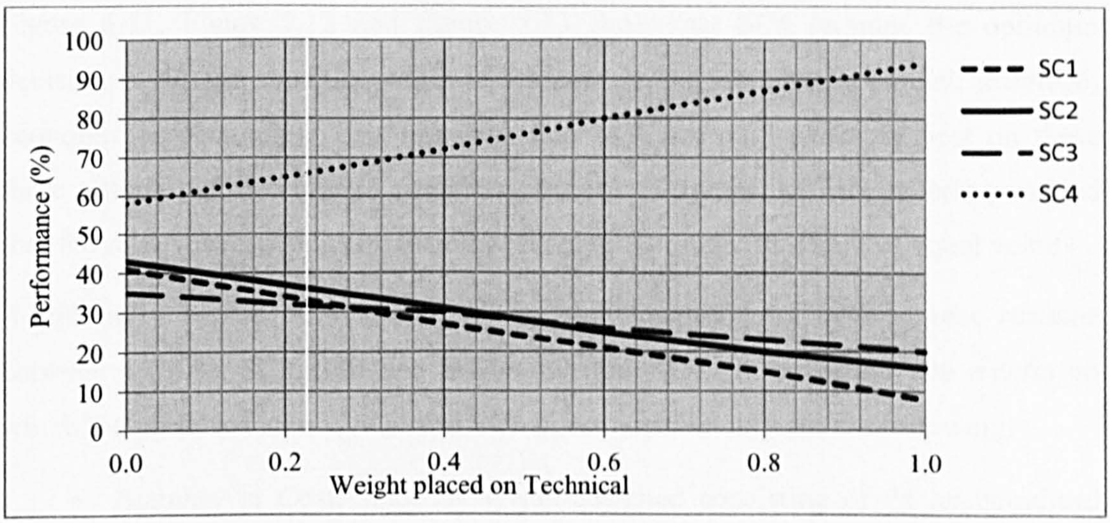

Figure 5.12: Sensitivity Graph of "Technical"

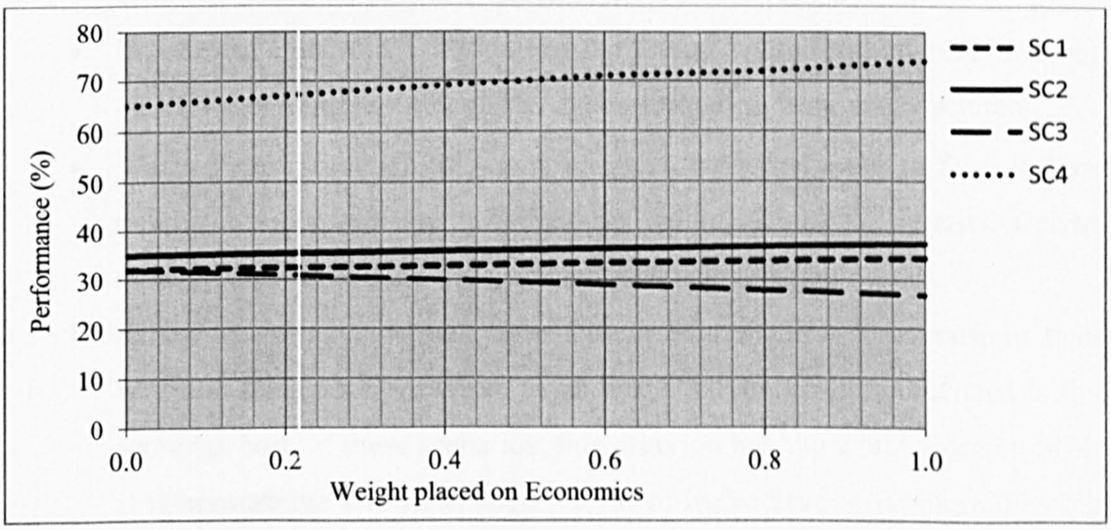

Figure 5.13: Sensitivity Graph of "Economy"

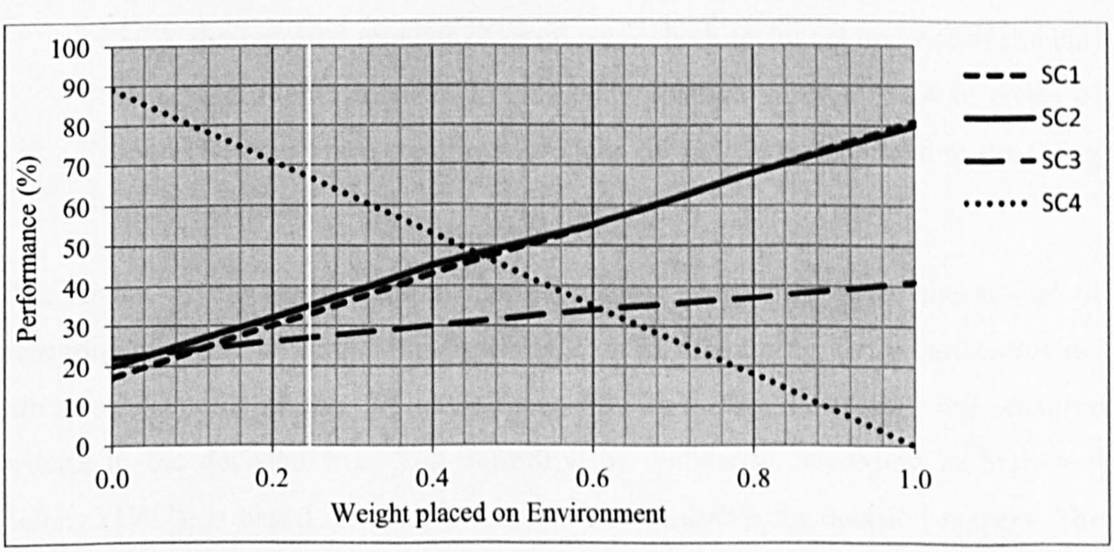

Figure 5.14: Sensitivity Graph of "Environment"

Figure 5.11, Figure 5.12 and Figure 5.13 show that SC4 remains the optimum decision, whatever specific weight is assigned to the test criteria (social, technical, economic respectively). This indicates that SC4 not only performs best on these three criteria but also best in complete absence of one of the four criteria provided that the relative weightings on the other three remaining criteria are of equal value.

Additionally Figure 5.14 shows that if the weighting of environment remains between 45-90%, SC2, SC1 and SC3 outweighs SC4. In particular, the criteria on which the performances of SC4 and SC2 differ considerably are the following;

- Stability in Cost; since SC4 was designed consisting of 24 decentralised hydroclaves on a flexible basis which could respond to the unpredicted future demand, this criterion has the highest score for SC4.
- Investment Cost; this criterion has the lowest value (highest performance) on SC4 according to the acquired data/information from manufacturers.
- Water Usage; although this criterion gives the worst score to SC4, it does not have a considerable influence on the results as the relative weight attained to "water usage" by the stakeholders is relatively small.
- Global Warming Potential; even though SC4 requires less transport than SC2 and the amount of waste to be landfilled and to be incinerated is the same for both of these scenarios, this criterion has the worst score on SC4. It is because the electricity requirement of hydroclave is far more than the electricity fired and fuel-oil fired autoclaves which are included in SC2.
- Employment; due to the high number of decentralised hydroclave units in SC4, the required number of employees (both technical and non-technical) in SC4 is higher than SC2. This adds positive value to SC4 in terms of social benefits since creating more jobs for people is beneficial to the living quality of local people.

The results of the analysis of this project allow narrowing down the spread of scenarios to a few by indicating either SC2 or SC4 could be a *rational /optimum/ satisfying* scenario among the other scenarios depending on scoring the sensitive criteria in the decision tree. The definition of *optimality*, according to Starr and Zeleny (1977), is based on what is feasible and desirable for decision makers. The concept of *satisfying* is often viewed as a suitable extension and modification of the concept of optimisation (Simon 1957). Furthermore the idealised concept of *rationality*, by Zeleny (1982), is assumed as maximization of a fixed or relatively stable objective, a known set of relevant alternatives and their outcomes, and a skill in computation that allows one to reach the highest attainable point with respect to the objective.

5.7 Conclusion

In the situations where the decision making process is limited by shortage of information and data, and public concerns are difficult to bring forward, some compromising solutions have to be found. In this regard, the central idea in this chapter of the project was to give stakeholders a powerful insight into the rationale of the decision problem by identifying the options which meet various criteria and to arrive at the compromising solution along with its constraints/conditions.

The results of this analysis show that the optimum alternatives for healthcare waste management in Istanbul could be SC4 or SC2 by emphasising the sensitiveness in scoring environment against the others. As a result, SC4 could appear as an economically, technically sound and socially viable option with limited performance on environment. On the other side, SC3 which consists of the recent alternative treatment technology, microwave, proves never to be a feasible option since its benefits on the technical, environmental and social sides do not overweigh its high cost.

The results of analysis are influenced mainly by the weightings assigned to branch nodes and also the performances of scenarios on them. In the cases where high difference in scenarios' scores (Best v Worst) couples with the high weighting of 1 unit of that node, this affects the overall results significantly. For instance, nodes of transport and traffic have the highest weightings in the branches they belong to (transport is 88% in technical and traffic is 60% in social branch node). The reason for that is; SC4 provides considerably higher savings in the length of route and time of transporting wastes from healthcare facilities to treatment plants compared to the other three scenarios and also 1 unit of saving in transportation (1km or 1 hour shorter route) is scored high by the stakeholders in the questionnaire (Appendix 1).

This brings SC4 forward as the most favourable option both technically and socially. Another example of this is the investment cost node which has the highest weighting (35%) in that branch coupled with the high performance of SC4 (100%).

A branch node of safety, as another example, has a very small influence (1%) in its branch. There are two reasons for it; (1) The difference between the mortality and morbidity values measured for the four scenarios do not differ a great deal, (2) 1 additional death or 1 hospital admission (1 unit) was not ranked high enough by the stakeholders to outweigh the relative weightings of the other nodes of social (traffic and employment).

The nodes which play a determining role in bringing forward SC4 and SC2 in terms of environmental friendliness were water usage and global warming since landfill requirement has a positive score only for SC3 (other scenarios are 0% as their performances were equally lower than SC3). The disadvantage of SC4 with respect to environmental criteria is a high weighting placed on GWP (60%) and Water Usage (18%) coupled with its poor performance on both of the nodes (0% for both) whereas SC2 performs 97% and 100% on them respectively.

CHAPTER 6: CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE STUDIES

Turkey, as a candidate country of the European Union, is obliged to make its national legislation and its implementations compatible with European Legislation. Regarding healthcare waste management, landfilling without pre-treatment has to be abandoned urgently and new healthcare waste management systems have to be developed. It is evident that putting the task of building a new healthcare waste management system on the agenda of the central government will require significant effort coupled with the cooperation between the stakeholders.

In this regard this study has shed light on the intricacies of interactions in healthcare waste management system components in Istanbul, and the types and quantity of healthcare wastes likely to be encountered. This information was used in the context of multi criteria decision analysis by identifying various criteria and testing their relative importance according to the view of key stakeholders within several future scenarios. This research provides both the data to develop practical technical options (scenarios) and a framework for comparing option performance. Instead of comparing individual options (e.g. incineration versus landfill), an attempt has been made to synthesise the healthcare waste management systems that can include the whole healthcare waste stream, and then compare their overall performances within MCDA.

The conclusion of this research confirms the feasibility of the MCDA method as a decision making tool in healthcare waste management. It is particularly useful in comparing the criteria in the units which they occur. In addition, criteria which have insufficient or inadequate data do not need to be eliminated from the evaluation but can be incorporated by the use of a ranking system. The technique provides a reliable tool to obtain ranking of scenarios. It also accommodates a multi stakeholder approach to decision support, well suited to examining tradeoffs between stakeholders to produce "defensible rationale" (underlying reason, logical basis) for choosing a particular option.

With the proposed decision making framework, this study pioneered a direction for the process of building a new healthcare waste management system in Istanbul by stimulating creativity and considering alternative scenarios to move towards it. The first set of results of this work entitled "A System Dynamics Approach for Healthcare Waste Management: A Case Study in Istanbul Metropolitan City, Turkey" was published as a journal article by the International Solid Waste Association (ISWA) in Waste Management & Research (WM&R) (Appendix 5).

6.1 Conclusions

1) Istanbul Metropolitan Municipality struggles to have sufficient budget and management capacity to maintain a complete database regarding the healthcare waste quantity. However making the best possible estimation on the waste generation by using any developed model is dependent on first availability and then quality of input data. It is therefore essential for healthcare institutions in Istanbul to record and report their *treatment types*, *patient episodes* and *waste generation profiles* regularly as well as Turkish Health Ministry developing a database to ensure the regular supply of up-to-date data. This kind of formal auditing is needed to deal with uncertainties of healthcare waste management system by reducing the data gap and also by improving the quality of data. Such data can then be used to further validate the HCW SD model over time.

2) The results acquired from the HCW SD model showed that the generation of HCW will undergo a general increase during the next 30 years, mainly due to the increase in the investment in hospital beds and population variables. Since throughput capacity of the existing healthcare waste treatment facility in Istanbul, Kemerburgaz Incinerator, is already exceeded, a new treatment technology or technologies are urgently required.

3) The best waste management practice is to minimise the generation of waste. However the potential for healthcare waste minimisation is limited because of the increased use of single-use-only disposable items. On the other hand, reducing healthcare waste could also be achieved through appropriate waste segregation. Based on reported analysis, the non-hazardous municipal fraction co-disposed with

healthcare waste is around 64% in Istanbul. Using the projected waste generation flows, reducing a municipal fraction to 30% has the potential to avoid some 8,000tpa of healthcare waste by 2025 and almost 10,000tpa by 2035. Even though the segregated MSW stream inevitably causes an increase in the amount of MSW at HCFs, a successful segregation scheme could still help reducing treatment cost as the processing of MSW requires less specialised techniques and methods than HCW. The performance of waste segregation depends on the knowledge of hospital staff at the points of generation. This brings forward the importance of training activities taking place at hospitals. In this respect, the development of staff training and raising awareness of building programmes in order to ensure successful segregation system implementation is anticipated to be an important factor in reducing healthcare waste quantities and costs in a long term.

4) Although incineration is suitable for most types of healthcare wastes and has several advantages (especially volume reduction, fail-safe and total solution for all types of HCW), it is a costly method and might cause the release of hazardous gas emissions. Further healthcare waste segregation provides substantial reductions in what would otherwise eventually end up in the incinerator. If further segregation practice ensured healthcare waste requiring incineration was also selectively managed, 77% of healthcare waste could be diverted to alternative treatment technologies. The development of alternative treatment technologies for healthcare waste should be encouraged and promoted to replace unnecessary incineration by potentially more environmentally friendly treatment methods.

5) The study provided an insight into the likely GHG emissions of various scenarios involving different technologies. The comparison of annual GHG emissions of SC1 (217 kgCO_2-e/tonne of waste) and SC2 (221 kgCO_2-e/tonne of waste) shows that building up a centralised treatment system on the Asian Side to avoid the HCW SAT generated on the Asian Side being transported to the central treatment facility located on the European Side does not make a large difference in terms of GHG emissions. The main share of these emissions was from methane which escaped from landfills and from indirect sources, e.g. electricity requirement of alternative technologies. Incinerating healthcare waste was also a significant contributor to CO_2-e emissions; even though displaced emissions by producing electricity recovered a high extent of the emission due to burning.

6) Investigation of stakeholder's views showed that investment cost and GWP are the most highly ranked criteria in the economic and environmental attributes respectively. The investment cost held the first place in economic valuing and CO_2-e emission was raised as an outstanding environmental concern because of the focus on environment protection.

7) Multi-criteria decision analysis indicates that either centralised autoclaves built on the European and Asian Side (SC2) or decentralised hydroclaves located at central hospitals across Istanbul (SC4) is an optimum solution depending on relative weights placed on the criteria identified in the decision tree by the decision makers. Incinerating all the healthcare wastes arise from Asian Side and operating a centralised microwave treatment plant along with the Kemerburgaz Incinerator on the European Side (SC3) is never a feasible option as it performs the poorest mainly due to high cost. This indicates that the well-proven autoclave/hydroclave technology option for the treatment of HCW SAT and then their disposal through landfilling with energy recovery should be given more attention by the authorities in Istanbul.

In general, the results and remarks of this study can be used as a basis of future planning and anticipation of the needs for investment in the area of HCW management in Istanbul.

6.2 Recommendations for Future Studies

Key points identified in this study, which require further investigation, include the following.

1) There is a data gap in determining the composition (plastic, textile, paper, and etc content) of incineration-only HCW and HCW SAT separately. It is an important knowledge gap in terms of estimating methane generation potential of the HCW SAT stream. A further study on this could help in evaluating the process performance and recovery potential of the incineration-only HCW stream through incineration.

2) There is limited information available on the potential environmental effects and health impacts of waste management processes. The results of many existing occupational studies are not satisfactory to establish a link between health outcomes and a specific waste operation, and therefore not adequate to complete an overall evaluation. It is suggested that more collaborative epidemiological studies using a rigorous approach along with an appropriate methodology should be conducted.

3) As the HCW SD model in this research is driven by a system dynamics core, the combinations of system parameters can be adopted for use in other places to solve similar problems. The modifications which are required for this adoption could include determining the strategic objectives of regulatory authorities as well as specific characteristics of the region under study.

4) The MCDA model presented in this study provides a decision making framework for a real-world healthcare waste management problem. Extensions of this model could be developed as it is anticipated that decision making process will incorporate more public participation in the future with the rise of public awareness on environmental issues in Turkey. Therefore the decision tree built up in this research could be extended further by including more criteria and related evaluations could be made.

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Appendix 1: Questionnaire for Assigning Relative Weights

Objectives of this questionnaire are;

1) To analyse relative importance of the factors, which are involved in decision making in "Healthcare Waste Management in Istanbul", such as environmental performance, public health and other related factors against cost.

2)To determine how effective/influential different stakeholder's decisions are in decision making in "Istanbul Healthcare Waste Management".

For this purpose, it is kindly requested from responders to answer the questions below according to their own views/thoughts by considering current healthcare waste management system in Istanbul.

1) As it is known, each healthcare waste technology (incinerators and alternative technologies) requires the use some amount of water. How much do you think it is worth saving 1m^3 of water?

A) 0 TL/m^3 (I do not think that "water consumption" is one of the criteria which is considered in decision making).

B) 125 kurus/m^3 (5p/m^3)

C) 250 kurus/ m^3 (10p/m^3)

D) 625 kurus/ m^3 (25p/m^3)

E) 1.25 TL/ m^3 (50p/m^3)

2) As it is known, carbon credits create a market for reducing greenhouse emissions by giving a monetary value to the cost of polluting the air. As far as it is considered that treating raw healthcare waste in incineration or landfilling treated healthcare waste emits CO_2, How much do you think it is worth saving 1 tonne of CO_2?

A) 0 TL/tonne (I do not think that "CO_2 emission" is one of the criteria which is considered in decision making).

B) 12.5 TL/tonne (£5/tonne)

C) 25 TL/tonne (£10/tonne)

D) 50 TL/tonne (£20/tonne)

E) 125 TL/tonne (£50/tonne)

3) It is a known fact that treating healthcare waste in incinration or alternative technologies and landfilling them after treating emit some toxic substances (air pollutants such as heavy metals (mercury, cadmium, lead etc) acidic and corrosive gases (hydrogen chloride, hydrogen fluoride, sulphur dioxide, and nitrogen oxides); products of incomplete combustion (carbon monoxide, dioxins, furans and polycyclic aromatic hydrocarbons)); and this causes some adverse health effects on human health.

a) How much is it worth avoiding 1 additional hospital admission due to disease from additional air pollution?

A) 2,500 TL/year (£1,000)

B) 12,500 TL/year (£5,000)

C) 25,000 TL/year (£10,000)

D) 50,000 TL/year (£20,000)

E) 125,000 TL/year (£50,000)

b) How much is it worth avoiding one death brought forward due to additional air pollution?

A) 50,000 TL/year (£20,000)

B) 125,000 TL/year (£50,000)

C) 250,000 TL/year (£100,000)

D) 625,000 TL/year (£250,000)

E) 1,250,000 TL/year (£500,000)

4) Collecting all types of healthcare waste *(infectious, pathologic, sharps, pharmaceutical, genotoxic, chemical, healthcare wastes inculuding heavy metals, pressurised containers)* in one type of waste bags (red bags), in other words, avoiding segregation of incineration-only healthcare waste *(pathologic, genotoxsic, pressurised containers)* from healthcare waste suitable for alternative treatment *(as it is in current system)* obviously brings forward more practicality for where healthcare waste occurs. As far as this is concerned, how much is it worth providing a system which requires less type of waste segragation in each hospital?

A) 0 TL

B) 1,000 TL (£400)

C) 5,000 TL (£2,000)

D) 10,000 TL (£4,000)

E) 20,000 TL (£8,000)

5) How much is it worth using a technology which is more flexible to any unpredictable change in the amount of healthcare waste in the future, in orher words, a technology which is not very costly to any increase in the capacity might be needed in later years?

A) 0 TL/year (I do not think that flexibilty is one of the criteria which is considered in decision making).

B) 5,000 TL/year (£2,000/year)

C) 10,000 TL/year (£4,000/year)

D) 20,000 TL/year (£8,000/year)

E) 40,000 TL/year (£16,000/year)

6) How much, do you think, it is worth saving 1tonne of waste from landfilling?

A) 0 TL/tonne (I do not think this is one of the criteria which is considered in decision making).

B) 1 TL/tonne (40p/tonne)

C) 2 TL/tonne (80p/tonne)

D) 5 TL/tonne (£2/tonne)

E) 10 TL/tonne (£4/tonne)

7) How much do you think, it is worth avoiding waste collection service in rush hours of traffic (working days between 6am-10am, 4pm-9pm) per year?

A) 5TL/hour (£2/hour)

B) 12.5TL/hour (£5/hour)

C) 25TL/hour (£10/hour)

D) 62.5TL/hour (£25/hour)

E) 125TL/hour (£50/hour)

8) As it is known that while all types of healthcare waste can be treated in incineration, alternative technologies (autoclaves, hydroclaves, etc) are only applicable for some certain fractions of infectious, pathologic, sharps and pharmaceutical waste.

In the cases where an integrated system including incineration and alternative technologies together are implied together, it is necessary for healthcare institutions to segregate healthcare waste fractions as incineration-only healthcare waste and healthcare waste suitable for alternative technology.

How much is it worth avoiding the risk due to wrong segregation of healthcare wastes by training the medical staff regularly at healthcare facilities on how to further segregate the healthcare waste (per hospital/year)?

A) 1,000 TL/hosp/year (£400)

B) 5,000 TL/ hosp/year (£2,000)

C) 10,000 TL/ hosp/year (£4,000)

D) 15,000 TL/hosp/year (£6,000)

E) 20,000 TL/ hosp/year (£8,000)

9) How much is it worth spending more on operating cost to save 1 million TL (£400,000) investment cost?

A) 100,000 TL/year (£40,000)

B) 250,000 TL/year (£100,000)

C) 500,000 TL/year (£200,000)

D) 1,000,000 TL/year (£400,000)

E) 2,500,000 TL/year (£1m)

10) How much do you think, it is worth saving 1km of transportation of healthcare wastes per year?

A) 500k (20p)

B) 1.25TL (50p)

C) 2.5 TL (£1)

D) 12.5TL (£5)

E) 25TL (£10)

11) How much do you think, it is worth creating a non-technical job position in healthcare waste management field in Turkey (per person)?

A) 2,500 TL (£1,000)

B) 5,000 TL (£2,000)

C) 12,500 TL (£5,000)

D) 25,000TL (£10,000)

E) 50,000TL (£20,000)

12) How much do you think, it is worth creating a technical job position (such as engineer, mechanic, technician) in healthcare waste management field in Turkey (per person)?

A) 2,500 TL (£1,000)

B) 5,000 TL (£2,000)

C) 12,500 TL (£5,000)

D) 25,000TL (£10,000)

E) 50,000TL (£20,000)

13) If you consider benefits of providing a mature alternative treatment system in the scale given below, how much do you think, it is worth stepping 1 level up/down?

Maturity of technologies could refer how widespread the technology is at both national and international level. This factor could be related to the resistance of a technology to failure or the ability of "fail well" (fail without catastrophic consequences).

1. Not present on the market at least in an experimental stage
2. Pilot plants
3. Start of market availability
4. Market availability of the technology for less than 10 years
5. Market availability of the technology for more than 10 years

a) Nationally (Turkey)

A. 25,000 TL (£10,000)

B. 50,000 TL (£20,000)

C. 125,000 TL (£50,000)

D. 175,000 TL (£70,000)

E. 250,000 TL (£100,000)

b) Internationally (Basically Europe)

A. 25,000 TL (£10,000)

B. 50,000 TL (£20,000)

C. 125,000 TL (£50,000)

D. 175,000 TL (£70,000)

E. 250,000 TL (£100,000)

14) As far as 3 main stakeholders are considered as individual bodies making decisions for the fate of healthcare waste management (please see below), how do you rank the decisive power of your institution (please mark your institution) in this system out of maximum 10?

1. Government Authority (Provincial Directorate of Environment and Forestry of Istanbul)
2. Academia (Universities, Institutions)
3. Private Sector (Alternative Technology Manufacturers)

Appendix 2: Validation of Methodology

How would you rate each item in the table according to the response scale given below?

1 = strongly agree 2 = agree 3 = disagree 4= strongly disagree

Q.1: A system dynamics approach to projecting future arisings is appropriate. *If 3 or 4, which approach would you recommend instead and why?*	1 2 3 4
Q.2: This sort of classification (Category 1 and 2) is appropriate in terms of estimating healthcare waste generation. *If 3 or 4, how should it be classified instead?*	1 2 3 4
Q.3: *Sensitivity analysis* is appropriate in estimating healthcare waste arisings under different MSW segregation schemes? *If 3 or 4, which method can be implemented instead and why?*	1 2 3 4
Q.4: Using "Lookup Function" is reasonable in order to differentiate the healthcare waste stream in transition-period? *If 3 or 4, why?*	1 2 3 4

Q.5: The structure of the decision tree into 4 main criteria grouping (and associated sub-criteria) provides a suitable/effective representation of the nature of the decision problem 1 2 3 4

If 3 or 4, what changes to the structure would improve clarity (e.g. reducing number of levels, swapping sub-criteria between group nodes, etc.)

Q.6: The set of criteria selected for the MCDA is comprehensive.

If 3 or 4, which additional criterion/criteria should be included? 1 2 3 4

Q.7: The criteria selected for the MCDA are appropriate.

1 2 3 4

If 3 or 4, which one(s) should be changed/replaced?

Q.8: Monetary scale to quantify weightings of the criteria is appropriate?

1 2 3 4

If 3 or 4, why?

Appendix 3: Formulation of the HCW SD Model

Type of the variable	Name	Unit	Equation	Value (European Side) (2007)	Value (Asian Side) (2007)
Stock	Young Population	people	INTEG (births + young migration in-maturation-young deaths-young migration out, initial young population)	-	-
Stock	Mature Population	people	INTEG (maturation + mature migration in –aging - mature deaths - mature migration out, initial mature population)	-	-
Stock	Elderly Population	people	INTEG (elderly migration in + aging - elderly deaths - elderly migration out, initial elderly population)	-	-
Constant	initial young population	people	-	2,687,100	1,375,000
Constant	initial mature population	people	-	4,816,660	2,626,730
Constant	initial elderly population	people	-	653,212	415,135
Constant	young migration in rate	1/year	-	0.0296	0.0296
Constant	young migration out rate	1/year	-	0.0237	0.0237

Please see next page

Type of the variable	**Name**	**Unit**	**Equation**	**Value (European Side) (2007)**	**Value (Asian Side) (2007)**
Constant	mature migration in rate	1/year	-	0.0324	0.0324
Flow	young migration out	people/year	young migration out rate* Young Population	-	-
Flow	mature migration in	people/year	mature migration in rate* Mature Population	-	-
Flow	mature migration out	people/year	mature migration out rate* Mature Population	-	-
Flow	elderly migration in	people/year	elderly migration in rate * Elderly Population	-	-
Flow	elderly migration out	people/year	elderly migration out rate * Elderly Population	-	-
Constant	average time to age	year	-	40	40
Constant	average time to mature	year	-	20	20
Flow	maturation	people/year	Young Population/average time to mature	-	-
Flow	aging	people/year	Mature Population/average time to age		
Constant	female fraction	women/people	-	0.5	0.5

Please see next page

Type of the variable	Name	Unit	Equation	Value (European Side) (2007)	Value (Asian Side) (2007)
Constant	births per mature female per year	people/(women*year)	-	0.055	0.055
Constant	mature migration out rate	1/year	-	0.0300	0.0300
Constant	elderly migration in rate	1/year	-	0.0118	0.0118
Constant	elderly migration out rate	1/year	-	0.0266	0.0266
Flow	young migration in	people/year	young migration in rate* Young Population	-	-
Auxiliary	total population	people	Young Population + Mature Population + Elderly Population	-	-
Auxiliary	mature females	women	female fraction* Mature Population	-	-
Flow	births	people/year	births per mature female per year* mature females	-	-
Constant	elderly mortality rate	1/year	-	0.0307	0.0307
Flow	elderly deaths	people/year	elderly mortality rate* Elderly Population	-	-

Please see next page

Type of the variable	Name	Unit	Equation	Value (European Side) (2007)	Value (Asian Side) (2007)
Constant	young mortality rate	1/year	-	0.0009	0.0009
Flow	mature deaths	people/year	mature mortality rate* Mature Population	-	-
Constant	mature mortality rate	1/year	-	0.0016	0.0016
Flow	young deaths	people/year	young mortality rate* Mature Population	-	-

Table A 1: Sub-System of Population

Type of the variable	Name	Unit	Equation	Value (European Side) (2007)	Value (Asian Side) (2007)
Stock	Hospitals	hospital	INTEG (growth in hospitals, Initial Hospitals)	-	-
Constant	Initial Hospitals	hospital	-	138	59
Auxiliary	growth in hospitals	hospital/year	rate new bed capacity/average beds per hospital	-	-
Constant	average beds per hospital	bed/hospital	-	141	140.2
Auxiliary	Current Bed Capacity	bed	Hospitals*average beds per hospital	-	-
Auxiliary	rate new bed capacity	bed/year	DELAY3[&](Demand for Extra Bed Capacity /TIME STEP, average time to increase hospital capacity)	-	-
Constant	average time to increase hospital capacity	year	-	2	2
Stock	Hospital Expansion in Progress	bed	INTEG (Demand for Extra Bed Capacity / TIME STEP - rate new bed capacity, 0)	-	-
Auxiliary	Demand for Extra Bed Capacity	bed	max (Desired Bed Capacity - Current Bed Capacity - Hospital Expansion in Progress ,0)	-	-

Please see next page

Type of the variable	Name	Unit	Equation	Value (European Side) (2007)	Value (Asian Side) (2007)
Constant	initial bed per head of population	bed/people	-	0.002385	0.00187
Constant	annual increase in bed per head	dmnl*	-	0.01	0.01
Auxiliary	Desired Bed Capacity	bed	total population*bed per head of population	-	-
Auxiliary	bed per head of population	bed/people	initial bed per head of population *(1+annual increase in bed per head) ^ ((Time-INITIAL TIME)/one year)	-	-
@DELAY3 (X,T) takes a third order exponential delay of X for time T conserving X *dmnl: dimensionless					

Table A 2: Sub-System of Hospital Bed Inventory

Type of the variable	Name	Unit	Equation	Value (European Side) (2007)	Value (Asian Side) (2007)
Constant	incidence rate per young inpatient	dmnl/year	-	0.0615	0.0555
Auxiliary	annual young inpatients	people/year	"Young Population (<20)"*incidence rate per young inpatient	-	-
Constant	incidence rate per mature inpatient	dmnl/year	-	0.1025	0.0925
Auxiliary	annual mature inpatients	people/year	"Mature Population (20-60)"*incidence rate per mature inpatient	-	-
Constant	incidence rate per elderly inpatient	dmnl/year	-	0.2419	0.2183
Auxiliary	annual elderly inpatients	people/year	"Elderly Population (>60)"*incidence rate per elderly inpatient	-	-
Auxiliary	annual inpatient demand	people/year	annual elderly inpatients + annual mature inpatients + annual young inpatients	-	-
Auxiliary	Total Bed Capacity	bed	Current Bed Capacity + Hospital Expansion in Progress	-	-
Auxiliary	bed days	bed*day/year	Total Bed Capacity*dpy		

Please see next page

Type of the variable	Name	Unit	Equation	Value (European Side) (2007)	Value (Asian Side) (2007)
Constant	dpy	day/year	365	-	-
Constant	beds per patient	bed/people	-	1	1
Constant	average inpatient stay	day	-	5.6	4.5
Constant	average HCW generation rate per bed	tonne/bed/day	-	0.0007	0.00056
Constant	municipality service provision	dmnl	-	1	1
Auxiliary	Category-1 HCW generation	tonne/year	annual inpatient bed occupancy* average HCW generation rate per bed*municipality service provision	-	-
Auxiliary	annual inpatient bed occupancy	bed*day/year	min(bed days, annual inpatient demand*beds per patient*average inpatient stay)	-	-

Table A 3: Sub-System of Category-1

Type of the variable	Name	Unit	Equation	Value (European Side) (2007)	Value (Asian Side) (2007)
Constant	average number of young outpatients	appointment/ (people*year)	-	1.6579	1.5753
Constant	average number of mature outpatients	appointment/ (people*year)	-	2.5571	2.4297
Constant	average number of elderly outpatients	appointment/ (people*year)	-	5.5638	5.2866
Auxiliary	annual number of appointments for youngs	appointment/ year	average number of young outpatients*"Young Population	-	-
Auxiliary	annual number of appointments for matures	appointment/ year	average number of mature outpatients*"Mature Population	-	-
Auxiliary	annual number of appointments for elderly	appointment/ year	average number of elderly outpatients*"Elderly Population	-	-
Auxiliary	outpatient demand	appointment/year	annual number of appointments for elderly + annual number of appointments for matures + annual number of appointments for youngs	-	-
Auxiliary	annual outpatient demand	appointment	outpatient demand*TIME STEP	-	-

Please see next page

Type of the variable	Name	Unit	Equation	Value (European Side) (2007)	Value (Asian Side) (2007)
Auxiliary	annual current outpatient capacity	appointment	current outpatient capacity*TIME STEP	-	-
Auxiliary	demand for extra capacity	appointment	max(0,(annual outpatient demand-annual current outpatient capacity-appointment capacity increase in progress))	-	-
Auxiliary	rate of new appointment capacity	appointment/ year	DELAY3[@](demand for extra capacity/TIME STEP, time to response)	-	-
Constant	outpatient capacity per hospital	appointment /hospital/year	-	147,546	181,270
Constant	time to response	year	-	2	2
Stock	appointment capacity increase in progress	appointment	INTEG(max(0,demand for extra capacity/TIME STEP-rate of new appointment capacity,0)	-	-

Please see next page

Type of the variable	Name	Unit	Equation	Value (European Side) (2007)	Value (Asian Side) (2007)
Auxiliary	current outpatient capacity	appointment/year	outpatient capacity per hospital*Hospitals	-	-
Auxiliary	outpatient appointments	appointment/year	min(outpatient demand,(current outpatient capacity + appointment capacity increase in progress/TIME STEP))	-	-
Auxiliary	Category-2 HCW generation	tonne/year	average HCW generation rate per outpatient*municipality service provision*outpatient appointments	-	-
Constant	average HCW generation rate per outpatient	tonne/appointment	-	3.5 * 10 ^ (-5)	4.0 * 10 ^ (-5)
[@]DELAY3 (X,T) takes a third order exponential delay of X for time T conserving X					

Table A 4: Sub-System of Category-2

Type of the variable	Name	Unit	Equation	Value (European Side) (2007)	Value (Asian Side) (2007)
Stock	Number of small HCFs	each	INTEG (increase in number over year, initial number)	-	-
Constant	initial number of small HCFs	each	-	4,281	2,718
Constant	increase rate in small HCFs	1/year	-	0.005	0.005
Flow	increase in number over year	each/year	increase rate in small HCFs*Number of small HCFs	-	-
Constant	HCW generation rate from small HCFs	tonne / (year*each)	-	0.05	0.05
Constant	municipality service provision to small HCFs	dmnl	-	1	1
Auxiliary	Category-3 HCW generation	tonne/year	HCW generation rate from small HCFs*municipality service provision to small HCFs*Number of small HCFs	-	-

Table A 5: Sub-System of Category-3

Type of the variable	Name	Unit	Equation	Value (European Side) (2007)	Value (Asian Side) (2007)
Auxiliary	HCW generation from hospitals	tonne/year	"Category-1 HCW generation"+"Category-2 HCW generation"	-	-
Auxiliary	HCW allocated to incineration	tonne/year	HCW generation from hospitals - HCW allocated to AT	-	-
Auxiliary	HCW allocated to AT	tonne/year	HCW generation from hospitals *proportion of HCW suitable for AT * proportion of hospitals with implemented further segregation	-	-
Constant	ratio of MSW mixing with inc-only stream	dmnl	-	0.05	0.05
Auxiliary	ratio of MSW mixing with HCW SAT	dmnl	1-"ratio of MSW mixing with inc-only stream"	-	-
Auxiliary	total HCW allocated to AT	tonne/year	HCW allocated to AT + MSW mixing*ratio of MSW mixing with HCW SAT	-	-

Please see next page

Type of the variable	Name	Unit	Equation	Value (European Side) (2007)	Value (Asian Side) (2007)
Auxiliary	pilot scale hospitals implemented further segregation	hospital	IF THEN ELSE[@](Time<2015, 3,0)	-	-
Lookup	schedule of hospitals to implement further segregation	dmnl	[(0,1)-(33,22)],(0,0),(1,0),(2,0),(3,0),(4,0),(5,0),(6,0),(7,0),(8,0.3),(9,0.5),(10,0.7),(11,0.9),(12,1),(13,1),(14,1),(15,1),(16,1),(17,1),(18,1),(19,1),(20,1),(21,1),(22,1),(23,1),(24,1),(25,1),(26,1),(27,1),(28,1),(29,1),(30,1),(31,1),(32,1),(33,1)	-	-
Auxiliary	proportion of hospitals with implemented further segregation	dmnl	pilot scale hospitals implemented further segregation/Hospitals + schedule of hospitals to implement further segregation(Time)	-	-
Constant	proportion of HCW suitable for AT	dmnl	-	0.5	0.5

Please see next page

Type of the variable	Name	Unit	Equation	Value (European Side) (2007)	Value (Asian Side) (2007)
Auxiliary	total HCW allocated to incineration	tonne/year	HCW allocated to incineration + MSW mixing*"ratio of MSW mixing with inc-only stream"+"Category-3 HCW generation"	-	-
Auxiliary	MSW mixing	tonne/year	HCW generation from hospitals*proportion of MSW mixed	-	-
Constant	proportion of MSW mixed	dmnl	-	1.9	1.7
[@]IF THEN ELSE (condition, X,Y) returns X if condition exists, otherwise Y					

Table A 6: Sub-System of Waste Segregation

Appendix 4: Formulation of the Employees' Health SD Model

Type of the variable	Name	Unit	Equation	Value
Stock	Susceptible Workers	people	INTEG(recovery-exposure,0)	-
Stock	Exposed Workers	people	INTEG(exposure-sickness, initial workers)	-
Constant	initial workers	people	-	*
Stock	Infected Workers	people	INTEG(sickness-mortality-recovery,0)	-
Stock	Deaths	people	INTEG(mortality,0)	-
Constant	exposure time	year	-	epidemiologic sources*
Flow	exposure	people/year	DELAY FIXED[@](recovery, exposure time , 0)	-
Constant	average time to get infected	year	-	*

Please see next page

Type of the variable	Name	Unit	Equation	Value (European Side) (2007)
Flow	sickness	people/year	Exposed Workers/average time to get infected	-
Constant	average time for mortality	year	-	*
Flow	mortality	people/year	Infected Workers/average time for mortality	-
Flow	recovery	people/year	Infected Workers/average treatment time	-
Constant	average treatment time	year	-	*

@ DELAY FIXED (X, T, I) delays the input X for a fixed time T starting with I

*For Details Please See Chapter 4.2 Employee's Health Model Development

Table A 7: Exposed Workers Health SD Model

Type of the variable	Name	Unit	Equation	Value
Stock	Susceptible Workers	people	INTEG(recovery-exposure,0)	-
Constant	initial workers	people	-	*
Stock	Infected Workers	people	INTEG(sickness-mortality-recovery,0)	-
Stock	Deaths	people	INTEG(mortality,0)	-
Constant	average time to get infected	year	-	*
Flow	sickness	people/year	Susceptible Workers/average time to get infected	-
Constant	average time for mortality	year	-	*
Flow	mortality	people/year	Infected Workers/average time for mortality	-
Flow	recovery	people/year	Infected Workers/average treatment time	-
Constant	average treatment time	year	-	*
*For Details Please See Chapter 4.2 Employee's Health Model Development				

Table A 8: Non-Exposed Workers Health SD Model

Appendix 5: Publication Based on This Thesis

Ciplak, N. and Barton, J.R. (2012). "A System Dynamics Approach for Healthcare Waste Management: A Case Study in Istanbul Metropolitan City, Turkey." Waste Management & Research **30**(6): 576–586