Use of Life Cycle Assessment (LCA) to Develop a Waste Management System for Makkah, Saudi Arabia

Khalid Abdullah Alkhuzai

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Declaration

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

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Abstract

Solid waste management has received increasing attention from researchers and decision makers, who are concerned about establishing sustainable waste management systems. The aim of the research was to improve a waste management system in Makkah, which has experienced significant variations in the amount of waste generated. The research was based on simulations of the consequences of different waste management treatment options and technologies, i.e. incineration, MRF, AD, composting and MBT. The methodology used to analyse and evaluate the data was based on life cycle assessment (LCA) and specialist packages such as the EASEWASTE tool. Makkah was selected as a case study for this research because it is the holiest city in the Islamic world. In 2012, for example, more than 13 million pilgrims travelled to Makkah during religious periods to perform Hajj or Umrah. Therefore, substantial changes in the population of Makkah throughout the year lead to a highly unstable rate of waste generation and characterisation. Furthermore, the only disposal method used in Makkah is landfill, without gas collection or leachate treatment systems. To the best of the author's knowledge, no LCA studies have been conducted on any aspect of waste management in relation to Saudi Arabia, or Makkah in particular. The research has provided an understanding of the existing system of Makkah's waste management during pilgrimage (Hajj and Umrah) and non-pilgrimage time periods. It has also provided a comprehensive approach to evaluate the current strategy of waste management used in Makkah, as well as the alternatives, by applying LCA methodology during different periods of pilgrimage.

Table of Contents

List of Figures

List of Tables

Abbreviations

AC	Acidification
AD	Anaerobic Digestion
APC	Air Pollution Control
C_2H_4	Ethene
CBA	Cost benefit analysis
CBHUK	Council of British Hajjis
CDSI	Central Department of Statistics and Information
CDW	Construction and Demolition Waste
CH_4	Methane
CHP	Combined Heat and Power Unit
CLO	Compost-Like-Output
CO	Carbon Monoxide
CO_2-eq.	Carbon Dioxide - equivalents
d	Duration (days)
DEFRA	Department for Environment, Food and Rural Affairs
DST	Decision Support Tool
DSTs	Decision Support Tools
DTU	Technical University of Denmark
EASEWASTE	Environmental Assessment of Solid Waste Systems and Technologies
EC	European Commission
EDIP	Environmental Design of Industrial Products
EIA	Environmental Impact Assessment
EMA	Environmental management accounting
EMS	Environmental Management System

EnA	Energy Analysis
ET	Ecotoxicity
ETs	Ecotoxicity via Soil
ETw	Ecotoxicity via Water
EU	European Union
FCA	Full Cost Accounting
G	Gregorian Year
GHGs	Greenhouse Gases
GW	Global warming, 100 years
GWP	Global Warming Potential
H	Hijri Year
HDPE	High Density Polyethylene
HT	Human Toxicity
HTa	Human Toxicity via Air
HTs	Human Toxicity via Soil
HTw	Human Toxicity via Water
IIINA	International Islamic News Agency
IPCC	Intergovernmental Panel on Climate Change
ISO	International Organisation for Standardisation
IWM	Integrated Waste Management
KAAU	King Abdulaziz University
KACST	King Abdulaziz City for Science and Technology
KAPL	King Abdulaziz Public Library
kt	Kilo tonne
kt/d	Kilo tonne per day
kt/y	Kilo tonne per year
LCA	Life Cycle Analysis
LCC	Life Cycle Costing

LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
$LCIA_{SC,Hajj}$	Impacts of Hajj period
$LCIA_{SC,i}$	Total impacts of the studied scenario (*i*) in a year
$LCIA_{SC,non}$	Impacts of non-pilgrimage period
$LCIA_{SC,Umrah}$	Impacts of Umrah period
LFG	Landfill Gas
MBP	Mechanical Biological Pre-treatment
MBS	Mechanical Biological Stabilisation
MBT	Mechanical Biological Treatment
MFA	Material flow analysis
Mg	Mega-gram
MIPS	Material-intensity per service-unit
MJ	megajoules
MOH	Ministry of Hajj
MPS	Mechanical Physical Stabilisation
MRF	Materials Recovery Facility
MSW	Municipal Solid Waste
MW	Municipal Waste
MWM	Municipal Waste Management
MWs	Megawatts
N_2O	Nitrous Oxide
NE	Nutrient Enrichment
NH_3	Ammonia
NOP	Nations Online Project
NO_x	Nitrogen Oxides
NPK	Nitrogen Phosphorous Potassium
OD	Ozone Depletion

OECD	Organization for Economic Cooperation and Development
ONEP	Office of Natural Resources and Environmental Policy and Planning
PE	Personnel Equivalent
PME	Presidency of Meteorology and Environment
POF	Photochemical Ozone Formation
RA	Risk Assessment
RD	Recourse Depletion
RDF	Refuse Derived Fuel
SC_{Hajj}	Sub-scenario for Hajj period
SC_i	Studied scenario for a year; SC_0 , SC_1 , SC_2... etc.
SC_{non}	Sub-scenario for non-pilgrimage Period
SC_{Umrah}	Sub-scenario for Umrah Period
SEA	Strategic Environmental Assessment
SETAC	Society Of Environmental Toxicity And Chemistry
SFA	Substance Flow Analysis
SGR	Spoiled Groundwater Resources
SGWR	Spoiled Groundwater Resources
SOD	Stratospheric Ozone Depletion
SWM	Solid Waste Management
t	Tonne
TCs	Transfer Coefficients
TEQ	Toxic Equivalence Factors
TS	Total Solid Content
TS	Transfer Stations
UNDSA	United Nation Department Of Economics And Social Affairs
UNDSD	United Nations Division for Sustainable Development
UNEP	United Nations Environment Programme

UOL	Use-On-Land
USEPA	United States Environmental Protection Agency
VS	Volatile Solid Content
WCED	World Commission on Environment and Development
WHO	World Health Organization
WRF	World Resource Foundation
WtE	Waste To Energy
WWTP	Wastewater Treatment Plant
ZSRC	Zamzam Studies and Research Centre

CHAPTER 1

Introduction

1.1 BACKGROUND FOR THE STUDY

Since the early 1970s, solid waste management in developing countries has received increasing attention from decision makers and researchers concerned with establishing a sustainable waste management system (Gerlagh *et al.*, 1999). The increasing level of industrial and economic activities, rising living standards and population growth has led to an increase in the amount of waste produced. The environment has a limited capacity for waste assimilation. Disposal of excessive amounts of waste rather than recycling or re-using these flows, leads to a lot of stress on the environment. This may result in environmental pollution and depletion of natural resources and thus lead to enormous economic damage (Folmer et al., 1995).

Additionally, it has been reported by United Nation Department of Economics and Social Affairs in Chapter 21(UNDSD, 1998), the action programme of the United Nations Conference on Environment and Sustainable Development in Rio in 1992 reaffirmed that establishing environmentally sound practices for waste management is one of the most important key activities that should be undertaken to protect the Earth's environment and achieve sustainable development. This management should seek to address the main causes of this problem by trying to change unsustainable patterns of consumption and production. This means that it is necessary to apply the concept of life cycle management to environmental issues as it provides a unique opportunity to merge environmental protection with development.

Environmental issues in most developing countries such as Saudi Arabia have not been given adequate attention by government agencies. The population of

Saudi Arabia has increased about 400% between 1974 and 2010. There has also been a dramatic improvement in various aspects of life. The associated environmental issues have not been a priority for the relevant authorities in Saudi Arabia during the past few decades. According to the report of King Abdulaziz City for Science and Technology 'Strategic Priorities for Environmental Technology Programme' (KACST, 2010), there were 11,369 articles published worldwide related to environmental issues such as pollution, waste, air quality and depletion of natural resources between 2005 and 2007. Despite this global activity only 12 articles were published in Saudi Arabia, as shown in Figure 1.1.

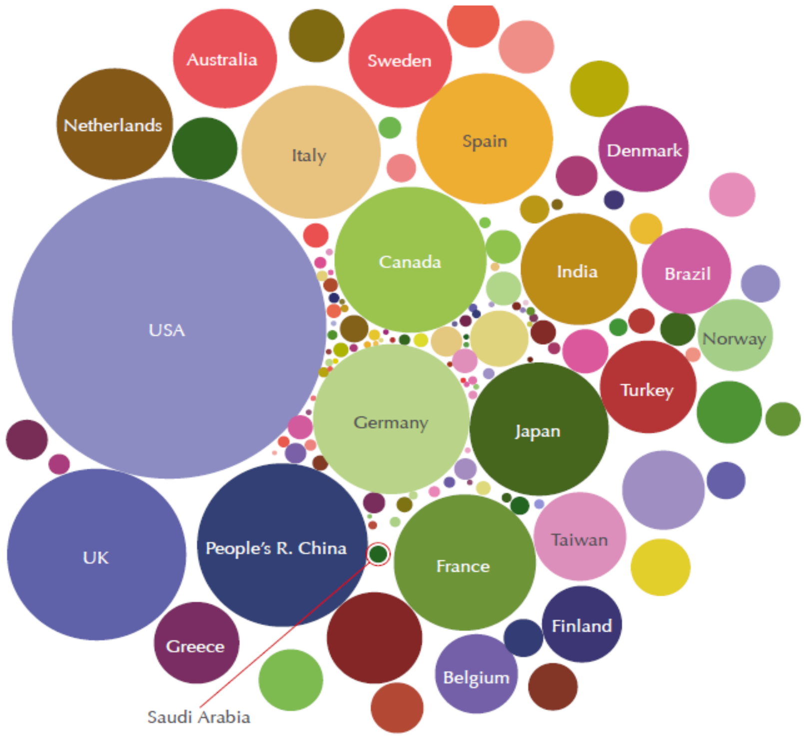

Figure 1. 1: Global environment-related publication activity between 2005 and 2007
Source: KACST (2010)

Recently, solid waste management has become a more significant issue in Saudi Arabia due to its direct relation to public health and the environment. The collection of municipal solid waste has been done without separation at source. Landfilling is the only disposal method for solid waste in most Saudi cities and is done without leachate treatment or the benefit of gas collection facilities. However, there have been limited attempts to gain a benefit from waste by producing compost, but these projects have not achieved the expected success (Alhumoud *et al.*, 2004).

Unlike any other city in Saudi Arabia, about 13 million of pilgrims come to Makkah (Mecca) in Saudi Arabia annually to perform Hajj and Umrah, while the local residents numbered about 1.7 million in 2012 (CDSI, 2013). Thus, large changes in the population of Makkah every year lead to a highly unstable rate of waste generation with about 40% of organic waste. The condition of solid waste management in Makkah is a serious concern. Waste management is one of the major challenges facing the local authorities of Makkah. In response to the change in population during religious events, the Municipality of Makkah has tried to increase staffing levels in waste management as well as investing in new collection vehicles and equipment for the events. However, the waste problems in Makkah are considered to have several dimensions. The waste management system has problems that are linked with finance, equipment, lack of data, attitude and behaviour of local residents and pilgrims, and waste management staff. With the absence of recycling programmes and low salaries for labourers in the cleansing sector, recyclable materials such as aluminium cans and cardboard are scavenged from street bins and the landfill site.

In Makkah, the main method of waste disposal is through legalised landfilling at Al-Misfalah landfill site without using any facilities for leachate treatment or gas collection. The current practice of disposing waste may lead to substantial negative environmental impacts such as emission of greenhouse gases. Typically, methane (CH_4) emissions from solid waste disposal sites are the largest source of greenhouse gas emissions in the waste sector (IPCC, 2007). Other emissions that can occur at waste disposal sites are nitrous oxide (N_2O), nitrogen oxides (NO_x), carbon monoxide (CO) and ammonia (NH_3). Further, there is serious concern over the environmental and public health implications of greenhouse gas emissions in the atmosphere.

There is a need for a systematic method for assessing opportunities to improve the environmental performance of the solid waste management system. Different waste management decision support tools like cost benefit analysis, multi-criteria analysis are available now. In fact, Life Cycle Assessment tool is has been recognised as one of the effective tools to assess the flow dynamics of the resources and waste management strategies and can give us the idea on potential environmental burdens per kg or tonne of waste generated (Ekvall *et al.*, 2007; Cherubini *et al.*, 2009). Collecting data on waste generation, waste composition and disposal is the starting point for applying life cycle assessment in this research. Moreover, it would be easier to assess the environmental suitability of a new and emerging technology through LCA model. Therefore, a strategic planning for sustainable waste management system is necessary for the future development.

The success of waste management planning and policy relies on the existing and forecasting data, and design of the technical development of waste treatment technologies in the future. Local authorisations of Makkah should thus take up the challenge to find out potential future solutions for waste management problems and hence draw closer to the sustainable waste management strategy. This study tries to show different strategies of reducing negative environmental impact by examining different scenarios of waste management in Makkah which has a large change in the amount waste generated throughout the year. The LCA procedure will be adopted in this study to assess the selected scenarios appropriate for Makkah by using databases on the solid waste generated and its characteristics. The best scenario, based on feasibility and least environmental impacts including a low carbon impact, will then be selected by using EASEWASTE 2012 modelling, which is a decision support tool for the environmental assessment of solid waste systems and technologies. Further, EASEWASTE uses LCA to evaluate the resources and emissions associated with solid waste management.

1.2 THE RESEARCH'S AIM AND OBJECTIVES

The aim of this thesis is to develop the current waste management system of Makkah and to accommodate fluctuations in waste flow and composition within different periods. The research is based on comparing of different waste management treatment options and technologies in Makkah by using LCA methodology.

To achieve this aim, the research focuses on a number of specific objectives as follows:

- To analyse the current waste management in Makkah based on waste material flow analysis,
- To identify an approach for data collection and assessment required for the modelling of waste management systems under specific conditions (i.e. instability in waste amounts and compositions within different periods),
- To develop an LCA model and assess the potential environmental impacts of the different waste management systems and technologies,
- To compare the existing with alternative systems and technologies using an LCA model.

1.3 SCOPE OF THIS RESEARCH

The research focuses on the LCA methodology in Makkah which has the significant changing waste generation characteristics in different conditions during pilgrimage and non-pilgrimage periods and their integration. It will concentrate practically on the waste disposal and treatment systems due its importance and problems while the required LCA literature will be fed also within the Environmental European database from EASEWASTE-model due to the shortage of Saudi literature in this area. In this research, the fieldwork data will be collected and the literature will be reviewed within Makkah only due to time and budget availability. Different scenarios will be developed for a waste management system based on available facilities and infrastructure for use in Makkah. Due to the importance of the religious events for the Saudi government, the preferred option of Makkah's waste management must provide a satisfactory environmentally acceptable treatment or recycling options as well as capability and flexibility enough to manage the significant increasing of Hajj waste. The system won't address health and safety issues only but it should conform to Islam believe system. It, then, should maximise the resource efficiency and minimise the potential environmental harms occur.

1.4 ORIGINAL CONTRIBUTIONS OF THIS RESEARCH

This research will make two main original contributions which are: firstly, it provides an applying of LCA methodology of waste management system in Makkah where there is no LCA studies have been conducted on any aspect of waste management in relation to Saudi Arabia, or Makkah in particular. Secondly, it provides an approach of using LCA methodology for assessing different waste management systems within different conditions and periods.

1.5 STRUCTURE OF THIS THESIS

This thesis contains a literature overview on solid waste management, Chapter two, which includes definition of waste, historical development of SWM, as well as methods for assessment of waste management systems, tools for LCA of waste management and EASEWASTE in particular. An overview of the current waste management situation of the study area, Makkah, is showed in Chapter

Three. This chapter evolves Makkah's population, climate, area profile, religious events related to Makkah, and the recent system of solid waste management. In Chapter 4, the scope of the investigation and the methodology used for the research are described. With consideration of the change in waste flow through the pilgrimage and non-pilgrimage periods, EASEWASTE is applied as a LCA tool to evaluate different waste management options for Makkah. A systematic approach for complete LCA methodology is also provided in this chapter to compare the environmental performance of different scenarios for management of solid waste in Makkah. Chapter Five shows the basic input data for the modelling of the existing waste management system as well as the alternative strategies of Makkah. The results of the evaluation of the current situation and the six set up scenarios from LCA are presented in Chapter six. In the last part, findings and challenges in waste management in Makkah are discussed in Chapter Seven with consideration the related requirements for the necessary infrastructure within the pilgrimage and non-pilgrimage periods. The thesis closes in Chapter Eight with research conclusions and gives recommendations which could develop new research ideas for future studies. Figure 1.2 illustrates the structure of this thesis, indicating the logical sequences of its chapters.

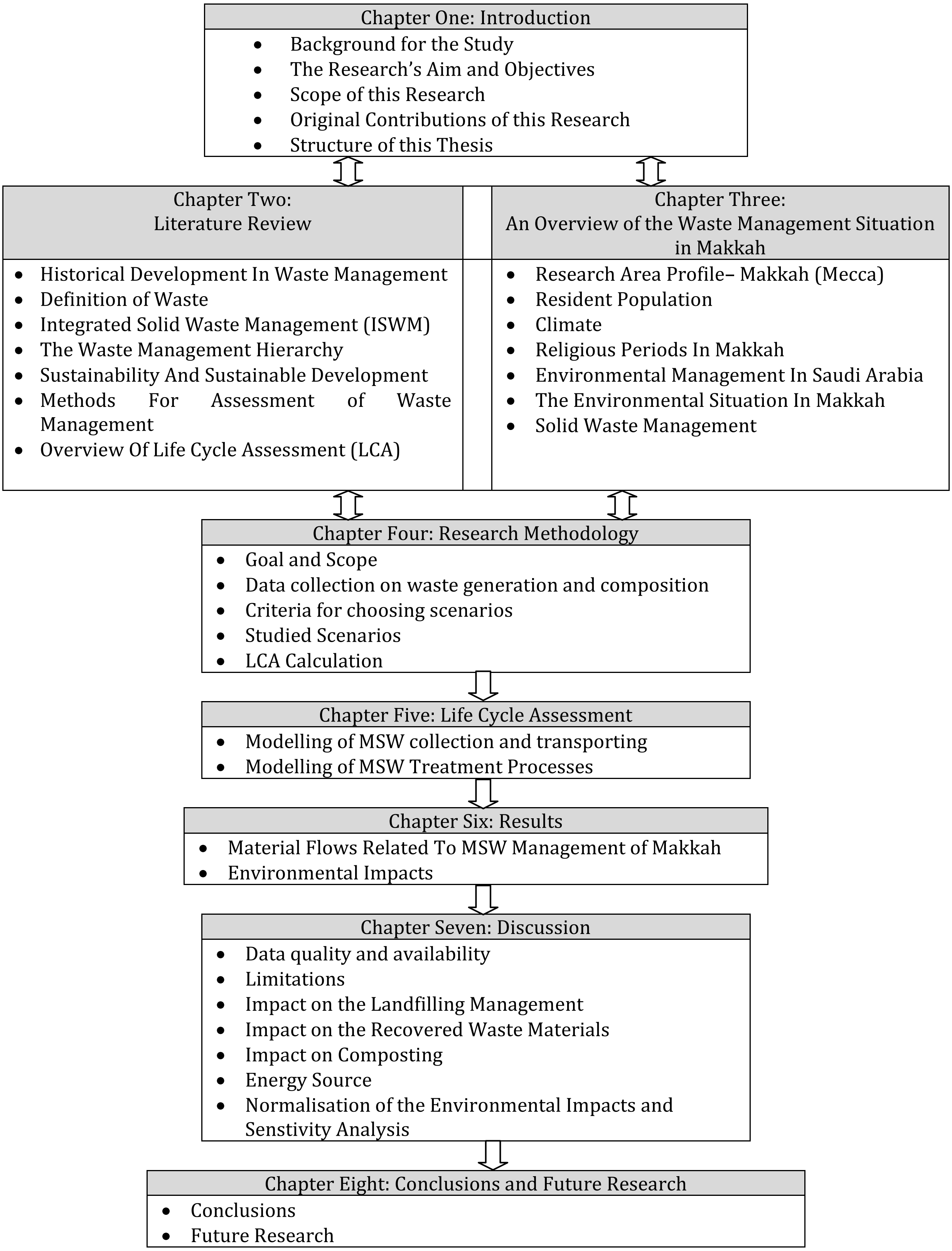

Figure 1. 2:Structure of the Thesis

CHAPTER 2

Literature Review

This chapter focuses on key issues in waste management, which form the general backbone of support for this research. It provides the definition of terminologies used and a literature review of research subjects relevant to the thesis. Integrated solid waste management (ISWM) and focusing on the waste management hierarchy are also provided. Sustainability issues related to waste management is discussed systematically in this chapter, its definition including the key principles of sustainability and sustainable development. A brief history of assessment methods for waste management is reviewed. It is also necessary to describe the specific method, LCA, used in this research and details of its theoretical basis are given.

2.1 HISTORICAL DEVELOPMENT IN WASTE MANAGEMENT

Virtually everything we do creates waste. People in earlier times disposed of human and other wastes in holes dug behind their houses or on their farmland. This practice did not pose a specific problem due to the population was small and the amount of land for the accumulation of waste was large. It, however, may help reduce waste and improve the quality of the crops but waste disposal became a concern for all as populations increased and towns were established (Wan-A-Kadir, 1997).

Dumping in ready dug holes may sound reasonable in the countryside but not in towns. Historically, people in the towns tended to dump their waste onto streets and "street dumping" became common practice throughout the world (Harris and Bickerstaffe, 1990). In order to try to curb this ill-practice of household and street dumping, the authorities introduced laws and regulations.

A law was brought in London at 1297 to ensure that householders kept the frontage of their houses clean but it produced less effect than expected. It was not until 1354 that assistants to the Beadle of each London ward, also called "rakers", were given the job of raking the rubbish together, loading it into carts and removing it once a week. By 1407 London's householders were ordered to keep their waste indoors until the rakers called for it. However, it was reported that not everyone followed this regulation and Beadles had to pay informers to report on people seen dumping rubbish carelessly. It is recorded that in 1515 Shakespeare's father was fined for depositing filth in Public Street (Harris and Bickerstaffe, 1990; Wan-A-Kadir, 1997; El-Hawi, 2004).

At the height of the industrial revolution there was minimal consideration on the likely health and environmental impact caused by industrial, commercial or hazardous wastes. By 1875 a Public Health Act was passed to regulate the disposal of household wastes in the UK requesting each householder to keep their rubbish in a 'movable receptacle' or commonly called today as dustbin. The Clean Air Act introduced in 1956 recorded an increase in the amount of putrescible domestic waste when this waste was no longer burned together with fuel in the open coal fires for heating homes. The increase in 'fly-tipping' of hazardous waste leads Parliament to introduce the Deposit of Poisons Waste Act in 1972. A Waste Management Strategy was produced in 1989 to provide guidelines on waste disposal methods. In January 1995, a consultation draft paper on a Waste Strategy for England and Wales was produced by the UK Government as part of Sustainable Development Strategy (El-Hawi, 2004). Waste cannot be made to disappear but it can be managed so that it minimises harm to human health and to the environment.

2.2 DEFINITION OF WASTE

There are two views of the term "waste". It refers to unwanted item, discarded in a `throwaway society' in the traditional view. It is also something to be removed as far away from us as possible and preferably "not in my back yard" (Tchobanoglous and Kreith, 2002). European Directive 75/442/EC contains, under the Waste Framework Directive, a key definition of waste: it is defined as follows: *"Once a substance or object has become waste, it will remain waste until it has been fully recovered and no longer poses a potential threat to the environment or to human health."* This definition was amended by the Waste Management Licensing Regulations 1994, which defined waste as *"any substance or object which the producer or the person in possession of it, discards or intends or is required to discard but with exception of anything excluded from the scope of the Waste Directive"* (Baker *et al.*, 2004). The alternative view sees waste as a raw material substitute with the resulting environmental advantages. Rather than being useless, waste then becomes purposeful for example as a potential "fuel" in composition operations designed to produce heat and generate stream (Diaz *et al.*, 1993).

Many materials can be considered as waste such as household rubbish, sewage sludge, waste from manufacturing activities, packaging items, discarded cars, old televisions, garden waste, etc. All our daily activities, thus, can give rise to a large variety of different waste arising from different sources (Tchobanoglous and Kreith, 2002).

The United Nations Environment Programme (UNEP) presented in The "*Vital Waste Graphics*" Report that there are overlapping definitions of waste, as shown in figure 2.1. The figure indicate that it refers to compost, e-waste, household waste and incineration residue, and sewage sludge in terms of management. As for waste composition, the definition is made based on the fractions of waste. While in terms of toxicity, the definition is more likely to be based on hazardous waste (Baker *et al.*, 2004).

According to Williams (2005), municipal Solid Waste (MSW) is defined as any of a wide variety of solid materials emanating from human and animal activities that are discarded as useless or unwanted. It includes industrial waste from the burgeoning new large scale manufacturing process, and although normally solid in form, it may include liquids.

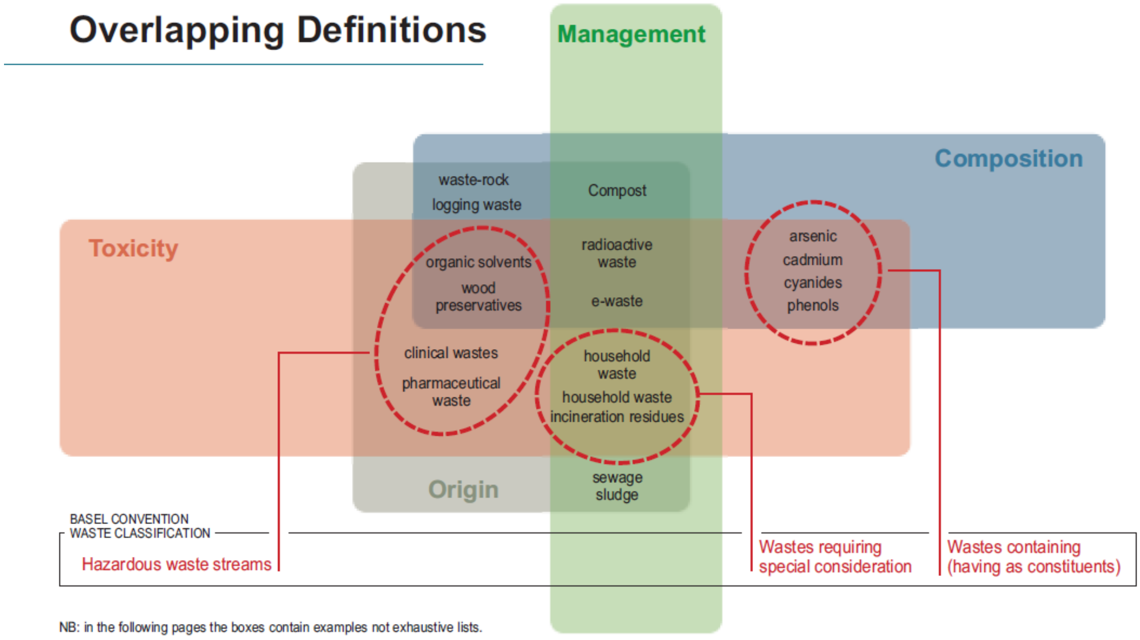

Figure 2. 1: Overlapping Definitions of Waste

Source: Baker *et al.* (2004)

Generally, Sources of solid wastes in a community are related to land use and zoning. Tchobanoglous and Kreith (2002) classified solid waste sources to 8 categories, as described in Table 2.1, including their typical facilities, activities, and locations. It is important to be aware that the definitions of terms and the classifications of solid waste vary greatly in the literature and in the profession. Consequently, the use of published data requires considerable care, judgment, and common sense (Tchobanoglous and Kreith, 2002).

Table 2. 1: Typical Solid Waste Generation Sources, Activities, and Locations Associated with Various Source Classifications

Source	Activities & location	Types of solid waste
Residential	Single-family and multifamily dwellings; low-, medium-, and high-density apartments; etc.	Food wastes, paper, cardboard, plastics, textiles, leather, yard wastes, wood, glass, tin cans, aluminium, other metal, ashes, street leaves, special wastes (including bulky items, consumer electronics, white goods, yard wastes collected separately, batteries, oil, and tires), and household hazardous wastes
Commercial	Stores, restaurants, markets, office buildings, hotels, motels, print shops, service stations, auto repair shops, etc.	Paper, cardboard, plastics, wood, food wastes, glass, metal wastes, ashes, special wastes (see preceding), hazardous wastes, etc.
Institutional	Schools, hospitals, prisons, governmental centres, etc.	Same as for commercial
Industrial (nonprocess wastes)	Construction, fabrication, light and heavy manufacturing, refineries, chemical plants, power plants, demolition, etc.	Paper, cardboard, plastics, wood, food wastes, glass, metal wastes, ashes, special wastes (see preceding), hazardous wastes, etc.
Municipal solid waste*	All of the preceding	All of the preceding
Construction and demolition	New construction sites, road repair, renovation sites, razing of buildings, broken pavement, etc.	Wood, steel, concrete, dirt, etc.
Municipal services *(excluding treatment facilities)*	Street cleaning, landscaping, catch-basin cleaning, parks and beaches, other recreational areas, etc.	Special wastes, rubbish, street sweepings, landscape and tree trimmings, catch basin debris; general wastes from parks, beaches, and recreational areas
Treatment facilities	Water, wastewater, industrial treatment processes, etc.	Treatment plant wastes, principally composed of residual sludges and other residual materials
Industrial	Construction, fabrication, light and heavy manufacturing, refineries, chemical plants, power plants, demolition, etc.	Industrial process wastes, scrap materials, etc.; nonindustrial waste including food wastes, rubbish, ashes, demolition and construction wastes, special wastes, and hazardous waste
Agricultural	Field and row crops, orchards, vineyards, dairies, feedlots, farms, etc.	Spoiled food wastes, agricultural wastes, rubbish, and hazardous wastes

* The term municipal solid waste (MSW) is normally assumed to include all of the wastes generated in a community, with the exception of waste generated by municipal services, treatment plants, and industrial and agricultural processes.

Source: Tchobanoglous and Kreith (2002)

2.3 INTEGRATED SOLID WASTE MANAGEMENT (ISWM)

With looking at historical citations, it can be assumed that the concept of integrated solid waste management (ISWM) developed gradually over the time. For example, in many European countries in the 1660s, burial in cotton or linen shrouds was banned to allow more cloth for paper making (World Resource

Foundation, 1997). In 1896, the first combined waste incineration and electricity scheme began operation in East London. Until the early 1890s, New York's waste was mainly dumped in the Atlantic Ocean, polluting the beaches and resulting in protests by the resorts on the shores of New Jersey and New York. Then a programme of source separation was implemented on the premise that mixed refuse limited the options for disposal, whereas the separation of wastes at the source allowed the city to recover some of the collection costs through the resale and reprocessing of materials (Gandy, 1994). In the early part of the 20th century, an ethnic minority in Cairo, Egypt, the “Zabbaleen”, was one of the world's first communities to integrate recovery and recycling of municipal waste (Van Beukering *et al.*, 1999).

There have been long discussions about the use of the term "integrated" in solid waste management. Diaz *et al.* (1993) highlighted the widespread use of the term integrated in SWM nomenclature. They argued that the term "integrated management" should be reserved for systems, schemes, operations or elements in which the constituent units can be designed or arranged in such a way that one meshes with another, to achieve a common overall objective.

Integrated Solid Waste Management (ISWM) is defined by Tchobanoglous and Kreith (2002) as a comprehensive system which involves various activities such as waste prevention, collection, recycling, composting, combustion and disposal programmes to achieve specific waste management objectives and goals. Each of these activities requires careful planning, financing, collection, and transport to ensure that there is effective protection of public health and the environment. An effective system of ISWM focuses on evaluating the management of solid waste, prevention and recycling, and then selecting the most appropriate solid waste management activities.

Tchobanoglous *et al.* (1993) define integrated waste management in terms of the integration of six functional elements. These are the following:

1. Waste generation - Assessment of waste generation and evaluation of waste reduction.

2. Waste handling and separation, storage and processing at source – Involves the activities associated with the management of wastes until they are placed in storage containers for collection.

3. Collection - This element of the waste management system covers the collection and transport of the waste to the location where the collection vehicle is emptied. This location may be, for example, a materials recycling facility (MRF), a waste transfer station or a landfill disposal site.

4. Separation, processing and transformation of solid waste - The recovery of separated materials, the separation and processing of waste components and transformation of wastes are elements, which occur primarily in locations away from the source of waste generation. This category includes waste treatment of materials at recycling facilities, activities at waste transfer stations, anaerobic digestion, composting and incineration with energy recovery.

5. Transfer and transport - This element involves the transfer of wastes from the smaller collection vehicles to the larger transport equipment and the subsequent transport of wastes, usually over long distances, to a processing or disposal site. The transfer usually takes place at a waste transfer station.

6. Disposal - Final disposal is usually landfill or land spreading i.e., the disposal of waste directly from source to a landfill site, and the disposal of residential materials from materials recycling facilities, residue from waste incineration, residue from composting or anaerobic digestion etc. to the final disposal in landfill.

It is important to look at solid waste management which can deliver both financial and environmental sustainability as an integrated problem instead of focusing separately on the technical, financial and social aspects. From an environmental point of view, no single method of waste disposal can deal with all materials (McDougall *et al.*, 2008). Therefore, a combination of many different methods of solid waste management activities must be considered which complement each other without any contradiction between them. The inter-relationships of the six functional elements of an integrated solid waste management system are shown in Figure 2.2.

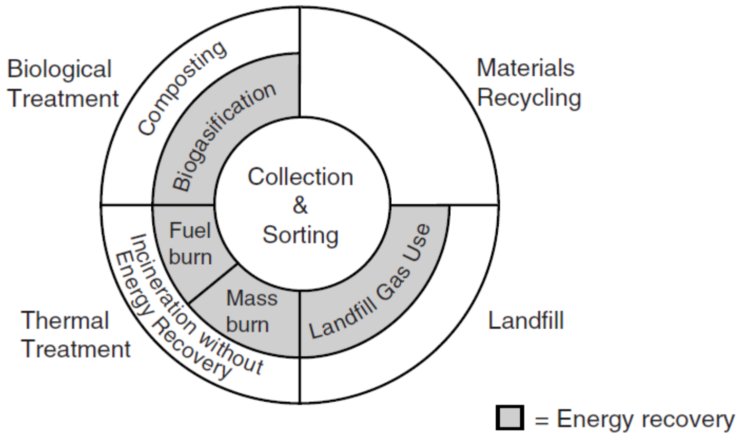

Figure 2. 2: Elements of Integrated Waste Management

Source: McDougall *et al.* (2008)

The UNEP International Environmental Technology Centre (1996) describes the importance of viewing solid waste management from an integrated approach:

- Some problems can be solved more easily in combination with other aspects of the waste system than individually;

- Adjustments to one area of the waste system can disrupt existing practices in another area, unless the changes a remade in a coordinated manner;

- Integration allows for capacity or resources to be completely used; economies of scale for equipment or management infrastructure can often only be achieved when all of the waste in a region is managed as part of a single system;

- Public, private, and informal sectors can be included in the waste management plan;

- An ISWM plan helps identify and select low cost alternatives;

- Some waste activities cannot handle any charges; some will always be net expenses, while others may show a profit. Without an ISWM plan, some revenue-producing activities are "skimmed off' and treated as profitable, while activities related to maintenance of public health and safety do not receive adequate funding and are managed insufficiently.

The treatment and disposal of waste has developed from its early beginnings of mere dumping to a sophisticated range of options including re-use, recycling, incineration with energy recovery, advanced landfill design and engineering, and a range of alternative technologies, including paralysis, gasification, composting and anaerobic digestion. The further development of the industry is towards integration of the various options to produce an environmentally and economically sustainable waste management system (McDougall *et al.*, 2008).

2.4 THE WASTE MANAGEMENT HIERARCHY

The waste management hierarchy is a tool that policymakers have used to rank waste management options according to their environmental benefits and it considers products from their `cradle' to their `grave'. According to Van de Beukering *et al.* (1999), the waste hierarchy is usually established to identify key elements of an ISWM plan. The hierarchy is based on environmental principles which propose that waste should be handled by different methods according to its characteristics, i.e. a certain amount should be prevented either by reducing the content of waste or by reusing the waste; another share of the waste stream should be converted into secondary raw materials; some parts can be composted or used as source of energy, and the remainder may be landfilled (see Figure 2.3). Reality does not adhere to this environmentally based sequence. Indeed, in developing countries, a large quantity of waste is dumped in an uncontrolled manner, or worse, burned in the open air. Obviously, these options do not belong to the waste hierarchy because of their unacceptable high levels of environmental damage. These latter two options are therefore added in the shaded area.

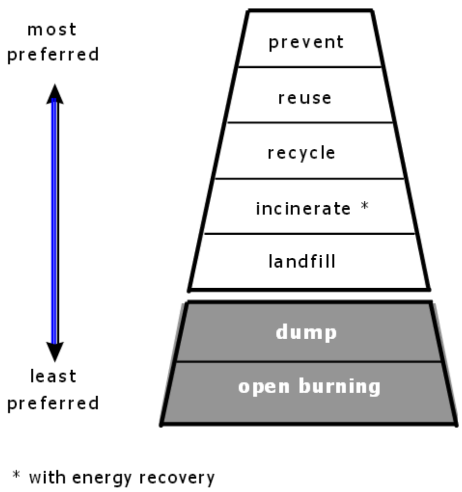

Figure 2. 3: A Hierarchy of Waste Management

Source: Van Beukering *et al.* (1999)

The selected waste management route is determined after considering the following hierarchy of options, which is stated in the European Union Solid Waste Strategy (EC, 1997).

- Waste reduction at source, waste minimisation in a prevention attitude.
- Waste reuse and recycling.
- Recovery of raw materials and/or of energy.
- Treatment of wastes.
- Disposal of the residues from treatment, and of other unavoidable waste.

In addition, the hierarchy promotes the recovery - through reuse, recycling and composting - of as many waste materials as possible before disposal or incineration.

According to Van de Beukering *et al.* (1999), addressing the advantages of reuse and recycling are:

- Reduction of the amount of materials requiring collection and disposal, which means:
  - Longer lifetimes for landfills; more capacity for waste in other kinds of treatment facilities.
  - Lower transportation and landfill costs.
  - More reliable and local supply of raw materials to local industries, avoiding using foreign exchange and import procedures
  - Reduced extraction of non-renewable raw or virgin materials and associated environmental devastation.
  - Reduced deforestation.
- Conservation of resources, energy and water;
- Provision of income and employment;
- Availability of affordable products for the poor.

Policies based on the hierarchy seek to maximise the recovery options and to minimise disposal through open dumping, controlled disposal and landfilling. Once possibilities for recovery have been exhausted, policies based on the hierarchy favour safe disposal, limiting negative impact on the environment and natural resources as much as possible.

The waste management hierarchy is an example of how ISWM adapts an existing environmental policy to support its environmental aspects in determining the form of the waste elements. Similar policy instruments support other aspects, such as non-discrimination policies, which support the social aspect. Like all policies, the hierarchy needs to be applied with certain flexibility. Sometimes recycling may not be the right solution and other solutions like incineration may be more appropriate, for example in the case of healthcare waste. Nevertheless, the waste management hierarchy is an important guideline for ISWM.

Although this ranking of waste management options provides policy makers with an effective base, integrated SWM goes beyond the waste hierarchy. It is generally known that the hierarchy has to be applied in a flexible way and it is only intended as a general guideline to achieve the best environmental solution in the long term. Still, the hierarchy has always been subject to fierce criticism for various reasons. First, although the ranking may indeed be correct in terms of environmental pressure for certain materials, this is not the case for all materials or products. For instance, it may be better to recycle an old refrigerator rather than reuse it because its inefficient energy consumption creates more environmental damage than the recycling related burdens. Second, the hierarchy only refers to environmental effects and not to economic or social criteria. Obviously, these aspects cannot be ignored.

Separation at source, reuse and recycling take an important place in the waste management hierarchy. Waste materials should be separated at source as much as possible to improve the quality of materials for reuse and recycling –

including organics for composting - to reduce energy use in collection and to improve working conditions at all stages. This will also benefit those earning a living from waste recovery (Lardinois and Furedy, 1999). Separation at source of hazardous waste has the additional advantage that it reduces the risks of handling municipal waste.

Therefore, many believe that the options should not be ranked in a particular order but should be considered as a "menu" of alternatives. "*It is not a question of good and bad waste management options or technologies. Rather, each option was equally appropriate under the right set of conditions addressing the right set of waste stream components*" (Schall, 1995). In an effort to determine whether the hierarchy is applicable in developing countries, the following section evaluates the essential differences between the North and the South.

2.5 SUSTAINABILITY AND SUSTAINABLE DEVELOPMENT

The ongoing and lengthy debate about the definition of sustainability has often revolved around the auditor's worldview. Different worldviews make different definitions and debates about these almost inevitable and often incompatible (Folmer *et al.*, 1995). The situation is further confused by the debate about sustainable development versus sustainability. A number of definitions of sustainable development that is likely to achieve lasting satisfaction of human needs and improvement of the quality of life (Allen, 1997).

According to Goodland and Ledec (1987), sustainable development is defined as a pattern of social and structural economic transformations, i.e. "*development, which optimizes the economic and social benefits available in the present, without jeopardizing the likely potential for similar benefits in future*". "*A primary goal for sustainable development is to achieve a reasonable (however defined) and equitably distributed level for economic well-being that can be perpetuated continually for many generations*".

Some definitions or interpretations have been criticised as too vague or even ambiguous (Mitchell, 1997). It should also be stated that sustainable development has attracted both criticism and support. There is considerable discussion over whether growth can be sustainable in all circumstances. The Brutland Commission was explicit that while growth is essential to meet basic human needs, sustainable development involves more than growth. It necessitates a change in the nature of growth, to make it less material and energy-intensive, and to make it more equitable in its impacts (Mitchell, 1997). The economist Herman Doyle clarifies the difference by defining "growth" as an increase in size through material accretion while referring to "development" as the realisation of fuller and greater potential. In short, growth means getting bigger while development means getting better (Wackernagel and Rees, 1996).

According to McDougall *et al.* (2008), the term "sustainable development" was developed by the World Commission on Environment and Development in 1987. The aim of the World Commission was to find practical ways of approaching the environmental and developmental problems of the world. Sustainable development has been defined the Brundtland report as *"development which meets the needs of the present without compromising the ability of future generations to meet their own needs"* (WCED, 1987). This is taken to mean that for those developing a waste service in a municipality, to be sustainable they should not use more resources - materials, labour, equipment and finance - than they have access to in their locality and that they should be used in such away as not to squander them or create lasting problems for future generations.

In 1992, a global action in sustainable development released the "Agenda 21" at the United Nations Conference on Environment and Development in Rio de Janeiro, Brazil (also called the Earth summit). Agenda 21 provides guidelines for sustainable development which each country has to implement. Program areas are closely related to resource conservation and environmental protection as follows:

a. Protection of the quality and supply of freshwater resources: application of integrated approaches to the development, management and use of water resources;
b. Promoting sustainable human settlement development;
c. Protecting and promoting human health conditions;
d. Changing consumption patterns.

With regard to the sustainable management of solid waste and sewage, Agenda 21 states in Chapter 21- paragraph 21.1 that "*environmentally sound management of wastes was among the environmental issues of major concern in maintaining the quality of the Earth's environment and especially in achieving environmentally sound and sustainable development in all countries*" (UNDSD, 1998). Accordingly, four major program areas, as follows, were proposed to attempt to provide a comprehensive and environmentally responsive framework for managing waste:

a) **Minimizing waste generation**; this principle aims to stabilise and reduce the production of wastes destined for final disposal by formulating goals based on waste weight, volume and composition and to induce separation to facilitate waste recycling and reuse.

b) **Maximizing environmentally sound waste reuse and recycling**; this framework aims to strengthen and increase national waste reuse and recycling systems. A model internal waste reuse and recycling program for waste streams shall be created.

c) **Promoting environmentally sound waste disposal and treatment**; the objective in this area is to treat and safely dispose of an increasing proportion of the generated wastes.

d) **Extending waste service coverage**; Extending and improving waste collection and safe disposal services are crucial to gaining control of the health and environmental impacts of inadequate waste management.

The four programme areas are interrelated and must therefore be integrated in order to change unsustainable patterns of production and consumption. According to Agenda 21- paragraph 21.4, this implies the application of the integrated life cycle management concept, which presents a unique opportunity to reconcile development with environmental protection (UNDSD, 1998). Consequently, the degree of sustainable waste management has a returned influence on the (a) reducing environmental impact through the treatment and disposal of waste, (b) reducing mining and its impact in the beginning of the life-cycle, (c) conservation of non-renewable resources.

McDougall *et al.*(2008) mentioned that the cost of the waste management system was the main factor in the past which affected the process of decision making, but now, the environmental burdens are the major controlling factor combined with the principles of sustainable development. Hence, the need for sustainable SWM systems is high and such a system must be environmentally effective, economically affordable and socially acceptable (see Figure 2.4), as follows:

1. Environmentally effective: the environmental burdens of managing solid waste which produce various emissions to air, water and land, must be reduced at the processes of the solid waste management system.
2. Socially acceptable: the system of solid waste management must operate in a way that is acceptable to the majority of the people in a society and meet their needs.
3. Economically affordable: the system of solid waste management must run at a cost acceptable to all sectors of the community served, including householders, businesses, industry, institutions and government.

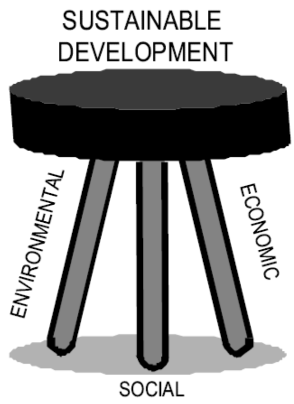

Figure 2. 4: The three pillars of Sustainable Development

Source: McDougall *et al.* (2008).

However, it is difficult to keep these three variables at the minimum level. Better decisions will be made if data on costs and environmental burdens are available, but for a balance to be achieved, the overall environmental burdens of the waste management system should be minimised as far as possible within acceptable levels of cost (McDougall *et al.*, 2008).

Brunner and Fellner (2007) compared different waste management systems in Vienna, Damascus and Dhaka, which have different GDP. They found that the current practices of solid waste management in countries with low GDP still do not meet the requirements of protection of public health and the environment.

2.6 METHODS FOR ASSESSMENT OF WASTE MANAGEMENT

Since the late 1960s, MSW and the environmental consequences associated with its management have received increasing attention worldwide (Eriksson *et al.*, 2003). With the growing complexity of waste management, the selection of the best alternative becomes a more difficult task. Consequently, system analyses combined with mathematic modelling have been developed. Regardless of the potential environmental impact, conventional models apparently focus on economic optimisation(Modak and Everett, 1996). Since then, IWM planning has increased attention to environmental impact, and material and energy recovery. Recently, the emphasis on both socio-economic and environmental factors became apparent (El-Fadel and Abou Najm, 2002).

Currently, a large number of assessment methods as shown in Table 2.2 have been developed to support decision making in waste management. Typically, the assessments tools may be divided into two categories, namely procedural and analytical tools (Wrisberg *et al.*, 2002). The procedural tools (e.g. Environmental Management System (EMS)) generally apply to procedures and decision circumstances in society and the environment. The latter tools (e.g. LCA) ordinarily provide information that could be used for system optimisation, comparison of alternatives, communication, etc. However, procedural tools in association with analytical tools are frequently applied (Moberg, 2006).

Which tool to use in a specific decision making situation depends on the decision context. When linking tools and decision context, some aspects can influence the choice of tool, whereas others influence how the tools are used. The choice of an appropriate tool in different contexts is largely decided by two aspects: the object under study (e.g. products, services, policies, plans, regions, organisations, etc.) and the impacts of interests (environmental, economic, social, etc.) (Finnveden and Moberg, 2005). At the same time there are many aspects which could influence how the selected tool is used. Some of them could also influence the choice of the tool. Examples are complexity, degree of aggregation and level of detail, scope, scale of the decision and preferences, credibility, cultural context (Finnveden and Moberg, 2005).

The scale of the decision will influence the amount of resources put into the analysis. This could influence how the tool is used. In a decision-making process, both local or site specific and site-independent information may be of interest. Some of the assessment tools are applicable more on site-specific objects while others may be used for different objects. For example, if the decision maker is concerned about local effects, e.g. when deciding the location for a waste incinerator, site specific assessment should be made using specific tools such as RA or EIA. If, on the other hand, there is a need to compare the environmental impacts of different waste management scenarios (e.g. recycling versus incineration), life-cycle based assessment tools such as LCA would be appropriate (Moora, 2009).

Different tools also can complement each other by adding different types of results. For example, the results of an EIA study could be combined with LCA results which give additional information in the life cycle perspective (Moora, 2009; Chanchampee, 2009).

Table 2. 2: Overview of the assessment tools for integrated waste management

Tools	Description
Procedural tools	
Environmental impact assessment (EIA)	EIA is a tool for analysis of environmental impact of projects where location is known. The social and economic aspects, as well as natural resource depletion are often integrated. The comparison of alternative site locations also applies. Normally, EIA approval is required in many countries for waste facilities permission.
Strategic environmental assessment (SEA)	Unlike EIA, SEA is intended for use in the early stages of strategic planning and policy making. Therefore, a site specific location is unknown. Nevertheless, the evaluation aspects are similar to EIA. Since the guideline is being developed, the application in waste management is limited.
Environmental management system (EMS)	EMS including environmental audit is standardized in ISO 14001. In general, EMS is applied for facilities or organizations i.e. landfill, municipalities. Environmental impact and resource consumption through operation are usually periodically being assessed.
Analytical tools	
Material flow analysis (MFA)	The idea is to analyze an input flow of material or substance and trace the output and stock. Substance flow analysis (SFA) which focuses on a specific substance is also a type of MFA. This method is often applied for the assessment of MSW flows through the complex waste management
Energy analysis (EnA)	Since energy can be gained and consumed from the waste industry, there are several studies that connect waste and energy flows. All energy consumptions throughout the waste treatment processes as well as secondary material processing are typically appraised.
Material-intensity per service-unit (MIPS)	MIPS, based on a life cycle perspective, determines the total mass flow per service unit, i.e. a production of 1 kg copper of material intensity cause by production, consumption, waste recycle. The tool is applied to assess dematerialization of input materials which are categorized into abiotic and biotic materials, soil, water, air and electricity.
Cost benefit analysis (CBA)	An evaluation of the costs and benefits of a project is harmonized with an environmental economy. All environmental impacts are transposed to a monetary system. Despite the fact that an establishment of waste project typically applied, CBA can be broadly approached at the national level.
Life cycle assessment (LCA)	LCA is applied to assess environmental impact and natural resource use for the life cycle of a product and service system. Like EMS, the standardization has been developed by the International organization for standardization (ISO, 1997)). There are a lot of case studies where LCA has been applied to IWM.
Life cycle costing (LCC)	LCC is used to assess cost of product or service based on life cycle thinking. Unlike CBA, LCC excludes external costs, for instance, the impact of pollution on society.
Environmental management accounting (EMA)	Initially used in business sector, EMA (it is also called full cost accounting- FCA in the USA) recently has been applied in worldwide government. Despite similar concepts of life cycle perspective as LCC, a budget allocation with a simple straight-line depreciation in EMA is performed instead of finding the maximum net saving in LCC. EMA takes into account all expenditure, overhead, equipment and maintenance, and past and future outlay of MSW management.
Risk assessment (RA)	The aim is to define target values and acceptable risks. The assessment is distinctively defined into chemical substances and accidents. *Chemical risk assessment*; the effect of nature, size, magnitude and duration of exposure is analyzed i.e. potential toxic risk of fly ash management. *Accident risk assessment;* unplanned incidents, i.e. it concerns fire and explosions. The probability of accident is combined. Environmental aspects may be integrated.

Source; US EPA (1997), OECD (2000), Finnveden *et al.* (2007) and Chanchampee (2009)

Compared to many other decision-support tools life cycle thinking and especially LCA have gained wide acceptance in providing policy relevant and consistent results (Björklund and Finnveden, 2005). It can be used both as a descriptive tool as well as a change-oriented tool with different choices of data and methodology. Recently also economic aspects have been integrated into LCA (input-output LCA, life cycle costing in LCA, etc.), which makes the tool even more suitable in the decision making process. Its strength compared to many other environmental system analysis tools is also that the framework, terminology and methodological choices of LCA are standardised by the International Standardisation Organisation (ISO) (ISO, 2006). This gives LCA greater credibility (Björklund and Finnveden, 2005).

2.7 OVERVIEW OF LIFE CYCLE ASSESSMENT (LCA)

The LCA is defined in ISO 14040 as a technique for evaluating the environmental impacts and consumption of resources and was initially developed for assessing the whole life cycle of products including extraction of resources, production, distribution, use and disposal "from cradle to grave" (ISO, 1997; Barton *et al.*, 1996). Environmental assessment of a product can be defined as: "*to define and quantify the service provided by the product, to identify and quantify the environmental exchanges caused by the way in which the service is provided, and to ascribe these exchanges and their potential impacts to the service*" (Wenzel *et al.*, 2000).

The term 'product' can include not only product systems but also service systems such as waste management. Nowadays, LCA is one of the most accepted methods applied for evaluating environmental aspects and potential impact starting from cradle (discarded materials from households) to grave (final disposal, substitution of raw materials) through human activities such as the waste management processes (Finnveden, 1999). According to McDougall *et al.* (2008), the tool of LCA can successfully be used to assess the environmental burdens and economic costs associated with Integrated Municipal Waste (IWM) systems.

2.7.1 LCA methodology

Based on the LCA workshops carried out by the Society for Environmental Toxicology and Chemistry (SETAC), the ISO has further developed, and has managed to reach agreement among its global membership on a series of standards. The ISO 14040 series on Life Cycle Assessment are:

- ISO 14040 Environmental management - Life cycle assessment - Principles and framework (1997).
- ISO 14041 Environmental management - Life cycle assessment - Goal and scope definition and inventory analysis (1998).
- ISO 14042 Environmental management - Life cycle assessment - Life cycle impact assessment (2000a).
- ISO 14043 Environmental management - Life cycle assessment - Life cycle interpretation (2000b).

As a result of intensive recent efforts to define LCA structure and harmonise the various methods used, complete LCA must follow a systematic approach with four distinct phases (ISO, 2006) (see Figure 2.5). The following phases in LCA according to the ISO standard are:

- **Definition of goal and scope**: attempts to define the extent of the inquiry as well as specify the methods used to conduct it in later steps. One selects a product system, functional units, system boundaries, allocation methods, and impact categories during this defining phase.

- **Life cycle inventory (LCI)**: an identification of involved processes and collection and allocation of all relevant data (input and output) is conducted.

The total LCI for a waste management system can be calculated as (Clift *et al.*, 2000):

+ direct burdens from waste management activities

+ indirect burdens associated with providing material and energy to the waste management activities

- avoided burdens associated with processes which are avoided because of production of materials and energy.

- **Life cycle impact assessment (LCIA)**: assigning inventory data to impact and resource categories. Normalisation and weighting can also be part of this phase.

- **Interpretation**: an iterative process of reviewing the LCI and the LCIA until the results comply with the goal and scope and trustworthy recommendations and conclusions can be made on the basis of sensitivity analysis.

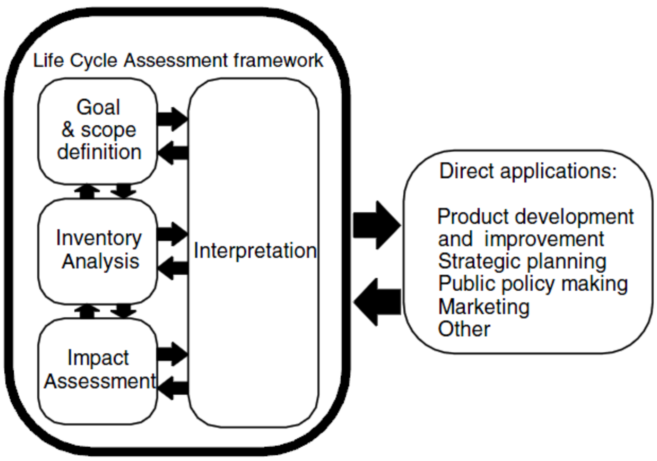

Figure 2. 5: Phases of an LCA

Source: ISO 14040 (1997) cited by McDougall *et al.* (2008)

In addition to the mandatory elements there are optional elements and information which can be included in a Life Cycle Impact Assessment (LCIA).

Weighting may be included to convert and possibly aggregate indicator results across impact categories, resulting in a single result. Normalisation is another optional element whereby the magnitudes of the impacts are related to reference values, e.g. total contribution to an impact category by nation.

A Danish methodology for conducting LCA for products was developed in the 1990's. The methodology is called EDIP 97 (Environmental Design of Industrial Products) and is in compliance with the ISO standards (Kirkeby and Christensen, 2005). The EDIP 97 methodology is the most widely used LCIA methodology in Denmark and is also the methodology used in this PhD project. In a life cycle assessment made with the EDIP 97 results can be viewed at four different levels:

1. Life cycle inventory
2. Impact characterisation
3. Normalisation
4. Weighting

A holistic and systematic approach is used to evaluate the environmental impacts when applying life cycle assessment on integrated solid waste management, here including consumption of resources and potential impacts on human health and on the environment. In principle, LCA attempts to model all important types of environmental impacts of the product system. In reality LCA will often be limited to the environmental impacts, which can be quantified using existing methodologies. For example, due to incomplete data and lack of consensus on assessment methodology, the environmental impacts of toxic chemical emissions and land use are poorly represented in many LCA models (Reap *et al.*, 2008).

The results for the environmental impact categories were either characterised (e.g. in kg CO_2-eq.) or normalised (presented in the unit 'person equivalents' (PE)). 1 PE expresses the average environmental impact generated from all of one person's activities in one year in the given category. The results for the resource consumptions were either shown as amounts (in kg) or normalised and weighted with regard to supply horizons (presented in the unit 'person equivalent (PE)). 1 PE, here, expresses the amount of a given resource available for one person and that person's descendants. If the functional unit is for instance one tonne of waste, it is more convenient to present the results in thousandths of PE, i.e. mPE or mPR. It makes the numbers more readable, even though these might be thought of as odd units (Moora, 2009).

2.7.2 LCA in integrated waste management

The method is not only applied in the production sector but has also become an increasingly standard practice in the management of solid waste. LCA is currently used to evaluate different strategies for integrated solid waste management and to evaluate treatment options for specific waste fractions (Finnveden *et al.*, 2005). Computer-based models and data bases were established in order to facilitate the calculation for repeating waste management process units (Björklund, 2000).

Figure 2.6 visualises a system boundary of the LCA of waste management compared to the LCA of product. The applications of LCA have shown the capability to improve the decision making process and to develop a long term IWM strategy (Hansen *et al.*, 2006a; 2006b).

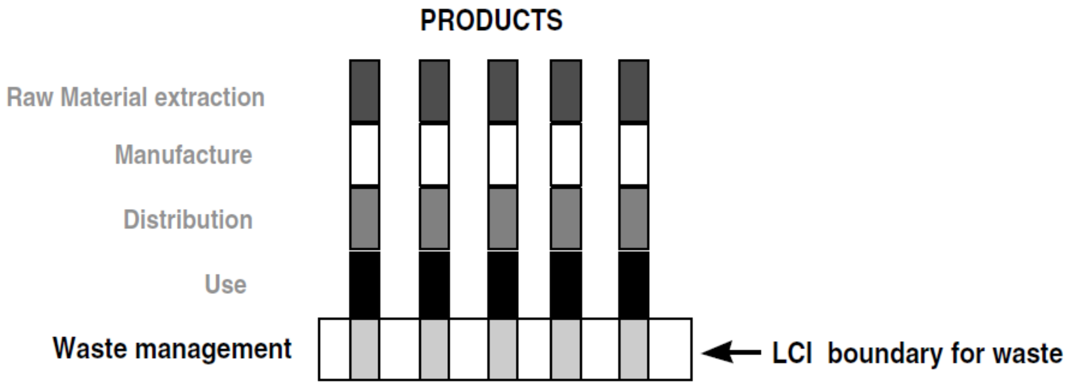

Figure 2. 6: Life cycle of solid waste and system boundaries

Source: McDougall *et al.* (2001)

2.7.3 Pros and Cons of LCA

There are many benefits arise from the application of the LCA studies – in particular, the fact that it is the only robust method of determining the wide range of environmental impacts across the life cycle of a product or service that avoids shifting impacts from one stage to another, and identifies impacts across a wide geographical range. The use of this environmental tool (Guinée, 2002; Horne *et al.*, 2009; Pennington *et al.*, 2004) can help researchers and decision makers to:

- Systematically estimate the environmental consequences and to analyse the exchanges that take place to the environment and are related to the examined product or process;
- Quantify the emissions into air, water and land that take place in every life cycle phase;
- Detect significant changes in the environmental effects between the life cycle phases;
- Estimate the effects of materials consumption and environmental emissions on human and the eco-system;
- Compare the consequences to human and to the eco-system of two or more competitive products or processes;
- Allocate the impacts of the examined product or process in one or more items of environmental interest.

In addition to the above, LCA has the potential to structure a flow of quantitative information between different stakeholders (industry, customers, researchers, governmental agents, decision makers, local communities and other groups). It can be used internally within an industry for process improvement, technology selection and reporting, and externally to support marketing and to inform different stakeholder groups. Finally, it must be noted that with the help of this methodology, producers take better decisions pertaining to environmental protection.

However, similar to other techniques, LCA studies present various limitations. The most common limitation in using LCA is a lack of clear definition of purpose and application before implementation. Undertaking an LCA can be very time-consuming and complex, particularly in terms of the demand for high-quality data and the complexity of the methodology. Issues arise with the availability, reliability and accuracy of data. There are many datasets and databases; each has its own embedded assumptions and the user also makes their own assumptions when undertaking an LCA. This state of affairs can result in the same inventory having different results. The selection of boundaries in LCA can also significantly affect the results.

In addition, there are two major challenges in the use of LCA in resource and waste management (Guldbrandsson and Bergmark, 2012). The first challenge is how to cover and quantify all interactions of the analysed resource and waste management system with its surroundings. A comprehensive analysis requires the collection of an enormous amount of data. In many cases it is not possible to obtain this data which leads to many assumptions and simplifications. Depending on the LCA's objective and scope, the error introduced by such assumptions and data substitutions can be small, or large. Often, the error introduced can be quantified and the assumptions thereby justified.

The second challenge of the use of LCA in waste and resource management is that the impact of these systems is very dependent on local, regional and national conditions, including consumer habits, mode of transport, generation of by-products and energy, or the energy supply systems in place (fossil fuels, biomass, hydropower, nuclear, wind). It is therefore important to make use of local data when possible, rather than importing external data or using the default data. To correctly set up the boundaries of a system requires specialised knowledge. Resource extraction and waste treatment processes are complex in the number of inputs and outputs, and have frequently outputs of energy (power from incineration plants or landfill gas plants) and by-products (compost, recovered glass, paper, metal). The energy and by-products can enter into other systems, substituting other materials or energy which otherwise would be used.

The characteristic of waste as a mixture of various materials adds another element of complexity to the use of LCA. Due to the mixed and variable composition of waste, it can be difficult to determine which the materials in waste are that cause a given emission. The lack of exact knowledge of the transfer processes during waste treatment makes it necessary to use different assumptions to allocate emissions to the inputs.

The results of an LCA can be complex and difficult to understand and so, as mentioned previously, it is important to be clear about the application of the LCA from the outset. It should be also remembered that LCA only furnishes environmental information to be used in decision making: it is not a decision-making tool itself. LCA also only considers the environmental impacts of a product or service, but there developments are being explored to integrate economic and social aspects (Guldbrandsson and Bergmark, 2012).

2.7.4 Studies in LCA for Waste Management

LCA is currently being used in several countries to evaluate solid waste management strategies or treatment options for specific waste fractions (Mendes *et al.*, 2004; Buttol *et al.*, 2007; Cherubini *et al.*, 2009; Banar *et al.*, 2009).

Cherubini et al. (2009) focused on a life cycle assessment of four waste management strategies in Rome (Italy): landfill without biogas utilization; landfill with biogas combustion to generate electricity; sorting plant, and direct incineration of waste. Results showed landfill systems as the worst waste management options and significant environmental savings at global scale were achieved from undertaking energy recycling.

Hong et al. (2010) assessed four solid waste management scenarios through LCA in China to assess the influence of various technologies on environment: (1) landfill, (2) incineration, (3) composting plus landfill, and (4) composting plus incineration. They reported that the technologies play only a small role in the impact of carcinogens, respiratory inorganics, and terrestrial ecotoxicity. Also, potential impacts generated from transport, infrastructure and energy consumption were quite small. In the global warming (climate change) category, the highest potential impact was observed in landfill because of the direct methane gas emissions. Furthermore, electricity recovery from methane gas was the key factor for reducing the potential impact of global warming.

Laurent et al. (2014a) and (2014b) reviewed 222 of published LCA studies and analysed them in terms of (1) the geographical distribution, (2) the time evolution, (3) the assessed waste management technologies, (4) the assessed waste types, and (5) the main findings of the mapped LCA studies and the lessons to be learnt in the broader context of solid waste management. The review showed that most of them have been conducted after 2008 but their coverage has largely been limited to developed countries, with a large proportion of studies focusing on SWMS located in Europe. As a result, the distributions of studies with regard to the assessed waste management systems and waste types reflect the environmental concerns specific to these regions. The lack of primary data and the under-representation of the life cycle thinking concepts in developing countries are probably the main reasons for the limited number of studies published for most developing regions (Laurent *et al.*, 2014a).

As most published studies have primarily been concentrated in Europe with little application in developing countries, only three studies of waste management systems through LCA in Middle East were conducted to assess the influence of various technologies on environment.

Abduli et al. (2011) assessed two solid waste management strategies through LCA in Tehran, Iran to have an environmental impact comparison between the current solid waste management (MSW) alternatives: (1) landfill, and (2) composting plus landfill. The Eco-Indicator 99 is applied as an impact assessment method considering surplus energy, climate change, acidification, respiratory effect, carcinogenesis, ecotoxicity and ozone layer depletion points of aspects. According to the comparisons, the composting plus landfill scenario causes less damage to human health in comparison to landfill scenario. However, its damages to both mineral and fossil resources as well as ecosystem quality are higher than the landfill scenario. Thus, the composting plus landfill scenario had a higher environmental impact than landfill scenario. However, an integrated waste management will ultimately be the most efficient approach in terms of both environmental and economic benefits. Results showed landfill scenario as the preferable option both in environmental and economic aspects for Tehran in the current situation.

Al-Maaded et al. (2012) focused on a life cycle assessment of four waste management strategies in Qatar: recycling of plastics compared to landfilling and composting. It was conducted by GaBi 4 life cycle analysis tool which showed the environmental impacts to the global warming and human toxicity. The analysis showed that Qatar produced around 2,000 kilo-tons of solid municipal waste annually, corresponding to a daily generation rate per capita of about 2.5 kg. Landfill and composting is considered the most appropriate waste disposal techniques in Qatar due to a high proportion (60%) of organic materials. The authors recommended that policy makers have encouraged recycling and reuse strategies to reduce the demand for raw materials and to decrease the quantity of waste going to landfill. Recycling, thus, is the favoured solution for plastic waste management, because it has a lower environmental impact on the defined impact categories, from Global Warming Potential (GWP) and Human Toxicity Potentials (HTP) indicators.

Al-Salem and Lettieri (2009) assessed three different municipal solid waste management scenarios in the state of Kuwait. Scenario 1 represents the current MSW management status in Kuwait, involving collection, transport and landfilling. Scenario 2 (direct incineration with energy recovery) incorporates a thermal treatment unit after the processing in a material recovery facility (MRF), while scenario 3 employs anaerobic digestion before landfilling. IWM-2 was applied as an LCA Model in order to determine the most environmentally friendly system scenario. Impact categories dealt with were: Global Warming Potential (GWP), Acidification Potential (AP), hazardous and non-hazardous final fraction of MSW and total fuel consumed. The recycling stage was associated with the highest environmental burdens in all three scenarios. The lowest contribution to the global warming category was calculated for the anaerobic digestion process (scenario 3).

To sum up, it can be said that LCA methodology can be successfully applied to assess various waste management strategies in developing countries and Middle East in particular. To the best of my knowledge, no LCA studies have been conducted on any aspect of waste management in relation to Saudi Arabia. The lack of primary data and the under-representation of the life cycle thinking concepts (Laurent *et al.*, 2014a) and inadequate attention to the environmental burdens might be the main reasons for the limited number of studies published for most developing countries.

2.7.5 Tools for LCA of Waste Management

To address the increasing complexity of the waste management landscape, a number of waste LCA models have been developed, often independently from each others in different countries and at different moments in time. White *et al.* (1999) published a book including a spreadsheet model, the IWM, (Integrated

Waste Management) for calculation of the life cycle inventory for waste management systems. The model was updated in a more user-friendly version with new books in 2001 (McDougall *et al.*, 2001) and the models give the results in life cycle inventories (LCI) but none of the models included life cycle impact assessment (LCIA).

The Mimes/Waste model was developed at Chalmers University of Technology in Sweden and used in evaluating waste systems in several municipalities and regions since 1992 (Kirkeby and Christensen, 2005). The purpose of the model is finding cost effective solutions that meet emission restrictions by a cost minimisation and emissions accounting.

A Swedish model, the ORWARE (ORganic WAste REsearch), has special focus on evaluating different strategies for organic waste from both households and industry (Björklund, 2000; Eriksson *et al.*, 2003; Kirkeby and Christensen, 2005). The Environmental Protection Agency of the United States developed the Integrated Solid Waste management Decision-Support-Tool (ISWM DST) for which the main objective is to optimise a waste system with respect to one of the given functions while the system complies with a set of restrictions. The ISWM DST does not include LCIA calculation but has a higher focus on the optimisation module (Kirkeby and Christensen, 2005).

A traditional LCA tool for industrial products, UMBERTO, has developed a module with special focus on solid waste management. This module has shown to have very little sensitivity to the type of waste input that is being chosen in the model (Winkler and Bilitewski, 2007). A spreadsheet model has been developed especially for estimation of emissions from landfills to be used in LCA. The model considers the components in the waste individually and emission estimates are calculated on the basis of the input quantity and type of components (Nielsen and Hauschild, 1998).

Table 2.3 summarised the developed LCA models which have been currently widely used in worldwide waste management analysis.

Table 2. 3: Compilation of LCA models in waste management

Model	Developer	Description
IWM2	Procter & Gamble, UK	• The first published specific LCA model for solid waste management (IWM1 in 1995), based on LCI application, is user friendly but is not flexible in all respects. • The nine different waste treatment processes are implemented in terms of MRF, Sorting, Incineration, RDF, and Landfill.
ORWARE	Swedish Royal Institute of Technology, Sweden	• The original model specifically focuses on organic waste and uses a combination of LCA and substance flow analysis (SFA) to translate the result into an environmental impact. • The model is very flexible but is difficult to use. • The LCI/LCIA approach model handles anaerobic digestion, composting, landfilling, incineration, thermal gasification, sewage water treatment and transports.
ISWM:DST	US EPA, NCSU16, RTI17, USA	• The complexity and flexibility of the LCI model are used to calculate emission, energy and cost. • The specific SWM model provides various options of collection, transfer station, MRF, composting, landfilling, and incineration.
LCA-IWM	Technical University Darmstadt, Germany	• The LCI/LCIA model proposes a specific assessment tool for IWM strategies in rapid growing economies cities and countries in Europe. • The model provides a large LCI data base for EU member states and new member states. The credits from recovery of secondary materials are included. E-waste recycling is also integrated.
UMBERTO	IFEU20, IFU21, Germany	• The general LCI/LCIA model is built for the purposes of comparison products or services based on the material flow methodology. • The database is taken from standard processes such as energy production, waste management, transportation, production of raw materials.
WISARD	Ecobilan (now Price Waterhouse Coopers), France	• WISARD, specific model for SWM, allows modelling alternative waste management systems including landfilling, incineration, sorting and recycling, composting and anaerobic digestion. • The LCI/LCIA approach model is user friendly but has been criticized for lack of transparency, clearly defined system boundaries and easily interpreted results.
SIMAPRO	PRé Consultants, The Netherlands	• The most widely used general LCA software provides a tool for analysis and a monitor of environmental performance of products and services. • The LCI/LCIA model is widely used in waste management. • The model is flexible and provides a number of LCI databases and impact assessment methods.
WRATE	Environment Agency, UK	• The LCA/LCIA approach provides a specific model for waste management. • User defines up to 10 waste streams and 15 functional components.
EASEWASTE	Technical University of Denmark, Denmark	• The user can define the necessary data for waste composition, collection, treatment, waste recovery, disposal and inventory data for materials and energy. • The LCI/LCIA approach provides a specific model for waste management. The model is user friendly and flexible. • The model covers the substitution of commercial fertilizer from compost on land use and remanufacturing of recyclable materials.

Source; Kirkeby *et al.* (2006a), Chanchampee (2009), Gentil *et al.* (2010)

Appropriate modelling can be achieved by different means, as long as the local specificities of the systems are taken into account. According to Clavreul *et al.* (2013), 204 published studies were reviewed and focused on their LCA software used. It was found that the EASEWASTE software has been used in about 13% of these studies (see Figure 2.7). The category "Other" in the Figure refers to DST, TEAM, TRACI, UMBERTO, GEMIS, WRATE, LCAiT, JEMAI-LCA, EIME, WAMPS software.

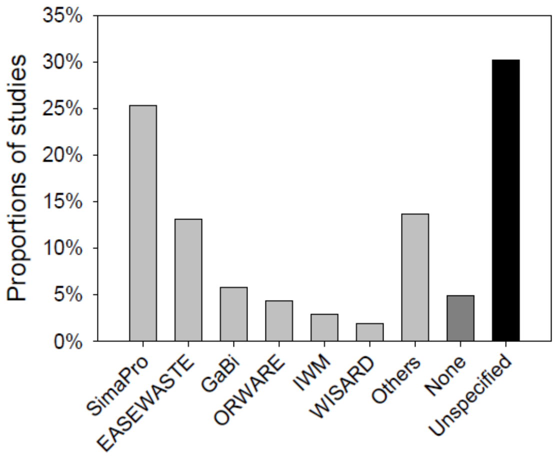

Figure 2. 7: LCA software used in total of 204 studies

Source: Clavreul *et al.* (2013)

2.7.6 EASEWASTE

EASEWASTE, an acronym for "Environmental Assessment of Solid Waste Systems and Technologies", is the LCA software specifically for the assessment of SWM related activities. The software is developed by the Institute of Environment & Resources at the Technical University of Denmark or "Danmarks Tekniske Universitet" (DTU) (Christensen *et al.*, 2007). The EASEWASTE model helps decision makers and waste managers to evaluate systems of solid waste management from an environmental point of view. The conventional LCA approach (ISO14040) using process analysis from the point of waste generation to final disposal is used for the analysis (Kirkeby and Christensen, 2005). It makes comparisons between several different strategies of waste management and waste treatment technologies for a region with a given population and a given waste production (Kirkeby *et al.*, 2006a). The model also enables the user to identify all necessary data used in the waste management system such as composition, collection and disposal, as well as the data of the life cycle inventory (LCI) for materials and energy. The software application is divided into three parts:

- **Waste generation:** The amount and composition of waste are defined.
- **Waste collection:** The source separation and efficiency as well as fuel consumption are defined.
- **Waste treatment, recovery and disposal:** All waste processing and recovery processes are defined according to desired technologies and treatment methods. The waste is analyzed from treatment facilities to final disposal or material recovery.

In contrast to the other available LCA models, the programme has the ability to appraise a detailed sub-model for the end of the waste management system: landfilling, use-on-land, material recycling and utilisation (Christensen *et al.*, 2007). The contribution of a waste management system to air emission, surface and ground water contamination, soil, as well as resource depletion are considered.

The system boundaries of the EASEWASTE model are identified from the point where household waste is generated and collected for final treatment, recovery and disposal, as shown in Figure 2.8 (Kirkeby *et al.*, 2006b).

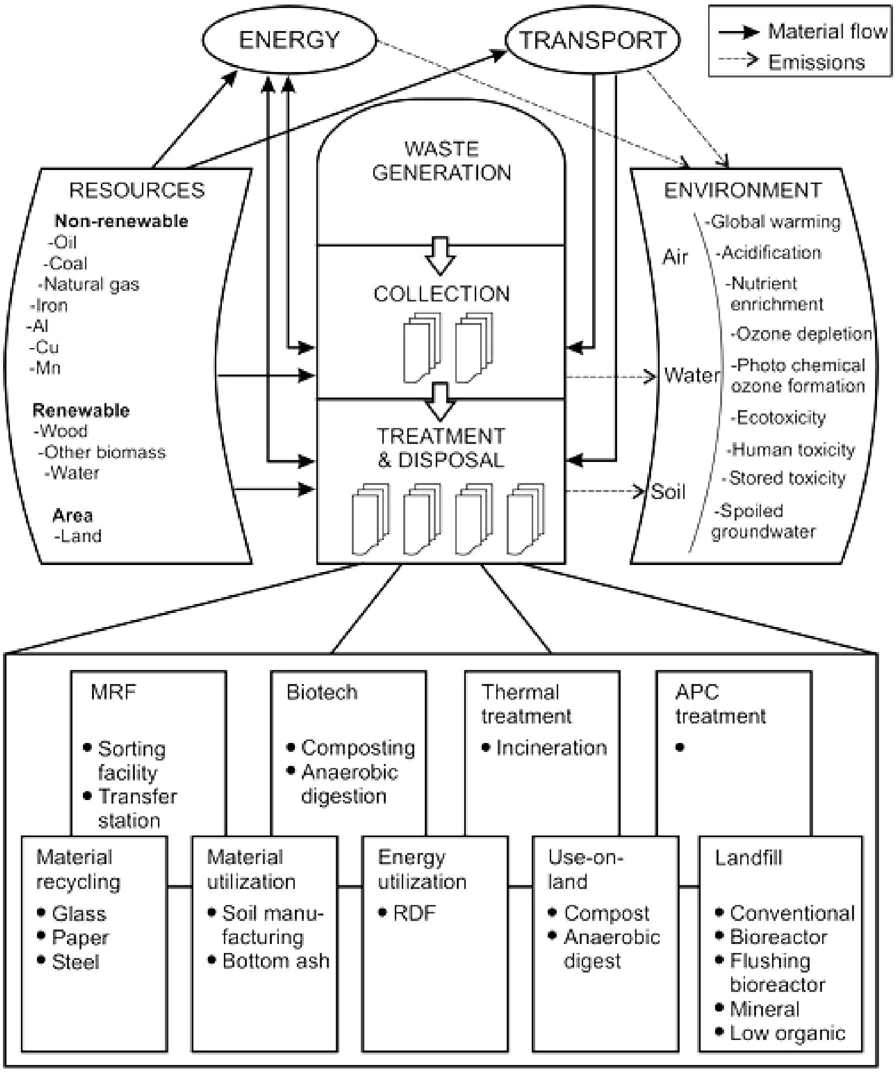

Figure 2. 8: Conceptual system structure of EASEWASTE

Source: Kirkeby *et al.* (2006b)

For the inventory, Environmental Design of Industrial Products (EDIP) databases provide information of materials and processes relating to the uses of resources and outlets to the environment. The model is developed with a database including all treatment, recovery and disposal options, as well as external processes that can occur either upstream or downstream of a solid waste management system. The user sets up a model of the solid waste management system by choosing types of source separation, collection methods and treatment, recovery and disposal technologies for the collected waste, and all arising residues. The changeable default data are mainly derived from Europe (Kirkeby *et al.*, 2006b).

For the impact assessment in EASEWASTE, the user can select two methodologies either Eco-indicator95 or the EDIP method. These two methods provide various impact categories. For example, the EDIP methodology considers global warming potential, stratospheric ozone depletion, photochemical ozone formation, acidification, nutrient enrichment, ecotoxicity and human toxicity. Furthermore, the model has introduced two additional impact categories: Spoiled Groundwater Resources (SGR) and Stored Ecotoxicity (Christensen *et al.*, 2007). The Eco-indicator95 provides pesticide, ozone depletion, ionizing radiation, global warming, acidification, heavy metals, carcinogenic substances, eutrification, winter smog, and photochemical oxidants.

Table 2.4 presents a description of EDIP impact categories. The EDIP method provides the results in four levels: life cycle inventory (LCI), potential impact characterisation and normalised potential impact characterisation. The normalisation (Equation 2.1) can compare the different impact categories in a common reference unit of person-equivalents (PE).

$$\text{Normalised Impact Potential (PE)} = \frac{\text{Potential Impact Categories (unit)}}{\text{Normalisation References (unit/cap/year)}} \qquad (2.1)$$

Table 2. 4: Impact categories based on EDIP method

Impact categories	Descriptions
Global warming potential (GWP)	To contribute the GWP substances (e.g. CO_2, CH_4, N_2O, CFC's, HCFC's, HFC's and several halogenated hydrocarbons etc.) which are absorbing infrared radiation or degraded into CO_2, the GWP is expressed as CO_2-equivalents, (CO_2-eq.).
Stratospheric ozone depletion	The potential depletion of stratospheric ozone (SOD) is quantified by normalizing the amount ozone depleting substances (e.g. CFCs, HCFCs, CCl_4, CCl_3CH_3) to the same effect like CFCs. Due to the largest effect on ozone depletion, CFC-11-equivalent (CFC-11-eq) has been chosen as a reference substance in the EDIP method.
Photochemical ozone formation	Photochemical ozone formation potential (POF) is generally presented as a relative value of the amount of ozone produced from certain volatile organic carbons (VOCs). Owing to being one of the most potent ozone precursors of all VOCs, ethene (C_2H_4) has been chosen as a reference gas.
Acidification	Having the same effect as SO_2 regarding acidification, the substances (e.g. NO_x, SO_x, and NH3) are used to quantify the acidification potential (AC).The AC potential is expressed as SO_2-equivalents (SO_2-eq).
Nutrient enrichment	The nutrient enrichment potential (NE) is defined as the man-made impact on aquatic or terrestrial systems of nitrogen, N, or phosphorus, P. The total nutrient enrichment potential expresses the emissions as an equivalent emission of the reference substance NO_3
Human toxicity	The human toxicity potential (HT) is expressed as the volume of all emissions of substances potentially affecting human health. In EDIP, the HTs of all kinds of substances (e.g. heavy metals, VOC, chlorinated organic compounds, POP, PM10, NO_x, and SO_x) are aggregated to three media values-critical volume of air (m^3 air/g substance), water (m^3 water/g substance), and soil (m^3 soil/g substance). Toxic equivalence factors (TEQ) for a number of substances are used.
Ecotoxicity	The ecotoxicity potential (ET) effects are expressed as a critical volume of certain media (aquatic and terrestrial environments) required to absorb a specific emission. The ETs of all kinds of substances (e.g. organotin compounds, metals, POP, and pesticides) are aggregated to three media values- acute toxicity of water (m^3 water/g substance), chronic toxicity of water (m^3 water/g substance), and chronic toxicity of soil (m^3 soil/g substance). The summations of a number of ET substances are used.

Source: Stranddorf *et al.*(2005)

Table 2.5 shows the impact categories that EASEWASTE uses for aggregating all the quantified emissions to air, soil, surface water and groundwater. Most of the impact categories are based on the EDIP 97 method (Wenzel *et al.*, 2000; Damgaard *et al.*, 2011; Stranddorf *et al.*, 2005). The table also presents the normalisation references used to convert the individual potential impacts into person equivalents (PE).

Table 2. 5: Potential impact categories included in EASEWASTE and normalisation references EU-15

Potential impact category	Acro nym	Unit	Physical basis	Normalization reference EU-15
Global warming, 100 years	GW	kg CO2-eq./person/yr	Global	8700
Photochemical ozone formation	POF	kg C2H4-eq./person/yr	Regional	25
Ozone depletion	OD	kg CFC-11-eq./person/yr	Global	0.103
Acidification	AC	kg SO2-eq./person/yr	Regional	74
Nutrient enrichment	NE	kg NO3-eq./person/yr	Regional	119
Human toxicity, soil	HTs	m3 soil/person/yr	Regional	157
Human toxicity, water	HTw	m3 water/person/yr	Regional	179 000
Human toxicity, air	HTa	m3 air/person/yr	Regional	2 090 000 000
Ecotoxicity, soil	ETs	m3soil/person/yr	Regional	964 000
Ecotoxicity, water chronic	ETwc	m3 water/person/yr	Regional	352 000
Spoiled groundwater resources	SGWR	m3 water/person/yr	Local	2900 *
Resource depletion	RD	PR/person/year	World	8.17E–01**

* The impact is calculated as the volume of Danish groundwater that the input to the groundwater can contaminate up to the drinking water criteria.

** The (RD) impact is calculated by EDIP97.

Source: Damgaard et al. (2011) and Laurent et al. (2011)

EASEWASTE is used to assess waste management systems in various studies including comparison of technologies: incineration and AD, assessment of material fractions, and comparison of models for specific application i.e. processed organic MSW to arable land (Hansen *et al.*, 2006a; Kirkeby *et al.*, 2006a). Nevertheless, the utilisation of the programme in the different conditions from a European groundwork requires careful examination for different environmental and operational conditions.

Climate in the case study, Makkah, is one of the environmental conditions that are different from Europe. High temperatures and humidity may affect on the degree of decomposition of the waste at the landfill. The scarcity of rainfall in Makkah has a significant impact on the leachate generation compared to European countries. The average rainfall in Makkah is 111 mm per year, while in Denmark (for example) is more than 400 mm per year. In addition, the availability of surface water in Europe is quite different from what it is in Makkah due to the lack of rivers and lakes. Regarding operational conditions, the absence of safe disposal of waste affects on the situation of solid waste management in Makkah. The recent uncontrolled landfill is the only method for waste disposal in Makkah compared to Europe. Therefore, the modelling of alternative technologies or processes such as incineration or recycling requires preliminary data are not available for Makkah. In addition, most LCA studies assumed that electricity and heat can be recovered to provide more environmental saving, the only electricity, however, is assumed to be utilised due to the high temperature.

However, it is important to indicate that a new modelling framework for environmental assessment of waste and energy systems “called EASETECH” developed by the Technical University of Denmark (DTU) (Clavreul *et al.*, 2012). EASETECH is a next generation model to the former model EASEWASTE and gives the user more flexibility and a large number of new functionalities. It allows the user to assess the environmental performance of complex systems that involve different materials and energy carriers. The specificity of EASETECH compared to other LCA software lies in the handling of material flows via a functional matrix characterising flows in terms of numerous chemical and physical properties and as mixtures of several material fractions. These flows are brought to different kinds of modules that can be combined freely to model processes and form complex systems.

In addition, some of the new functionalities in EASETECH compared to the earlier versions EASEWASTE (Clavreul *et al.*, 2012; Clavreul *et al.*, 2013) are:

- Graphical drag and drop construction of complex scenarios, allowing the user to see material and substance flows of the modelled system by using Sankey diagrams
- The possibility of importing datasets in the ecospold v2 format
- Generic toolbox modules allowing for design of new treatment technologies

- Ability to perform sensitivity and uncertainty assessment in the software via the use of parameters; and
- The possibility of changing the time horizon for inventory calculation of particular processes (landfilling and use on land).

EASEWASTE software has been selected for this study for several reasons. The EASEWASTE model is flexible, easy to modify and provides default data for waste composition, collection, transport, several treatment processes (incineration, landfilling, use on land, material recycling, material utilization) as well as upstream and downstream processes (for example, electricity consumption and heat production). In contrast to most other LCA models available (Wizard, WRATE, DST, ORWARE, Proctor & Gamble, LCA-IWM), EASEWASTE provides detailed sub-models for the 'end-of-the-waste-management-system': landfilling, use-on-land, material recycling and utilization. Two or more model alternatives including scenarios, technologies, or external processes can be compared (Bhander *et al.*, 2010; Christensen *et al.*, 2007).

In addition, EASEWASTE calculates waste flows, resource consumption and environmental emissions from waste management systems and provides a comprehensive environmental impact assessment (Kirkeby *et al.*, 2007). EASEWASTE has been used in the modelling of a number of real case studies, and much data have been incorporated into it. There are, however, still many issues that have to be improved significantly to facilitate application by other users than model developers. The improvements in consideration are to provide data for more treatment and disposal technologies and more flexibility (Laurent *et al.*, 2014a; Christensen *et al.*, 2007).

The model helps overcome the practical problems of modelling a complex system by supporting the user's construction of a model of the waste system's life cycle and providing data for many of the processes which are involved. The resulting model is a simplified (aggregated) representation of the integrated waste management system. Moreover, the EASEWASTE model is a deterministic model formulated using mathematical equations. It is constructed from individual elements describing the unit processes of the waste management system, like waste collection by truck or an incineration technology and the quantitative relations between these elements (Bhander *et al.*, 2010).

In general, the model has a very holistic approach to assessment of the impacts and attempts to cover all relevant resource and environmental impacts and it fully supports LCA performed according to the International Standard Organization (ISO) 14044 standard (Christensen *et al.*, 2007).

Other reasons for selection EASEWASTE modelling as an LCA tool in this study, the cost of the programme, EASEWASTE has been provided for free to the author by the Technical University of Denmark (DTU) since the author attended a training course. The software EASEWASTE has been allocated for research use only, namely, its application to the solid waste management problems of Makkah. Finally, it is necessary to say, with many thanks, that the course staffs are very happy to provide technical support on using EASEWASTE modelling at any time by contacting them via email.

The lack of using EASETECH software in this study was due to time and budget limitation. Since the EASETECH has been developed recently, the attendance of a training course at the Technical University of Denmark (DTU) in June 2013 was required and it was not possible to attend due to time constraints and the statutory procedures to obtain a visa to Denmark.

2.8 SUMMARY

The meaning of waste management and its terminologies used related to the thesis were provided in this chapter. Integrated solid waste management (ISWM) and the key principles of sustainability were also discussed in order to contribute for more comprehensive picture to the issues of waste management.

The moving toward for sustainable waste management systems is highly recommended where the system must be environmentally effective, economically affordable and socially acceptable. While the cost of the waste management system was the main factor and the decision making can be affected, the environmental burdens nowadays, are the major factor combined with the principles of sustainable development (McDougall *et al.*, 2008). Therefore, this research focused on how to improve the existing system of SWM for Makkah in environmental point of view. This is due to lacking of economic and social data of Makkah as well as time and budget limitation.

Assessment tools for waste management were reviewed briefly and LCA, as one of the most accepted methods used for evaluating environmental aspects and potential impact from cradle to grave (Finnveden, 1999; McDougall *et al.*, 2008), was also focused on. EASEWASTE was described in this chapter in order to provide a deep understanding in the LCA tool applied. This model can make comparisons between different alternatives of waste management and waste treatment technologies (Kirkeby *et al.*, 2006a). EASEWASTE was chosen for this study due to the ability of evaluation sub-models for the waste management system (e.g. landfilling, material recycling and utilisation) regarding contribution to air emission, surface and ground water contamination, soil, and resource depletion (Christensen *et al.*, 2007).

CHAPTER 3

An Overview of the Waste Management Situation in Makkah

This chapter describes the current environmental issues related to the population and infrastructure in Makkah city. These issues are: air pollution and limited water resources and wastewater treatment, in addition to solid waste management. To ensure a thorough understanding of the environmental situation of Makkah, several topics are discussed, such as religious events in Makkah (the Hajj and Umrah) and the Hijri or Islamic calendar, which is used as an official calendar in Saudi Arabia, and its relationship to religious events.

The environment in Makkah has suffered in the past from insufficient attention. Shortage and pollution of natural resources coupled with high fluctuation in the number of pilgrims over the year, local population growth and long years of negligence have created many environmental hazards. However, the government has focused more attention on improving Makkah's infrastructure during the last five years by constructing many projects that could serve the local residents of Makkah and pilgrims. Unplanned neighbourhoods and unorganised residential areas surrounding the Holy Mosque were removed and new railways were constructed to link the holy sites "Al-Masha'er" to each other. In addition, sewage and flood networks are being constructed for uncovered neighbourhoods to protect Makkah from the risk of flooding during the monsoon rains, as well as the environmental risks of wastewater to groundwater and Zamzam in particular. These projects, after completion, will help to reduce air pollution resulting from the use of trains instead of public and private buses in Hajj periods.

This chapter will focus on the recent system of municipal waste management in Makkah. Many issues related to waste management will be highlighted and discussed, such as waste characteristics and quantity and the collection, transport and disposal of waste during the religious periods (Hajj and Umrah) as well as the rest of the year.

Although the Saudi authorities are making efforts to improve infrastructure and services, the environmental situation in Makkah is in a disastrous state and is deteriorating further. The situation has reached a stage that is threatening to health and is below acceptable standards. Therefore, dealing with the environment in Makkah in an effective way has become an absolute priority.

3.1 RESEARCH AREA PROFILE– MAKKAH (MECCA)

Makkah or Mecca is a city in the western region of Saudi Arabia, as shown in Figure 3.1. Its coordinates are 21°25′20″N 39°49′34″E. The resident population of Makkah was 1.7 million in 2012, although visitors coming to Makkah to perform specific worship more than triple this number every year during the period of the Hajj (the greater pilgrimage) held in the twelfth Muslim lunar month of Dhul-Hijjah (MOH, 2013). Because Makkah is home to the Ka'aba (Sacred House) in the Holy Mosque (Al-Masjid Al-Haram) as well as the birthplace of the Prophet Muhammad, it is the centre of the Islamic universe. It is also considered as the holiest city in the faith of Islam and a pilgrimage to it, known as the Hajj, is obligatory once a lifetime for all able Muslims (Nomachi and Nasr, 1997). Another reason for the importance of Makkah is that it is the destination for more than seven million people throughout the year who come to perform the lesser pilgrimage, called the Umrah (MOH, 2013).

Makkah is located about 75 kilometres from the city of Jeddah, which is home to the King Abdulaziz International Airport as well as the Jeddah Islamic Sea Port. The total area of Makkah is about 550 km^2 at an average height of 273 m above sea level (MOH, 2013).

Figure 3. 1: Location of Makkah

Source: NOP (2013)

3.2 RESIDENT POPULATION

In terms of population, according to the Saudi Arabian census, Makkah is the third largest city after Jeddah and the capital city, Riyadh. Since the mid-20th century, many pilgrims have remained and become residents of Makkah city. These pilgrims are from varying ethnicities and backgrounds, mainly Central Asia, South Asia, Southeast Asia, Europe, the Middle East and Africa (CDSI, 2013). The area surrounding the Holy Mosque, the old city, is the most desirable for long-term residents of Makkah to live in. This has led many people to work in pilgrimage services, known locally as the "Hajj Industry": as the former minister for Hajj, Dr. Iyad Madani, said, *"We never stop preparing for the Hajj"* , as visitors also stream into the city all year round to perform the rites of Hajj and Umrah (Al-Jazirah, 2001). Furthermore, the oil exploration in Saudi Arabia in the 1960s has brought hundreds of thousands of working immigrants to Makkah.

According to CDSI (2013), in 2012, only 54% of the population of Makkah were Saudi citizens, which is the lowest proportion of any city in Saudi Arabia. However, non-Muslims are not permitted to enter Makkah under the Islamic and local laws, which are based on the Holy book of Islam, the Qura'an: *"O ye who believe! Truly the Pagans are unclean; so let them not, after this year of theirs, approach the Sacred Mosque" Surat Al-Tawbah* 9:28 (Abdul-Rahman, 2009).

According to the Population and Housing Census of Saudi Arabia published by the Central Department of Statistics and Information, Ministry of Economy and Planning, the population density in Makkah is very high, while the local population has grown by a cumulative annual growth rate of 2.9 %. By using actual population census data that has been collected, it can be noticed that the population of Makkah was nearly a million in 1992 and that this had increased to 1.4 million by 2004. This increase in population continued and by 2010 the population had reached 1.7 million. The total population of Makkah is expected to be 2.4 million in 2025, as shown in Figure 3.2 (CDSI, 2013).

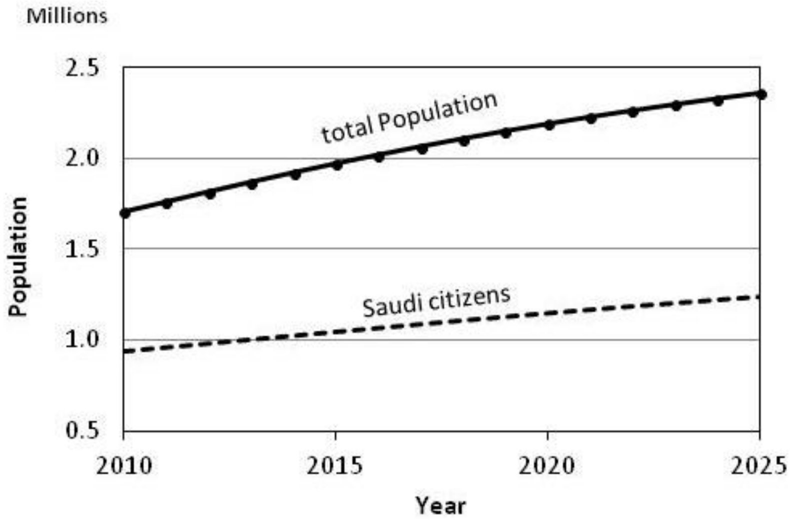

Figure 3. 2: Residential Population Growth of Makkah (2010-2025)

Source: CDSI (2013)

Figure 3.3 shows the huge urban sprawl in Makkah from 1990 to 2010: the total residential area have doubled to 160 km^2 in 2010 (Al-Ghamdi *et al.*, 2012). With an average of 6.16 capita per household, the number of households in Makkah was 165,000 in 1990 and 291,000 in 2010. Approximately 65 % of families in Makkah live in apartments in high-rise buildings or in houses and the rest live in villas, single and traditional houses (CDSI, 2013).

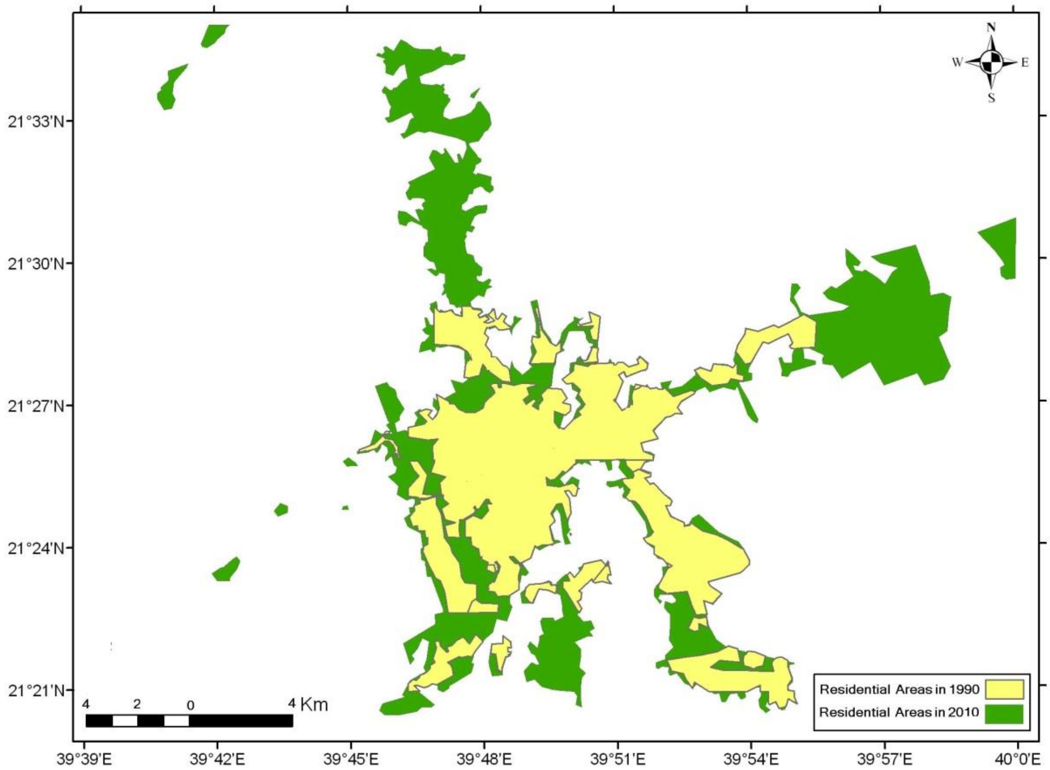

Figure 3. 3: Urban sprawl patterns of Makkah city for 1990 and 2010

Source: Al-Ghamdi *et al.* (2012)

In short, unlike other Saudi cities, Makkah is considered a global Islamic city whose residents are from different socio-economic and cultural backgrounds. This diversity often leads to differences in the standard of living and the quality of food. As a result of the unique demographic situation of Makkah, the amounts of MSW produced and their compositions are very different from other cities in Saudi Arabia and neighbouring cities in particular.

3.3 CLIMATE

Like most cities of the Arabian Peninsula, Makkah has a desert climate due to its tropical location. In summer, the climate of Makkah is considered very hot in the afternoon and the high temperature exceeds 46°C, dropping to around 30°C in the evening (Almazroui, 2011). In 2012, June was the hottest month, with an average daily high temperature of 44°C. The second of June was the hottest day in 2012 where the temperature was 50°C (Figure 3.4). Unlike other Saudi Arabian cities, Makkah retains its warm temperature in winter, and this can range from 17 °C at midnight to 30 °C in the afternoon. January was the *coldest month* of 2012 with an average daily low temperature of 19°C and the 15th day was the coldest day with a low temperature of 15°C (WeatherSpark, 2012). Rain usually falls in Makkah in small amounts of between 20–80 mm on average during November, December and January, with 111mm as the average annual amount, as shown in Figures 3.5 and 3.6. It has also been recorded that humidity ranges between 32% and 57% annually and that the daily average is around 48% in October (Al-Ghamdi *et al.*, 2012).

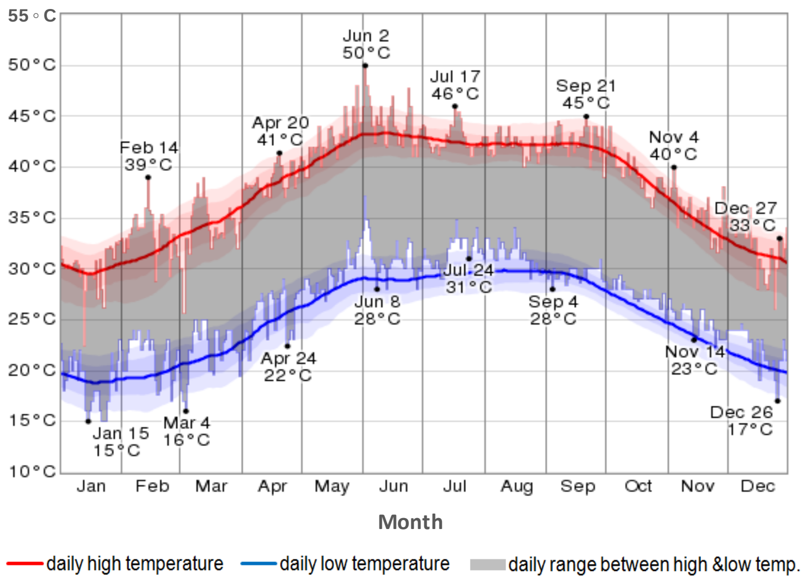

Figure 3. 4: Daily temperatures for Makkah in 2012

Source: WeatherSpark (2012)

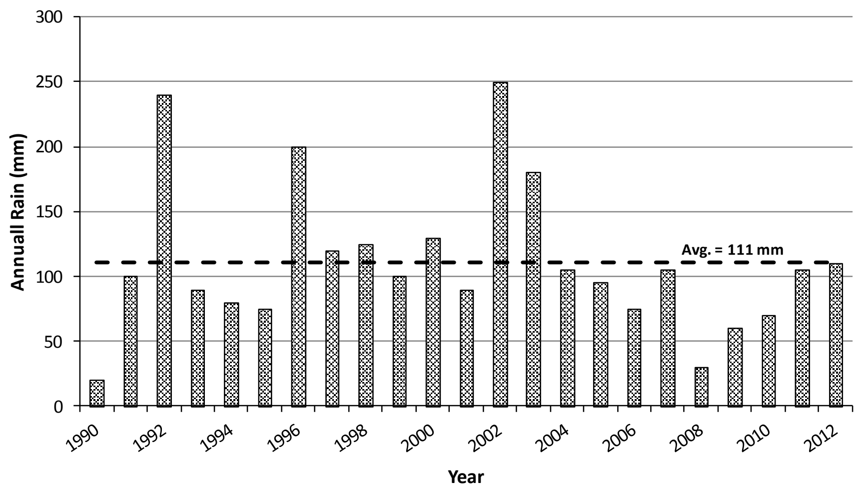

Figure 3. 5: Annual rainfalls in Makkah city from 1990 to 2012

Source: Almazroui (2011), Al-Ghamdi *et al.* (2012) and PME (2001)

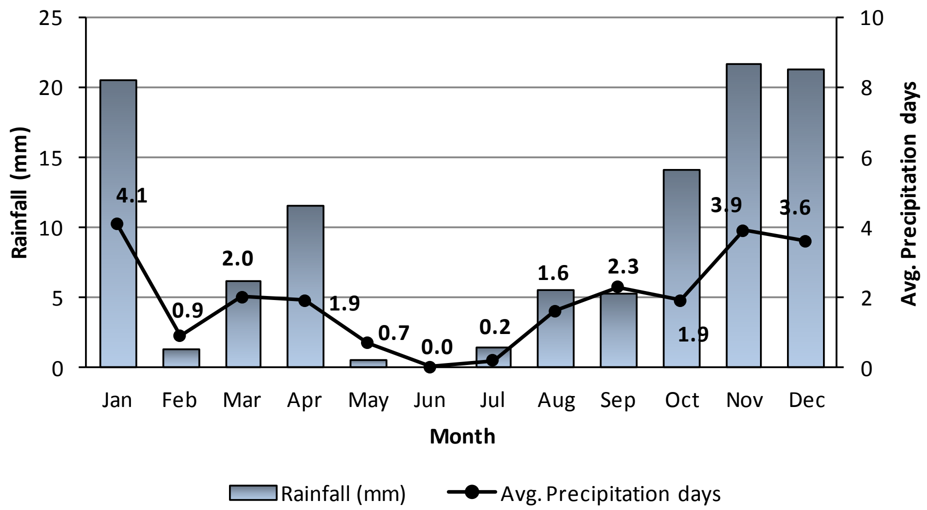

Figure 3. 6: Average monthly rainfall and precipitation days for Makkah in 2012

Source: Al-Ghamdi *et al.* (2012)

3.4 RELIGIOUS PERIODS IN MAKKAH

As mentioned earlier, Makkah receives about thirteen million pilgrims and visitors every year for the purpose of performing the Hajj and Umrah. Most of them come to Makkah to pray at the Holy Mosque (Al-Masjid Al-Haram) and perform the Umrah, which can be performed at any time of the year. Unlike the Umrah, the greater pilgrimage or Hajj is performed on certain days of the twelfth month of the Hijri year, called "Dhul Hijjah". The Prophet Mohammad has described the great merits of performing the Hajj and Umrah. He has said: *"The people who come to perform Hajj or Umrah are the guests of Allah because they visit His House on His Call; therefore, Allah grants them what they ask for"* (MOH, 2013).

The local authorities in the Kingdom of Saudi Arabia have specified two intervals in the Hijri year, namely the Hajj and Umrah periods, so that they can be on full alert and ready to provide all the necessary services for pilgrims in Makkah. Before examining the details of the Hajj and Umrah periods, it is important to understand the Islamic or Hijri calendar in relation to these religious events.

3.4.1 The Islamic or Hijri Calendar

The Islamic calendar (Hijri calendar) was officially established by the second Khalifah, Omar (634-644 AD). The Islamic calendar is a lunar calendar and is based on the Hijra (migration) when the Prophet Muhammad left Makkah for Yathrib - later to be renamed Madinah - on 16th of July 622 in the Gregorian calendar (G). The Hijri year contains 354 days (twelve months) with eleven leap years of 355 days in each cycle of thirty years and is based on the motion of the moon. As a result, it can be said that the Hijri year (H) is shorter by eleven days than a Gregorian year (G). Vincent (2008) stated simple formulas to provide approximate conversions between the Hijri (H) and Gregorian (G) calendars:

$$G = \left(\left(\frac{32}{33}\right) \times H\right) + 622 \qquad (3.1)$$

$$H = \frac{33}{32} \times (G - 622) \qquad (3.2)$$

Each lunar month of the Hijri year alternates between twenty-nine and thirty days. These months are as follows:

1. Muharram,
2. Safar,
3. Rabi Al-Awwal,
4. Rabi Al-Akhir,
5. Jumad Al-Awwal,
6. Jumad Al-Akhir,
7. Rajab,
8. Sha'ban,
9. Ramadan,
10. Shawwal,
11. Dhul Qadah, and;
12. Dhul Hijjah.

The Hijri calendar also leads to the rotation of the Hajj period among different periods and it takes place during a different month each year because this calendar does not follow the four seasons. As a final point, the Gregorian date of the start of the Hajj period changes from year to year. For example, in 1433 H., the Hajj period began on 24th October 2012, whereas in 1429 H it was on 4th November 2011.

The Hijri calendar is the official calendar in countries around the Arabian Gulf, especially in Saudi Arabia. Some other Muslim countries use the Gregorian calendar for civil purposes and turn to the Islamic calendar for religious purposes.

3.4.2 Hajj Period

The Hajj is the annual pilgrimage to Makkah, Saudi Arabia. It now seems to be the largest annual pilgrimage in the world. The Hajj is the fifth pillar of Islam and a religious duty; it must be performed at least once in their lifetime by every able-bodied Muslim, man and woman, around the world who can afford to do so. The Hajj takes place in the twelfth month of the Islamic calendar, Dhul Hijjah, between the eighth and twelfth days. Hundreds of thousands of pilgrims meet in Makkah and at the Al-Masha'er sites (Mina, Arafat and Muzdalifah), which are very close to Makkah. Pilgrims must perform at the same time a series of rituals at these sites that are symbolic of the lives of Abraham (Ibrahim in Arabic) and his wife Hagar (Hajar in Arabic) (Figure 3.7).

(a) Mina

(b) Arafat

Figure 3. 7: Pilgrims in (a) Mina and (b) Arafat during Hajj 1430 H (2011)

Source: Umm Al-Qura University (2012)

Al-Masha'er sites that must be visited by pilgrims are Mina, Muzdalifah and Arafat, which are 8 km^2, 12 km^2 and 13 km^2, respectively. These sites lie about 4 to 10 km from the Holy Mosque (Al-Massjid Al-Haram) in Makkah. Figure 3.8 shows the route of the Hajj pilgrimage, setting out from Makkah to the first town, Mina, on the eighth day of Dhul Hijjah. All pilgrims spend the rest of the day in thousands of large white tents which are put up by the Saudi government at Mina town. On the ninth day, pilgrims leave Mina for Arafat, where they must stay until after sunset, as their Hajj is considered invalid if they do not spend the afternoon on Arafat. As soon as the sun sets, the pilgrims must leave Arafat for Muzdalifah, an area between Arafat and Mina, to spend the night sleeping on the ground under the open sky. The next morning, pilgrims return to the tents in Mina, where they stay for three days and perform rituals such as throwing stones at the Devil (*Ramy Al-Jamarat* in Arabic) and the slaughter of animals to commemorate the story of Abraham and his son, Ishmael. Finally, pilgrims must leave Mina for Makkah before sunset on the 12th day. If they are unable to leave Mina before sunset, they must stay and then return to Makkah on the 13th of Dhul Hijjah.

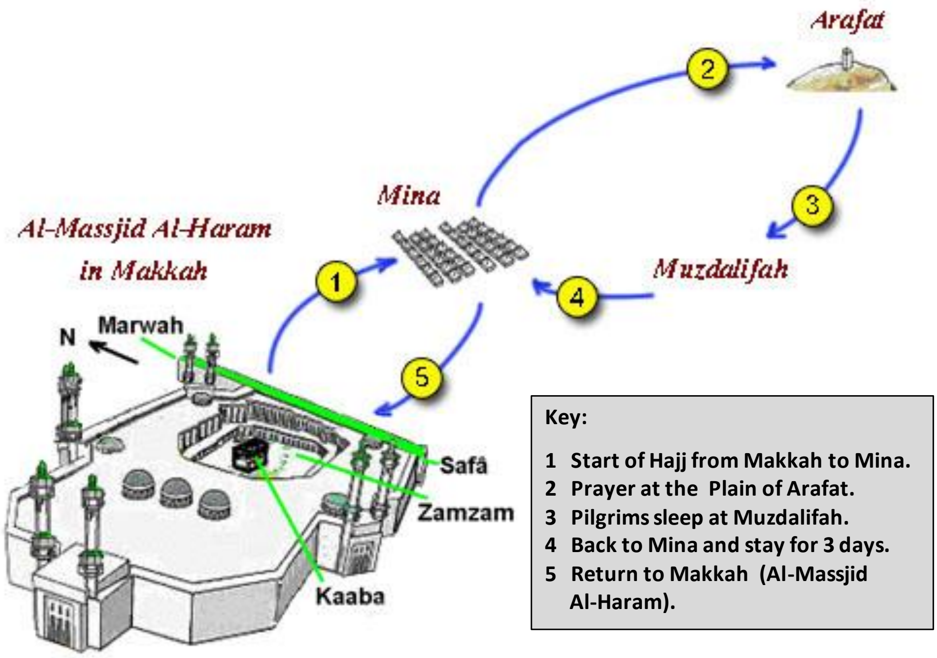

Figure 3. 8: Route of Hajj

According to the Population & Housing Census of Saudi Arabia (CDSI, 2013), the number of pilgrims in 1996 was more than 1.87 million. This number grew to 3.16 million in 2012. Figure 3.9 shows the official numbers of pilgrims between

1416 H (1996) and 1433 H (2012). This figure shows that the number of pilgrims has increased by 41% over the past eighteen years. However, the total number of pilgrims in years 1429 and 1430 H have decreased slightly compared to the former two years. Some observers attribute this drop to the spread of swine flu in these years, as some pilgrims were afraid of the spread of the disease during the Hajj period and decided to postpone their Hajj (Othman, 2009). In addition, Okaz (2010) noted that more than four million pilgrims came to Makkah for the Hajj in 2011. It is noteworthy that internal pilgrims specifically from Makkah are not included in Figure 3.9, as there are no accurate statistics available and it is difficult to control these numbers.

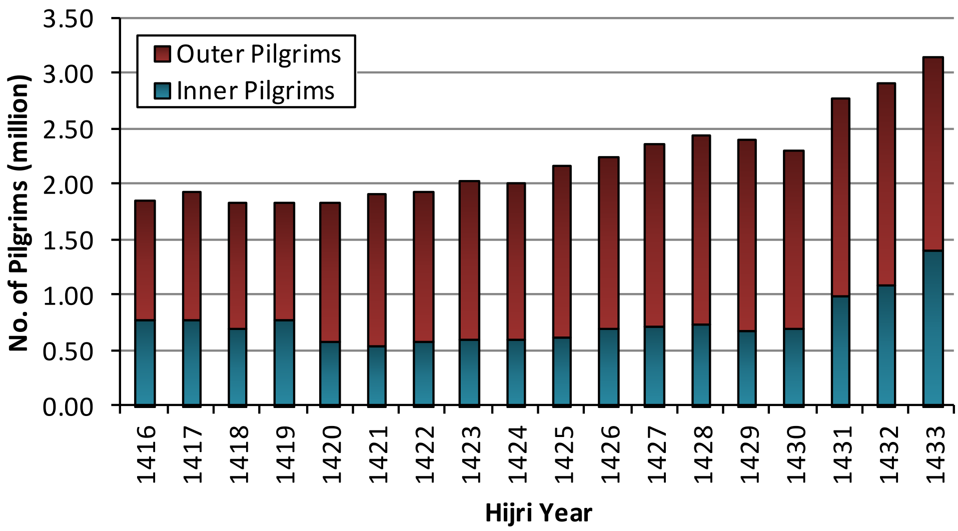

Figure 3. 9: The Number of Pilgrims from 1416 H. (1996) to 1433 H. (2012)

Source: MOH (2013)

Officially, the twelfth month, Thul Hijjah, is considered as a sensitive and important month for the Saudi government, particularly the Ministry of Hajj and the Municipality of Makkah, where the alert level is raised in preparation for catering for hundreds of thousands of internal and external pilgrims from their arrival until their departure. The main purpose of this is to implement all necessary actions and plans by increasing staff numbers, equipment, etc. to provide all municipal services and logistics to enable pilgrims to perform the Hajj easily and conveniently.

3.4.3 Umrah Period

The Umrah, which means in Arabic 'to visit a populated place', is a minor pilgrimage to Makkah in Saudi Arabia, performed by Muslims around the world at any time of the year (MOH, 2013). Table 3.1 lists the top ten sources of pilgrims for the Umrah in 1430 H (2009). Although the Hajj is compulsory for every able-bodied Muslim who can afford it, the Umrah is not compulsory, although it is highly recommended. In the Umrah, the pilgrim performs a series of ritual acts in the Holy Mosque (Al-Massjid Al-Haram) which are symbolic of the lives of Ibrahim and his wife Hajar.

Table 3. 1: Top Ten Countries as a Source of Pilgrims for Umrah in 1430 H (2009)

No.	Country	Number of Pilgrims in thousands
1	Iran	866
2	Egypt	563
3	Pakistan	272
4	Jordan	268
5	Syria	241
6	Turkey	211
7	Iraq	173
8	Algeria	137
9	UAE	120
10	Indonesia	108

Source: MOH (2010)

The performance of the Umrah during Ramadan is considered most commendable and equal to the Hajj in terms of the merit and excellence granted to one who performs a Hajj. In addition, thousands of non-residents of Makkah visit the Holy Mosque every day in Ramadan, not for Umrah, but only to pray. Consequently, Ramadan (the ninth month of the Hijri year) is a month that is venerated in the Islamic religion, as shown in Figure 3.10, and it is distinguished from the other months by a number of characteristics and virtues. However, this act does not substitute for the performance of the Hajj, which is imperative for all Muslims (Hajjumrahguide, 2011). As a result, most of the annual visitors prefer to come to Makkah to perform the Umrah and visit the Holy Mosque in the Hijri month, Ramadan (MOH, 2013).

As a result, the Saudi authorities state that the month of Ramadan is the peak of the Umrah and visiting period, which means that the Ministry of Hajj and other governmental sectors in Saudi Arabia should be on full alert to provide all required services to pilgrims and visitors, as shown in Figure 3.10.

Figure 3. 10: General view of the Holy Mosque (Al-Masjid Al-Haram) in Ramadan 1429 H (2008)

Source: Umm Al-Qura University (2012)

Figure 3.11 demonstrates the number of Muslims coming to Makkah to perform Umrah from abroad. It shows that the number of pilgrims from outside Saudi Arabia has increased by more than three times over the past ten years. Furthermore, there are no exact statistics on visitors who come to Makkah to perform Umrah from inside Saudi Arabia. Unlike the Hajj situation, residents of Saudi Arabia do not need permission to participate in the Umrah ritual. This is because the Saudi authorities believe that the Hajj ritual is limited to certain areas and specific times.

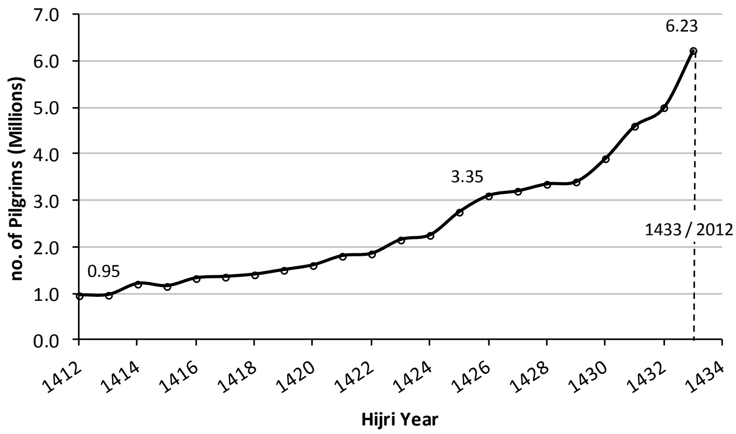

Figure 3. 11: Number of Pilgrims coming to Makkah to perform the Umrah from 1412 to 1433 H (1992-2012)

Source: MOH (2013)

However, it is very important to note that the Hajj and Umrah periods do not overlap and the time between these periods is also considered to be a busy time, as some pilgrims decide to remain until the Hajj.

3.5 ENVIRONMENTAL MANAGEMENT IN SAUDI ARABIA

Attention to issues related to natural resources and development has appeared on the Basic Rule System in Saudi Arabia. Environmental management, like all other aspects of life, is run by the civil administration through an environmental department, which was established in 1981 under the Presidency of

Meteorology and Environment (PME). The Saudi government, represented by the PME, developed the essential laws for protecting the environment in 2001 and issued the "General Environmental Law and its Rules for Implementation" to conserve, protect and develop the environment, and guard it from pollution (PME, 2001).

A number of other ministries have established environmental departments to deal with related issues, such as the Ministry of Health and the Ministry of Agriculture. The Ministry of Municipal and Rural Affairs in Saudi Arabia, represented by municipalities, holds complete responsibility over environmental services, i.e. solid waste collection and disposal, wastewater treatment, pest control and so on. Despite the creation of laws and regulations in Saudi Arabia to protect the environment from hazardous and non-hazardous waste, the current system is still in need of more effective monitoring and management.

3.6 THE ENVIRONMENTAL SITUATION IN MAKKAH

3.6.1 Air Quality

In Makkah, the high density of traffic and narrow streets are the main causes of air pollution, especially at peak times (Hajj and Umrah periods). According to Al-eqtisadiah (2010), scientific research conducted by a team from the Custodian of the Two Holy Mosques Institute for Hajj Research revealed that the level of CO in Makkah exceeded the World Health Organization standard and concentrations of airborne dust were five times the limit. The main sources of air pollution can be summarised as:

- Dense traffic, particularly in Makkah centre, during Hajj and Umrah periods;
- Dust and particulate matter from dust storms;

- Solid waste disposal at open dumpsites; and
- The recent wastewater treatment plant.

3.6.2 Water Resources

Desalinated sea water is currently the largest source of water for drinking and domestic usages for the residents of Makkah and is considered to represent more than 85 % of the total water consumption. According to Al-eqtisadiah (2010), the daily per capita consumption in Makkah has reached record levels of 330 litres in 2010 compared to 285 litres in Jeddah. In addition, water consumption in Saudi Arabia is 300 litres per day per capita and this is considered one of the highest levels in the world (Al-Themali, 2013). Desalinated water is pumped from the "Al-Shuaibah" plant (140 km south of Makkah city) at a rate of about 560,000 m^3 per day on normal days. The volume of pumped water exceeds 620,000 m^3 during the pilgrimage periods to cover the pilgrims' needs for water at the Makkah and Al-Masha'er sites (Al-Themali, 2013).

Another source of drinking water is groundwater, which is already a big issue in Saudi Arabia and Makkah, particularly due to the shortage of groundwater resources. In view of the demographic and economic developments as well as the increasing annual number of pilgrims, water demands in Makkah are expected to grow further, aggravating the problem of depletion of groundwater (Al-eqtisadiah, 2010).

The most important environmental aspect with regard to landfills in Makkah is possible water pollution caused by leachate from the decomposing waste and run-off from the fills. Al-eqtisadiah (2010) pointed out that groundwater in Makkah is polluted by e-coil microbes at a level of 65%. This study attributed the reasons for groundwater pollution in Makkah to the dilapidated water supply and incomplete sewerage systems as well as the discharge of untreated wastewater into valleys, while only 60% of Makkah's households have a piped water supply. This groundwater situation thus represents a serious health risk in Makkah.

In connection to the subject of groundwater in Makkah, the issue of holy water "Zamzam" must be addressed in this study. This is because Zamzam is considered as the holy water in the religion of Islam and also because of the environmental situation of waste management systems. The next section will therefore address the issue of Zamzam water in more detail.

3.6.3 Zamzam Water

Since ancient times, many religions and beliefs have used ''holy water'' for either medicinal or religious purposes (Shomar, 2012). Zamzam is the name of the well that provides the groundwater called "Zamzam water". The Well of Zamzam is located only a few metres east of the holiest place in Islam, the "Kaaba" in the heart of the Holy Mosque "Al-Masjid Al-Haram" in Makkah, as shown in Figure 3.12 (ZSRC, 2010). Muslims believe that the Zamzam well is a miraculously-generated source of water from God and a contemporary miracle which has never run dry. They also believe that Zamzam water has the ability to satisfy both thirst and hunger and is a cure for sickness, based on the Prophet Mohammed's words: "*The best water on the face of the earth is the water of Zamzam; it is a kind of food and a healing from sickness*" (Shil and Abdulwahid, 2008). Millions of pilgrims thus visit the well every year while performing the Hajj or Umrah pilgrimages, in order to drink its water and collect it in bottles to bring back to their home countries for family and friends (ZSRC, 2010).

The Zamzam Well is about 30 m deep and 1.08 to 2.66 m in diameter. Originally water from the well was drawn by ropes and buckets, but nowadays the well itself is in a basement room and water is drawn by electric pumps (ZSRC, 2010). In 1424 H (2003 G), the main entrance to the Zamzam well inside the Holy Mosque was closed in order to increase the capacity of pilgrims in the surrounding Kaa'ba as well as to protect Zamzam water from wastage in use (Figure 3.12).

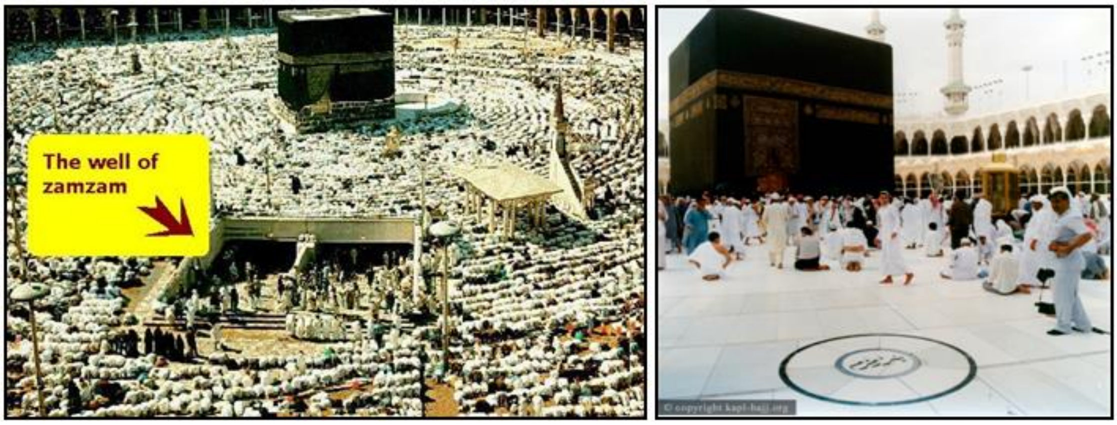

Figure 3. 12: Location of Zamzam Well, before and after 2004

Source: Obaid (2012) and KAPL (2012)

Figure 3. 13: Zamzam water bottling plant

Source: Sada (2012) and Abdullah (2010)

The Saudi authorities then set up a plant for bottling Zamzam water in plastic bottles instead of the manual filling by the pilgrims themselves. It is located outside the Holy Mosque and has a daily production capacity of 200,000 ten-litre plastic bottles (Figure 3.13). The plant was built in order to preserve the high purity of Zamzam water and to pack and distribute it in a modern way (KAPL, 2012; Sada, 2012; Abdullah, 2010).

The well is in the Valley of Abraham and the source of the groundwater comes from absorbed rainfall, as well as run-off from neighbouring mountains around Makkah. However, the amount of water from absorbed rainfall on the Valley of Abraham has decreased since the area has become more settled (ZSRC, 2010).

Zamzam water has no colour or smell, but it has a distinct taste, and its average pH is 8.0, indicating that it is alkaline and similar to seawater. Heated scientific and political debates have appeared in last three years. In May 2011, a BBC investigation revealed that the Zamzam water contained arsenic at levels three times the legal limit in the UK as well as dangerous levels of potentially harmful bacteria and nitrates. According to Shomar (2012), thirty samples of Zamzam water from different locations and at different times were tested by the Institute of Earth Sciences at The University of Heidelberg in Germany. These samples were collected from ten pilgrims living in different locations in Germany in 2007, ten samples from shops in Frankfurt and Berlin in 2011, and ten samples directly from Makkah in 2011. The author found that the total concentration of arsenic in Zamzam water is three times higher than the World Health Organization standards for drinking water.

On other hand, the Council of British Hajjis (CBHUK) stated that drinking Zamzam water was safe and disagreed with the BBC investigation. The Saudi government has announced that water from the Zamzam well was tested after the BBC report and it was found that the level of arsenic, where taken at its source, is much lower than the maximum amount permitted by the World Health Organization (WHO) (ZSRC, 2010).

However, no scientific studies have stated the effects of Makkah's landfill on Zamzam water. Adequate scientific research on the quality of Zamzam water in the long term is needed due to its significance in the faith of Islam (Shomar, 2012).

3.7 SOLID WASTE MANAGEMENT

As mentioned previously, the large changes in the number of pilgrims who are coming to perform Hajj and Umrah affect the management of solid waste in Makkah. These changes directly affect the amount of waste generated and its characteristics from one month to another as well as from one season to another in the same year. So, for ease of analysis, it is useful to look at each period separately. The Hijri year can be divided into three periods of time:

- **Umrah Period** –the 9th Hijri month, Ramadan, which is when the greatest numbers of pilgrims and visitors prefer to perform the lesser pilgrimage, the Umrah;
- **Hajj Period** –the 12th Hijri month, Dhul Hijjah, during which the greater pilgrimage, Hajj, must be performed. Although the Hajj ritual lasts about one week, pilgrims tend to stay in Makkah for several weeks.
- **Non-Pilgrimage Period** – represents the rest of the Hijri year (ten Hijri months) and covers the local residents only.

The term 'solid waste' in the Makkah Municipality covers all garbage, including domestic refuse and other discarded materials, such as those from public places, commercial and industrial activities. While very few field tests have been conducted on solid waste characterisation in Makkah, it can be generalised that among domestic premises, offices, institutions, hotels, shops and factories, household waste accounts for more than 75% of the total in cities like Riyadh, Jeddah and Makkah (Municipality of Makkah, 2011). It is divided into two main categories of waste, namely municipal waste and hazardous waste. Municipal waste includes refuse normally generated by residences and pilgrims that is collected from public places, construction and demolition and commercial activities. Hazardous waste in Makkah is explained in more detail in section 2.9.

3.7.1 Current Situation of SWM in Makkah

The management of solid waste in Makkah falls under the control and supervision of the municipality of Makkah. The "Alwan" Company is currently responsible for the management of solid waste in Makkah, which includes collecting waste from bins, transporting it directly to the landfill or via transfer stations and then disposing of it in landfill, as shown in Figure 3.14.

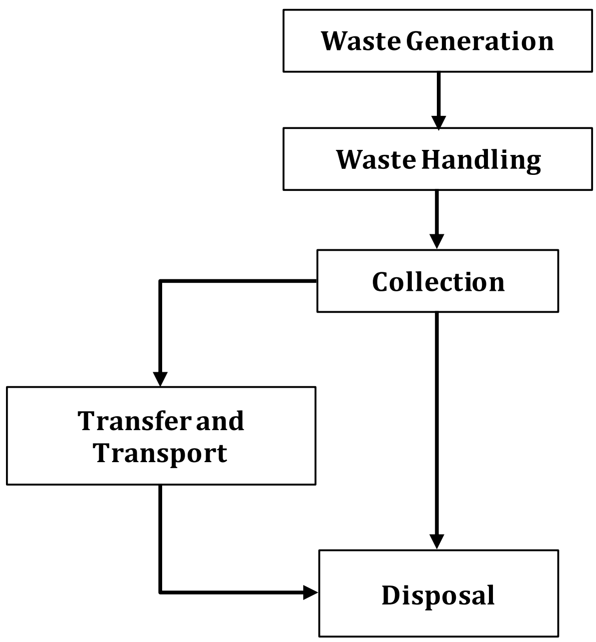

Figure 3. 14: The Existing System for Solid Waste Management in Makkah

3.7.2 Waste Quantities and Characterisation

The quantities of waste collected in Makkah are usually obtained based on the loads transported to the landfill. The current contractor, "Alwan", is responsible for this task and must submit all the data collected on waste quantities during the year to the Municipality of Makkah. According to Abdulaziz *et al.* (2008), the Makkah's landfill receives 2,000 to 1,800 tonnes per day of municipal waste in the non-pilgrimage period over the Hijri year. This amount increases to 3,000 tonnes per day in the month of Ramadan (in the Umrah period); while up to 4,500 tonnes per day are received during the month of Dhul Hijja (in the Hajj period). Figure 3.15 and (Appendix A1) illustrate the waste generated in Makkah between 1416 H (1996) and 1432 H (2011). It can be seen from the figure that the amount of waste produced has taken an ascending trend during the years from 1416 H (1996) until 1426 H (2005), then decreased until it stabilized at 600 kilotons in the last four years. This retraction, according to Makkah Municipality (2012), occurred due to the global economic crisis as well as increasing awareness of the importance of waste minimisation among residents in order to preserve their environment.

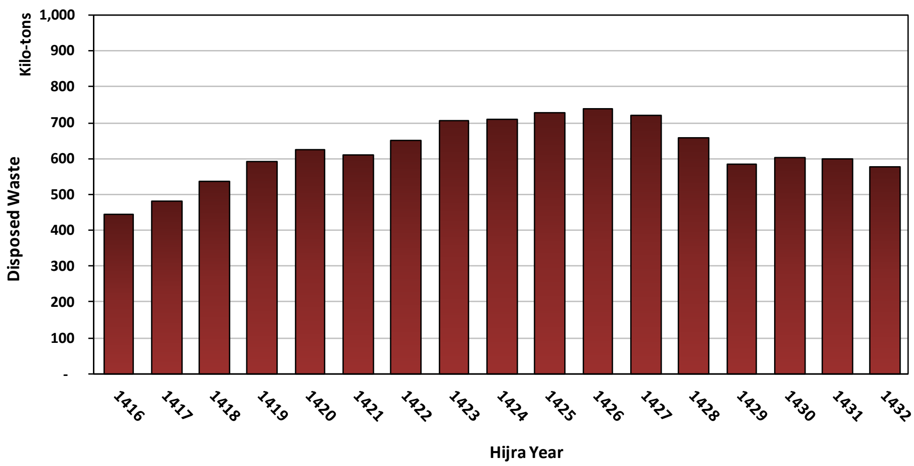

Figure 3. 15: Waste Generation in Makkah between 1416 and 1432 H (1996 and 2011)

Source: Municipality of Makkah (2012)

Figure 3.16 and (Appendix A4) show the monthly amount of waste produced in Makkah, including the Hajj and Umrah periods, for four Hijri years from 1429 to 1432 (2008 to 2011) (Municipality of Makkah, 2012). It can be seen that there is no significant difference in the quantities of waste reaching the landfill during the non-pilgrimage period with about 40 kilotons per month. The amount of waste produced in Ramadan was about 40% greater than in the non-pilgrimage period and double the amount of waste produced in the month of Dhul Hijah, except for the Hajj period in 2010. It was almost 130 kilotons, which is very high compared to other Hajj periods. The lack of accuracy at the Makkah Municipality may be the reason for this difference, although the number of pilgrims and the annual quantities of waste did not differ much from other years.

According to Abdulaziz *et al.* (2008), however, the daily waste generated per pilgrim and local resident in 1426 (2007) was 2.05 kg and 1.6 kg, respectively. Approximately one million tons of municipal waste went into the landfill in 1426 (2007), including waste generated by pilgrims in the Umrah and Hajj periods. The different sources of waste quantities in Makkah caused variations in data on waste produced during the same period. This difference was because the data used by (Abdulaziz *et al.*, 2008) were from published papers and former contractors, while the Makkah Municipality's data (2012) were derived by taking samples from the recent landfill site.

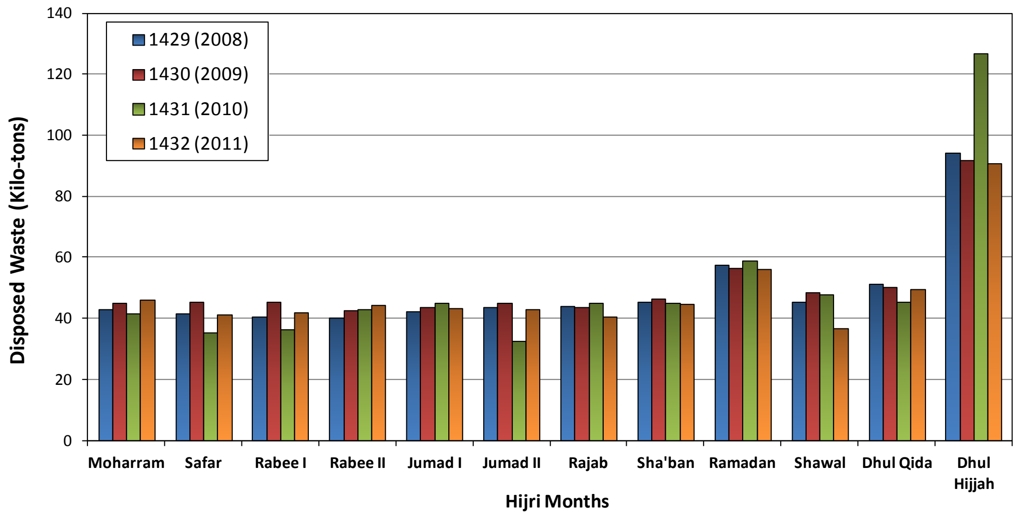

Figure 3. 16: Quantities of Waste Generated for each Hijri Month in Makkah from 1429-1432 H (2008-2011)

Source: Municipality of Makkah (2012)

Municipal solid waste can be described by its composition, moisture content and density (Kaosol, 2010). As a result of the large changes in population during pilgrimage and non-pilgrimage periods in Makkah, waste composition also changes. In a recent report from the Municipality of Makkah, it was found that about 60% of the waste is organic kitchen waste. Waste density was also estimated as 250-600 kg/m³ (Municipality of Makkah, 2012). Generally, typical waste composition in Makkah is as illustrated in Figure 3.17:

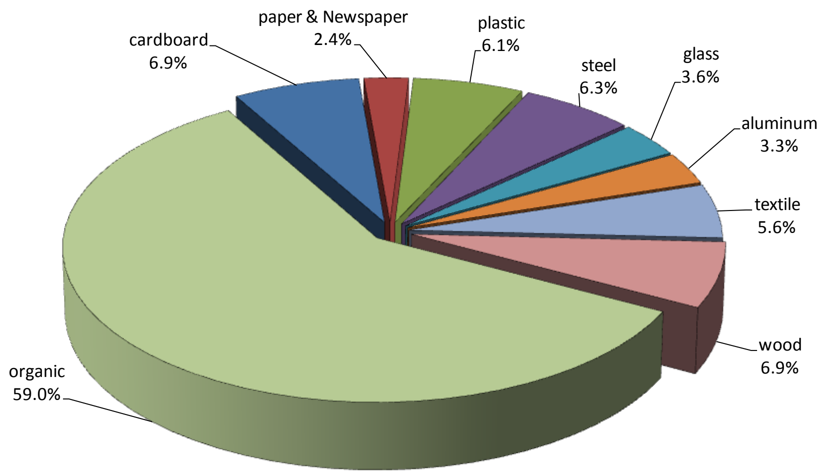

Figure 3. 17: The solid waste composition in Makkah (Appendix A2)

Source: Municipality of Makkah (2012)

By comparing pilgrimage and non-pilgrimage periods in Makkah in terms of waste characteristics, it was found that the organic fraction in the Umrah period (Ramadan month) is significantly less than in either the Hajj or non-pilgrimage periods, as shown in Figure 3.18. This is because Ramadan is the month of fasting in the Islamic faith, during which Muslims cannot eat and drink during the day. Dry waste also represents a high proportion during the pilgrimage periods, as most pilgrims consume prepared foods which have paper, cardboard or plastic packaging. Furthermore, although more pilgrims arriving at Makkah in the month of Ramadan than during the Hajj period, less waste is produced during the Umrah period than during the Hajj. This is because pilgrims must stay in Makkah and other holy sites "Al-Mash'er" for at least a week, while they are free to go wherever they prefer during Ramadan.

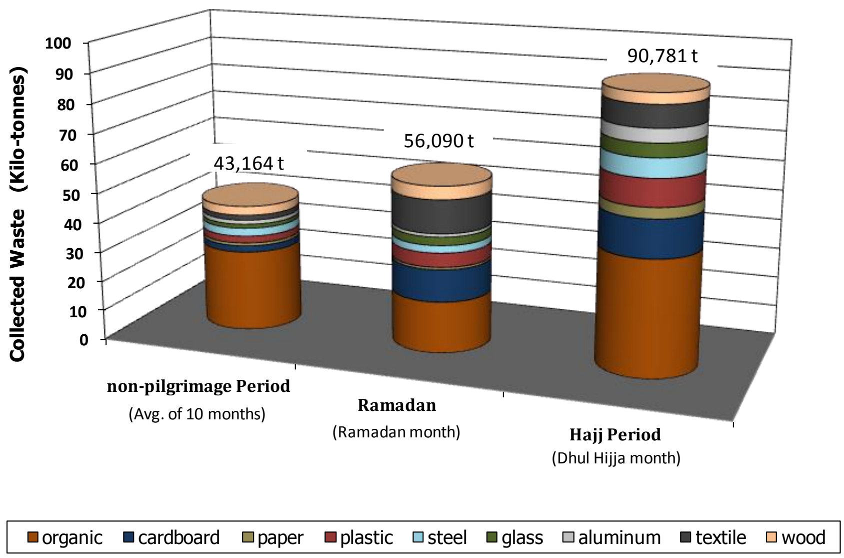

Figure 3. 18: Typical Waste Characterisation of Makkah in 1432 H (2011) for Pilgrimage and Non-pilgrimage periods (Appendix A3)

Source: Municipality of Makkah (2012)

3.7.3 Waste Collection and Transfer

Solid waste in Makkah is collected in metallic containers of 4m^3 capacity. These containers are distributed in most of the city's streets. Residents put waste in the containers without segregation. There are also plastic bins of 0.5m^3 capacity distributed in commercial areas and public places. Building materials resulting from construction and demolition are collected in containers of 8–12 m^3 capacity. All waste in non-pilgrimage periods is collected by 6,500 labourers in plastic bins transferred manually to the vehicle (Abdulaziz *et al.*, 2008; Fakieh, 2008). Metallic containers are used in some neighbourhoods for collecting municipal waste and the waste is transported to the transfer stations by using mechanical collection to the rear of vehicles. Figure 3.19 shows the waste containers used in Makkah for household waste and commercial waste. Further, there are seven transfer stations around Makkah, each with a capacity of 35 tons, and these stations receive most of the waste; the rest is transferred directly to the landfill (KAAU, 2008; Alwan Company, 2008). Figure 3.20 shows the vehicles used for waste collection and transporting to the transfer stations and landfill site.

Figure 3. 19: Collection bins used in Makkah for municipal waste

Source: taken by author (2011)

Figure 3. 20: Collection vehicles used in Makkah for municipal waste

Source: Alwan Company (2008)

It has been estimated that 131 underground storage facilities and 940 compacting containers are used to store waste in the Al-Masha'er sites (Mina, Muzdalifah and Arafat) during Hajj, as shown in Figure 3.21 (Alwan Company, 2008; Municipality of Makkah, 2012). These storage facilities are considered to be temporary storage locations that are used for a week, due to the huge number of pilgrims and the difficulty of using collection vehicles in Al-Masha'er sites. These sites are divided into twenty-five individual zones. Each zone is supported with all required equipment, labourers and supervisors. Waste is then transferred after the pilgrimage period to the final disposal site (Municipality of Makkah, 2012). Table 3.2 summarises the various equipment and vehicles used in waste collection in Makkah during pilgrimage and non-pilgrimage periods (Alwan Company, 2008).

Figure 3. 21: Underground storage facilities in Mina during the Hajj Period

Source: Taken by Al-sebaei (2008)

Table 3. 2: Summary of different equipment and vehicles used in waste collection in Makkah during pilgrimage and non-pilgrimage periods

Item	Non-pilgrimage period	Pilgrimage periods (Umrah & Hajj)	Total
Compactor vehicles *(20 tons, 8 tons, 3 tons)*	145	110	255
Bins and containers *(various capacity)*	24,500	18,500	43,000
Labourers	6,500	2,500	9,000
Tippers *(20 tons, 8 tons, 3 tons)*	162	210	372
Underground storage *(in Mina only)*	131	-	131
Permanent compactor boxes *(20 m^3)*	1,200	-	1,200
Transfer stations *(35 tons)*	7	-	7

Source: Alwan Company (2008); KAAU (2008) and Municipality of Makkah (2012)

3.7.4 Materials Recovery and Recycling

One of the obstacles faced by those controlling solid waste management in Saudi Arabia and in Makkah particularly is waste scavenging by women and children from African countries (Figure 3.22). Most of the waste scavengers are looking for aluminium cans and cardboard items, which represent approximately 40% of municipal waste. Figure 3.23 shows the traditional and primitive way of storing and transporting recyclables and cardboard in particular. However, in the absence of recycling programmes and low salaries for labourers in the cleanliness sector, recyclable materials are scavenged from the street containers and the landfill.

Figure 3. 22: Waste Scavenging in Makkah

Source: Salim (2008) and KAAU (2008)

Figure 3. 23: Transport and Storage of scavenged cardboard in Makkah

Source: Salim (2008) and KAAU (2008)

3.7.5 Waste Disposal

According to the Municipality of Makkah (2011) and Abdulaziz *et al.* (2008), most of the municipal waste in Makkah is disposed of by landfilling, whereas the rest is lost due to scavenging processes. There are two municipal landfill sites in Makkah, as follows:

3.7.5.1 New Landfill

In the south of Makkah, the Al-Mis'falah landfill is the newest landfill site, with an area of 452,000 m^2. It was opened in 1423 H (2003) and used as an official waste disposal site (Municipality of Makkah, 2011). It is actually just an open dump site, as shown in Figure 3.24. The landfill is divided into cells; each cell is approximately 75 m in length, 25 m in width and 15 m in height. A single cell is completed every six to seven days (Municipality of Makkah, 2011). The dumping is designed for four layers of cells with a final cover of one metre thickness. Two weighbridges are provided at the reception area at the entrance gate for the accurate weighing of incoming waste, as shown in Figure 2.24 (KAAU, 2008).

The amount of leachate that is produced in a landfill depends on the amount and intensity of rainfall, evaporation and run-off from the landfill itself. The mean annual rainfall on an open surface in this area is 111mm, as mentioned in Section 2.3. It is expected that the leachate production from landfills in Makkah will be less than 20% of the rainfall (KAAU, 2008). While the main purpose of the landfill is the disposing of waste on land to protect human health and the environment, it needs immediate attention, especially regarding the possible leachate and gas migration to the surrounding environment (Abdulaziz *et al.*, 2008). It is thus expected that the Al-Misfalah landfill site will be closed in 1439 H (2018).

Figure 3. 24: The new landfill in Makkah

Source: Taken by Al-sebaei (2008)

3.7.5.2 Old landfill

The old landfill in Makkah, called “Al-Muaisim landfill”, is located in the northeast of the city. Solid waste from Makkah was dumped in Al-Muaisim landfill between 1406 and 1423 (1986 & 2003) (Abdulaziz *et al.*, 2008). There were about ten layers of waste dumped at this site. The dumpsite does not have a leachate collection system or a suitable design for the final cover. Only a fraction of the landfill gas (LFG) has been collected and burned due to the lack of a properly functioning flare, and the rest of the LFG escapes into the atmosphere (Figure 3.25).

Figure 3. 25: Gas collection and burning flare of the old landfill in Makkah

Source: Taken by Al-sebaei (2008)

In short, it can be said that most of the reports issued by the Municipality of Makkah or other institutions indicate that the recent system of waste management in Makkah is unsatisfactory and there is an immediate need to upgrade collection and safe landfilling systems. In addition to the inadequate number of staff and labourers, the MW containers and vehicles are also inadequate for proper waste collection and the method of disposal in the current landfill is disastrous. The following pictures (Figure 3.26) show the seriousness of the current situation of the waste management system for human health and the environment in Makkah during pilgrimages and non-pilgrimage periods.

Figure 3. 26: Current situation of waste collection in Makkah

Source: Taken by Shiq'dar (2013)

3.8 SLAUGHTERHOUSE WASTE

At the end of the Hajj period, Muslims throughout the world celebrate the Festival of Sacrifice (Eid Al-Ad'ha) every year and perform animal sacrifice in commemoration of Abraham sacrificing his son. When performing the Hajj, Muslims have to sacrifice an animal if they commit any wrongdoing during the Hajj rituals.

In 1433 H (2012), the slaughterhouse in Mina site at the Hajj period handled approximately 986,000 goats and 2,400 cows and camels (IINA, 2012). The slaughterhouse, which meets all pilgrims' needs for animal sacrifices during the Hajj period, may significantly contribute to the increase in the amount of waste (Figure 3.26). According to Abdulaziz *et al.* (2008), each goat is estimated to contribute 7.0 kg of solid waste and 1.5 litres of blood. A slaughter waste treatment plant was established in 2001 to receive about 500 tons of the sacrificed animals per day and convert organic waste into fertilizer. Less than 10% of the total slaughterhouse waste, however, is treated by the plant, while untreated waste is disposed in certain undesignated dump sites (Al-Ahmad, 2011).

Figure 3. 27: The new slaughterhouse in Mina

Source: Al-Ahmad (2011)and Basheer (2009)

In short, this practice of dumping slaughterhouse waste is expected to pollute the groundwater, as shown in Figure 3.28. Slaughterhouse waste requires treatment prior to discharge. Abdulaziz *et al.* (2008) suggested an anaerobic or aerobic treatment plant to treat all the organic waste through the year and during the Hajj period in particular. Slaughterhouse waste in Makkah requires further studies to reduce the negative environmental impacts as well as generate income.

Figure 3. 28: The Old Way of Slaughterhouse Waste Disposal

Source: Albar (2006)

3.9 HAZARDOUS WASTE

The amount of hazardous waste generated in Saudi Arabia is approximately 900,000 tons per year, including 127,000 tons of medical waste. Due to the lack of specialised plants for hazardous waste management, most of these wastes are disposed of improperly and in violation of required regulations (Daoud, 2012). According to PME authorities, hazardous waste in Saudi Arabia is produced mostly from industrial activities, petroleum and medical activities. Makkah province ranked as the third in terms of the hazardous waste quantity after the Eastern Region and Riyadh in Saudi Arabia (KAAU, 2008). The most significant reasons for the current situation with regard to hazardous waste management in Saudi Arabia can be summarised as follows:

- Lack of engineered disposal sites for hazardous waste,
- Absence of monitoring and controlling in the production and disposal of hazardous waste,
- Lack of obligation for the industrial sectors to follow the environmental policies in terms of hazardous waste management,
- Weak encouragement for the industrial sector to use recycled materials instead of importing large quantities,
- Lack of required marketing of recycled hazardous materials, and;
- Mixing of household waste with hazardous materials such as paints, medicines and other chemical substances.

There is currently no accurate definition to specify which waste is considered hazardous in Makkah. Hazardous waste is defined by the Municipality of Makkah as waste generated by the health care services, such as hospitals, and waste generated by industrial operations. This type of waste is handled by a special contractor. Medical waste is collected, sorted, stored, transferred and then combusted in incinerators. Some of the large hospitals in Makkah have their own incinerators (Municipality of Makkah, 2011).

There are only six treatment plants for hazardous waste in Saudi Arabia. The Chief Executive Officer of "Tadawolat", one of the hazardous waste treatment companies in Saudi Arabia, said that only 60,000 tons (7%) of hazardous waste goes to the current treatment plants every year. He suggested that the Saudi authorities must move to export hazardous wastes as a temporary solution while establishing new plants to accommodate all existing waste (Daoud, 2012).

3.10 TRENDS OF DEVELOPMENT AND WASTE MANAGEMENT IN MAKKAH

Fakieh (2008) argues that Makkah is covered with uncontrolled dump sites that are currently used for the disposal of solid waste. This is very unsatisfactory from many environmental and aesthetic standpoints, causing air and water pollution, contaminating soil and spoiling the surroundings.

Saudi Arabia and Makkah in particular is currently undergoing unprecedented development in urban and economic aspects. With the projects that are currently under construction, the Saudi authorities aim to improve the existing infrastructure of Makkah city for pilgrims and visitors as well as to double the number of pilgrims coming to perform the Hajj and Umrah. It is consequently doubly appropriate to examine the potential for establishing a new system of municipal waste management and constructing facilities for materials recovery. This is certainly reflected in public health and the health of pilgrims. The lack of environmental regulations related to solid waste activities has negatively affected the management of solid waste.

3.11 SUMMARY

The study area, Makkah, of this research considered as the holiest city in the faith of Islam and more than 13 million pilgrims who come to perform Hajj and Umrah throughout the year. An overview of Makkah city, such as location, climate, local and Pilgrims population was covered. The religious events in Makkah (Hajj and Umrah), an official calendar in Saudi Arabia the Islamic calendar and the Holy water (Zamzam) were provided to make sure a good understanding of the situation of Makkah. The recent environmental issues related to the population of Makkah and its infrastructure e.g. air pollution, lacking of water resources, wastewater treatment and solid waste management were also illustrated briefly. In particular, the existing system of municipal waste management in Makkah was discussed in terms of waste characteristics and quantity and the collection, transport and disposal of waste during the pilgrimage time periods (Hajj and Umrah) as well as the non-pilgrimage. Other waste such as hazardous and slaughterhouse wastes were showed briefly and were not conducted in this study because of insufficient information availability and these types of wastes are collected and treated by privet contractors.

Although the recent infrastructure and services of Makkah are being improved compare to the last decade, the existing environmental situation is considered in worst case and it needs to pay further attention in order to protect human health and environment from burdens. Integration with literature review (chapter 2), an overall background of the search in terms of understanding waste management and the study area, are completed in order to go through the research methodology used in this research.

CHAPTER 4

Research Methodology

The purpose of this chapter is to present the scope of the investigation and the methodology used for the research. To evaluate different waste management options in Makkah from an environmental point of view, EASEWASTE modelling was applied in this study as a LCA tool. It took into account the change in waste flow through the pilgrimage and non-pilgrimage periods. The research boundaries were also identified and all assumptions that were made for the assessment are presented. The different scenarios proposed were based on data collection of MSW from the municipality of Makkah.

As described in (section 2.8.1), the LCA is defined in ISO 14040 as a technique for evaluating the environmental impacts and consumption of resources and provides a comprehensive view of the processes and impacts. Complete LCA must follow a systematic approach with four phases (ISO, 2006) to compare, successfully, the environmental performance of different scenarios for management of solid waste in Makkah. According to Kirkeby et al. (2006a), the phases were described as the structure of the LCA applied in EASEWASTE which include:

- Goal and scope definition:
    - What is the purpose of the investigation?
    - What is the functional unit?
    - What are the system boundaries?
    - What are the comparative systems?

- Inventory:
  - What are the data requirements?
  - Data collection
  - What is the quality of the data?
- Impact assessment:
  - Which environmental impacts and resource consumptions does the system contribute with?
  - Which contributions are the most significant?
  - Which sources in the system are the most important?
  - Which uncertainties are the most important?

4.1 GOAL AND SCOPE

The study aims to assess the environmental impacts generated by different waste management scenarios of Makkah with regard the fluctuating in waste flow through Hajj, Umrah and non-pilgrimage periods. In order to evaluate the waste management system in Makkah based on the goal and objectives as reported in Chapter 1, LCA was selected as support tool for quantifying the environmental impact following the cradle to grave approach. The limitations of this study were mainly related to missing standardised methods and inventory data in Makkah. Due to a lack of ecological assessment of MSW in Makkah, the environmental data obtained in this study, however, are suitable to carry out an assessment of MSW.

4.1.1 Functional unit

The functional unit is a key element of a life cycle assessment study and one of the critical stages of LCA. It can be defined as a measure of the performance of the functional outputs of the Product System and it provides a reference to which the inputs and outputs can be related (McDougall *et al.*, 2008). The functional unit is also the basis on which the products or systems will be compared. Otherwise any comparison on LCA study will not be made on a fair and equivalent basis (White *et al.*, 1999; Finnveden, 1999).

The main study results for the impact assessment are presented relative to a functional unit of one metric tonne or Mg (mega-gram) of municipal solid waste. A one year timeframe was used for the collected data, which included the monthly variations. The most recent complete set of data was for the year 1432 AH (7^{th} December 2010 to 25^{th} November 2011) which was used as the reference year for this research.

4.1.2 System Boundaries and Limitations

System boundaries recognise which unit processes should be included in a LCA study. LCA is based on the material and energy flows over system boundaries. It is of absolute necessity to have clearly defined system boundaries to ensure that the obtained results are unambiguous (Moora, 2009).

The EASEWASTE model boundaries was used in this study as system boundaries which cover bin-to-grave, i.e., from the point where products become waste and put into the waste bin at the waste generation source to the point where the waste either has been converted into a useful material or has become part of the environment after final disposal as shown in Figure 4.1. The foreground system is the system under analysis and the background system is the system in which the former operates. Some processes in the background system could be replaced by the processes in the foreground system. For example, waste recycling (foreground) replaces the production of products or services from virgin materials (background system).

In the EASEWASTE model, the foreground system embraces all the processes directly related to the waste management operations: waste collection, transportation, composting, digestion, recycling, incineration, and landfilling. The background system consists of all other processes influenced by the measures taken in the foreground system, namely electricity production or raw material manufacturing systems. Analysing the environmental effects of products (electricity or recycled materials) implies the analysis of the environmental effects of the background system within the extended system boundaries, i.e. the production of energy and virgin materials (Figure 4.1).

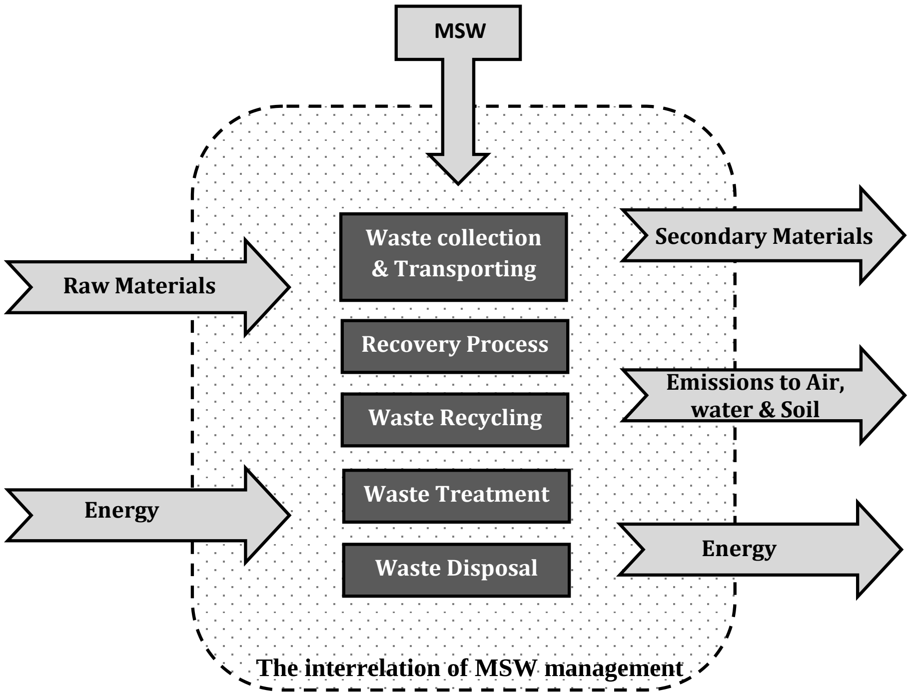

Figure 4. 1: The research boundary considered in the study, which was the municipal boundary of Makkah

The production of machinery, capital goods and supplementary infrastructures such as roads and buildings are not included in this boundary. The environmental impacts related to the activities of household waste generators (e.g. washing waste packaging, citizen driving to a waste sorting station, etc.) are also excluded from the model.

The model characterises the emissions by accounting waste composition and quantities, production of both products and by-products, and accompanied emissions. The net emissions from the life-cycle of a studied waste management system are calculated as (Moora *et al.*, 2006):

$$E_{net} = E_{Foreground} - E_{Background} \quad (4.1)$$

where $E_{Foreground}$ is emissions from waste valorisation processes and $E_{Background}$ is emissions from the virgin production in the background system.

The net emissions with a negative value are thus to be interpreted as a positive environmental impact from waste recovery. For instance, recycling may yield net emissions lower than those of the replaced processes using virgin resources.

The subsystems included in this case are; waste collection, sorting of materials at a materials recovery facility (MRF), recycling of materials, waste bio-treatment (composting and anaerobic digestion), use-on-land (UOL), thermal treatment, waste landfill, material utilisation, energy utilisation, Air Pollution Control (APC) treatment, and bottom ash treatment (Bhander *et al.*, 2010).

In this research, all the environmental impacts throughout the system boundary and credit from energy recovery were appraised and covered by the LCA. In Makkah city, the recycling of paper and cardboard, plastic, aluminium and steel which are mainly the largest secondary materials, was taken into account within the LCA starting from sorting to manufacturing.

Due to EASEWASTE has been mainly developed for waste types from households and small commercial business units, the management of other waste streams such as demolition and construction waste are not addressed.

The disposing of construction and demolition waste in Makkah is under contractors' responsibilities. Construction and demolition waste must be disposed of by backfilling in private excavated sites under the Act 2-12 based on the General Environmental Laws and Rules in Saudi Arabia (PME, 2001). However, the municipality is not responsible for taking construction and demolition waste into account for MSW collection. Consequently, construction and demolition waste was not included in this study.

Industrial waste is also excluded in this investigation due to the absence of factories in Makkah and the fact that it was regulated under the Factory Rules 14-2-4 by the government (PME, 2001). Scavenging activity was also omitted in this research. This was thought to be acceptable as all the available data, in terms of waste quantities and composition, was taken from trucks arriving at the current dumping site, i.e. before any scavenging took place. In addition there was no data available for scavenging activities.

Bulky and inert fractions of the household waste such as electrical and electronic equipment are not included in the study, as these are assumed to be separately collected and treated, at least in future waste management systems. According to the definition of waste in Chapter 2, Municipal Solid Waste (MSW) was selected in this study as an input to the system. Other wastes such as medical waste and wastewater sludge from the current wastewater treatment plant, waste from the slaughterhouse which catered for animal sacrifices were not taken into account in this study. Special treatment plants are available for these wastes and they do not go straight to the MSW stream in Makkah.

4.3 DATA COLLECTION ON WASTE GENERATION AND COMPOSITION

4.3.1 Evaluation of available data

With respect to MSW quantities of Makkah, the official data available from the Municipality of Makkah of annual collected waste were for sixteen Hijri years between May 1995 and November 2011 (Figure 2.16). In order to accommodate fluctuations in waste flow and composition within different periods in Makkah, monthly MSW quantities, which are available only for four Hijri years (9 January 2008 to 25 November 2011), are required. Therefore, the monthly amounts of MSW for the latest year available 1432 AH (7th December 2010 to 25th November 2011) have been selected to evaluate the MSW flows in Makkah and as the basis to assess environmental emissions. Information regarding operation of the waste management system i.e. energy and resource demand for waste collection, waste treatment and disposal, is necessary for modelling, in particular for LCA. Since official data on this have never been officially reported, data collection was carried out as part of this study to determine representative information for actual operations from EASEWASTE database.

According to Guinée (2002) and Larsen (2009), LCA models are typically linear steady-state models of physical flows based on the assumption of a linear relationship between waste quantities and environmental impacts. The LCA results can indicate what waste-management option contributes the least to different environmental impacts. However, in reality the environmental burdens of collection and recycling are likely to be a non-linear function of the collection rate: there will be initial activities and environmental burdens when a collection system is established; at very high recycling rates, the required extra transports and processing of materials may increase fuel consumption and emissions greatly for each additional tonne of material that is collected. The environmental optimal collection rate will be somewhere in between. However, since LCA results are linear, they cannot be used for identifying the optimum mix of waste-management options: recycling, landfilling and incineration. This means that typical LCA models cannot be used for identifying optimal reuse and recycling rates.

In the case study of Makkah, the required data such as waste amounts and their composition should be entered in EASEWASTE software for one Gregorian year. This implies that the only period that can be entered in EASEWASTE is one Gregorian year and cannot enter monthly figures. This procedure may not describe accurately the current waste system in Makkah because of large changes in waste quantities and compositions from one period to another during a year. For example, the average daily production of MSW in a non-pilgrimage period in the year 1432 AH (7^{th} December 2010 to 25^{th} November 2011) was about 1,453 tonnes, which increased by 30% in Umrah period and 112% in the Hajj period (Municipality of Makkah, 2012). Figure 4.2 presents the quantities of collected waste that arrived at the current landfill in Makkah during pilgrimage (Umrah and Hajj) and non-pilgrimage periods. It was decided that each period would be modelled individually as a MSW system in order to make a system that would best reflect Makkah's MSW system.

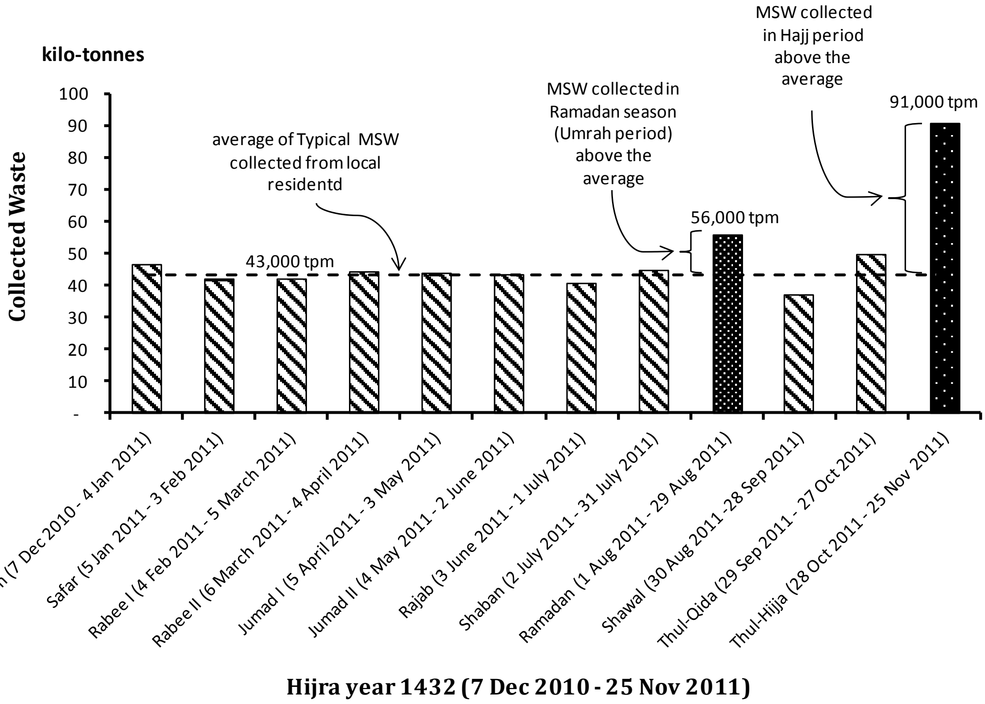

Figure 4. 2: Actual MSW quantities for Makkah in year 1432 H (Appendix A3, A4)

Source: Municipality of Makkah (2012)

The amount of MSW generated and its composition are considered to be the most influential elements in the LCA modelling and used as the input data. It is important to mention that the annual data available for the MSW quantities for the study area, Makkah, only listed under the Islamic calendar (Hijra calendar). This means that the MSW data is based on a 355 days (year 1432 AH) instead of 365 days for the Gregorian year which is needed in the EASEWASTE modelling software. In order overcome this difference, the waste quantity of non-pilgrimage period was increased by adding the amount of 10 days to the actual MSW amount of non-pilgrimage period. The amount of waste generated of the non-pilgrimage period then became 595,000 tonnes for one Gregorian year (365 days) from 7 December 2010 until 6 December 2011 instead of 579,000 tonnes for Hijri year (355 days). Based on Figure 4.2, Table 4.1 explains the actual waste expressed in units of "tonnes per year" which applied in the chosen LCA tool for the three cases, Umrah, Hajj and non-pilgrimage periods.

Table 4. 1: MSW quantities of Makkah during the Hijri year of 1432 AH and (from 7th December 2010 to 6th December 2011)

item	Non-pilgrimage Period **(10 Hijri months)**	Umrah Period **(1 Hijri month)**	Hajj Period **(1 Hijri month)**
Duration (days)	297	29	29
Actual collected MSW, (kilo-tons. Hijra year^{-1})	432	56	91
Actual daily collected MSW, (tonnes.day^{-1})	1,453	1,934	3,130
Calculated collected MSW for 365 days, (kilo-tonnes. Year^{-1})	530 kt.y^{-1}	706 kt.y^{-1}	1,142 kt.y^{-1}

4.3.2 Determining the waste composition

Decisions on waste management, such as selection of waste treatment processes, require information on the materials mixture of the MSW input. Since the specific data available for Makkah were limited mainly to the monthly waste compositions, the study relies mostly on the recent data available on the MSW composition from Makkah's Municipality in 1432 AH (7th December 2010 to 25th November 2011) as indicated in Figure 2.18 (Chapter 2). This official data was derived from direct analysis of the waste on the trucks bringing waste to the landfill site. In this study, field data collection could not carry out due to the limitation of budget and time. Table 4.2 shows the waste composition of Makkah in and out of the pilgrimage periods which are used in EASEWASTE software.

In order to carry out the LCA, the physical and chemical characteristics, i.e. water content, substance concentration and calorific value of individual waste fraction is important for the environmental impact assessment. Since there was no data available in Saudi Arabia, this information was adopted from the EASEWASTE database. The EASEWASTE data is all based on a European MSW background.

Table 4. 2: MSW composition for the different pilgrimage periods in Makkah

Type of solid waste	Composition (% by weight)			
	Average for Non-period	Umrah period	Hajj period	Average for a whole year
cardboard	4.95	19.5	14.00	6.92
paper	2.36	1.50	4.00	2.43
plastic	5.41	8.50	10.00	6.05
steel	6.36	4.50	7.00	6.26
glass	3.26	5.00	5.00	3.55
aluminium	3.26	2.00	5.00	3.30
textile	3.95	20.00	8.00	5.63
wood	7.05	8.00	4.00	6.88
organic	63.40	31.00	43.00	59.00
total	100	100	100	100

Source: Municipality of Makkah (2012)

4.4 CRITERIA FOR CHOOSING SCENARIOS

In order to reach to the appropriate scenarios, several criteria for choosing the scenario would be taken into account such as the importance of Makkah in Islamic faith, the cultural and behavioural issues of the resident population and pilgrims, the nature of Makkah and its climate. These criteria can be listed as follow:

- **Less negative environmental impacts**

  The suggested scenario could be a lower environmental impact than the current MSW system in Makkah to achieve the goal of the research by choosing different and modern technologies in waste treatment or disposal.

- **Costs**

  Although the cost is important at any project particularly at waste treatment or utilisation of recycled materials, for example, the cost of such vital projects in Saudi Arabia, now, is not a high priority. This is because of that the government is trying to do the best with regard developing the infrastructure in Makkah and the other holy places "Al-Masha'er" for local population and pilgrims.

- **Ability to accommodate high changes in waste amounts**

  Studied scenarios could be flexible enough to accommodate unexpected MSW quantities during the Hajj and Umrah periods as well as non-pilgrimage period.

- **Changing behaviour requirements**

  The awareness of the waste management issues greatly affects on the system building. This is due to the higher people's awareness of the importance of separating waste for recycling, for example, contributes the reduction of sending waste to the treatment plants or landfill. The culture in terms of food consumption, resources protection and waste preventing can be additionally led to select an appropriate technology used in the waste management system. So, during the process of setting up the scenario, the needing for a change in public behaviour will be discussed.

- **Suitable for future increases of pilgrims and local population**

  The future rising on MSW amounts must be involved in the designed Scenario to accommodate the future rising on pilgrims and local residents of Makkah. However, the limited spaces on Makkah and Al-

Masha'er with the current infrastructure don't allow for absolute pilgrims' increasing. So, the technology of waste treatment and disposal, which used in the scenario, should be able to cover the excess waste at least in the nearest future.

- **Changes to the current situation (current infrastructure)**

  While choosing scenario, it should be considered whether there is a real need to change the existing infrastructure to Makkah or not as well as the extent of this change.

- **How to accommodate the hot weather and geographical conditions of Makkah**

  The chosen scenario would be ability for applying in above 50◦C in summer for example. It would also be commensurate to with the varied terrain of Makkah i.e. mountain residential areas and narrow neighbourhoods.

- **Should have no adverse effect on religious practices i.e. keeping Zamzam water safe as possible**

  Zamzam water is a very sensitive subject among Muslims. Therefore, protection of groundwater and Zamzam water in particular is one of the priorities in the selected Scenario. To achieve this, it should be to make sure that the landfill leachate, for example, doesn't reach to the groundwater without treatment as much as possible.

4.5 STUDIED SCENARIOS

As mentioned earlier, the main goal of this study is to evaluate the environmental performance of different waste management options for Makkah taking into account the pilgrimage periods. In order to reflect the actual system of MSW generation in Makkah, three sub-scenarios were set up in EASEWASTE for non-pilgrimage, Umrah and Hajj periods respectively. These three sub-scenarios then combined together for modelling the baseline scenario, for example, and calculated in Equation 4.1.

$$\mathrm{SC}_i = \mathrm{SC}_{non} + \mathrm{SC}_{Umrah} + \mathrm{SC}_{Hajj} \qquad (4.1)$$

Where: SC_i = Studied scenario for a year; SC_0 , SC_1 , SC_2... etc.

SC_{non}= sub-scenario for the non-pilgrimage period (10 months)

SC_{Umrah}= sub-scenario for the Umrah period (1 month)

SC_{Hajj}= sub-scenario for the Hajj period (1 month)

The EASEWASTE model was used to assess different options of MSW in Makkah as well as the current system of MSW. The choice of strategies allows a direct comparison of different disposal and treatment facilities such as MRF, incineration, and MBT in different periods. These processes would make a significant change to environmental impacts compare to the recent uncontrolled landfill of Makkah. However, it was decided not to focus on various collection and transporting vehicles in this study. This was due to the fact that collection and transporting contributes a small fraction of the environmental impact, even though it is usually one of the most costly aspects of waste management (Larsen and Christensen, 2009). The collection of waste itself is considered as a complicated process with many alternative options, for example, mixed and sorted waste can be collected individually from each home, or from collection points. Collection can also occur daily, weekly or fortnightly with the use of the same trucks or special trucks. As a result, MSW collection and transport methods are often selected according to economical considerations (Larsen and Christensen, 2009).

The treatment and disposal options for collected MSW in Makkah involved different technologies such as sanitary landfilling with/without energy recovery, mechanical biological treatment systems, and waste combustion with energy recovery. Therefore, six different scenarios of MSW management were compared with the recent practice which occurs in Makkah, the baseline scenario (SC0) and evaluated by the means of LCA as described in the following sections:

4.5.1 Scenario 0 (SC0) – Baseline

The Baseline Scenario represents the waste management situation in Makkah in 2011 and assumes that the relative waste composition according to the case in 2011 has not changed (Figure 4.3).

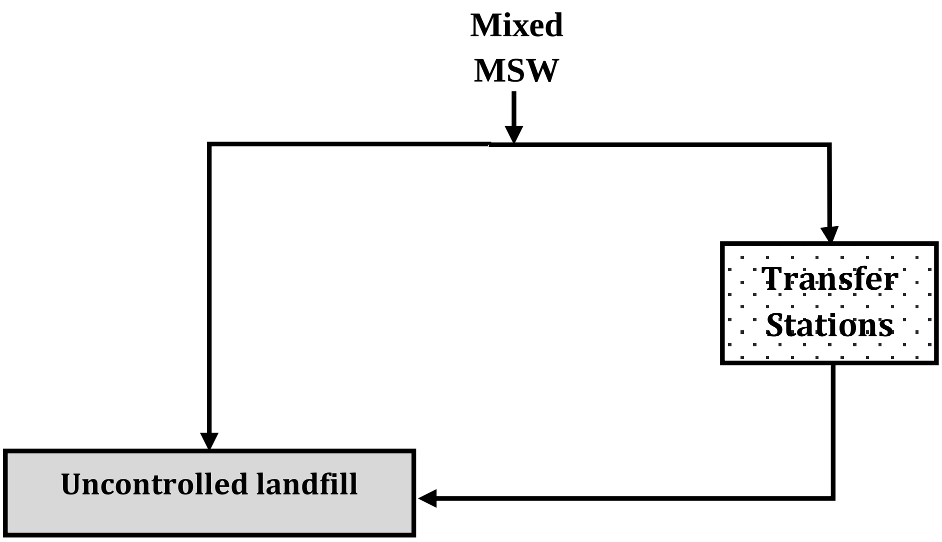

Figure 4. 3: Scenario 0 (SC0), the Baseline system

A bring collection system operates in Makkah, which requires the residents to take mixed waste to kerbside collection points. Only one type of bin is used for all MSW waste, with no special containers for collecting recycled materials or organics. These bins are emptied by a contract waste collection company at least twice per day in the central area of Makkah (around Al-Haram mosque) particularly in the pilgrimage periods, and once per day in the rest of Makkah.

Waste collection and transport in Makkah is carried out by diesel-fuelled lorries which pick up the MSW from neighbourhoods or roadsides. Throughout the year, most of the collected waste in Makkah is sent directly to the current uncontrolled landfill while the rest is sent to transfer stations and then to the landfill as shown in Table 4.3.

Table 4. 3: The percentage of directly and indirectly collected MSW that are sent to the landfill during a year

Period	% MSW going Directly to Makkah's landfill	% MSW going to Makkah's landfill via transfer stations
Non-Pilgrimage	80 %	20%
Umrah	78 %	22 %
Hajj	81 %	19 %

Source: Calculations based on collected data from Municipality of Makkah (2012)

As mentioned earlier (Chapter 3), uncontrolled landfilling is the only option available for MSW disposal in Makkah. With no liner system, this dump site has neither landfill gas collection nor leachate treatment systems.

4.5.2 Scenario 1 (SC1) – Sanitary Landfilling

This scenario, shown in Figure 4.4, is also based on real data from Makkah. A sanitary landfill was assumed to take all the collected mixed waste in scenario (SC1) instead of the uncontrolled landfill that was used in the baseline scenario. This sanitary landfill was equipped with leachate treatment. Gas capturing system with 70% of the LFG is being utilised for electricity production using gas-engine/generator units and the remainder is being flared. All the collected leachate is treated on site and discharged into the nearby valleys. This landfill can accommodate change in the waste quantities throughout the year regardless of religious events. These assumptions used in this scenario were made to suit the case of Makkah as it has no appropriate infrastructure for waste management as yet.

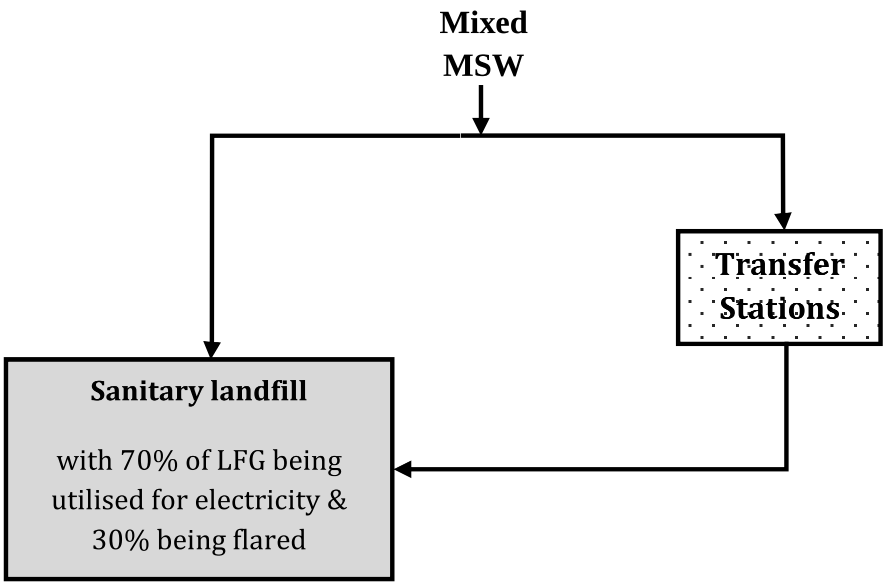

Figure 4. 4: Scenario 1 (SC1), sanitary landfill option with energy recovery

4.5.3 Scenario 2 (SC2) – Incineration (combustion with energy recovery)

The third scenario describes the combustion of waste with electricity generation option for the management of MSW in Makkah. This scenario considers that there is no change to the collection and transporting processes, these are as used in the baseline scenario.

Regardless of the pilgrimage events, scenario (SC2) assumed that approximately 40,000 tonnes per month of mixed waste was combusted at two Grate incineration plants with 30 ton per hour capacity each while the rejected waste was landfilled in a sanitary landfill. The third Grate incinerator will need to be installed in 2020 to accommodate the expected increases of waste. The incineration was assumed to have energy recovery which produced electricity and was sold to the local grid. The landfill has both biogas and leachate collection systems. All the collected leachate was treated on site while all the collected landfill gas was burnt. The bottom ash was assumed to be disposed in the sanitary landfill. Figure 4.5 describes the waste stream in scenario (SC2).

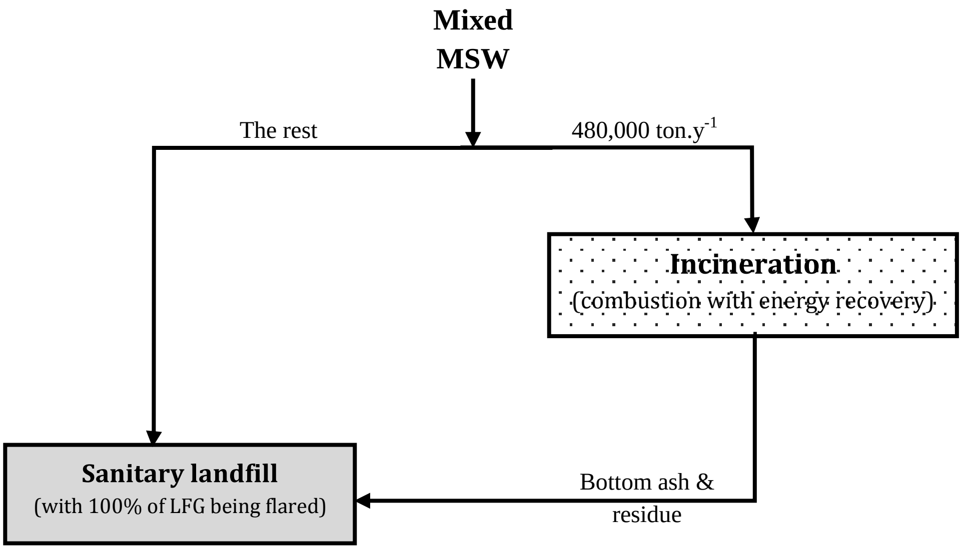

Figure 4. 5: Scenario 2 (SC2), Incineration (Combustion with energy recovery)

4.5.4 Scenario 3 (SC3) – MBT with composting

The fourth scenario in this study focused on mechanical biological treatment (MBT) with the composting option for the management of MSW in Makkah. Similar to scenario (SC2), this scenario assumed that there was no change in the collection and transporting processes from the current situation.

The MBT facility was assumed in this scenario to receive approximately 45,000 ton per month of typical MSW stream which presents the average of the waste collected during non-pilgrimage period. During Umrah and the Hajj periods, the waste that was collected above this tonnage was assumed to go directly to a sanitary landfill with flaring of all captured landfill gas and treatment of the leachate.

Inside the MBT facility, when the mixed waste is tipped by vehicles it is inspected and large objects which are unsuitable for treatment are removed. The waste is then fed into a shredder and undergoes some mechanical sorting (magnetic and eddy current separation) to remove ferrous and non-ferrous metals which are recovered and sent for recycling. Any material that is unsuitable for treatment or recycling is disposed of to the landfill. In-vessel composting, as the biological process, was used to treat the residual waste. The screened and shredded waste (fine organic fraction) was taken into halls and arranged in rows where it was kept at a controlled temperature and moisture levels to ensure the waste was composted and the biodegradable content stabilised. In the next stage, the composted waste was screened again for recyclables. Any rejects were assumed to be landfilled at sanitary landfill or if suitable were returned to the process for further composting. The stabilised Compost-Like-Output (CLO) production could be used for landfill restoration. Figure 4.6 shows the suggested waste stream in scenario 3.

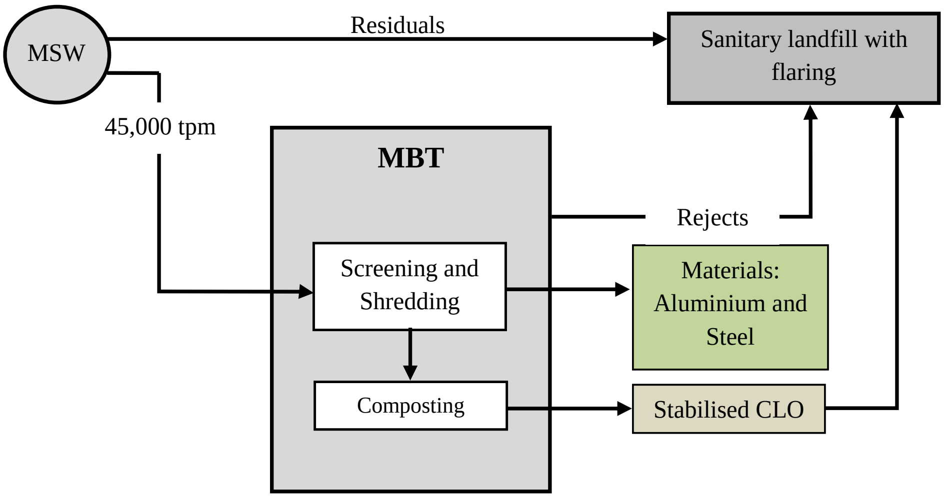

Figure 4. 6: Scenario 3 (SC3), MBT with composting

4.5.5 Scenario 4 (SC4) – MBT with RDF

This scenario focuses on mechanical biological treatment (MBT) with RDF production for the management of MSW in Makkah. The MBT facility was considered as scenario (SC3) to receive approximately 45,000 ton per month of the MSW of Makkah. The rest that was collected waste in the pilgrimage events was assumed to be sent directly to a sanitary landfill.

It was assumed that commingled waste in the MBT facility was shredded before being placed into a biological treatment area. A mechanical segregation process was then used to remove ferrous, non-ferrous metals and a glass / aggregate fraction from the dry material to produce a high calorific value waste. This remaining dried waste, the high calorific value waste stream, consisted of paper, cardboard, plastics, dried organics and other materials and it was used as a Refuse Derived Fuel (RDF). The RDF was used as a replacement fuel i.e. fossil fuel in a cement kiln. Any rejects were assumed to be landfilled. Figure 4.7 describes the waste stream in scenario 4.

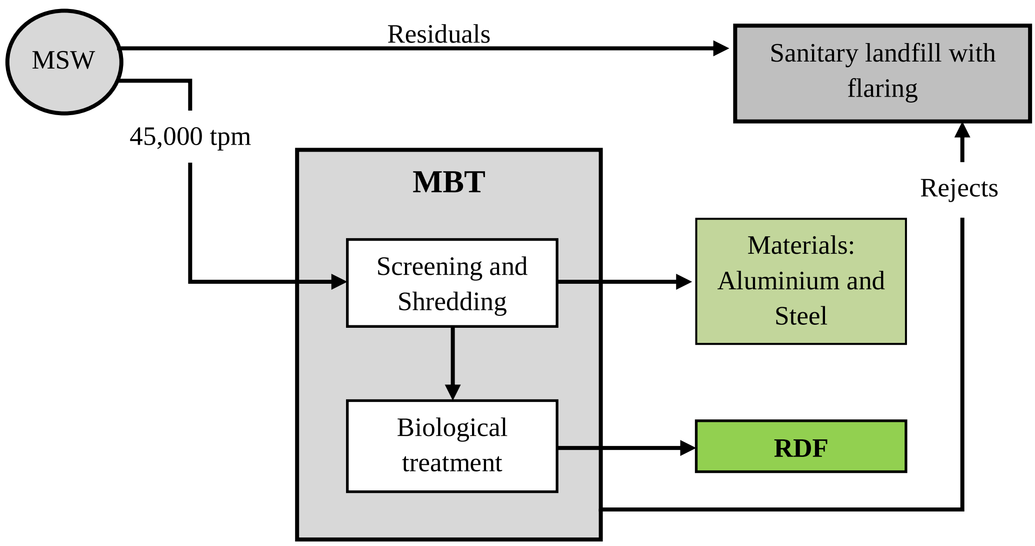

Figure 4. 7: Scenario 4 (SC4), MBT with RDF production

4.5.6 Scenario 5 (SC5) – Recycling and composting

The scenario 5 describes the option of source separating waste for the management of MSW in Makkah. In this system, food waste was assumed to be collected together with other wet materials in black coloured bins and the dry recyclable materials (e.g. paper, cardboard, steel, aluminume and plastics) in green bins. It was assumed that all waste, which was produced by pilgrims during Umrah and Hajj periods, was sent to sanitary landfill with flaring of the captured landfill gas and the leachate being treated on site (Figure 4.8).

The dry waste was assumed to be sent to a Materials Recovery Facility (MRF) where the recyclable materials are sorted semi-automatically. The residue from the MRF is sent then to the landfill while the recycled materials are sent directly to reprocessing. Wet waste was assumed to be composted by open composting technology (window composting). Sorting processes such as manual sorting for recyclable materials and mechanical screening will be performed prior to composting. The resulting compost will be finally screened in order to separate contaminants from the compost product. The screened residues from mechanical pre-treatment were disposed of at the landfill.

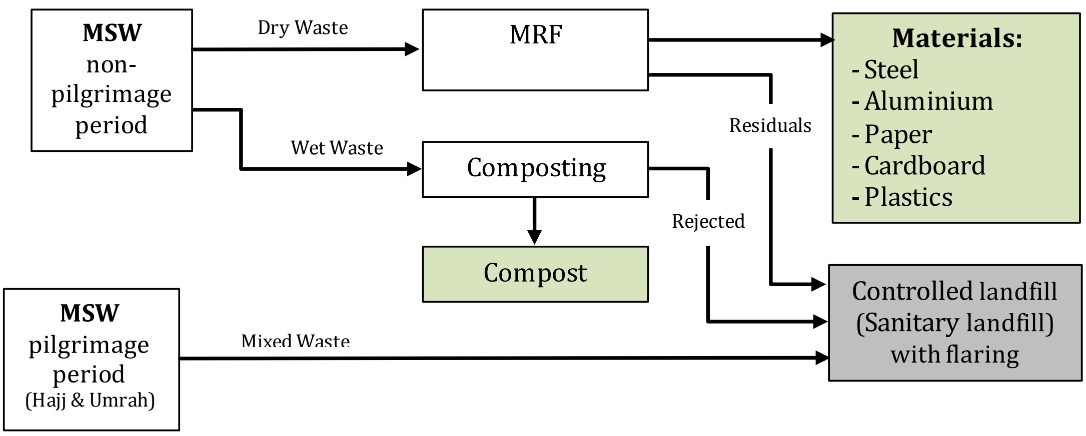

Figure 4. 8: Scenario 5 (SC5), Recycling and composting

4.5.7 Scenario 6 (SC6) – Recycling and anaerobic digestion

The final proposed scenario was similar in most respects to scenario 5 where three bins were used, one for recyclable materials, one for organic waste and the other for residual wastes. In Scenario 6 instead of composting as a biological treatment system, anaerobic digestion (AD) was used to treat the organic and food waste fraction. The anaerobic digestion facility is employed to process the fine organic fraction. The anaerobic digestion process is designed to process up to 1,700 tonnes per month. The plant uses a two-stage process: in the first stage, the fines are made into wet slurry that is then pumped with air during a 24 hour aerobic hydrolysis process; and in the second stage, this pre-treated (biologically heated and acidified) slurry is then sent to an 18 day thermophilic wet AD process. Following 18 days digestion the digestate undergoes further treatment to produce a CLO (DEFRA, 2007b). Figure 4.9 shows the waste stream in scenario 6.

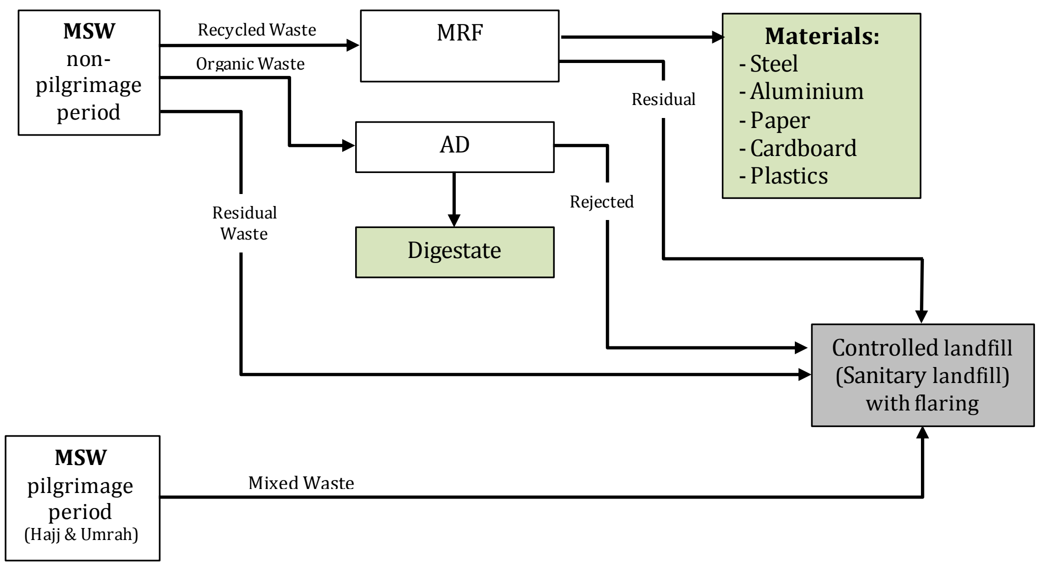

Figure 4. 9: Scenario 6 (SC6), Recycling and anaerobic digestion

4.6 LCA CALCULATION

This section explains the overall scope of the life cycle assessment study. The system boundary presents the margin of inflow and outflow. Brief information on life cycle inventory (LCI) and life cycle impact assessment (LCIA) is also given. In order to accommodate variations on MSW flow and compositions of the case Makkah, each period was considered as a single scenario in EASWEASTE. This implies that each studied scenario consists of three sub-scenarios; Umrah, Hajj and non-pilgrimage. Therefore, Figure 3.10 shows the four phases of LCA, which must be followed, in order to ensure successfully comparing the environmental performance of different scenarios for management of solid waste in Makkah.

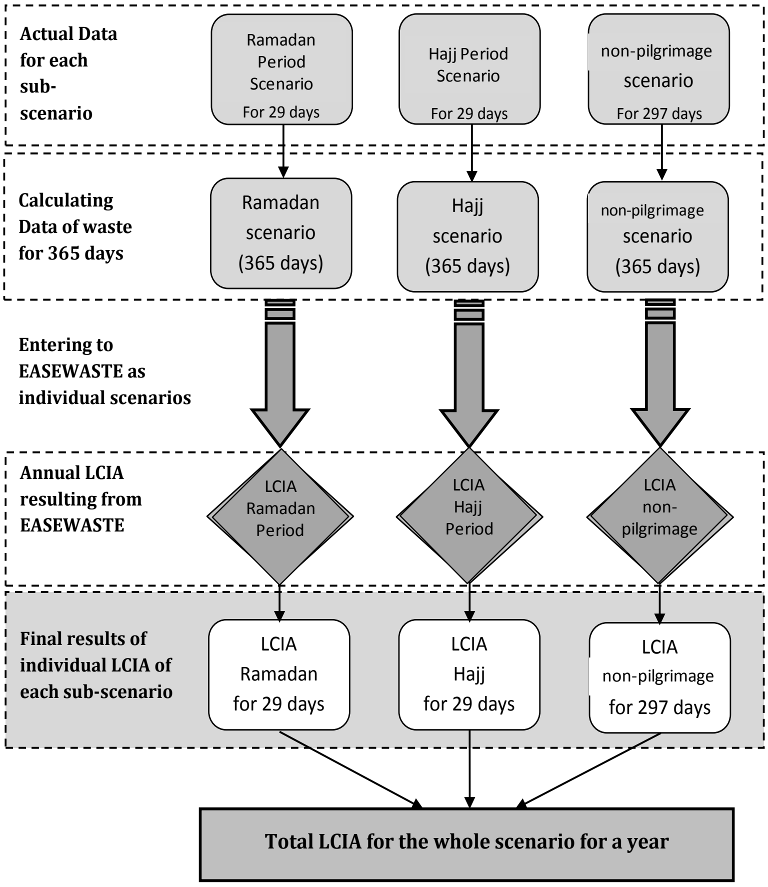

Figure 4. 10: Flow diagram of the four-stages of research methodology

4.6.1 Life Cycle Inventory (LCI)

The environment and resource aspect for the different scenarios for Makkah's waste management were analysed based on the LCA software, EASEWASTE version 2012. In this study, the LCA analysis was adapted according to the process inventory for different waste management technologies from DEFRA and the EASEWASTE database as shown in Table 4.4. The operational information was obtained or derived from the literature, official documents from the Municipality of Makkah.

In EASEWASTE, the external processes consist of up-stream (i.e. production of electricity or materials) or down-stream (i.e. material and energy recovered) activities. The external processes provide life cycle inventory (LCI) of details of processes and materials that are used in the waste management system (Christensen *et al.*, 2007; Damgaard *et al.*, 2011).

According to Bhander et al. (2010), EASEWASTE has been developed from a Scandinavian perspective, and when it is implemented in other regions, the need may arise for creation of technology modules that are not known or applied in the Scandinavian context. Likewise, some of the parameter settings may need to be changed to reflect differences in the environmental conditions (e.g., water infiltrating into landfills). The flexibility of the waste input, waste collection method and all treatment and disposal options means that modifications are easily done by the user. At the same time the model suggests realistic (in a Danish context) default values for most choices, which caters the model for abroad target audience including research staff, waste planners, and legislative consultants. Due to lack of LCI data available in Saudi Arabia, and Makkah in particular, the external processes were normally taken from the default data in the software. Although the environmental impact of materials and processes for a Danish LCI will be different from a Saudi LCI, it was thought acceptable to use the Danish life-cycle-inventory (LCI) database and the resulting life cycle impact assessment (LCIA) results because for comparison purposes, all the proposed scenarios were analysed based on the same database.

As with most scenarios of the type considered here the system boundaries involved go from the waste bins to the grave (Kirkeby and Christensen, 2005). Resource consumption and environmental impact were considered in this study as an input and output to the system. The transportation from source to recycling, treatment and disposal processes was also involved.

Table 4. 4: Brief Description of Input Data Required for the EASEWASTE Software

Inventory categories	Descriptions	References
Waste generation		
Multi family housing	Collected MSW	Based on Makkah Municipality
Waste composition		
Collected MSW	Average based on weighing waste generated	Table ... in Chapter 2
Waste collection		
Collected MSW	Actual operations based on Euro3 emission reference	Detail in Chapter 5
Transportation technologies		
Technologies used for transportation activities	Based on the Euro3 emission reference	Detail in Chapter 5
Sub-models		
MRFs	Actual operation and recycling activities, Makkah (2012)	Detail in Chapter 5
Composting	Jora reactor, Sweden, 2003	Detail in Chapter 5
AD	Koh Chang Biogas plant, Trad, Thailand, (2008) *Same comment as previously	Detail in Chapter 5
Incineration (combustion with energy recovery)	Incineration, grate furnace, Malmö (Sysav), Sweden, 2007 (wet & dry)	Detail in Chapter 5
Uncontrolled landfill	Actual operation based on current landfill. Landfills - MBP-waste landfill, 100 years	Detail in Chapter 5
Sanitary landfill	Conventional, Energy Recovery, Spillpeng, Sweden, 2007	Detail in Chapter 5
MBT	Detail in Chapter 5	Detail in Chapter 5
Material recycling		
Paper and cardboard	Paper (Cardboard and mixed paper) to cardboard, Fiskybybruk, Sweden, 2006	EASEWASTE 2012
Plastic	Plastic to granulate, SWEREC, Sweden, 2006	EASEWASTE 2012
Steel	Steel scrap to steel sheets, Sweden, 2007	EASEWASTE 2012
Aluminium	Aluminium scrap to new alu sheets (remelting), Sweden, 2007	EASEWASTE 2012
Material utilisation		
Compost	NPK and peat substitution. Composting, Windrows (Green Waste), High quality product, generic, USA, 2003	EASEWASTE 2012
RDF	RDF in cement work substituting hard coal, Europe, 2003	
External processes		
Electricity	Saudi electricity grid mixed in 2002	Saudi electricity (2002)

One of the requirements for the input data in EASEWASTE is identifying the type of housing that the MSW was generated from. It can either be a single family or Multi-family housing. The MSW collection and transporting were affected by the type of housing. For instance, single family housing consumes more fuel than multi-family housing to collect one tonne of MSW. More than 75% of the housing system in Makkah was multi-family housing and this increased to more than 90% during the Hajj and Umrah period. It was assumed that all MSW collected was multi-family housing in order to reduce the complexity of modelling in EASEWASTE.

The waste collections were mainly evaluated as the first activity of waste management. The sub-models for the methods of treatment or disposal processes used in this study covered open dumping, sanitary landfilling, incineration, mechanical biological treatment (MBT) with anaerobic digestion and Refuse Derived Fuel (RDF), and recycling of paper and cardboard, plastic, steel, and aluminium. To sum up, all detailed criteria of the treatment/disposal, manufacturing of material input to the system, as well as avoiding primary production from substituted materials are described in Chapter 5.

4.6.2 Life Cycle Impact Assessment (LCIA)

The assessment in this study considers three potential impact categories which covering potential impacts in several environmental compartments in order to evaluate the waste management activities. The EDIP method was used by EASEWASTE to characterise emissions to air, groundwater, and soil (Damgaard, 2006). However, the interpretation of the assessment focused on the following three environmental impacts categories: Global Warming Potential (GWP); Resource Depletion (RD); and Spoiled Groundwater Resources (SGR).

The selection of impact categories depends on the purpose of the LCA, e.g. what kind of decision is going to be taken based on the LCA. Obviously, the choice also depends on the type of application of the LCA. Basically, selection of impact categories is a matter between the commissioner and the practitioner, and no methodology includes specific guidelines on which impact categories that have to be included in LCA (Stranddorf, 2005).

According to Hansen et al. (2006), the environmental impact categories are divided into three groups: standard environmental impacts, toxicity-related impacts and impact on groundwater resources. The standard impact categories include global warming (GW), photo-chemical ozone formation (POF), ozone depletion (OD), acidification (AC) and nutrient enrichment (NE). The toxicity-related impact categories include ecotoxicity in soil (ETs) and in water chronic (ETwc), human toxicity via soil (HTs), via water (HTw), and via air (HTa). The potential impact on groundwater resources is represented by the single impact spoiled groundwater resources (SGR) and is calculated based on the amount of groundwater that may be contaminated from an input of leachate by diluting the leachate to the drinking water standard, as described by the guidelines provided by WHO (2006). In addition, the assessment of resources depletion (RD) impact category is performed with the EDIP97. It was adapted to enable the aggregation of the results—commonly obtained per resource—into one single score (similarly to any other impact category (Larsen 2011).

Although the above list of the environmental impact categories is comprehensive, it should be noted that it does not include all possible types of impacts. If other types of impacts are of relevance for an LCA study, a suitable method for their assessment should be defined and documented thoroughly, fulfilling the general requirements and recommendations in the ISO standards (Stranddorf, 2005).

In the original EDIP and many other LCA methodologies the potential global warming or greenhouse effect is quantified by using *global warming potentials* (GWP) for substances having the same effect as CO2 in reflection of heat radiation (Wenzel *et al.* 1997; Hauschild & Wenzel 1998). Global warming potentials for the known greenhouse gasses are developed by the "Intergovernmental Panel on Climatic Change" (IPCC) and they are revised continuously as the models used in the calculations are developed (Stranddorf, 2005). GWP impact category was selected to obtain the effect of different waste system including the current system in Makkah on the global warming.

Additional impact has been introduced in EASEWASTE 'Spoiled Groundwater Resources' in order to represent the environmental concerns and features of waste management. Leaching from landfills, from bottom ashes used in road construction, and from compost spread on land are important environmental concerns. The majority of technical measures and cost of landfilling are introduced in order to limit the migration of leachate into groundwater. However groundwater pollution is traditionally not included in LCA impact assessment because no exposure and hence toxicity are related to leachate entering groundwater. The exposure and potential toxicity depend on how the groundwater is used and where it discharges into surface water. In addition many substances in leachate that potential could spoil groundwater are not as such toxic. The Spoiled Groundwater Resource is quantifying the leaching into groundwater by the amount of groundwater that is needed to dilute the leachate so that it meets drinking water standards. The impact is the sum of each substance assuming that the diluting groundwater does not contain the substance.

LCIA of each whole scenario, which resulted from modelling of the three sub-scenarios on EASEWASTE, were calculated for studied scenarios as indicated in Equations 4.2 and 4.3 below. This was done to obtain simulations of the MSW of Makkah for non-pilgrimage periods, Umrah and Hajj periods. Consequently, only three impact categories were chosen in order to simplify the modelling as well as reduce the complexity on the results and the final decision to achieve the minimum requirements for covering different environmental issues such as protection of natural resources, groundwater and air.

$$\text{LCIA}_{\text{SC},i} = \text{LCIA}_{\text{SC},non} + \text{LCIA}_{\text{SC},Umrah} + \text{LCIA}_{\text{SC},Hajj} \tag{4.2}$$

With,

$$\text{LCIA}_{\text{for any period}} = \text{LCIA}_{resulting\ from\ EASEWASTE} \times \frac{\text{Duration},d\ \text{(days)}}{365\ \text{(days)}} \tag{4.3}$$

Where: $\text{LCIA}_{SC,i}$ = Total impacts of the studied scenario (i) in a year;

$\text{LCIA}_{\text{SC},non}$= Impacts of non-pilgrimage period (10 months)

$\text{LCIA}_{\text{SC},Umrah}$ = Impacts of Umrah period (1 month)

$\text{LCIA}_{\text{SC},Hajj}$ = Impacts of Hajj period (1 month)

d = duration of each period (days).

It should be noted that impact categories do not measure real impacts. These categories address the potential effect on the environment and to humans. In order to obtain a better understanding, positive potential impacts are burdens to the environment, while negative potential impacts are savings to the environment. Since there is no national target of environmental impact in Saudi Arabia, the weighting factor according to the political goal was omitted.

Normalisation provides a relative impression of the environmental impact or resource consumption compared to the impact from one average person. The yearly contributions from the defined system are divided by the normalization reference, which are the yearly total missions (global/regional/local) per person (worldwide/regionally/locally). This yields a normalised impact potential in the unit ‘person equivalent’. To compare the impacts of each scenario in this study, a global normalisation was calculated to the unit of person-equivalents (PE) in line with the normalisation references.

To compare the different impact categories however, weighting according to seriousness of each category is performed. The weighting factors are based partly on scientific criteria, partly on political priorities. Based on Hansen *et al.* (2006b), EASEWASTE model offers normalisation and weighting of the results as an integrated part of the assessment, where the user can choose between four different levels of results: LCI, LCIA, normalised data and weighted data.

4.7 SUMMARY

This chapter presented the methodology used for the study to assess different waste management options in Makkah by using EASEWASTE model as a LCA tool based on the goal and objectives. The different scenarios proposed were based on data collection of MSW from the municipality of Makkah. The change in MSW flow and its compositions through the pilgrimage and non-pilgrimage periods was accommodated by modelling each period as a single scenario in EASWEASTE and, thus, each studied scenario consisted of three sub-scenarios; Umrah, Hajj and non-pilgrimage. In order to compare, successfully, the environmental performance of different scenarios for management of solid waste in Makkah, a systematic approach with four phases of LCA based on ISO (2006) were followed; goal and scope definition, life cycle inventory (LCI), life cycle impact assessment (LCIA) and interpreting of reviewing the LCI and the LCIA until the results comply with the goal and scope. In addition, three environmental impact categories (Global Warming Potential, Spoiled Groundwater Resources and Resource Depletion) were chosen from a list of impact categories. A normalisation was calculated to the unit of person-equivalents (PE) in order to compare the impacts of each scenario. Six different scenarios of MSW management were compared with the baseline scenario (SC0) in Makkah and evaluated by the means of LCA. The treatment and disposal options for collected waste in Makkah involved different technologies such as sanitary landfilling with/without energy recovery, mechanical biological treatment systems (MBT), waste combustion with energy recovery (incineration), anaerobic digestion (AD) and composting.

CHAPTER 5

Assessment of MSW management

This chapter explains how the individual phases of the waste management system are modelled and the potential size of their environmental impact. The purpose is to show a consistent way of setting up different scenarios of waste management by analysing the waste management system step-wise. The operational information of municipal solid waste management is significant in order to understand the existing operation in Makkah and provide the required input data for modelling. In this section, the current MSW treatment and disposal facilities (sub-models) are described and evaluated according to the requirements of the decision support tool. However, one of the challenges to waste management evaluation in developing countries is that less official information and statistics for waste collection, transporting and landfill is available from the informal sector.

According to the definition indicated in the Directive on Waste 2006/12/EC (European-Parliament-and-Council, 2006) the current sub-models are divided into three processes. The first process is waste collection and transporting, followed by waste treatment processes such as MRFs, composting and incineration with energy recovery, and the final process is waste disposal i.e. incineration and landfilling, which marks the end of waste routes. In general, the technologies selected for each scenario in this study are described according to the general and current method of operation in Makkah.

5.1 MODELLING OF MSW COLLECTION AND TRANSPORTTION

MSW collection is defined as a process of picking up waste, which is loaded them into a truck, from collection points (at neighbourhoods, or various collection stations) and transporting it to transfer, or disposal sites. Transfer is the process of moving waste from a collection truck to a larger transfer truck that relocates waste to remote recovery facilities such as MRFs, incinerators or landfill sites (UNEP, 1996)

According to McDougall *et al.* (2001), MSW collection is generally divided into two systems. The first is "kerbside collection" which requires households to put their MSW in containers at a place close to their houses. The second system of MSW collection is the "bring system" which requires households to take their waste to material banks or collection points.

In Makkah city, the bring system is normally performed by municipal service for MSW collection of mixed waste. So, the mixing of household waste, hazardous waste and e-waste has been applied in this study. The direct collection of MSW at the collection points in the neighbourhoods, and the transporting to a nearby location for storage or transferral to larger recovery facilities, are included in the collection process (Dalemo *et al.*, 1997).

In EASEWASTE software, collection activities are evaluated according to the amount of fuel consumption per ton of waste collected and expressed in unit litres/tonne. These activities are quite different from the transporting activities of waste where the amount of fuel consumption and distance travelled by trucks to treatment or disposal sites are considered on LCA and thus expressed in the unit litres/tonne/km (Damgaard, 2006). As mentioned earlier, about 20% of the waste collected from Makkah's neighbourhoods is transported to transfer stations (TS), while the rest is sent directly to the current landfill site. To meet the requirements of the EASEWASTE modelling, the transfer station should be included in a LCA assessment and used as a changing point from collection to transporting activities. Consequently, a transfer station is assumed to be located at an average of 5 km from the point where the last waste container was collected in order to comply with the software. Overall, figure 5.1 shows the model considering waste collection and transporting according to EASEWASTE.

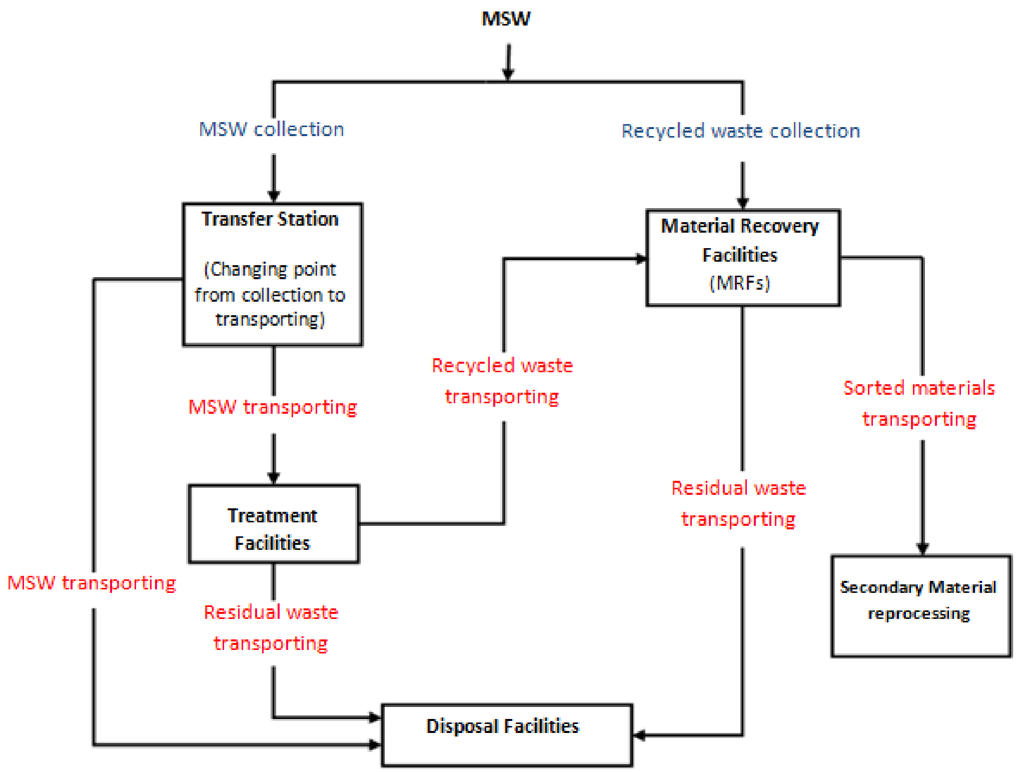

Figure 5. 1: Model considering MSW collection and transportation

According to the EASEWASTE software, the environmental load from producing and using waste containers, sacks and bins, and from producing and maintaining trucks is considered to be negligible (EASEWASTE, 2011). Table 5.1 illustrates the data input on EASEWASTE for collection and transporting activities obtained from the actual data collected by Makkah Municipality. It should be noted that the fuel combustion technology was chosen from the EASEWASTE database according to different types of vehicles and diesel demands. In addition, the EURO 3 emission standard of transport activities was adapted. It was assumed that six wheels trucks (EURO 3) were used to collect MSW and mixed recycled waste. In contrast, ten wheels trucks (EURO 3) were employed in the transporting activities in order to transfer collected MSW from transfer stations to the disposal/ treatment units as well as mixed recycled waste to the MRF. Generally, all treatment facilities, including MRF, were assumed to be located outside of the urban boundary of the city of Makkah and about 5 km away from the existing landfill. It can be also noted that there are many factories in Jeddah city, located 80 km from Makkah, which could use recycled materials as second substances. It is assumed, however, that the products from MRF's are sent to final reprocessing manufacturers. Table 5.1 expresses inputs to EASEWASTE for collection and transporting activities.

Table 5. 1: EASEWASTE inventories of collection and transportation

Input Data	Waste combustion technology	Weight (t/load)	Distance (km)	Fuel consumption rate (litre/km)
Collection				
MSW	Diesel, Truck Euro 3, 6 wheels, Urban traffic	6	5	1.70 l/t
Mixed recycled waste	Diesel, Truck Euro 3, 6 wheels, Urban traffic	6	5	1.70 l/t
Residual waste	Diesel, Truck Euro 3, 6 wheels, Urban traffic	6	5	1.70 l/t
Transporting				
MSW to MRF, disposal site/treatment facilities	Diesel, Truck Euro 3, 10 wheels, max weight 25 tonnes, Urban traffic	15	25	0.05 l/km/t
Rejected waste from MRF/ treatment facilities	Diesel, Truck Euro 3, 10 wheels, max weight 25 tonnes, Urban traffic	15	5	0.05 l/km/t
Recycled waste from treatment facilities to MRF	Diesel, Truck Euro 3, 10 wheels, max weight 25 tonnes, Urban traffic	15	5	0.05 l/km/t
Sorted materials from MRF to secondary material reprocessing	Diesel, Truck Euro 3, 10 wheels, max weight 25 tonnes, Urban traffic	15	80	0.05 l/km/t

5.2 MODELLING OF MSW TREATMENT PROCESSES

Solid waste treatment can be defined as the process of any method or technique that is used to remove pollutants from waste which may negatively affect the environment (Worldbank, 2000). Treatment processes, such as incineration, AD, MBT, MRF and composting, are considered to be the second stage of the MSW system after collection and transfer activities. The waste is transported to the desired treatment unit, where it is distributed depending on quantities and characterisation, as well as the available treatment technology. In this section, the analysis of considered treatment processes is described in detail based on material flow and the potential environmental impact on the city of Makkah.

5.2.1 Modelling of Material Recovery Facilities (MRFs)

MRFs are treatment units designed to receive mixed recyclable materials such as paper, cardboard, glass, metals from households, shops etc. The mixed recycled waste can also be sorted, stored and prepared for use as second materials. The separation process is usually performed by manual sorting, mechanical sorting, magnetic sorting for metals and/or density sorting for plastics.

In Makkah, there are no legal MRFs available to receive recyclable materials. In contrast, scavenging activities are noticeable particularly in the old neighbourhoods and current landfill site by illegal labourers as mentioned previously in section 3.7.4. According to the Municipality of Makkah (2012), cardboard and paper, metal and plastic are the only recyclable materials prized by the scavengers while glass is neglected due to a lack of demand. Figure 5.2 shows the input and output of materials for three different periods taken from actual mass flows in Makkah.

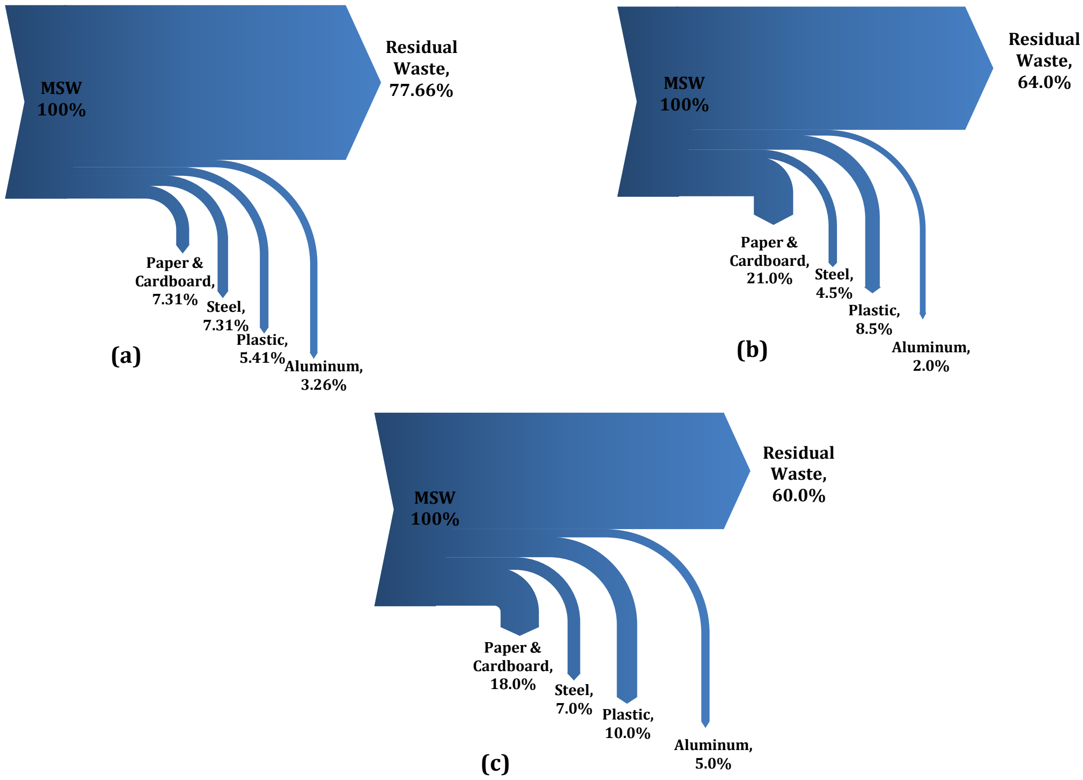

Figure 5. 2: Input and output of materials from actual mass flows in Makkah (1432H) for three different periods: (a) non-pilgrimage period, (b) Umrah period and (c) Hajj period

Regarding the input data of LCA for MRF, the input and output of material as well as energy consumption are required. Due to the absence of legal MRF in Saudi Arabia, Table 5.2 provides assumptions of energy usage including electricity from sorting activities in MRF for the three different periods in Makkah. In addition, the efficiency of the separation of the MSW stream at source is considered to be one of the most important factors due to the affect on the quality of MRF produced materials. It is, therefore, assumed that the MSW sorting efficiency at source was 35%.

Table 5. 2: EASEWASTE input data of the suggested MRF

Sorted material	Energy consumption		Contaminations (%)
	Electricity (kWh/t)	Fuel (litre/t)	
Paper & cardboard	5.0	0.6	3.0
Aluminium	4.0	0.6	0.7
Steel	4.0	0.6	0.7
Plastic	6.4	0.6	1.0

To decrease the complication of modelling MRF in EASEWASTE, all sorting fractions obtained from MSW collection activities from neighbourhoods, shops and treatment/disposal facilities within all different periods were aggregated. It is assumed that these sorted materials were sorted from typical MSW streams at source. Based on this assumption, the sorting at incineration, AD, composting, and landfill accrued by scavengers was hence negligible. Due to a limitation of the EASEWASTE software, the different sorted materials were transported to different MRFs according to their technologies. For example, the sorted plastic was managed by a plastic MRF. In order to ensure mass conservation, a transfer coefficient taken from the percentage contaminant was used to contribute to the output of MRFs. The output materials of MRF were then transferred to reprocessing manufacturers in Jeddah to be used as secondary materials. The residual waste or contaminated materials from MRF were routed to landfill site in accordance with conditions stated in the scenario assumption.

5.2.2 Modelling of Incineration

Incineration of waste involves a technical unit and equipment dedicated to the thermal treatment of wastes with or without recovery of the combustion heat generated base on Directive 2000/76/EC (European-Commission, 2000). The incinerator is the most efficient method of dealing with various types of waste in order to minimise the negative environmental impacts as well as provide the ability to recover energy. Heat and electricity are enhanced by a combined heat and power (CHP) unit. The primary purpose of incineration is to reduce waste by up to 90% by volume and 70-75% by weight (McDougall *et al.*, 2001). However, the use of incineration is expensive compared to other alternative solutions to the treatment of solid waste. This high cost could be reduced via the sale of generated energy or using it to run the incinerators. It also required highly skilled labourers for the operation and maintenance processes.

Incineration technologies are applied broadly in developed countries due to a significant improvement in the treatment of gas emissions (Rylander and Haukohl, 2002). Incineration is also widely utilised outside of Europe with facilities in operation in most developed countries. According to DEFRA (2007a), there were 291 large scale incinerators in the year 2000 in the European continent.

In the United Kingdom, there were 19 incinerators in operation processing MSW between 1973 and 2005; their scale in terms of annual waste throughput varied from 23 to 600 kilo-tonnes as listed in Table 5.3 (DEFRA, 2007a). Modern large scale incinerators were established in the UK after that; for example, the Alington facility in Kent. An integrated waste management facility called "Allington Quarry Integrated Waste Management Facility" began operationing in late December 2008. This facility, managedby Kent Enviropower, can take up to 500 kilo-tonnes a year of mixed waste to recover up to 43 megawatts of electricity and a further 65 kilo tonnes of sorted materials suitable for recycling from Kent and the surrounding area (KentEnviropower, 2012). Furthermore, the incinerator at Allington Quarry operates in line with the highest environmental standards in the UK and Europe where similar plants are located in Germany, Denmark, Sweden, USA, Japan, Thailand, Spain, France Switzerland, and Austria (KentEnviropower, 2012).

Table 5. 3: MSW incineration plants in the UK from 1973 to 2005

Incinerator plant	Scale (kilo-tonnes)	Energy Recovery	Established
Edmonton	500	Electricity, 32MW	1975
SELCHP	420	Electricity, 32MW	1994
Tysesley Birmingham	350	Electricity, 25MW	1996
Cleveland	245	Electricity, 20MW	1998
Coventry	240	Electricity, 17.7MW & Heat	1975
Stoke	200	Electricity, 12.5MW	1997
Marchwood	165	Electricity, 14MW	2004
Portsmouth	165	Electricity, 14MW	2005
Nottingham	150	Electricity & Heat (max 20MW heat)	1973
Sheffield	225	Electricity, 19MW (max) & 39 MW Heat (max)	2006
Dundee	120	Electricity, 8.3MW	2000
Wolverhampton	105	Electricity, 7MW	1998
Dudley	90	Electricity, 7MW	1998
Chineham	90	Electricity, 7MW	2003
Kirklees	136	Electricity, 9MW	2002
Douglas (Isle of Man)	60	Electricity, 6MW	2004
North East Lincolnshire	56	Electricity, 3MW & Heat, 3MW	2004
Shetland	23	Heat	2000
Isles of Scilly	37	No energy recovery	1987

Source: DEFRA (2007a)

Municipal incinerators are divided into thermal units and flue gas cleaning processes. Waste handling, feeding, and combustion, as well as heat recovery with steam and electricity production, all fall into the thermal category. In general, the operation of incineration must have a controlled minimum temperature of 850°C for at least two seconds of residence time in accordance with the EC directive on the incineration of waste (European-Commission, 2000). In the second part, namely flue gas cleaning, the incinerator is equipped with the emission treatment. This legislation aims to ensure the complete destruction of harmful organic chemicals during combustion.

In Makkah, incineration technology ceased to be used as a MSW treatment solution more than 30 years ago by order of the Ministry of Municipal Affairs of Saudi Arabia. This decision was the result of the use of primitive waste incineration, which caused environmental burdens. Recently, the principle of using waste for energy (WtE) has begun to be considered in Saudi Arabia, although it has been neglected over the past few decades. All the evidence indicates that there has recently been concern in Saudi Arabia over dependency on fossil fuel, as well as pollutants emitted into the atmosphere.

Regarding LCA input data, the model represents the thermal conversion of waste resulting in emissions to air, solid outputs, and energy production. The emissions were entered into EASEWASTE software based on chemical composition, water content, and calorific values of the material fractions (see Appendix B1). The credit of energy production recovered from the thermal treatment is specified to provide an efficient evaluation of recovered resources and emissions.

In this study, it is assumed that a large scale incineration plant with energy recovery is set up and located outside of the urban boundary of Makkah. This facility is considered to be similar to the Danish incineration plants, with an annual capacity of 500 kilo-tonnes of mixed MSW from Makkah. In other words, this factory is assumed to be worked at fully functional capacity and approximately 40 kilo-tonnes of MSW are assumed to be received monthly, regardless of the periods of Hajj and Umrah. Moreover, Table 5.4 shows the input and output data of the MSW incineration plant and the assumptions. The EASEWASTE dataset was used as a source for transfer coefficients in order to link substances between input and output (EASTWASTE, 2011).

Table 5. 4: EASEWASTE resources and the emission inventory of the incineration plant

Information	Value	Unit
Input (material & energy)		
Electricity	60.2	kWh/t input
Diesel	0.42	Kg/t input
Input (sources & materials)		
NaOH	0.026	Kg/t input
Lime	6.54	Kg/t input
Water	356	Kg/t input
Output		
Heat recovery	N/A	
Output (air emission)		
Carbon dioxide (CO_2)-Biogenic carbon	152.20	kg CO_2/t input
Carbon dioxide (CO_2)-Fossil carbon	62.17	kg CO_2/t input
Nitrogen dioxide (N2O)	0.05	kg N_2O /t input
Unspecified dust (TSP)	0.049	kg TSP/t input
Nitrogen oxides (NO_x)	1.13	kg NO_2 /t input
Sulphur dioxide (SO_2)	0.016	kg SO_2/t input
Carbon monoxide (CO)	0.35	kg CO/t input
Hydrogen Chloride (HCl)	0.024	kg HCl/t input
Dioxin	5.06E-07	kg/t input
Transfer coefficients	Obtained from Dataset	
Electricity recovery	4.9%	% of LHV

Bottom ash and air pollution control (APC) residues, as incineration outputs, were defined from the dataset of the furnace incinerator on the EASEWASTE 2012 dataset. The bottom ash was assumed to be disposed of as landfill mineral waste, when the dataset was attained from the software. The percentage of energy recovery and type of energy substitution, i.e. coal, gas, or energy mix are important in impact assessments in terms of energy credits. In this study, the substitution of the Makkah electricity grid mix is specified. There is no delivery of heat production in Saudi Arabia; therefore, heat recovery is neglected in this study.

5.2.3 Modelling of MSW Landfilling

Landfilling as defined as the process by which solid waste and solid waste residuals from treatment processes, for example bottom ash from incineration, are placed in a land in a manner that protects human health and the environment (McDougall *et al.*, 2001). The landfill site refers to the location of the waste disposal onto or into land according to Directive 1999/31/EC on the landfill of waste (European-Union, 1999).

In this study, both controlled and uncontrolled landfill sites are considered in order to meet the requirements of modelling all suggested scenarios including existing landfill. "Sanitary landfill" is often used for controlled landfill site to describe an engineered method in which the disposal of the waste meets most of the standard specifications, including site location, site preparation, daily and final cover, complete access control, record keeping and appropriate leachate, and gas management and monitoring (UNEP, 1996).

In contrast, with reference to uncontrolled sites the term "Open dumping landfill" is often used for sites where mixed wastes is deposited without control or regard for the protection of the environment (McDougall *et al.*, 2001). Contamination of air, water and soil occurs as well as methane gas migration. In addition, scavenging activities by illegal labourers are common. Generally, open dumping landfills are normally operated in developing countries due to limited technologies and budget.

In Saudi Arabia, landfilling is the only disposal method used for MSW. As mentioned earlier, most of the municipal waste in Makkah is disposed of via open dumping landfill, whereas the rest goes missing due to scavenging processes. The disposal of residual waste from the MSW stream, from other treatment processes, and from recycling activities is, therefore, assumed to be accomplished at landfills.

Regarding LCA input, EASEWASTE software is able to evaluate material and energy used as well as emissions to air, water and soil. This programme can also evaluate a range of inputs such as mixed waste containing organic and non-organic matter. Moreover, landfilling technologies are provided; for example, conventional landfills, bioreactors, flushing landfills or semiaerobic reactor landfills, and mineral landfills. In line with gas management in landfills, EASEWASTE accounts for gas generation, gas utilisation, gas flaring, and gas oxidation in landfill covers. Leachate generation, leachate entering into the treatment plant, and leachate migration to surface water and groundwater are integrated for environmental impact assessment in the programme.

The inputs for both open dumping and sanitary landfills modelling are provided in Table 5.5. The impact of clay and soil extraction for bottom lining and capping has not been taken into account, while emissions from the transporting of the input material to landfill are considered. An eight tonne truck capacity emission standard was assumed for hauling earth-extracted materials, in line with Euro3.

According to the studied scenarios including the current setup, three landfills were assessed via EASEWASTE, where an open dumping landfill was used to simulate the existing landfill in Makkah. The other scenarios were assumed to be sanitary landfills in the form of a landfill utilising 70% of captured gas for electricity production while flaring the rest and another that is burning all captured landfill gas (LFG). With regard to sanitary landfill conditions, the collection of leachate and gas generated from waste degradation was assessed. In accordance with (Niskanen *et al.*, 2009), the four periods of gas generation and leachate generation were defined within a 100 year time horizon.

Table 5. 5: Technical measures for gas and leachate generation, collection and management in the assessed technologies of different landfills

Items	Open dumping landfill	Sanitary landfill (Controlled LF)	Sanitary landfill (Controlled LF)
Technology	Open dump	Conventional, with flaring	Conventional, with flaring
Time horizon	0-100 years	0-100 years	0-100 years
General inputs			
Soil	0.1 t/t waste	0.3 t/t waste	0.3 t/t waste
Clay	0.1 t/t waste	0.28 t/t waste	0.28 t/t waste
Landfill height	15 m	15 m	15 m
Bulk density	0.5 t/m^3	1.0 t/m^3	1.0 t/m^3
Electricity	None	2.65 kWh/t	2.65 kWh/t
Diesel	None	0.63 l/t	0.63 l/t
Landfill gas			
Gas information	No gas collection	EASEWASTE dataset for conventional landfill	EASEWASTE dataset for conventional landfill
Percentage of collected landfill gas	None	70%	70%
Treatment technology	None (Vent)	Flare, 30%, electricity recovery, 70%	Flare, 100%, with no electricity recovery
Efficiency of electricity production (%)	None	25%	None
Leachate generated (mm/y)	111 mm/y	111 mm/y	111 mm/y
Leachate collected (% of generated)	None	90 %	90 %
Leachate entering groundwater (% of generated)	All	10 %	10 %
Electricity for leachate treatment	None	5.3 kWh/m^3 leachate	5.3 kWh/m^3 leachate

With regard to the modelling of the environmental impact of open dumping landfills, the missing control of gas and leachate is explained by the lack of engineering controls. Unlike sanitary landfills, the input materials for landfill construction and operation were not accounted for. The missing gas and leachate emission information for the current Makkah landfill was taken from the open dumping dataset of EASEWASTE 2012. In this study, the LFG of the existing landfill (open dumping) was assumed to be emitted directly into the atmosphere, although the dispersion of leachate was assumed to migrate to groundwater.

5.2.4 Modelling of Anaerobic digestion (AD)

Anaerobic digestion (AD), as an alternative treatment for biodegradable MSW, is a process used for organic waste materials which are encouraged to break down in the absence of oxygen to produce biogas, in addition to a stabilised residue called digestate (Figure 5.3) (Møller *et al.*, 2009). Digestion technology can be divided into wet and dry processes. The dry method is typically operated with 25-40% total solid TS, which is able to use MSW as a main input of the digestion process. The wet concept is performed with a water content of 10-15% of total solid TS (Chanchampee, 2009). Moreover, the digestion process is accomplished either by thermophilic or mesophilic conditions. Due to the advantage of faster degradation, destruction of pathogens and a higher biogas yield, thermophilic decomposition has become a more commonly used technology (Chanchampee, 2009).

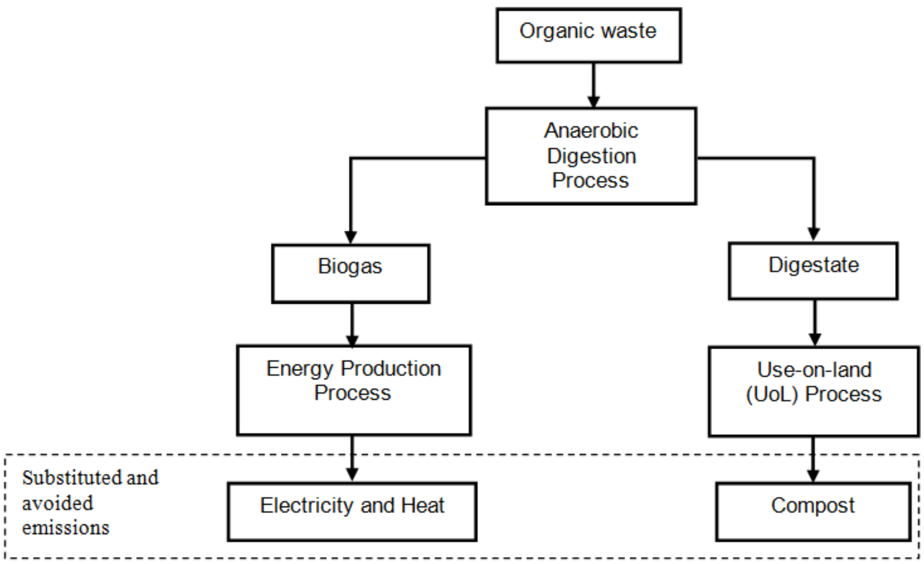

Figure 5. 3: Conceptual overview of Anaerobic Digestion (AD) and digestate use

Source: (Møller *et al.*, 2009)

Biogas production is associated with efficiency in the conversion of volatile solid (VS) biodegradability (Gunamantha, 2011; Murphy and McKeogh, 2004). The composition of methane (CH4) in the biogas is to be assumed 60%. It is also assumed that biogas is burnt in gas turbines to produce electricity with a 10% loss due to lackage in operations (Gunamantha, 2011). Emission factors in anaerobic digestion system operations were allocated on the basis of total solid (TS) contents. These factor values were considered according to (Börjesson and Berglund, 2006), as shown in Table 5.6

Table 5. 6: Emissions from natural gas-based electricity production in the operation of biogas plants

Emissions	Value	Unit
CO_2	15	kg/ton TS
CO	11	kg/ton TS
NO_x	46	kg/ton TS
SO_2	1.7	g/ton TS
HC	3.0	g/ton TS
CH_4	4.0	kg/ton TS
Particles	1.5	g/ton TS

Source: Börjesson and Berglund (2006)

Similar to other alternative treatments of biodegradable MSW in Saudi Arabia and Makkah in particular, anaerobic digestion (AD) has never been considered according to the best of the author's knowledge. Thus, a new AD treatment plant with biogas recovery is assumed in this study to deal with organic fraction of MSW in Makkah. Moreover, the electricity generation from biogas recovery is only assumed to be used onsite.

To assess emissions from the AD process in the EASEWASTE model, the anaerobic digestion module describes the input and output of a system consisting of the digestion of organic waste from Makkah MSW and the combustion of produced biogas. Biogas production is related to the content of volatile solids (VS) which is required in software modelling. The percentage degradation of volatile solid contents (VS) of each material fraction was provided by the EASEWASTE 2012 database (as shown in Appendix B2).

In this research, non-recycled waste from typical days (from the non-pilgrimage period) is considered as an input of the AD process for suggested scenarios. A manual sorting was applied along a conveyor in order to distinguish the contaminants and recyclable materials to be forwarded to a landfill site and secondary recycling shops, respectively. The reused water from the dewatering process was fed back into the reactor to increase moisture content. In terms of the credit from energy production and potential compost production, the methane produced from the process was used for the generation of electricity, which was only used onsite. Heat recovery was omitted due to there being no delivery of heat production in Saudi Arabia. In addition, energy recovery and compost as products of the AD process showed the credit from avoiding the production of commercial fertiliser. The dewatered digestion sludge was used as a soil conditioner on land and the wastewater was treated onsite. Table 5.7 summarises the information for the assessment of AD.

Table 5. 7: EASEWASTE resources and emission inventory of the incineration plant

Information	Value	Unit
Biogas yield	100	Nm^3/t input
Biogas heating value	20-25	MJ/Nm^3
Methane content	52.8%	% of biogas produced
Unburned methane	2%	% of CH_4 produced
Energy recovery		
Electricity recovery	14%	% of potential energy generation
Heat recovery	N/A	% of potential energy generation
Unburned methane	2%	% of CH4 produced
Input (materials and energy)		
Electricity	89	kWh/t input
Diesel	0.05	L/t input
Output (materials)		
Digesting residue output	70.1%	%output
Residual waste output	29.9%	%output
Solid content of digesting residue	60%	%TS
Solid content of residual waste	70%	%TS
Output (air emission)		
Methane (CH_4)	9.14	kg CH_4/t input
Carbon dioxide (CO_2)	49.6	kg CO_2/t input
Nitrogen oxides (NO_x)	1.38	kg NO_x /t input
Sulphur dioxide (SO_2)	0.042	kg SO_2/t input
Carbon monoxide (CO)	0.153	kg CO /t input

5.2.5 Modelling of Mechanical Biological Treatment (MBT)

MBT is a generic term used with regard to systems developed for the treatment of MSW or residual MSW via a combination of mechanical processing, such as size reduction and air classification, with biological processing, such as composting or anaerobic digestion (Gioannis *et al.*, 2009). In an MBT plants, waste treatment is performed to reduce the volume of waste and to modify its chemical–physical properties. Mechanical processes aim at opening bags, shredding, removing problem components, sorting high calorific fractions and creating optimal conditions for the biological phase. Biological processes, in contrast, seek the degradation to carbon dioxide (CO_2) and water of degradable organic fractions and the production of stable substances (Gioannis *et al.*, 2009). However, according to Velis *et al.* (2009), MBT technologies are become more attractive options for developing countries whilst these technologies have established their presence in Europe over the last 15 years.

Regarding the biological treatment module in EASEWASTE, MBT processes are can normally be classified, into three types, according to the technology employed and the nature of materials recovered (Boldrin *et al.*, 2011):

- *Mechanical Biological Pre-treatment prior to landfill (MBP):*

  A mechanical step is employed to crush, sieve and recover different material fractions. In addition, a Refuse Derived Fuel (RDF) fraction is used for energy production. Because the residual stream contains large amounts of organic fraction, it can be biodegraded via aerobic or anaerobic treatment or disposed of in landfills.

- *Mechanical–Biological Stabilization (MBS):*

  MBS technology aims to dry waste while preserving the energy content. Mechanical processes are anticipated in MBS afterwards to recover valuable materials such as metals, while the remaining fraction is used as Refuse Derived Fuel (RDF) for energy production.

- *Mechanical Physical Stabilisation (MPS):*

  MPS technology follows the same principle as MBS, but additional energy in the drying process is required for the physical process.

Since there is no MBT technology established in Saudi Arabia, it has been assumed in this research that two different MBT plants are set up for two different suggested scenarios. All these plants are assumed to be located outside of the urban boundary of Makkah. Screening (sorting) is performed in both suggested plants as a mechanical process to recover different material fractions. Composting is considered to be a biological treatment process in the MBT plant in scenario SC3, where this treatment is performed to produce Refuse Derived Fuel (RDF) in scenario SC4.

In EASEWASTE software, an MBT plant can be defined in different ways, depending on the types of processes adopted (Gioannis *et al.*, 2009). The Mechanical Biological Pre-treatment (MBP) plant is employed in this study as an MBT of MSW of Makkah. A mechanical treatment (screening) is performed in the MBP before the biological treatment in order to recover valuable materials, as well as reduce the MSW size. The mechanical treatment in this case is modelled in EASEWASTE by using a Material Recovery Facility (MRF) module before the biological technology module. Anaerobic Digestion (AD) is modelled in EASEWASTE as described in section 5.2.4. The Refuse Derived Fuel (RDF) produced can be routed to energy utilisation by thermal treatment via incineration in the RDF power plant.

5.3 SUMMARY

After demonstrating the research methodology in (Chapter 4), this part of the research focused on giving details on the modelled individual phases of the waste management system and how large their environmental impact potentially was. The recent operational information and waste treatment and disposal facilities in Makkah were evaluated according to requirements of the decision support tool EASEWASTE. The input data on EASEWASTE for collection and transporting activities were obtained from the actual data collected from Makkah Municipality. The fuel combustion technology of collecting and transporting vehicles was chosen from different types of vehicles from EASEWASTE database. The waste was assumed to be transported to different treatment technologies such as incineration, AD, MBT, MRF and composting according to scenario consideration. However, a challenge in waste management evaluation in developing countries and Makkah particularly was that less official information and statistics of waste collection, transporting and landfilling by the informal sector are not provided.

CHAPTER 6

Results

The waste flows for the current MSW of Makkah are outlined in this chapter, as well as the anticipated flows when considering various scenarios. The results of the environmental impact assessment present the environmental effects of seven waste management scenarios in three selected impact categories. These categories are; Global Warming Potential (GWP), Spoiled Groundwater Resources (SGR) and Resource Depletion (RD). All the modelling was performed using the 2012 version of the EASEWASTE LCA-tool (Kirkeby *et al.*, 2006a). The categories are provided according to the Environmental Design of Industrial Products (EDIP) method as the default mid-point impact assessment method (Wenzel *et al.*, 2000). The given impact potential is presented in each reference unit. Using a base case comparison, the influence of the established waste management options on the environment is described.

6.1 MATERIAL FLOWS RELATED TO MSW MANAGEMENT OF MAKKAH

6.1.1 Existing MSW management – baseline scenario (SC0)

A total of 578.1kilo tonnes of waste were generated in Makkah from December 7, 2010 to November 25, 2011. While this amount was calculated based on the official statistics on waste collection, scavenging and other informal recycling were omitted. Waste generated during the Umrah and Hajj time periods was also considered. As illustrated in Figure 6.1, 100 % of MSW was collected and sent directly to the recently established uncontrolled landfill, and approximately 20% of that was sent via transfer stations. Therefore, it should be noted that there is no waste recycling or energy recovery within this scenario. Additionally, the current landfill disposal lacks a lining system for collecting and treating leachate to protect the groundwater, moreover, no gas collection or flaring was noted.

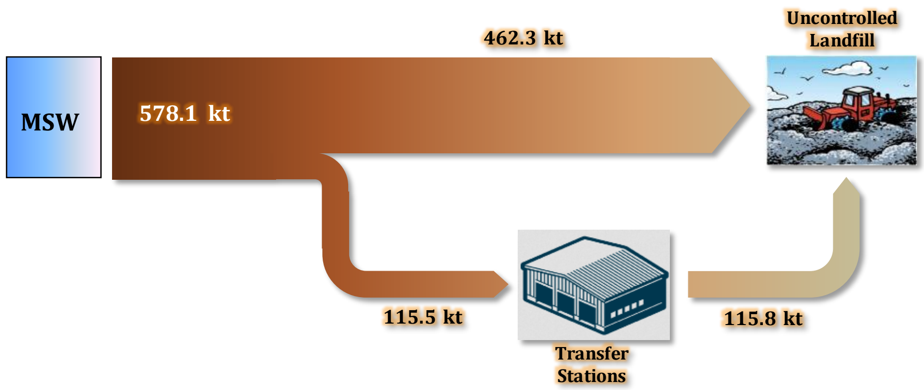

Figure 6. 1: Annual MSW flows of Makkah, Baseline Scenario (SC0)

6.1.2 Scenario (SC1)

Scenario (SC1) was created in order to assess the effect of replacing the current landfill of Makkah with a sanitary landfill featuring a gas collection system for energy utilisation to produce 7.8 megawatts of electricity (Figure 6.2). Leachate collection and treatment were introduced to isolate groundwater from any pollution caused by landfill leachate. This landfill received the same amount of waste as in the baseline scenario (SC0) either directly from commingled municipal waste or via transfer stations without large changes in the infrastructure. The significant increase of MSW during the pilgrimage months (Hajj and Umrah periods) was delivered to the landfill as normal. Compared with the current waste management, this system therefore still required almost the same area space for the landfilling process and no recycled waste materials were assumed to be recovered.

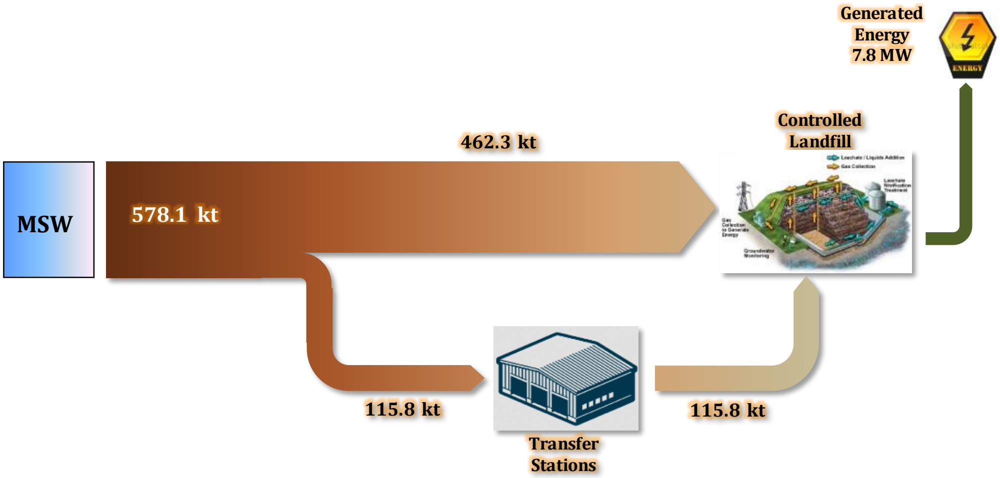

Figure 6. 2: Annual MSW flows of Makkah, Scenario (SC1)

6.1.3 Scenario (SC2)

This scenario was set up to show the effect of the combustion of Makkah's MSW and to recover energy to supply the local electricity grid. Similar to scenarios (SC0) and (SC1), there was no significant change in the collection and transporting systems. However, a total of 40 kilo-tonnes per month (1.3 kt/d) of collected waste was sent to the incineration facility to generate 80 megawatts of electricity while the rest was placed in sanitary landfill with gas and leachate collection systems (Figure 6.3). A total of 75.5 kilo tonnes of Ash and APC produced by the incinerators were also assumed to be landfilled. Unlike scenario (SC1), all landfill gas was assumed to be flared and no energy utilisation was introduced in this landfill. In addition, a reduction in the disposal of waste at the landfill of about 68%, as compared to scenarios (SC0) and (SC1) resulted in extra available landfill capacity. During pilgrimage time periods, a fixed monthly amount of MSW was assumed to be incinerated due to the capacity limitation of the incinerators. When applying this scenario, the transfer stations were indispensable as the residual waste was sent directly to landfill.

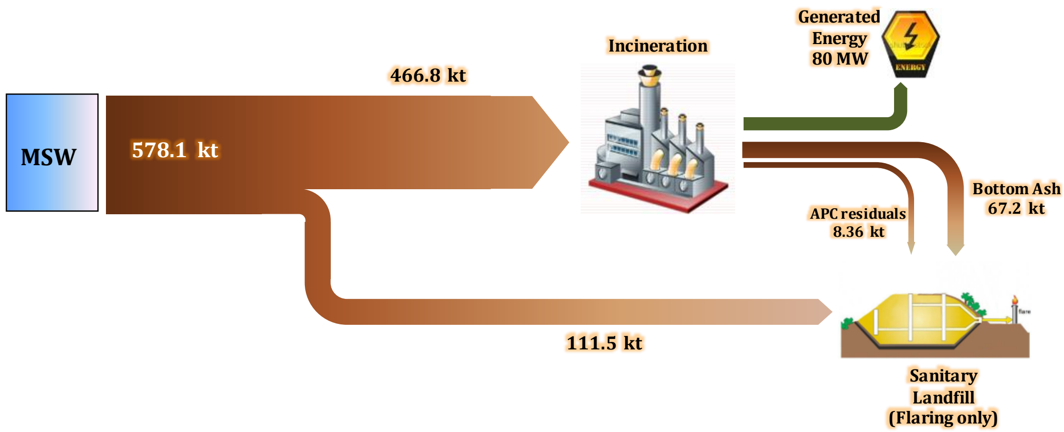

Figure 6. 3: Annual MSW flows of Makkah, Scenario (SC2)

6.1.4 Scenario (SC3)

Scenario (SC3) was created to show the effect on the waste management system in Makkah of applying MBT with composting. Approximately 80% of the total collected commingled waste was handled by the MBT while the rest, including waste generated during pilgrimage periods, was directly transported by waste collection trucks to sanitary landfill with flaring only. As shown in Figure 6.4, the recycled materials, steel and aluminium, were only extracted by mechanical treatment at the MBT facility. Other recycled materials such as paper, cardboard and plastic were considered to be non-recoverable due to contamination from a significant proportion of food and organic waste. In addition, the MBT residuals were then sent for composting and the rejected waste was transported to the sanitary landfill. Based on the characteristics of input material for the biological treatment of "commingled waste", a yield of about 127.8 kilo-tonnes of compost could be gained. In general, in this scenario recycled materials comprised 44.6 kilo-tonnes per year or 7.7% of the total annual recovered materials while 50% was landfilled from either MBT as a rejected waste and from households directly. Including organic waste recovery, a total of 30% of the MSW in Makkah was recovered as a secondary material.

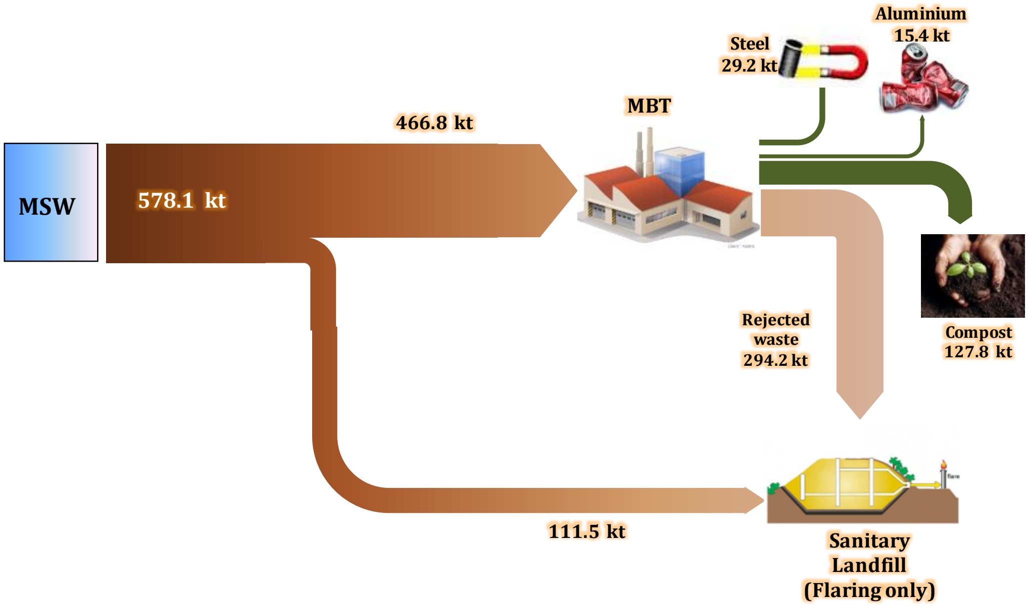

Figure 6. 4: Annual MSW flows of Makkah, Scenario (SC3)

6.1.5 Scenario (SC4)

Scenario (SC4) was created to examine the impact of using the MBT facility alongside other biological treatments applied in the previous scenario (SC3). Instead of using composting as in scenario (SC3), a biological treatment was set up in scenario (SC4) in order to produce 2.77E+9 megajoules (MJ) of RDF, which was used instead of fossil fuel to heat up the cement kiln systems in cement plants. Approximately 466 kilo-tonnes per year (80%) of the total MSW of Makkah was received at the MBT facility. The rest of the collected waste (111.5 kilo-tonnes), including waste collected during the pilgrimage events, was assumed to be transported directly by waste collection trucks to a sanitary landfill (Figure 6.5). A similar mechanical treatment was used to scenario (SC3) at the MBT facility, and 29.2 kt/y and 15.4 kt/y of steel and aluminium were gained respectively, and the rejected waste (16.5 kilo tonnes) was also sent for landfilling. As a result, this scenario contributed to reduction in the disposal of waste at the landfill of about 78%, as compared to baseline scenarios (SC0), which resulted in extra available landfill capacity.

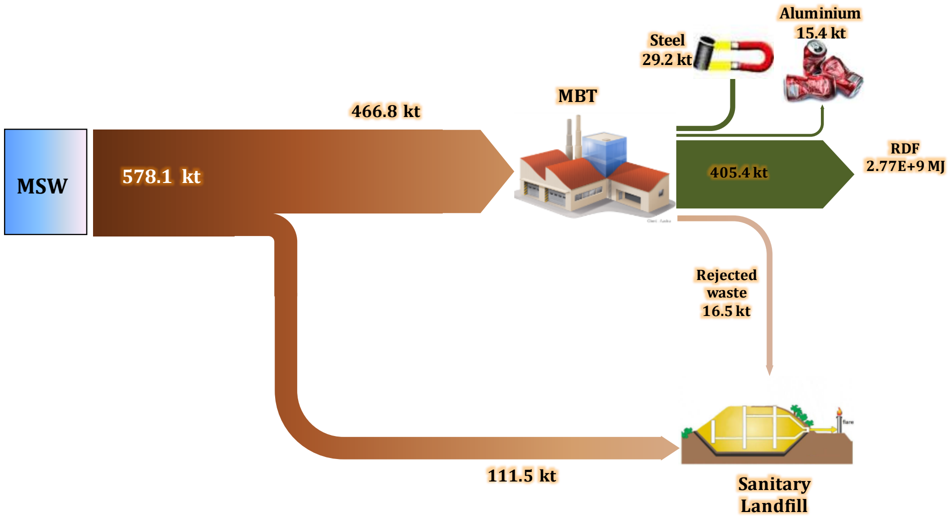

Figure 6. 5: Annual MSW flows of Makkah, Scenario (SC4)

6.1.6 Scenario (SC5)

In scenario (SC5), the effect of material recycling that is sorted at source was anticipated. The "green bin" for collecting dry materials was considered to be handled by MRF. Excluding biological waste recovery, a total of 34.1 kilo-tonnes of recycled materials that can be utilised as virgin materials was separated at the household level in Makkah. This figure represents only 5% of the total waste collected and about 20% of the recycled waste materials. As illustrated in Figure 6.6, the recycled ferrous metals, steel and aluminium, contributed 7.8 % of the total MSW per year or 37% of the total recovered materials, followed by cardboard 9.1 kt/y (30%), plastic 7.5 kt/y (24%) and paper 3.0 kt/y (10%). The refuse materials (30.7 kilo tonnes), resulting from MRF, were delivered to the sanitary landfill which featured a flaring system. In addition, a composting process for wet waste in a "black bin" was introduced to produce 118.1 kilo-tonnes of compost annually while the rejected 207.5 kilo tonnes (36% of total collected waste) was landfilled. It was also considered that all waste produced during pilgrimage periods was sent to sanitary landfill. To sum up, this scenario required significant changes in the infrastructure of Makkah in the form of a new recycled materials collection system and an established MRF as well as a sanitary landfill for the rest of the rejected waste.

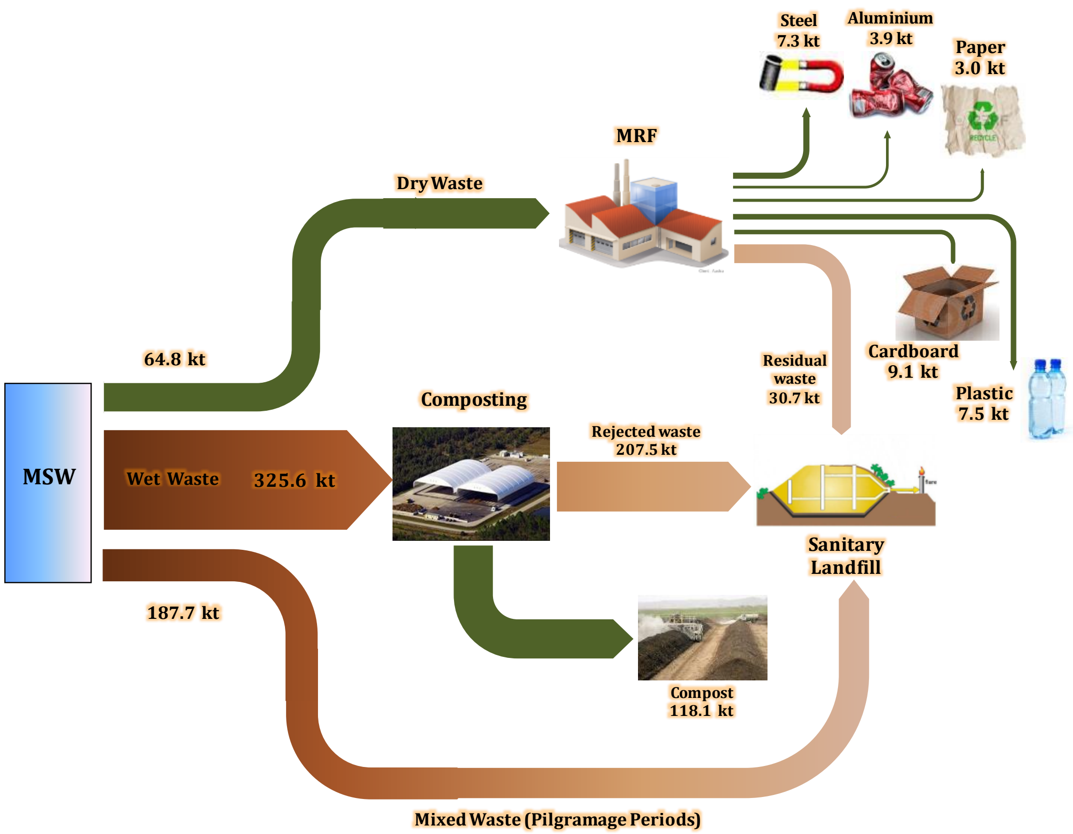

Figure 6. 6: Annual MSW flows of Makkah, Scenario (SC5)

6.1.7 Scenario (SC6)

In scenario (SC6), the effect of an alternative increase in the recycling rate for recycled materials was anticipated. Excluding biological waste recovery, a total of 46 kilo-tonnes of recycled materials that can be replaced a virgin materials, was separated on a MRF. This figure represents only 8% of the total waste collected and about 30% of the recycled waste materials. A total of 196 kilo-tonnes of MSW was estimated to be transported for treatment in AD. As shown in Figure 6.7, organic waste shifted to AD and thus the degree of organic waste treatment was significantly decreased as part of the biological treatment infrastructure compared to scenario (SC5). Nevertheless, about 11.5% of collected organic waste was obtained for producing digestate and then used as a filling material for landscaping the landfill. It can be seen that the large fraction of residues from both MRF and AD still remained for disposal at the sanitary landfill. The recovery of organic waste in AD decrease disposal quantities by 16% compared to scenario (SC5), while a 2.5% increase compared to the "recycling" is shown.

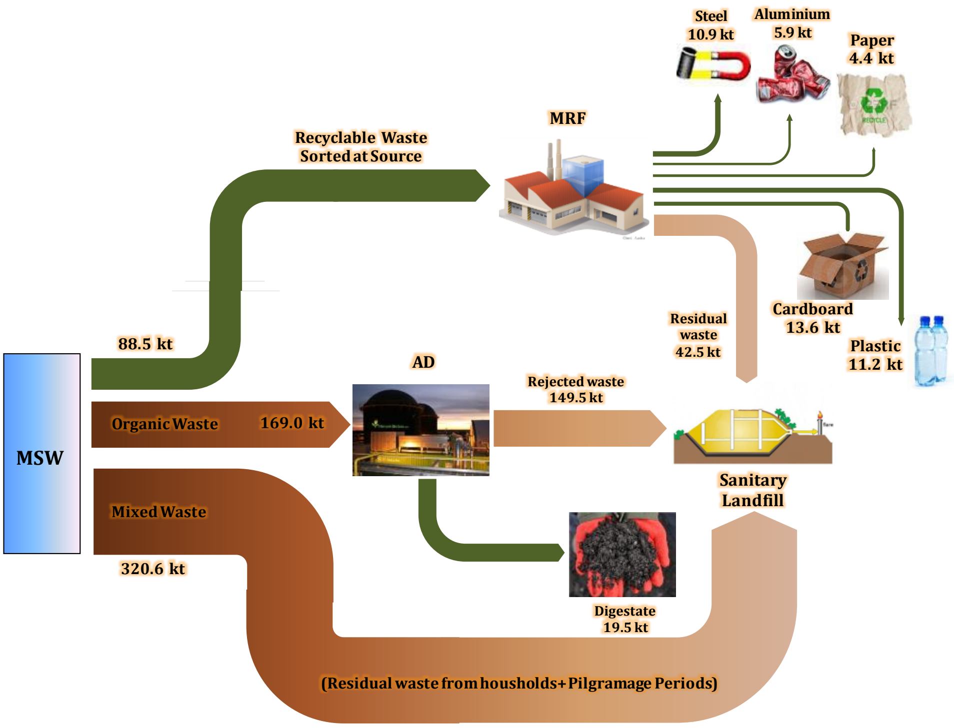

Figure 6. 7: Annual MSW flows of Makkah, Scenario (SC6)

6.2 ENVIRONMENTAL IMPACTS

This section shows the results of the life cycle assessment of the three environmental impact categories: Global Warming Potential (GWP), Spoiled Groundwater Resources (SGR) and Resource Depletion (RD). When looking at the different tables and diagrams in this section, it should be noted that the data shown are net emissions from the waste management system minus saved emissions in the background system, i.e. results for each of the included impact categories are often the sum of both positive and negative values from the waste management system. When the emissions are lower than the saved emissions in the background system, the net result is negative. Negative results thus represent impacts that are avoided. In addition, (Appendix C1) shows more details of LCA results.

6.2.1 Global Warming Potential (GWP)

The global warming category aggregates greenhouse gas emissions into CO_2-equivalents in a 100-year perspective. Figure 6.8 indicates the global warming potential (GWP) of the introduced scenarios. It shows emissions and emissions savings with respect to climate change as well as the net change in impact for each scenario. Landfill is a major source of greenhouse gas emissions (mainly CH_4) despite the fact that landfill gas is recovered at a high rate (Kirkeby *et al.*, 2006b). Therefore, because no gas collection system is involved, and there is thus no credit for secondary material recovery or energy utilisation, the base case (SC0) has the greatest net contribution to climate change impact (see Figure 6.8). This impact essentially results in the anaerobic degradation of organic waste from recent uncontrolled landfill in Makkah where greenhouse gases, i.e. CH_4, CO_2 and N_2O are released without collection. In scenario (SC1) the amount of waste landfilled is still rather high and therefore this scenario has a negative net contribution to climate change. Sanitary landfill with electricity production in SC1, however, reveals a significant improvement compared to the net GWP from unsafe waste disposal in the base case scenario by avoiding methane emissions from landfilling, which has a characterisation factor twenty-three times higher than CO_2. This is because fossil fuels are saved when landfill gas is collected in scenario (SC1) and the electricity generated substitutes that produced from oil shale in the background system. Thus, upgrading unsafe waste disposal plays a key role in GWP reduction, as can be shown in other scenarios.

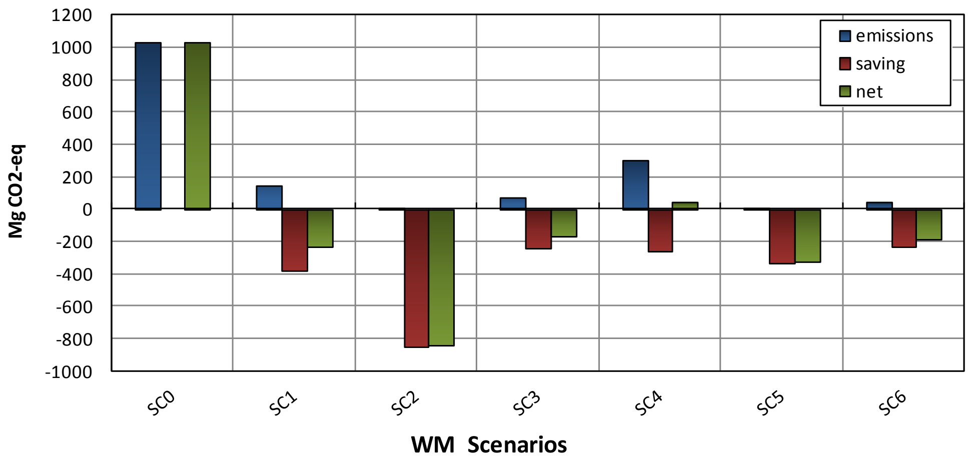

Figure 6. 8: Global Warming Potential of Waste Management Scenarios in Makkah

The GWP for remanufacturing processes is subtracted from the virgin processes (Kirkerby et al., 2006). In scenario (SC2) electricity via incineration and the reduction in the amount of waste sent to landfill therefore result in a remarkable increase in savings of GHG emissions despite the current waste disposal in the base case scenario. MBT with composting in scenario (SC3) and MBT with RDF in scenario (SC4) make almost the same savings but show different net values in terms of climate change impact. This is due to the greenhouse gas emissions from the use of RDF in cement plants in the city of Yanbu (300 km from Makkah) as well as the fact that emissions from longer periods of transport have contributed significantly to the higher environmental impact in scenario (SC4) compared to the use of residual waste as compost in scenario (SC3).

More sorted materials are sent to recycling and an anaerobic digestion plant for organic waste is set up in scenario (SC6), resulting in almost one-forth net contribution of the GWP from the incineration scenario (SC2). In addition, the reason why the incineration scenario (SC2) generally performs rather better than the MBT scenarios (SC3) and (SC4) for the GW 100 impact category is better utilisation of the waste, since the MBT scenarios still have a large amount of unutilised waste that goes to landfill. Although the materials recycling scenarios (SC5) and (SC6) indicate burdens from recycling and biological treatments are avoided, waste incineration with sthe afe landfilling of the residual in scenario (SC2) is also considered to be one of the best options in terms of its impact on global warming, as shown in Figure 6.8.

While the religious periods (Hajj and Umrah) in Makkah last for fewer than sixty days a year, about 20% of the environmental impact is produced during this time. This is because the amount of waste generated in the months of Ramadan and Dhul-Hijjah represents approximately 25% of the total annual waste generated in Makkah, but comprises less organic waste compared to the non-pilgrimage period. Figure 6.9 illustrates the net environmental impact of the global warming potential (GWP) of the scenarios analysed during Hajj, Umrah and non-pilgrimage periods. Electricity recovery in scenario (SC2) results in greater savings of GHG emissions despite the current uncontrolled landfill in the base case scenario.

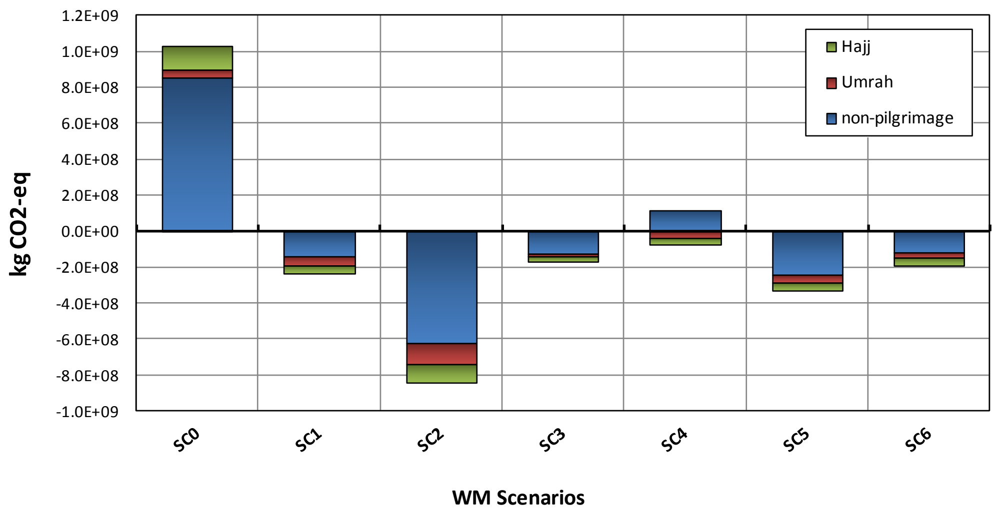

Figure 6. 9:Global Warming Potential of Waste Management Scenarios in Makkah during pilgrimage and non-pilgrimage periods

Figure 6.10 shows the changes in global warming impact per ton of waste generated during pilgrimage and non-pilgrimage periods for the six scenarios compared to the current scenario. The remarkable reduction in GWP during the Umrah period (the month of Ramadan) is considered to be due to the higher proportion of recycled materials per ton of waste, while the non-pilgrimage period contributed higher net GHG emissions.

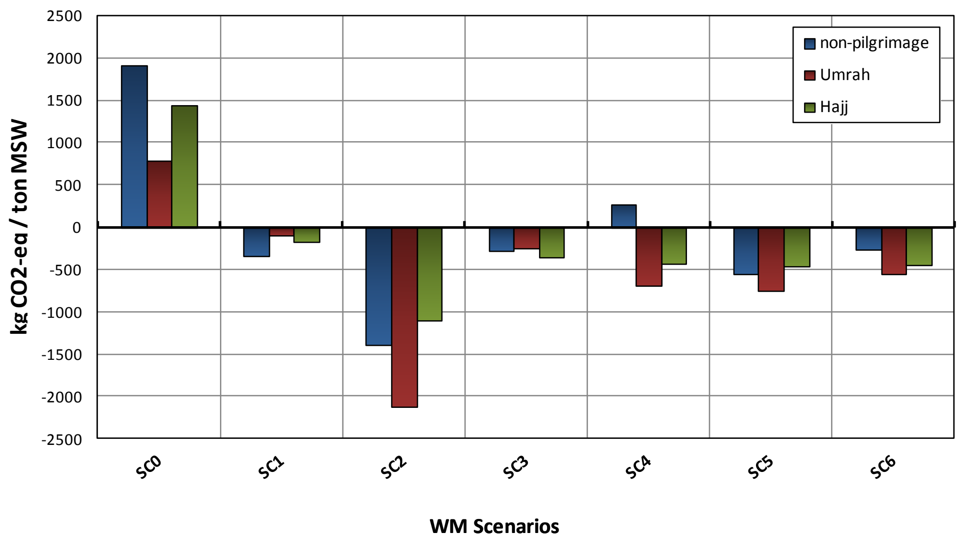

Figure 6. 10: Global Warming Potential of Waste Management Scenarios in Makkah during pilgrimage and non-pilgrimage periods (per ton)

6.2.2 Spoiled Groundwater Resources (SGR)

The impact on groundwater is addressed in the EASEWASTE model as Spoiled Groundwater Resources (SGR). The model calculates the amount of groundwater that the leachate can discharge from bottom ash residues into groundwater (Manfredi and Christensen, 2009). Figure 6.11 illustrates the trend in potential Spoiled Groundwater Resources (SGR) of various scenarios representing different religious periods in Makkah. The baseline scenario (SC0) indicates the greatest impact on spoiled groundwater. The reason for this is the absence of a leachate collection system in the current landfill. This impact declines from 1.26E+9 m^3 of groundwater to 94% of this amount in scenario (SC1) when leachate is collected. However, the uncollected fraction of the generated leachate is assumed to reach the groundwater, while the small amounts of contaminants (10%) remaining in the treated leachate are assumed to be released through emissions of treated wastewater to surface water. Leachate collection thus has a small impact on spoiled groundwater resources in scenarios SC2, SC3, SC4, SC5 and SC6, as similar sanitary landfill is used for residual waste.

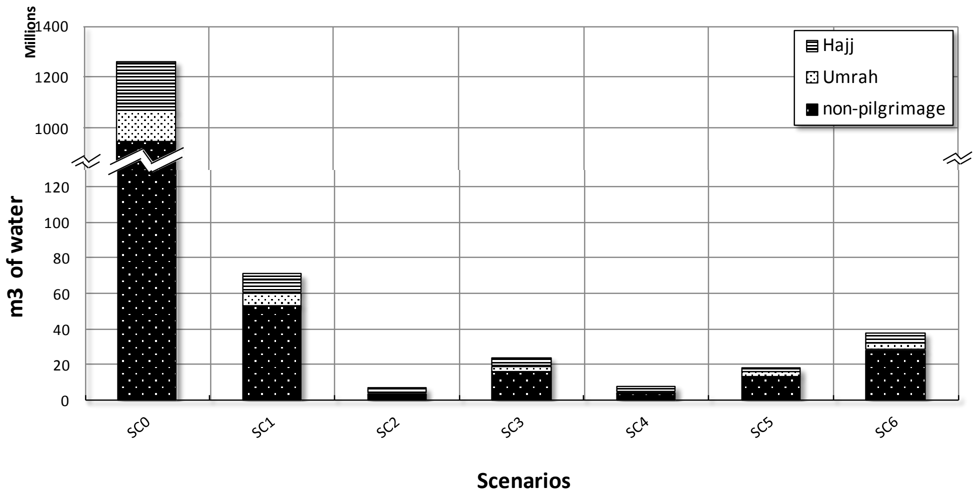

Figure 6. 11: Spoiled Groundwater Resources (SGR)

In the presence of waste recovery or treatment facilities such as incineration and MBT, the waste that goes into landfill in scenarios SC2 to SC6 is less than the waste landfilled in SC0 and SC1. As a result, the need for a leachate collection and treatment system decreases and this leads to a reduction in the pollutants discharged to groundwater. Table 6.1 presents the spoiled groundwater resources from the analysed scenarios for Makkah. SC2 followed by SC4 demonstrates significant reductions in spoiled groundwater resources of 69E+6 m^3 and 78E+6 m^3 respectively. This is because most of the waste generated in Makkah is assumed to be recovered in incineration and MBT facilities. When comparing the two recycling scenarios SC5 and SC6, for which waste sorting at source is assumed, less biological waste treated in AD in scenario (SC6) led to increase the waste being sent to landfill while more recycled materials were recovered. Thus, more amounts of contaminants were released to groundwater.

Table 6. 1: Spoiled Groundwater Resources in waste management scenarios in Makkah

Period	Spoiled groundwater resources (m^3)						
	SC0	**SC1**	**SC2**	**SC3**	**SC4**	**SC5**	**SC6**
Non-pilgrimage	9.50E+08	5.35E+07	2.65E+06	1.59E+07	3.33E+06	1.36E+07	2.84E+07
Umrah	1.20E+08	6.76E+06	1.09E+06	3.18E+06	1.19E+06	2.23E+06	3.50E+06
Hajj	1.93E+08	1.04E+07	3.17E+06	4.67E+06	3.28E+06	1.98E+06	5.58E+06
Total	1.26E+09	7.07E+07	6.90E+06	2.38E+07	7.80E+06	1.78E+07	3.75E+07

Figure 6.12 illustrates the changes in spoiled groundwater resources per ton of waste generated during pilgrimage and non-pilgrimage periods for the analysed scenarios. The baseline scenario (SC0) has the same amount of pollutants as the generated leachate per ton MSW during the Hajj, Umrah and non-pilgrimage periods. In scenario SC2, it can be noted that the SGR during the Hajj period represents the greatest value throughout the year. The reason for this is that the amount of incinerated waste is limited and therefore any increase in waste is landfilled directly.

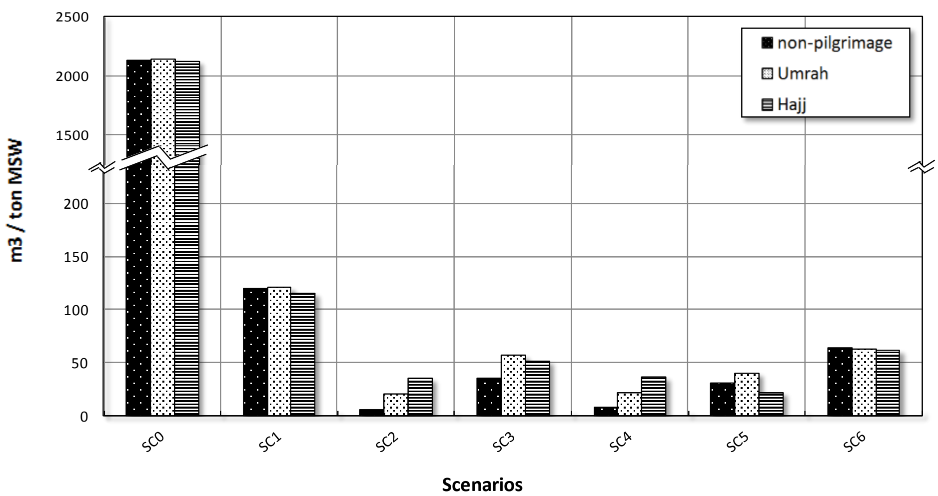

Figure 6. 12: Spoiled groundwater resources from waste management in Makkah during pilgrimage and non-pilgrimage periods per ton MSW

6.2.3 Resource Depletion (RD)

The resource depletion impact category is an aggregation of the use of fossil fuels, metals and renewable resources (Slagstad and Brattebø, 2012). Use of gravel, sand, clay and limestone are not included. Except for the baseline scenario (SC0), the net impacts of RD for the suggested scenarios are negative and they indicate a net saving in resources (Figure 6.13).

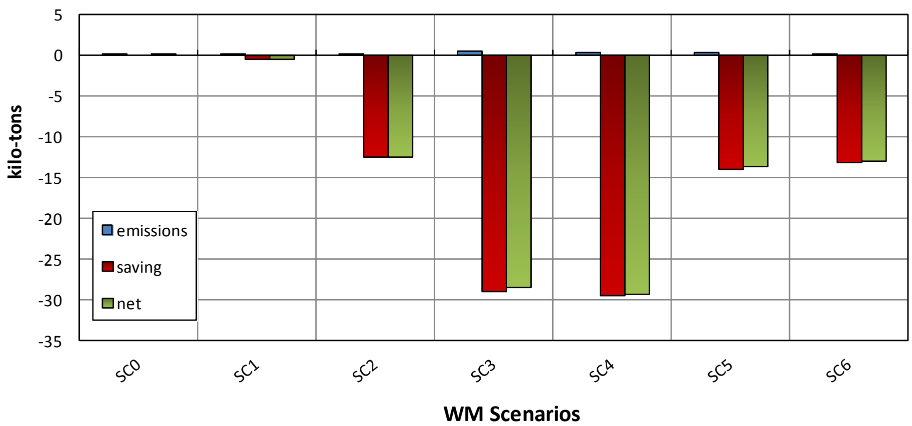

Figure 6.13: Resource Depletion impact category of waste management in Makkah during pilgrimage and non-pilgrimage periods

Figure 6.13 shows that a remarkable saving is achieved in SC4 where all collected waste was sent for MBT to produce RDF. With almost the same result as SC4, SC3, which also used MBT, achieved the second largest saving with regard to resource depletion. The slight differences between these two scenarios are the use of RDF as a fuel for cement plants rather than fossil fuels used in SC4 and using rejects from MBT as a (Compost-Like-Output) CLO stabilised for the landfill restoration in SC3. Scenarios SC2, SC5 and SC6 achieve approximately the same net savings and indicate that the lower sorting efficiency in scenarios SC5 and SC6 and the large amounts of waste that are incinerated in SC2 will improve the system by less than half of the savings achieved in SC3 and SC4.

Considering Figure 6.14, it is noted that one ton of waste generated during the non-pilgrimage period in SC3, SC4, SC5 and SC6 has a greater environmental impact compared to pilgrimage periods. The reasons for this impact on the Resources Depletion category are the change in the characteristics of waste between pilgrimage and non-pilgrimage periods and the use of different treatment methods. Revenue from MBT facilities (in SC3 and SC4) will significantly contribute to the preservation of resources because less waste will be sent to landfill. In short, the best system of waste management for Makkah in terms of Resource Depletion is SC4, while the current scenario is the worst.

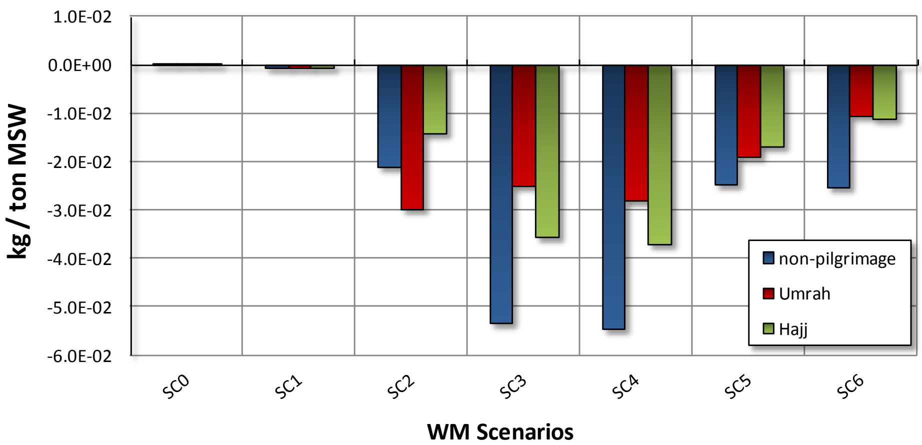

Figure 6. 14: Resource Depletion impact category of waste management in Makkah during pilgrimage and non-pilgrimage periods per ton MSW

6.3 SUMMARY

This chapter showed the waste flows for the studied scenarios including the existing system of SWM of Makkah. These flows helped local authorities and waste managers in Makkah to understand the waste management scenario in addition to monitoring the quantities of waste from collection phase to treatment/disposal processed. The results of life cycle assessment (LCA) of the seven waste management scenarios regarding three environmental impact categories: Global Warming Potential (GWP), Spoiled Groundwater Resources (SGR) and Resource Depletion (RD) are also provided. These categories are provided according to the Environmental Design of Industrial Products (EDIP) method. The given impact potential was presented in each reference unit. To sum up, the results showed that the current WM system of Makkah (SC0) was the worst in terms of the studied categories while the best systems were scenario (SC2) in terms of GWP category, scenario (SC2) followed by (SC4) in terms of SGR category and scenario (SC4) in terms of Resource Depletion category.

CHAPTER 7

Discussion

This chapter discusses data management with reference to an analysis of the decision support tool EASEWASTE. In order to ensure a comprehensive understanding that could help decision makers and LCA practitioners to achieve their objectives; this part also focuses on the environmental impact of landfills across the studied scenarios. Quantities of waste sent to the landfill, the amount of flared, collected and uncollected gas and the amount of uncollected and treated leachate at the wastewater treatment plant (WWTP) will be discussed. The impact of recycled materials is also assessed as well as energy sources of incineration and sanitary landfill. Finally, normalisation of the environmental impact across the studied impact categories is presented to facilitate comparisons of the alternative waste management scenarios.

7.1 DATA QUALITY AND AVAILABILITY

The applicability of LCA is restricted by certain limitations. As the case study shows there are several data gaps and critical assumptions that could have a significant impact on the final results of the LCA. For decision-makers, this indicates that the interpretation of the results of LCA studies should be conducted with caution. Most of these assumptions relate to recent situations (e.g. waste generation and compositions in different time periods). Investments in the waste management arena can be long-term. At the same time changes in waste generation and composition as well as energy prices could significantly influence both environmental impacts and the economics of waste management. It is therefore important to be able to calculate in which scenarios would the technology used be economically feasible and the environmental consequences.

This research shows that the essential data relevant for the LCA tool are in particular related to the waste characteristics and waste management technologies in order to evaluate the flow of materials and to estimate potential environmental impacts. Data on waste generation and composition in Makkah are quite poor in terms of availability, comparability, consistency and quality. Official information on waste management in pilgrimage and non-pilgrimage periods is scarcely available. The alternative approach was therefore implemented, based on the fact that all activities related to waste management in Makkah are in the responsibility in Makkah municipality. This cource of action was also chosen due to lack of time and budget as well as difficulty requesting permission from a number of government agencies which cannot be easily obtained for field studies, even for research purposes.

Based on the reports issued by the municipality of Makkah, it is found that there are inaccuracies in some of the reported waste quantities and compositions during the pilgrimage and non-pilgrimage periods from previous years. This is due to some of the data for waste characteristics of Makkah being based on different sources of regarding the amount of waste delivered to landfill in addition to the fact that waste scavenging has not been addressed in these reports. Scavenging activities are considered by Fakieh (2008), in order to estimate the types and amounts of materials scavenged from Makkah's waste (Fakieh, 2008). Inaccurate data, in this case, have contributed to inaccurate results through LCA. Despite the social and health burdens, scavenging is considered to be a form of waste recycling that could reduce negative environmental impacts. The current research has therefore been built according to the most accurate and latest data available from the waste management of Makkah. In this research, the input data for the LCA tool, EASEWASTE, were obtained from the researcher's own calculations from documents and reports provided by various municipal administrations and the Hajj Ministry. Moreover, additional information, in particular regarding treatment and disposal technologies, was gained from the operational data of European installations where conditions vary in comparison to Makkah.

7.2 LIMITATIONS

The scope of this research was limited to the chosen waste management options/technologies (landfilling, incineration, composting and material recycling), considering wastes already generated. Although the studied waste management technologies represent the most likely options for MSW treatment in Makkah, this study has been based on specifically described current best available and future technologies (e.g. incineration, mechanical biological treatment, anaerobic digestion, etc.) that may have different performances to those described in this study.

There are several sensitive assumptions and data gaps that could influence the ranking of the studied waste management scenarios and treatment options. It is important to note that not all relevant environmental impacts are included in this study. While the impact assessment methods applied cover only three environmental impact categories related to waste management activities, the results could significantly influence the ranking of studied scenarios when choosing of more or other categories.

The scenarios applied in this study, as well as the associated emissions and results, are not actual predictions of future situations, as these can be influenced by changes in waste generation and composition (which was kept constant in this study). The data on waste composition reflected the past situation. In reality, it may be expected that waste generation and composition will change over time. How rapid and severe the change will be is an uncertainty. Therefore it is important to study the possible future change in the waste amounts and compositions as well as their possible impact on the results.

This study does not investigate reuse materials as an alternative to material recycling. The environmental merits of reuse systems are very dependent on local transport distances, and the cost is often decisive.

Another major sensitive regional factor, that could significantly influence the ranking of studied scenarios, is the future marginal electricity source. Additionally, it should be noted that there are many likely data gaps in the emissions and resource consumption inventory and possibly in the impact assessment. Nevertheless, this study is based on current state-of-the-art information and practice. Preliminary approaches were adopted to highlight uncertainties associated with available data, suggesting the overall conclusions and main findings are likely to remain robust. As climate change is a dominant impact category in determining the societal optimum solution, uncertainties associated with the emission of greenhouse gases are important.

Some of the above mentioned specific local data caps and assumptions, that could influence the results of LCA, are discussed in more detail in section 7.7. Modern waste management presents a high level of complexity and thus, also other local and regional aspects (e.g. land use, toxicological impacts and social aspects) have to be considered selecting a most optimal waste management scenario for a specific region.

7.3 IMPACT ON THE LANDFILLING MANAGEMENT

Landfilling, in this study, is considered to be the last stage of the waste management system of Makkah with/without other treatment and disposal technologies used in the studied scenarios. Landfill receives all waste in the baseline scenario (SC0) and (SC1) while it receives the excessive waste during pilgrimage periods in Hajj and Umrah as well as that rejected from treatment technologies in the rest of the scenarios. The aim of this section is to compare the types of landfills used in the scenarios in terms of the quantities of waste that arrive, landfill gas (LFG) and leachate collection and treatment systems.

7.3.1 Amount of Landfilled Waste

Figure 7.1 presents the annual amounts of waste delivered to the landfill during pilgrimage and non- pilgrimage periods in Makkah. While all collected waste was sent for landfilling in scenarios SC0 and SC1, the lowest amount of waste was found in SC4 where only one fifth of the collected waste went into the landfill. This is because the landfill received, in this scenario, the overflow waste during pilgrimage and non- pilgrimage periods as well as that rejected from the MBT. The use of RDF as an alternative fuel in the cement plants contributes, then, to the amount of rejected waste that goes into the landfill. This indicates that the lifetime of Makkah's landfill could be longer about four times by using MBT with a 40 kilo-tonnes capacity per month as described in scenarios SC3 and SC4.

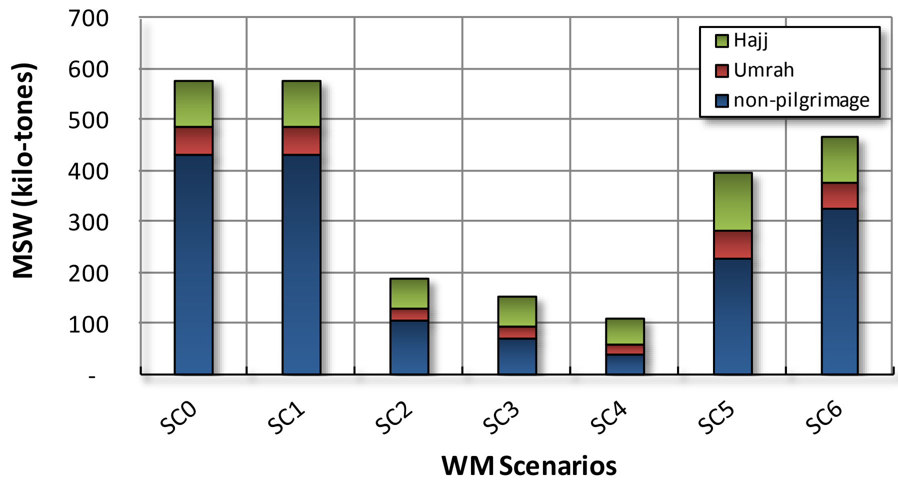

Figure 7. 1: The annual amounts of municipal waste sent to the landfill for the studied scenarios

In terms of recycling, due to the low efficiency of the sorting of recycled materials at source as seen in scenarios SC5 and SC6, about 72% and 84% of total waste goes into landfill respectively. In particular, AD in scenarios SC6 requires high efficiency separation of the organic materials at source. The annual amounts of waste sent to the landfill are about 400 and 480 kilo-tonnes in scenarios SC5 and SC6, respectively, compared to 578 kilo tonnes in SC0. The waste incineration in scenario SC2 causes a decrease of 33% in the amount of waste sent to landfill, which results from overflow waste due to the limited capacity of the incinerators over the cource of a year. The lowest amount of landfilled waste (about 100 kilo-tonnes) was found in scenario SC4 when the rejected waste is used at MBT to produce RDF.

7.3.2 Landfill Gas Collection

Uncollected LFG

As mentioned earlier, an uncontrolled landfill was used in the baseline scenario (SC0), which presents the current situation in Makkah, as the only disposal method used for the collected waste. This landfill has no collection or treatment systems for the landfill gases while an engineering landfill was employed in scenario SC1. In this landfill, 95% of the produced gases, resulting from the anaerobic digestion of organic fractions, are collected in the gas collection system. Around 70% of the collected landfill gases are used for energy recovery while the rest are flared. Sanitary landfill is also used in scenarios SC2, SC3, SC4, SC5 and SC6 but all collected landfill gases are flared without energy recovery.

As shown in Figure 7.2 and (Appendix D1), a higher amount of uncollected landfill gases was found in the baseline scenario SC0 due to the absence of gas collection system. This amount decreased to 60 million kg when the landfill was upgraded to a sanitary landfill in scenario SC1. Additionally, it was found that scenarios SC2 and SC4 had lowest amount of uncollected landfill gases due to receiving less rejected wastes from incineration and MBT technologies.

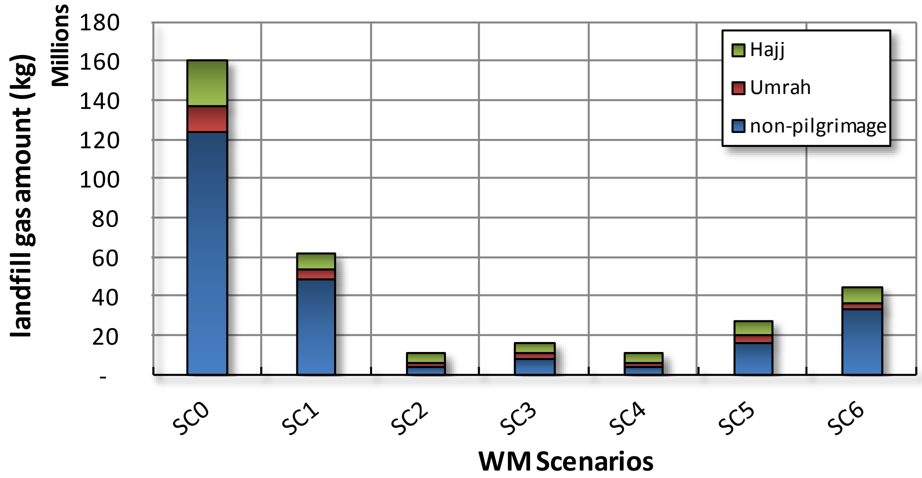

Figure 7. 2: Amounts of uncollected landfill gas for the studied scenarios

Flared collected LFG

Figure 7.3 shows the quantities of flared landfill gases from the landfill site for each studied scenario. It can be seen that the current landfill at the baseline scenario (SC0) has no flared system while in scenario SC1 about 20 million kg of collected gases was flared, which comprised 30% of the collected landfill gases. Due to use of other treatment technologies, such as; MBT, incineration, AD and composting in scenarios SC2, SC3, SC4, SC5 and SC6, it was concluded that 100% of collected landfill gases were flared. Thus, the amounts of gases flared, these scenarios are varying according to the quantities of the rate of gases collection. Scenario (SC6) has is the largest amount of flared gas, while scenarios SC2 and SC4 show the least because of the low amount of collected gases. However, the using of landfill with electricity recovery, as seen in scenario SC1, contributed significantly to the reduction in emissions and therefore reduced the negative environmental impacts in this study.

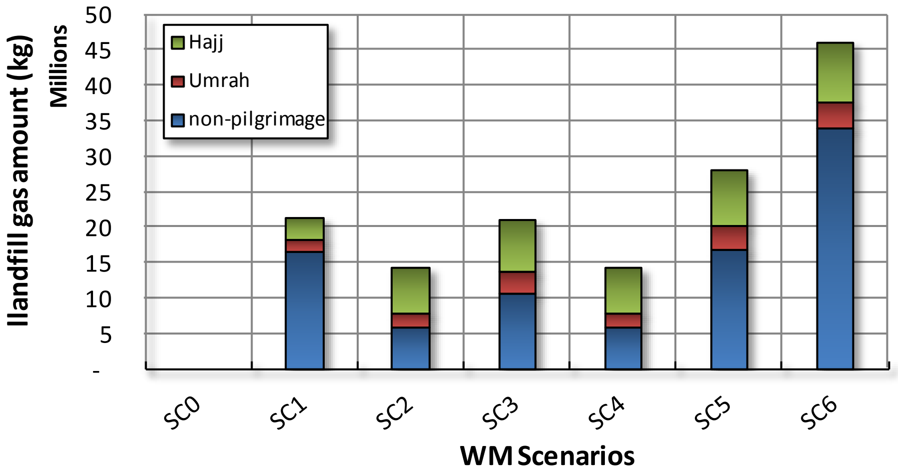

Figure 7. 3: Amounts of flared landfill gas for the studied scenarios

7.3.3 Leachate Collection

Landfill leachate is a potentially polluting liquid, generated principally by liquids existing in the waste as it enters a landfill or from rainwater that passes through the waste. An important part of maintaining a landfill is managing the leachate through proper treatment methods designed to prevent pollution spreading into surrounding ground and surface waters. Due to the absence of a membrane between the waste and the underlying geology in Makkah's landfill (baseline scenario), the leachate is free to egress the waste directly into the groundwater and which could affect groundwater and Zamzam.

Unlike the current landfill in scenario SC0, a leachate collection and treatment system at the landfill was assumed for the alternative scenarios. Figure 7.4 illustrates the amount of uncollected leachate generated by the landfill for each studied scenario. Based on an assumption that 90% of the total generated leachate is collected, about 3 million kg of uncollected leachate is released to the groundwater in scenario SC1. This amount represents about 33% of the total amount of uncollected leachate at the recent landfill in scenario SC0, which has no leachate collection system. It was also found that the landfills in the remainder of the scenarios recorded under 0.3 million kg of uncollected leachate due to a lowest amount of waste being placed into the landfills. Scenario SC3, generally, had the lowest amount of uncollected leachate and was found to produce 0.1 million kg (Appendix D2).

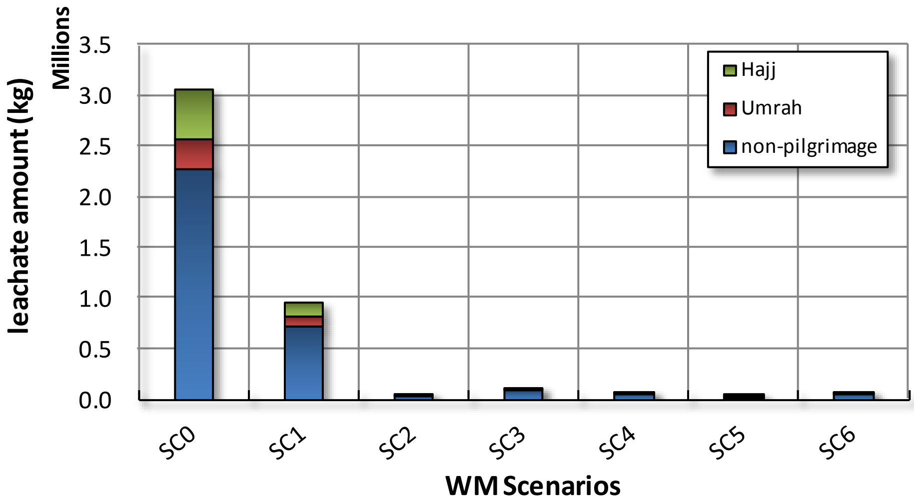

Figure 7. 4: Amounts of uncollected landfill leachate for the studied scenarios

It should be noted that, with the xception of baseline scenario, the landfills in the alternative scenarios assumed that only 95% of the collected leachate is treated at the wastewater treatment plant (WWTP) at the landfill site. As shown in Figure 7.5, the amount of treated leachate reached about 1.6 million kg in scenario SC1 with about 0.1 million kg in scenario SC4, which features the most collected waste delivered to the MBT. The amounts of treated leachate in this study, therefore, mainly depend on the amount of waste arriving at the landfill.

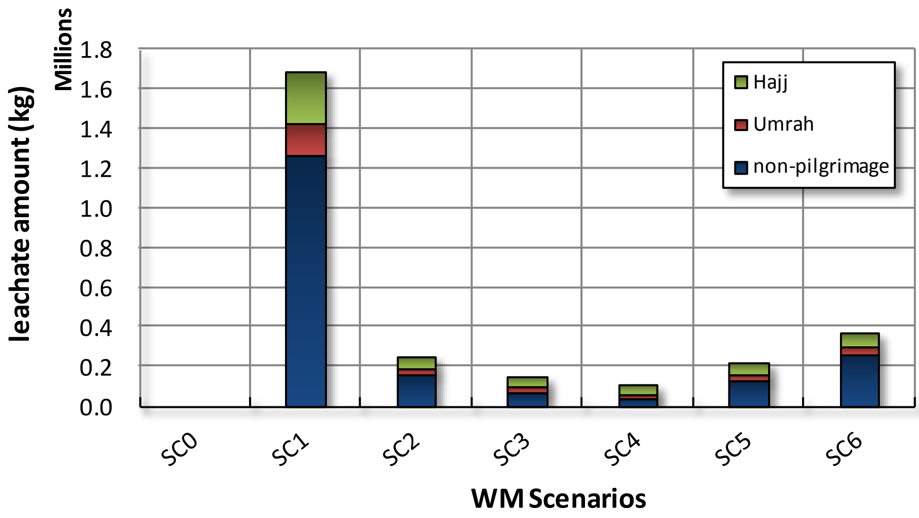

Figure 7. 5: The amount of treated leachate at the wastewater treatment plant (WWTP) at the landfill site for the studied scenarios

7.4 IMPACT ON THE RECOVERED WASTE MATERIALS

Recovered waste materials, from either mechanical or biological treatment processes, can replace the use of virgin materials and provide environmental benefits including less air pollution and energy usage, a reduced impact of extracting materials and a more efficient use of finite resources. Recovered materials could also be a real opportunity to gain financial benefits by selling a wider selection of resources such as paper, cardboard, plastics, ferrous and nonferrous items. Although recycling costs money, it reduces the overall cost of waste management services. Depending on the status of markets, the sale of recyclable materials could offset the cost of operating expenses.

In this study, the cost or financial benefits of infrastructural projects, especially to lower Makkah's exposure to pollution, are not a major obstacle to the government and decision-makers in Saudi Arabia. The decision-makers will not hesitate to pursue the development and improvement of the solid waste management system in Makkah in order to protect the water of Zamzam from leachte when the harm is proven. Therefore, this section focuses on the outputs of the studied scenarios in terms of the recycling that could attract local authorities or private sectors to invest in this area. This option, consequently, could contribute to offsetting the expense of construction and operation.

The size of the fraction of recovered waste is an important issue related to sensitive data for LCA. There are several factors that could limit the final recovery of the waste fraction and therefore affect the studied waste management system. When performing a LCA study, it is important to consider the following factors:

- The quality of collected recyclable waste fractions
- Possible market for recyclable waste fractions

Due to the absence of an effective waste recycling system in Makkah, the quality of source separated waste materials was assumed to be relatively low. Therefore, the percentage of losses and sorting during the process was relatively high. Low-quality and dirty materials were however treated as waste (landfilled).

The comparison of recycled waste material quantities is shown in Figure 7.6 and (Appendix D3). It should be noted that the MBTs in scenarios SC3 and SC4 assume that steel and aluminium are the only recovered materials because of the difficulty of separating the rest such as paper and plastic from contaminated, food and organic waste. Therefore, the amounts of steel and aluminium in scenarios SC3 and SC4 are the same. In terms of sorting at source, additional materials such as paper, cardboard and plastic were recovered in scenarios SC5 and SC6 but scenario SC6 has slightly more materials due to apply higher recycling rate and the use of three different bins instead of two in scenarios SC5 as well as the assumption of a higher recycling rate.

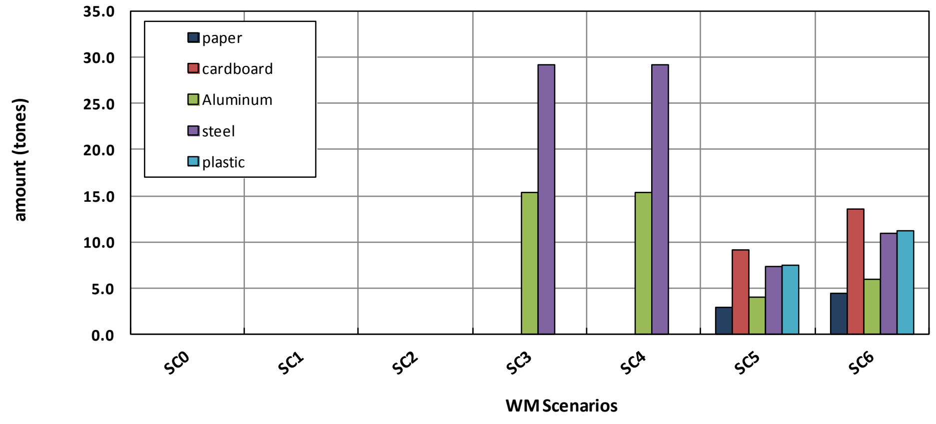

Figure 7. 6: Amount of recycled materials for the studied scenarios

One of the major challenges regarding recycling processes in Makkah is the weakness of awareness among the population. Publicity is necessary to achieve maximum advantages from recyclable materials, as well as support the rising economic feasibility of the establishment of MRF. Therefore, local authorities must begin to develop a programme to increase awareness of the importance of recycling and its impacts on the existing situation due to loosing valuable materials from waste.

Other issue related to amounts of recycled materials is scavenging activities. The lack of achieving desirable benefits from recycling process in Scenario SC5 and SC6 was due to presence of scavenging activities in Makkah while data collected. Although the scavenging is a form of recycling, it leads to inaccuracy amounts of recycled materials in the system of waste management. Thus, the development of waste collection system will contribute significantly to success the recycling process.

7.5 IMPACT ON COMPOSTING

Composting is a microbial process for converting decomposable organic materials into useful stable products. The product, compost, can be used on land as soil conditioner or can be upgraded to fertiliser with chemical amendments. The quality of compost is related mainly to a source-separated of food waste collection system, to ensure the collected organic waste is of sufficient quality. It is often assumed that the quality of compost is good and therefore a relatively high share of produced compost replaces mineral fertilisers. This is not the case in Makkah where the experiences of composting of the organic waste from households show that the quality of compost is nonexistent. The limitation of an environmentally beneficial use of compost is the very low market demand for such product in Makkah. Today most of the municipal biomass waste based compost is used as a filling material and for landscaping the landfills.

In terms of the production compost and digestate to be used as CLO in this study, Figure 7.7 shows the quantities of annual compost generated from composting and AD facilities for the studied scenarios. Three scenarios have introduced biological treatments to produce compost. The treating of the collected food and organic waste at the AD, as considered in scenario SC6, contributed to a decrease in the quality of compost that can be used as a filling material at the landfill due to the limitation of AD facility. The scenario, compared to the waste management practice in scenario SC5, presents a considerable decrease in the production of compost. However, commingled waste collection in scenario SC3, which uses MBT, led to a low amount and a low quality of compost. Waste composting is not applied in Makkah yet, however, it could reduce the amount of landfilled waste when establishing a modern composting facility in the future. It may therefore be assumed that the maximum amount of compost produced in Makkah will stay far below the average of the current practice in developed countries such as those Europ where the average utilisation of produced compost for agricultural purposes is 40% (Moora, 2009).

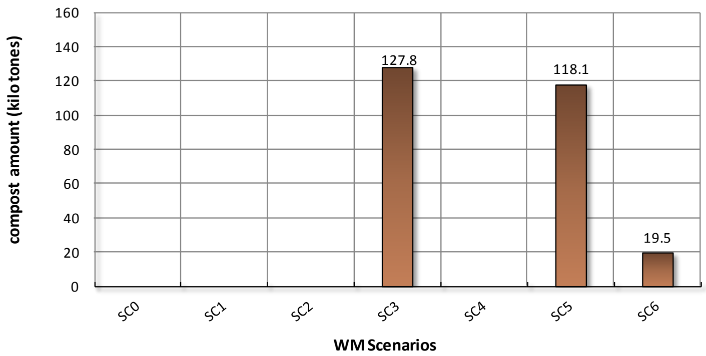

Figure 7. 7:Comparison of annual compost produced for the studied scenarios.

7.6 ENERGY SOURCE

Energy is a major consideration in LCA, many LCA studies use average data (e.g. the average electricity mix of a certain region or country) to model the background systems that are indirectly affected by the actual system under study. The use of average data to model these systems may be relevant if the aim is to analyse the impacts of past activities. However, if the aim is to model the future consequences of a decision, the use of average data may be misleading, since these data are historical and therefore cannot capture future consequences resulting from changes to the system (e.g. changes in electric power production). It should be noted that when applying average power production data, the results can be seriously affected by the delimitation of the market from which the action is taken.

Modern waste management systems are closely connected to energy systems. WTE facilities, such as waste incineration in combined heat and power plants, reduce the need for other energy sources and can therefore be expected to have marginal effects on the production of energy carriers such as heat and electricity.

As the results from LCA show in this study, about 7.8 megawatts and 80 megawatts was gained from energy generation at the sanitary landfill in scenario SC1 and the incinerators in scenario SC2 respectively. In addition, the energy produced from using refuse derived fuel (RDF) in cement manufacturing plants, which is used to heat up the cement kiln systems instead of fossil fuel, in scenario SC4 reached 2.77E+9 MJ.

There is no doubt that most of the countries around the world are working hard to benefits from as many existing energy sources as possible; for example, the increase in the use of wind energy in Scandinavia and natural gas in Russia and Qatar, and oil in the Gulf countries and Venezuela. However, the high prices of oil and natural gas in Europe as well as the negative environmental impact of coal have pushed European countries to investigate renewable energy. So, regardless of environmental issues, the investment in a particular source of energy varies from one country to another depending on the competitiveness of other sources. The low price of oil in Saudi Arabia makes the search for other energy sources less attractive. This may delay serious investment in the use waste rather than oil as an alternative source for electricity production.

Since the choice of energy is significant for the results in many LCA studies, it is important that the LCA practitioners and decision makers form an understanding of the development of energy systems at the local and regional level. To ensure that the selected energy data are consistent with the rest of the system analysis, it might be necessary to carry out a separate energy system study. However, this could add significantly to the cost of the assessment.

7.7 NORMALISATION OF THE ENVIRONMENTAL IMPACTS AND SENSITIVITY ANALYSIS

In order to facilitate comparisons of the environmental impact across the categories of the alternative waste management scenarios, normalisation, namely the calculation of the magnitude of the category indicator results relative to reference values where the different impact potentials and consumption of resources are expressed on a common scale through relating them to a common reference, facilitates comparisons across impact categories (Stranddorf *et al.*, 2005). To allow comparison among different impact categories, the normalisation references for each individual impact category are calculated and expressed in units of "person-equivalents" (PE).

In terms of the performance of the WM system as a whole, Figure 7.8 shows the multi life cycle impact assessment results for all scenarios when whole WM systems are compared, including all processes from collection to landfill. The baseline scenario (SC0) scores the worst (positive PE values) for all impact categories, confirming the higher impacts of a WM system based on unsafe waste disposal at the current landfill without recycling or energy recovery. All alternative scenarios reduce GW, SGR and RD emissions.

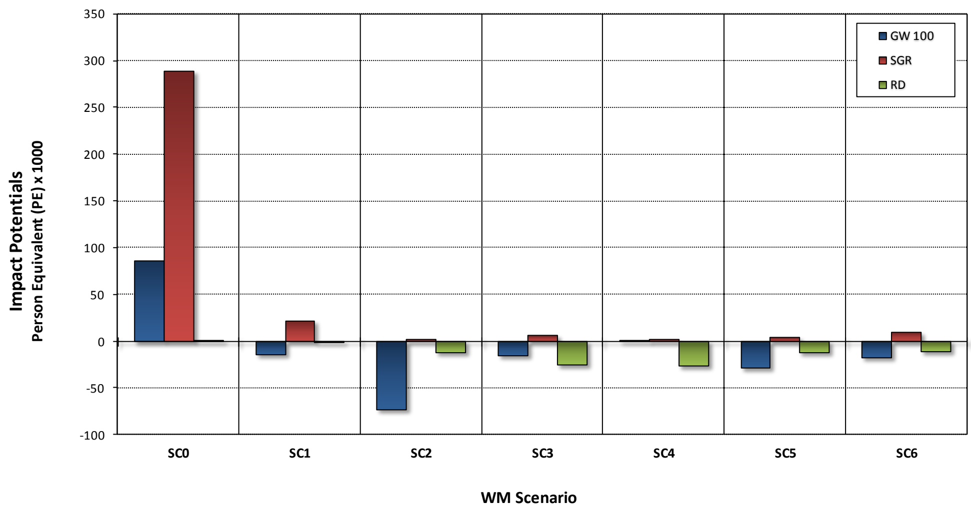

Figure 7. 8:Multi life cycle impact assessment results comparing whole waste management systems with respect to the chosen impact categories

As it can be observed from Figure 7.8, the main credit (negative PE values) to the system originates from recycling and energy utilisation acting as a substitute fossil fuel, especially in terms of global warming. The incineration of waste also contributes credits to the system, together with compost and the RDF that is routed to the cement plants. These credits are due to the electricity produced by the WTE plant offsetting the production of fuel-based energy elsewhere in the energy system.

Replacing the current unsafe landfill with a sanitary landfill, as seen in scenario SC1, is surprisingly superior and shows a significant improvement, especially with respect to the global warming category. In this impact category, the least burden was originating from Scenario SC2, due to reduction of greenhouse gas emissions by energy generation as a result of the incineration. The global warming potential of Scenarios SC1, SC3 and SC6 were found to be very near to each other and as the mostly contributing scenarios. In all the scenarios, the saving contribution to global warming was caused by almost the same amount of waste sent to the controlled landfills. Additionally, more saving contribution to global warming was obtained from Scenario SC5 when less waste was sent for landfilling than scenarios SC1, SC3 and SC6. In comparison with the recycling scenarios SC5 and SC6, the impacts of scenario SC5 are very similar to scenario SC6. This reveals a larger reduction of environmental impact potentials because of the credit from commercially recovered materials and fertiliser substitution. If the only concern was the global warming impact category, the best available option would be Scenario SC2 which considered as the best management application. The highest effect to global warming was originated from the current system (Scenario SC0), because CO2 was the only major GHG.

With respect to Spoiled Groundwater Resources (SGR) impact category, the highest contribution was obtained from the current waste management system of Makkah (SC0) due to the absence of leachate collection system. Scenario SC2 followed by scenario SC4 demonstrate significant reductions comparing to the rest options due to the most of the waste generated in Makkah is assumed to be sent to incineration and MBT facilities. When comparing the two recycling scenarios SC5 and SC6, for which waste sorting at source is assumed, less biological waste treated in anaerobic digestion in scenario SC6 led to increase the waste being sent to landfill while more recycled materials were recovered. Thus, more amounts of contaminants were released to groundwater.

When considering the impact category of Resource Depletion (RD), a different diversion of waste to mechanical or biological treatments shows a significant improvement compared to the base case. The MBT scenarios SC4, SC3 have found almost the same largest saving impacts. However, scenarios SC2, SC5 and SC6 achieve approximately the same net savings and indicate that the lower sorting efficiency in scenarios SC5 and SC6 and the large amounts of waste that are incinerated in scenario SC2 will improve the system by less than half of the savings achieved in scenarios SC3 and SC4. To sum up, the findings in Figure 7.8 confirm that the environmental impact of the current waste management system, with uncontrolled landfill, is much more severe than using well-controlled treatment and disposal processes (Lemieux *et al.*, 2004).

This research was conducted from an environmental perspective and therefore the choice of best scenario is influenced by indentifying which has the least potential for environmental impact. The fuel consumption of collection and transport vehicles, the collection period, transporting distance, and truck loading rate are essential pieces of information when assessing the logistical and thus financial elements of waste management since they can cause emissions too. Based on Finnveden *et al.* (2007) and Eriksson *et al.* (2003) who indicate that the transporting of waste is of little significance and has no influence on the ranking of treatment options based on the LCA study, the scenario comparison in this research was conducted by considering waste collection, transporting, treatment, and disposal activities together as a whole WM system.

With regard to establishing priorities for a waste management policy, the decision makers should be attentive to the objectives of the policy makers, for instance, whether to address the least environmental impact potentials in the global warming category. In this study, incineration with the rest of the waste being placed in a sanitary landfill scenario SC2 is identified as the most attractive waste management system. If the decision-makers set their objectives for solid waste management on the protection of groundwater (Zamzam in particular) as well as human health and the environment, scenarios SC2 and SC4 are good choices.

An LCA of a waste management system is uncertain with respect to both the system (definition and boundaries) and the data used. The system definition is usually the main responsibility of the modeller, since the users of the resulting output very often do not have the experience to judge the choices made. On the other hand, the users of the model results will not have confidence in the LCA results if the waste flows estimated as the basis for the assessment do not fit with the actual data for the system that the model represents. This suggests that an effort should be put into modelling the actual flows as accurately as possible and that an extensive, but sensitivity analysis should be performed to address the significance of parameters and data suffering from large uncertainty and determine how a model is sensitive to changes in the value of the parameters of the model. Moreover, sensitivity analysis helps to build confidence in the model by studying the uncertainties of modelling where some parameter values are estimated. In LCAs on the waste management systems the result verification is based on sensitivity analysis (Kirkeby *et al.*, 2006a; Moberg, 2006).

In a large model, sensitivity analysis of all parameters is often impossible. The greatest influence or the greatest uncertainty in the model behaviour, thus, is usually determined (Frey *et al.*, 2003). In this way, LCA modelling is more likely to be accepted by the result users and LCA model results can become a balanced platform for decision making. The parameters of the sensitivity analysis are identified on the base of the data quality. In this study, various main points for the sensitivity analysis have been identified and tested whether cause changes in the results.

The variation of sensitive parameters shows different effects on the results. According to Laurent *et al.* (2014b), the parameters for collection and transportation were the most commonly tested although LCA studies typically concluded that their influence on the final results was limited. From modelling results, it is established that the environmental outcomes of different waste management systems are not very sensitive to transportation distances. It is calculated that only when transportation distances exceed 600 km there will be an effect on scenario ranking, which is clearly visible in the global warming potential impact category. In reality, however, it is impossible to reach such distances unless waste is exported to neighbouring countries.

The variation of MSW composition by changing organic waste and plastic waste fraction shows less impact to LCA result. This result confirms that the direct process of specific emissions from open dumping ratio has greater importance to the LCA result than the changing MSW composition. Additionally, the variation of population is significant because the analysis is conducted based on waste amounts where mass fluxes (fraction of waste mass divided by population) are directly calculated.

Since methane gas recovery has not been introduced yet in the recent landfill in Makkah, figures from typical European applications were taken from 30% to a maximum 50% of gas recovery efficiency. At the maximum rate, the results generally do not affect scenario ranking. Nevertheless, they show fewer emissions in the global warming category and reduce the difference between incineration option and MBT options.

The variation of open dumping ratio is remarkably sensitive to impact potentials rather than recycling rate. On the other hand, the recycling rate affects the total expenses and the net cost more than open burning diversion.

With regard to open dumping emissions, dioxin (both air emission and ground emission) is dominantly sensitive to impact potentials rather than the other output emissions. It should be remarked that composting is insignificant for estimating sensitivity of environmental impact.

Over the years, a large variety of dedicated waste-LCA software such as EASEWASTE, ORWARE, WRATE or WAMPS has been developed, typically designed to be applied in the countries where they were developed. According to Laurent *et al.* (2014a), a review study of the different assumptions embedded in large group of LCA software has demonstrated that LCA results are independent from the choice of software as long as the models are based on the same assumptions while it has also highlighted the need for harmonisation of some of the technical modelling aspects, e.g. non-geographic assumptions like time horizons for landfill emissions (Gentil *et al.*, 2010).

However, although waste-specific LCA software are overall demonstrated to be consistent between each other, they typically have different levels of refinements. Therefore, practitioners should be careful to select one that can capture with sufficient accuracy the complexity of the analysed SWMS in relation to its defined scope (Laurent *et al.*, 2014a). It can be concluded that the rank order of the assessment results are similar, but not exactly the same.

The results of this study might be used to help decision makers in Makkah municipality to change the current system of waste management gradually. Although EASEWASTE have list of waste management technologies and systems, it is necessary to remember that the studied scenarios were adopted in this research based on the current situation of Makkah as well as its infrastructure (Chapter 3). The chosen scenarios however could be changed or replaced according to the recent infrastructure, costs and social conditions.

While the EASEWASTE model can help evaluating the environmental impacts arising from a solid waste management system, other concerns must also be addressed when choosing the proper treatment routes and technologies. Costs are one of the most important factors which plays a decisive role but also issues like odour, hygiene, and social acceptability for waste generators as well as for waste collectors and workers must be taken seriously.

Despite the abovementioned important factor ‘cost’ it can be said that the cost of such projects in Saudi Arabia, now, is not a high priority. This is because of the government is trying to improve the recent infrastructure in Makkah for local population and pilgrims with omitting financial issues.

While the use of incinerators in Scenario SC2 does not require any change in the process of waste collection and transfer, it is considered, even has the least environmental impacts, therefore the most expensive in terms of construction and operational costs and the need for skilled labours. In contrast, the set up of controlled landfill seems to be less expensive than the incineration scenario, although these two scenarios are similar regarding the need of changing in the collection and transporting processes as well as the change people's behaviour. In recycling scenarios, significant changes in public awareness recycling importance as well as collection method are required. However, MBT scenarios seem to be acceptable solutions while they have acceptable negative environmental impacts as well as less costs that incineration scenario and no need for changing of residents’ behavior. In addition, the developing of transporting RDF or organics from MBT units to the cement plants or composting units is only required in these scenarios.

Regarding use of LCA as a tool for decision making, it can be concluded that the results of the research are fairly robust and in general similar to many of the more in-depth LCAs in waste management. However, as discussed above in this thesis, LCA is not the only tool for environmental system analysis of waste management. This method should be used in combination with other tools (such as EIA) to give more comprehensive decision support.

7.8 SUMMARY

In order to choose the most preferable waste management system from different WM options, a discussion of data quality and availability with regard to LCA was conducted as a first issue in this study. This is due to ensure enough understanding that could help decision makers in Makkah. Quantities of waste sent to landfill, gas that is flared collected and uncollected, uncollected and treated leachate at the treatment unit, recycled materials and the energy sources of the studied scenarios were also discussed. Normalisation of the environmental impact across the studied impact categories has been discussed to assist comparisons of the alternative waste management scenarios. For most impact categories, there is a general ordering of the scenarios from best to worst (if the priorities for all categories are equal): SC2 > SC5 > SC4 > SC6 > SC3 > SC1 > SC0, although the differences between SC6, SC5 and SC3 are insignificant. However, the differences - even for scenarios SC3 and SC4 – are significant for most impact categories. The results demonstrated that an improvement in the disposal process in developing countries is the most effective method to reach the objectives of solid waste management for the protection of the environment and human health.

CHAPTER 8

Conclusions and Future Research

8.1 CONCLUSIONS

This research has explored the insights of using LCA methodology as a decision support tool (DST) for waste management. General method-related conclusions concerning the use of DST in regard to data management, specifically under the conditions of developing countries, can be drawn. The main aim of the thesis is to improve the current waste management system and evaluate the environmental performance of alternative technological options for municipal waste management in Makkah due to the large variation in the amount of waste generated. It is obvious from the results of this research that greater attention must be paid to the existing waste management system in Makkah and new technologies on waste treatment/disposal are required with the aim of protecting public health, the environment and groundwater. Based on the results of LCA modelling (through use of the EASEWASTE model) the following conclusions concerning the comparison of the studied waste management options have been reached.

1. The landfilling of municipal solid waste is the least preferred waste management option regarding environmental impact. This is valid even if landfill gas is recovered at a high rate. Therefore, landfilling of MSW should be avoided as far as possible, both because of the environmental

impact, such as discharging leachate to groundwater, and because of the low recovery of resources.

2. Waste incineration shows the best results in terms of the studied environmental impact categories. It is important to stress that if high rates of incineration with energy recovery are attained, net emissions may even become negative. This means that this waste management option can partly offset the emissions that occur when energy is produced from fossil fuels.

3. Materials recycling could also help the waste management system to achieve negative net emissions. These results occur when the products are manufactured from virgin materials. A high rate of more preferable in order to ensure less harmful effects on the environment.

4. Mechanical Biological Treatment (MBT) provides acceptable results especially through RDF production. This is due to the fact that RDF could substitute fossil fuel at cement plants and therefore lead to an offset in emissions in respect of the studied environmental impacts. MBT may, however, be avoided in this study when the rejected waste is landfilled without any recovery processes. This is because the waste from Makkah contains high amounts of food and organic fractions that may contaminate the recyclable materials.

5. Composting offers hardly any advantages with respect to the environment and energy turnover when compared to other waste recovery options (such as recycling and incineration). However, composting has potential if landfilling is avoided and incineration or anaerobic digestion is not feasible.

6. Regarding pilgrimage periods, it has been taken into account that any unexpected increase in waste (that exceeds the capacity of the treatment

facility) during Hajj and Umrah events will be delivered direct to sanitary landfill in all studied scenarios. It means that no particular solution to the religious events in Makkah was obtained in this study and further in-depth research will need to be carried out.

7. The type of waste collection system and the transport distance have a low influence on the total environmental impacts compared to other waste treatment options. However, the design of a collection system may significantly influence its economic cost.

A conclusion may be drawn that the scenario where a maximum amount of collected waste is incinerated for energy recovery and the rest of the waste is sent to sanitary landfill with gas flaring, is the optimal scenario for Makkah, possibly forming a basis for the development of a future waste management system. In terms of the best scenarios and least environmental impacts, however, incineration and recycling whereby a high rate of recyclable waste fractions are sent to material recycling and the rest is incinerated with energy recovery seems to be the most favourable system of waste management.

An LCA of a waste management system includes a number of uncertainties with respect to both the system (e.g. definition and boundaries) and input data and assumptions. As the case study shows there are several data gaps and critical assumptions that could have a significant impact on the final results of the LCA. It is important that LCA practitioners and decision-makers have sufficient knowledge and understanding of those characteristics and an adequate the possible restrictions related to the choices that could have the strongest influence on the results. Most of those assumptions relate to future situations and developments.

The results of the research lead to the conclusion that two main characteristics (waste and energy data) need more attention when an assessment of a life cycle based on the environmental performance of a waste management system is undertaken. The most sensitive input data and assumptions are as follows:

1. Data on waste generation and composition are the common basis for environmental assessment of waste management systems. Therefore, it is important to make all waste management planning decisions on the basis of more carefully designed long-term forecasts of waste generation and composition.

2. As the recent developments in waste generation in Makkah indicate, fluctuations in the pilgrimages numbers every year during the periods of Hajj and Umrah may lead to significant changes in waste generation and compositions.

3. The choice of a replaced marginal energy source in the background system could be critical for the results of waste management related LCA studies. For example, the results for incineration will change significantly if it is assumed that energy produced from the incineration of wastes replaces electricity from fossil fuels or non-fossil fuels.

Since there are many waste management facilities (using different methods of waste collection and transportingn trucks, with varying fuel consumption, and various landfilling conditions), average data from actual operations is necessary in order to represent information for use in a standard model. In developing countries, the use of LCA, which are generally developed in industrialised countries, requires additional attention. For instance, the software of the EASEWASTE programme is not able to cover informal recycling waste collection schemes. Thus, the integration of all recycled waste from the entire process placed as source separated fraction is recommended.

Finally, it may be concluded that LCA can provide useful information to evaluate the different waste management options and technologies applied in developing countries. As a result, default values of EASEWASTE based on developed countries were used to represent the existing conditions in Makkah. However, LCA and other system analysis tools should be considered as decision support tools that provide relevant information but cannot substitute the crucial role of a decision maker.

8.2 FUTURE RESEARCH

The scope of this research is limited to the chosen waste management systems and technologies. Although the studied waste management technologies represent the most likely options for MSW treatment in Makkah, there are also other existing and future technologies to be taken into account. Thus it is necessary to widen the research scope to explore the advantages and disadvantages of these new waste management technologies in future life-cycle based environmental assessment. For this, the technical and environmental parameters of these technologies should be studied while taking into account the existing situation of Makkah's infrastructure.

Development of effective policy and regulations for solid waste management (including e.g. materials recycling and energy recovery) in Saudi Arabia and Makkah in particular is a priority to which attention must urgently be paid. It is also interesting to follow the developments of the connections between energy and waste management in terms of policy instruments and technology developments. Also other possible future development trends (e.g. waste generation and composition) need more in-depth research. In addition, major characteristics with a possible influence on future developments in the waste and energy sector need to be specified more accurately.

This research is also limited to the evaluation of the existing system of waste management in Makkah from an environmental point of view only. Modern waste management presents a high level of complexity, thus the selection of a better waste management scenario requires the consideration of many aspects. Social elements play an important role in the planning of sustainable waste management systems. In order to be able to better explain the dynamics of future socio-technical waste system, social aspects need to be integrated into system analysis tools such as LCA. Additionally as mentioned earlier, in-depth research for the Hajj period is necessaryto gain sufficient knowledge and understanding of the waste management system in the pilgrimage area in Makkah as well as achieving the possible benefits such as waste minimising and recovery.

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Appendix

APPENDIX A:

Municipal Solid Waste Management in Makkah, Saudi Arabia

Table A. 1: Annual Collected Waste of Makkah between 1416H -1432H (30 May 1995 – 25 Nov 2011)

Hijra Year (Gregorian year)	Generated Waste Quantities (tonnes)
1416 (30 May 1995 – 17 May 1996)	446,216
1417 (18 May 1996 – 6 May 1997)	482,529
1418 (7 May 1997 – 26 April 1998)	537,002
1419 (27 April 1998 – 16 April 1999)	592,837
1420 (17 April 1999 – 4 April 2000)	628,604
1421 (5 April 2000 – (25 March 2001)	612,002
1422 (26 March 2001 – 14 March 2002)	654,358
1423 (15 March 2002 – 3 March 2003)	708,160
1424 (4 March 2003 – 20 Feb 2004)	712,735
1425 (21 Feb 2004 – 8 Feb 2005)	730,144
1426 (9 Feb 2005 – 29 Jan 2006)	740,133
1427 (30 Jan 2006 – 19 Jan 2007)	720,928
1428 (20 Jan 2007 – 8 Jan 2008)	658,604
1429 (9 Jan 2008 – 27 Dec 2008)	586,365
1430 (28 Dec 2008 – 17 Dec 2009 25)	604,406
1431 (18 Dec 2009 – 6 Dec 2010)	602,507
1432 (7 Dec 2010 – 25 Nov 2011)	578,506

Table A. 2: Percentage of Waste Composition of Makkah for the Hijra year 1432H (7 Dec 2010 – 25 Nov 2011)

	Monthly Waste Composition (%)												
Waste Fraction	**Muharram** (7 Dec 2010 - 4 Jan 2011)	**Safar** (5 Jan 2011 – 3 Feb 2011)	**Rabee 1** (4 Feb 2011 – 5 March 2011)	**Rabee 2** (6 March 2011 – 4 Apr 2011)	**Jumad 1** (5 Apr 2011 – 3 May 2011)	**Jumad 2** (4 Jan May – 2 June 2011)	**Rajab** (3 June 2011 – 1 July 2011)	**Shaban** (2 July 2011 – 31 July 2011)	**Ramadan (Umrah Period)** (1 Aug 2011 – 29 Aug 2011)	**Shawal** (30 Aug 2011 – 28 Sep 2011)	**Thul Qida** (29 Sep 2011 – 27 Oct 2011)	**Thul Hijja (Hajj Period)** (28 Nov 2011 – 25 Nov 2011)	**Average**
cardboard	4.0	3.0	3.0	3.0	4.0	3.5	7.5	7.5	19.5	4.0	10.0	14.0	6.92
paper & N/P	2.5	2.0	2.0	2.5	2.0	3.0	1.3	1.3	1.5	3.0	4.0	4.0	2.43
plastic	5.5	4.0	4.0	5.0	4.0	4.0	6.8	6.8	8.5	5.0	9.0	10.0	6.05
steel	5.0	3.0	4.0	4.0	3.5	3.0	14.8	14.8	4.5	4.5	7.0	7.0	6.26
glass	3.0	2.5	2.5	3.0	3.5	4.0	2.8	2.8	5.0	5.5	3.0	5.0	3.55
aluminium	3.0	3.0	2.5	3.0	2.5	3.0	3.8	3.8	2.0	4.0	4.0	5.0	3.30
textile	4.0	3.0	4.5	4.0	3.0	3.0	4.5	4.5	20.0	4.0	5.0	8.0	5.63
wood	8.5	7.0	8.0	6.0	5.0	4.0	10.5	10.5	8.0	6.0	5.0	4.0	6.88
organic	64.5	72.5	69.5	69.5	72.5	72.5	48	48	31	64	53.0	43.0	59.00
total	100	100	100	100	100	100	100	100	100	100	100	100	100.00

Table A. 3: Amounts of Waste Composition of Makkah for the Hijra year 1432H (7 Dec 2010 – 25 Nov 2011)

	Monthly Waste Composition (tonnes)														
Waste Fraction	**Muharram** (7 Dec 2010 - 4 Jan 2011)	**Safar** (5 Jan 2011 – 3 Feb 2011)	**Rabee 1** (4 Feb 2011 – 5 March 2011)	**Rabee 2** (6 March 2011 – 4 Apr 2011)	**Jumad 1** (5 Apr 2011 – 3 May 2011)	**Jumad 2** (4 Jan May – 2 June 2011)	**Rajab** (3 June 2011 – 1 July 2011)	**Shaban** (2 July 2011 – 31 July 2011)	**Ramadan (Umrah Period)** (1 Aug 2011 – 29 Aug 2011)	**Shawal** (30 Aug 2011 – 28 Sep 2011)	**Thul Qida** (29 Sep 2011 – 27 Oct 2011)	**Thul Hijja (Hajj Period)** (28 Nov 2011 – 25 Nov 2011)	**total**	**Average for whole year**	**Average for non-pilgrimage Period**
cardboard	1,846	1,238	1,257	1,327	1,739	1,510	3,032	3,351	10,938	1,475	4,949	12,709	45,371	3,781	2,172
paper	1,154	825	838	1,106	869	1,294	525	,581	841	1,107	1,980	3,631	14,752	1,229	1,028
plastic	2,538	1,651	1,676	2,212	1,739	1,725	2,749	3,038	4,768	1,844	4,454	9,078	37,472	3,123	2,363
steel	2,308	1,238	1,676	1,770	1,522	1,294	5,983	6,612	2,524	1,660	3,464	6,355	36,404	3,034	2,753
glass	1,385	1,032	1,047	1,327	1,522	1,725	1,132	1,251	2,805	2,029	1,485	4,539	21,277	1,773	1,393
aluminium	1,385	1,238	1,047	1,327	1,087	1,294	1,536	1,698	1,122	1,475	1,980	4,539	19,728	1,644	1,407
textile	1,846	1,238	1,885	1,770	1,304	1,294	1,819	2,011	11,218	1,475	2,474	7,262	35,597	2,966	1,712
wood	3,923	2,889	3,351	2,655	2,174	1,725	4,244	4,691	4,487	2,213	2,474	3,631	38,458	3,205	3,034
organic	29,767	29,917	29,112	30,753	31,519	31,272	19,403	21,446	17,388	23,606	26,229	39,036	329,448	27,454	27,302
total	46,150	41,265	41,888	44,249	43,474	43,134	40,423	44,679	56,090	36,884	49,489	90,781	578,506	48,209	43,164

Table A. 4: Amounts of Collected Waste of Makkah and transported for the Hijra years 1429 H - 1432H

Hijra Year	Collected waste to:	Muharram	Safar	Rabee 1	Rabee 2	Jumad 1	Jumad 2	Rajab	Shaban	Ramadan (Umrah Period)	Shawal	Thul Qida	Thul Hijja (Haji Period)	total
1429 (9/1/2008 - 27/12/2008)	landfill	29,857	29,264	29,570	29,764	33,342	35,568	34,043	35,892	44,360	37,084	39,395	72,723	450,862
	Trans. St.	12,719	11,799	10,731	9,923	8,310	7,468	9,192	8,939	11,914	7,797	11,307	15,609	125,708
	Comp. Box	481	418	360	547	545	537	633	692	1,311	692	745	2,657	9,618
	G. Storage	0	0	0	0	0	0	0	0	0	0	0	3,177	3,177
	Total waste to LF	43,057	41,481	40,661	40,234	42,197	43,573	43,868	45,523	57,585	45,563	51,457	94,166	589,365
1430 (28/12/2008 - 16/12/2009)	landfill	33,359	33,598	34,824	32,749	34,093	36,254	35,359	38,265	42,244	36,755	36,152	68,673	462,325
	Trans. St.	11,313	11,357	10,094	9,388	8,941	8,157	7,652	7,428	13,000	11,125	13,350	16,904	128,709
	Comp. Box	483	431	475	609	649	628	631	682	1,104	635	616	2,268	9,211
	G. Storage	0	0	0	0	0	0	0	0	0	0	0	4,156	4,156
	Total waste to LF	45,155	45,386	45,393	42,746	43,683	45,039	43,642	46,375	56,348	48,515	50,118	92,001	604,401
1431 (18/12/2009 - 6/12/2010)	landfill	32,041	29,525	30,674	34,487	36,780	24,665	38,089	36,334	49,291	40,626	38,712	108,097	499,321
	Trans. St.	9,313	5,475	5,337	8,063	7,850	7,509	6,572	7,980	8,731	6,740	5,898	11,140	90,608
	Comp. Box	396	280	346	502	528	483	569	630	957	616	686	4,217	10,210
	G. Storage	0	0	0	0	0	0	0	0	0	0	0	3,368	3,368
	Total waste to LF	41,750	35,280	36,357	43,052	45,158	32,657	45,230	44,944	58,979	47,982	45,296	126,822	603,507
1432 (7/12/2010 - 25/11/2011)	landfill	37,926	32,570	33,181	35,145	35,902	35,379	33,167	37,275	43,775	25,465	39,121	73,567	462,473
	Trans. St.	7,708	8,297	8,268	8,563	6,992	7,257	6,758	6,707	11,198	10,685	9,728	11,633	103,794
	Comp. Box	516	398	439	541	580	498	498	697	1,117	734	640	2,197	8,855
	G. Storage	0	0	0	0	0	0	0	0	0	0	0	3,384	3,384
	Total waste to LF	46,150	41,265	41,888	44,249	43,474	43,134	40,423	44,679	56,090	36,884	49,489	90,781	578,506

APPENDIX B

Life Cycle Inventory (LCI)

B.1 INCINERATION

Table B. 1: Transfer coefficients of selected substances

Substances	Output air emission (% input)	APC residue (% input)	Bottom ash (% input)
H_2O	100	0	0
Ash	0	24.2	75.8
C-biological	100	0	0
C-fossil	100	0	0
Ca	0	11.4	88.6
Cl	7	81.8	11.2
K	0	38.9	61.1
Na	0	20.3	69.7
P	0	13.4	86.6
S	0.0862	53.6	46.31
Al	0	4.2	95.8
As	0.641	32.6	66.76
Cd	1.806	82.1	16.1
Cr	0.1875	8.3	91.51
Cu	0.0043	2.8	97.2
Fe	0	1.1	98.9
Hg	86.63	12.9	0.5
Mg	0	11.5	88.5
Mn	0.03	7	93
Mo	0.1743	15.3	84.53
Ni	0.138	2.8	97.06
Pb	0.089	31.1	68.81
Sn	0.1	23.7	76.2
Zn	0	47.3	52.7

Source ; Incineration dataset, (EASEWASTE, 2012)

B.2 Anaerobic digestion

Table B. 2: Percent degradation of material fractions in aerobic digestion process

Material fractions	Degradation compost (% TS)
Vegetable food waste	70%
Animals and excrements	70%
Animal food	70%
Yard waste and flowers	70%
Wood	5%
Newsprints	5%
Magazines	5%
Other cotton	5%
Other cardboard	5%
Milk carton	5%
Kitchen tissue	5%
Office paper	5%
Other clean paper	5%
Advertisement paper	5%
Cotton stick	5%
Cigarette buts	5%
Diaper & tampons	5%
Dirty cardboard	5%
Other cardboard	5%
Dirty paper	5%
Paper and cardboard container	5%
Books	5%
Textiles	5%
The rest fractions	0%

Source ; Anaerobic digestion dataset (EASEWASTE, 20012)

B.3 COMPOSTING

Table B. 3: Percent degradation of material fractions in composting process

Material fractions	Degradation compost (% TS)
Vegetable food waste	75.54%
Animals and excrements	73.54%
Animal food	73.54%
Yard waste and flowers	63.79%
Wood	20%
Newsprints	20%
Magazines	20%
Other cotton	10%
Milk carton	10%
Office paper	10%
Other clean paper	10%
Advertisement paper	10%
Diaper & tampons	10%
Dirty cardboard	10%
Other cardboard	10%
Dirty paper	10%
Paper and cardboard container	7%
Books	5%
Textiles	5%
Juice carton with aluminium	5%
The rest fractions	0%

Source ; Composting dataset (EASEWASTE, 2012)

APPENDIX C

Life Cycle Assessment

Table C. 1: Result of life cycle impact assessment

Scenario (SC0)

periods	GWP (kg CO2-eq)			SGR (m3)			RD (kg)		
	emissions	saving	net	emissions	saving	net	emissions	saving	net
non-pilgrimage	8.52E+08	0	8.52E+08	9.5E+08	0	9.5E+08	121	0	121
Umrah	4.41E+07	0	4.41E+07	1.2E+08	0	1.2E+08	15	0	15
Hajj	1.31E+08	0	1.31E+08	1.93E+08	0	1.93E+08	24	0	24
total	1.03E+09	0	1.03E+09	1.26E+09	0	1.26E+09	160	0	160

Scenario (SC1)

periods	GWP (kg CO2-eq)			SGR (m3)			RD (kg)		
	emissions	saving	net	emissions	saving	net	emissions	saving	net
non-pilgrimage	1.28E+08	-2.70E+08	-1.42E+08	53,479,320	0	53,479,321	50	-341	-292
Umrah	6.65E+05	-4.98E+07	-4.91E+07	6,760,077	0	6,760,077	7	-32	-25
Hajj	1.33E+07	-5.93E+07	-4.60E+07	10,448,184	0	10,448,185	10	-59	-49
total	1.28E+08	-2.70E+08	-1.42E+08	53,479,320	0	53,479,321	50	-341	-292

Scenario (SC2)

periods	GWP (kg CO2-eq)			SGR (m3)			RD (kg)		
	emissions	saving	net	emissions	saving	net	emissions	saving	net
non-pilgrimage	4.83E+06	-6.27E+08	-6.22E+08	2,645,663	0	2,645,663	70	-9,521	-9,451
Umrah	5.85E+05	-1.20E+08	-1.19E+08	1,087,727	0	1,087,727	11	-1,680	-1,669
Hajj	8.99E+05	-1.01E+08	-1.00E+08	3,170,366	0	3,170,367	22	-1,307	-1,286
total	6.31E+06	-8.48E+08	-8.41E+08	6,903,757	0	6,903,757	103	-12,509	-12,406

Scenario (SC3)

periods	GWP (kg CO2-eq)			SGR (m3)			RD (kg)		
	emissions	saving	net	emissions	saving	net	emissions	saving	net
non-pilgrimage	5.52E+07	-1.80E+08	-1.25E+08	15,900,362	0	15,900,362	433	-24,177	-23,743
Umrah	6.65E+06	-2.03E+07	-1.36E+07	3,176,349	0	3,176,349	47	-1,450	-1,403
Hajj	5.93E+06	-3.90E+07	-3.30E+07	4,674,686	0	4,674,686	55	-3,293	-3,237
total	6.78E+07	-2.39E+08	-1.72E+08	23,751,397	0	23,751,397	536	-28,920	-28,384

Scenario (SC4)

periods	GWP (kg CO2-eq)			SGR (m3)			RD (kg)		
	emissions	saving	net	emissions	saving	net	emissions	saving	net
non-pilgrimage	2.94E+08	-1.76E+08	1.18E+08	3,333,400	0	3,333,400	227	-24,496	-24,268
Umrah	1.69E+06	-4.02E+07	-3.85E+07	1,192,612	0	1,192,612	23	-1,601	-1,577
Hajj	1.98E+06	-4.14E+07	-3.94E+07	3,275,156	0	3,275,156	28	-3,392	-3,363
total	2.98E+08	-2.57E+08	4.03E+07	7,801,168	0	7,801,168	279	-29,489	-29,209

Scenario (SC5)

periods	GWP (kg CO2-eq)			SGR (m3)			RD (kg)		
	emissions	saving	net	emissions	saving	net	emissions	saving	net
non-pilgrimage	4.63E+06	-2.49E+08	-2.45E+08	13,599,050	0	13,599,049	346	-11,303	-10,958
Umrah	5.68E+05	-4.27E+07	-4.22E+07	2,234,983	0	2,234,983	33	-1,102	-1,069
Hajj	8.85E+05	-4.30E+07	-4.21E+07	1,976,632	0	1,976,631	21	-1,551	-1,530
total	6.08E+06	-3.35E+08	-3.29E+08	17,810,665	0	17,810,664	400	-13,957	-13,557

Scenario (SC6)

periods	GWP (kg CO2-eq)			SGR (m3)			RD (kg)		
	emissions	saving	net	emissions	saving	net	emissions	saving	net
non-pilgrimage	4.11E+07	-1.58E+08	-1.17E+08	28,409,238	0	28,409,238	112	-11,432	-11,320
Umrah	4.30E+06	-3.54E+07	-3.11E+07	3,498,690	0	3,498,690	15	-606	-591
Hajj	1.48E+06	-4.24E+07	-4.09E+07	5,580,707	0	5,580,707	25	-1,036	-1,011
total	4.69E+07	-2.36E+08	-1.89E+08	37,488,636	0	37,488,636	153	-13,074	-12,921

Table C. 2: Normalisation of impact potentials

Global Warming 100 Years (EDIP97): [PE]

WM Scenario	Non-pilgrimage	Hajj Period	Umrah Period	Total
SC0	6.64E+04	1.52E+04	5.08E+03	8.63E+04
SC1	-1.20E+04	-1.91E+03	-5.99E+02	-1.45E+04
SC2	-4.82E+04	-1.15E+04	-1.37E+04	-7.34E+04
SC3	-9.69E+03	-3.80E+03	-1.57E+03	-1.50E+04
SC4	9.16E+03	-4.53E+03	-4.43E+03	2.10E+02
SC5	-1.90E+04	-4.84E+03	-4.85E+03	-2.87E+04
SC6	-9.04E+03	-4.67E+03	-3.57E+03	-1.73E+04

Spoiled Groundwater Resources: [PE]

WM Scenario	Non-pilgrimage	Hajj Period	Umrah Period	Total
SC0	2.18E+04	4.67E+04	2.91E+04	9.77E+04
SC1	4.88E+03	1.05E+04	6.49E+03	2.19E+04
SC2	6.15E+02	1.09E+03	3.75E+02	2.08E+03
SC3	3.70E+03	1.61E+03	1.10E+03	6.40E+03
SC4	7.75E+02	1.13E+03	4.11E+02	2.32E+03
SC5	3.16E+03	6.82E+02	7.71E+02	4.61E+03
SC6	6.61E+03	1.92E+03	1.21E+03	9.74E+03

Resource Depletion - Aggregated: [PE]

WM Scenario	Non-pilgrimage	Hajj Period	Umrah Period	Total
SC0	1.20E+02	3.53E+01	2.24E+01	1.78E+02
SC1	-2.16E+02	-5.32E+01	-2.64E+01	-2.95E+02
SC2	-7.80E+03	-1.57E+03	-2.04E+03	-1.14E+04
SC3	-1.96E+04	-3.96E+03	-1.72E+03	-2.53E+04
SC4	-2.00E+04	-4.12E+03	-1.93E+03	-2.61E+04
SC5	-9.04E+03	-1.87E+03	-1.31E+03	-1.22E+04
SC6	-9.34E+03	-1.24E+03	-7.23E+02	-1.13E+04

APPENDIX D

Other Results from EASEWASTE

Table D. 1: Results of Landfilling processes (in terms of Gas Collection)

scenario	period	duration (days)	waste ammount (tons)	Gas Collection		
				uncollected gas	collected gas (electricity recovery)	collected gas (flare)
SC0	non-pilgrimage	297	431,260	1.24E+08	0.00E+00	0.00E+00
	Umrah	29	56,093	1.30E+07	0.00E+00	0.00E+00
	Hajj	29	90,734	2.33E+07	0.00E+00	0.00E+00
	total	355	578,088	1.61E+08	0.00E+00	0.00E+00
SC1	non-pilgrimage	297	431,260	4.85E+07	2.07E+07	1.66E+07
	Umrah	29	56,093	5.06E+06	2.13E+06	1.71E+06
	Hajj	29	90,734	9.06E+06	3.82E+06	3.06E+06
	total	355	578,088	6.26E+07	2.67E+07	2.14E+07
SC2	non-pilgrimage	297	104,165	4.55E+06	0.00E+00	5.79E+06
	Umrah	29	24,126	1.60E+06	0.00E+00	2.03E+06
	Hajj	29	58,796	5.18E+06	0.00E+00	6.59E+06
	total	355	187,087	1.13E+07	0.00E+00	1.44E+07
SC3	non-pilgrimage	297	71,462	8.38E+06	0.00E+00	1.07E+07
	Umrah	29	24,703	2.45E+06	0.00E+00	3.11E+06
	Hajj	29	57,531	5.79E+06	0.00E+00	7.37E+06
	total	355	153,696	1.66E+07	0.00E+00	2.11E+07
SC4	non-pilgrimage	297	40,970	4.55E+06	0.00E+00	5.79E+06
	Umrah	29	17,950	1.60E+06	0.00E+00	2.03E+06
	Hajj	29	52,626	5.18E+06	0.00E+00	6.59E+06
	total	355	111,545	1.13E+07	0.00E+00	1.44E+07
SC5	non-pilgrimage	297	228,815	1.67E+07	0.00E+00	1.69E+07
	Umrah	29	52,866	3.39E+06	0.00E+00	3.45E+06
	Hajj	29	112,995	7.51E+06	0.00E+00	7.64E+06
	total	355	394,676	2.75E+07	0.00E+00	2.80E+07
SC6	non-pilgrimage	297	326,065	3.33E+07	0.00E+00	3.39E+07
	Umrah	29	49,305	3.53E+06	0.00E+00	3.60E+06
	Hajj	29	92,277	8.49E+06	0.00E+00	8.67E+06
	total	355	467647	4.53E+07	0.00E+00	4.62E+07

Table D. 2: Results of Landfilling processes (in terms of Leachate Collection)

scenario	period	duration (days)	waste ammount (tons)	Gas Collection		
				Uncollected gas	Collected gas (electricity recovery)	Collected gas (flare)
SC0	non-pilgrimage	297	431,260	2.28E+06	0.00E+00	0.00E+00
	Umrah	29	56,093	2.97E+05	0.00E+00	0.00E+00
	Hajj	29	90,734	4.79E+05	0.00E+00	0.00E+00
	total	355	578,088	3.06E+06	0.00E+00	0.00E+00
SC1	non-pilgrimage	297	431,260	7.18E+05	1.26E+06	3.39E+05
	Umrah	29	56,093	9.33E+04	1.64E+05	4.41E+04
	Hajj	29	90,734	1.48E+05	2.65E+05	7.13E+04
	total	355	578,088	9.59E+05	1.69E+06	4.54E+05
SC2	non-pilgrimage	297	104,165	2.53E+04	1.56E+05	6.89E+04
	Umrah	29	24,126	5.30E+03	2.99E+04	1.04E+04
	Hajj	29	58,796	1.23E+04	6.44E+04	2.07E+04
	total	355	187,087	4.29E+04	2.50E+05	1.00E+05
SC3	non-pilgrimage	297	71,462	8.92E+04	7.11E+04	2.12E+04
	Umrah	29	24,703	5.00E+03	2.46E+04	7.33E+03
	Hajj	29	57,531	1.16E+04	5.65E+04	1.71E+04
	total	355	153,696	1.06E+05	1.52E+05	4.56E+04
SC4	non-pilgrimage	297	40,970	4.98E+04	4.08E+04	1.21E+04
	Umrah	29	17,950	2.18E+03	1.79E+04	5.33E+03
	Hajj	29	52,626	6.39E+03	5.16E+04	1.57E+04
	total	355	111,545	5.84E+04	1.10E+05	3.31E+04
SC5	non-pilgrimage	297	228,815	1.81E+04	1.28E+05	3.17E+04
	Umrah	29	52,866	4.06E+03	2.93E+04	7.65E+03
	Hajj	29	112,995	1.50E+04	6.30E+04	1.68E+04
	total	355	394,676	3.72E+04	2.21E+05	5.61E+04
SC6	non-pilgrimage	297	326,065	5.27E+04	2.59E+05	7.74E+04
	Umrah	29	49,305	7.97E+03	3.92E+04	1.17E+04
	Hajj	29	92,277	1.49E+04	7.35E+04	2.19E+04
	total	355	467647	7.55E+04	3.72E+05	1.11E+05

Table D. 3: Outputs of recycled materials from the studied scenarios

scenario	period	duration (days)	recycled materials (tons)				
			paper	cardboard	Aluminium	steel	plastics
SC0	non-pilgrimage	297	0	0	0	0	0
	Umrah	29	0	0	0	0	0
	Hajj	29	0	0	0	0	0
	total	355	0	0	0	0	0
SC1	non-pilgrimage	297	0	0	0	0	0
	Umrah	29	0	0	0	0	0
	Hajj	29	0	0	0	0	0
	total	355	0	0	0	0	0
SC2	non-pilgrimage	297	0	0	0	0	0
	Umrah	29	0	0	0	0	0
	Hajj	29	0	0	0	0	0
	total	355	0	0	0	0	0
SC3	non-pilgrimage	297	0	0	1.27E+04	2.49E+04	0
	Umrah	29	0	0	7.63E+02	1.72E+03	0
	Hajj	29	0	0	1.91E+03	2.67E+03	0
	total	355	0	0	1.54E+04	2.92E+04	0
SC4	non-pilgrimage	297	0	0	1.27E+04	2.49E+04	0
	Umrah	29	0	0	7.63E+02	1.72E+03	0
	Hajj	29	0	0	1.91E+03	2.67E+03	0
	total	355	0	0	1.54E+04	2.92E+04	0
SC5	non-pilgrimage	297	2,555	6,184	3,456	6,495	6,087
	Umrah	29	119	1,784	154	334	697
	Hajj	29	276	1,106	335	451	7,10
	total	355	2,950	9,074	3,945	7,280	7,494
SC6	non-pilgrimage	297	3,585	7,962	4,869	9,226	8,315
	Umrah	29	256	3,506	334	729	1,460
	Hajj	29	585	2,144	712	967	1,465
	total	355	4,425	13,611	5,915	10,921	11,241