Life Cycle Assessment and Cost-Benefit Analysis of Landfill Mining at the City of Denton Landfill

by

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Abstract

LIFE CYCLE ASSESSMENT AND COST-BENEFIT ANALYSIS OF LANDFILL MINING AT THE CITY OF DENTON LANDFILL

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The concept of landfill mining has evolved the way of transforming the existing landfills from a final waste disposal site to a temporary storage location for the potentially valuable resources. The convergence of the sustainable material management and environmental protection issues have emerged the demand for the feasibility study of the landfill mining both in environmental and economic aspects considering the scope of potential resource recovery. Few studies have been conducted either on the environmental impacts on waste management (especially incineration) and operational options or generalized cost-benefit estimation for landfill mining project. Therefore, the present study aims to evaluate both the environmental and economic feasibility of an unlined cell (cell 1590A) of the City of Denton Landfill (Texas) which is containing approximately 2.6 million tons of Municipal Solid Waste (MSW) for around 30 years. Life Cycle Assessment (LCA) and Cost-benefit Analysis (CBA) has been adopted as analyzing tools for the environmental and economic studies respectively. Two landfill mining alternatives (mining with waste relocation and mining with material recovery) were compared with no-mining (do-nothing) condition for both of the approaches. Comparative LCA results showed that the mining of 1 ton of MSW with material recovery can reduce about 0.1 million kg of equivalent CO_2 than no-mining condition of landfill which worth of removing about 21 thousand cars from road per year. In cost benefit analysis the landfill mining with material recovery has been found to achieve a benefit to cost ratio of 2.20 gaining $37.4 million of total net benefit which worth a total Net Present Value (NPV) of $34.1 million in 10 years of project period. Therefore, the landfill mining with material recovery has been found to be most feasible options among the alternatives in both environmental and economic analysis. Separate LCA studies have been conducted to assess the energy saving potential of reusing the mined papers and plastics instead of virgin materials for producing plastic lumber and paperboard respectively. The reusing of mined plastics and papers have been found to save 1.8 million MJ and 2300 MJ of energy respectively for 1 ton of functional unit of product. It can also reduce about 0.4 million and 1300 kg of equivalent CO_2 as well for 1 ton of plastics and papers respectively which is worth of removing 85 thousand and 276 cars from road per year respectively.

Although the environmental and economic profiles of landfill mining would vary from case to case, the results of these analyses can be used as a baseline for future landfill mining projects.

Table of Contents

List of Illustrations

List of Tables

List of Figures

Chapter 1

Introduction

1.1 Background

Waste management is becoming challenging day by day due to the global awareness for environmental protection, sustainable development in material management and campaign of recycling and reusing materials as well as worldwide space and economic constraints. The worldwide municipal solid waste management techniques have shifted to different pattern during last 50 years as shown in Figure 1-1. Though in the solid waste management hierarchy landfilling is least preferred option, it is still the most practiced approach of waste management in USA (USEPA, 2016).

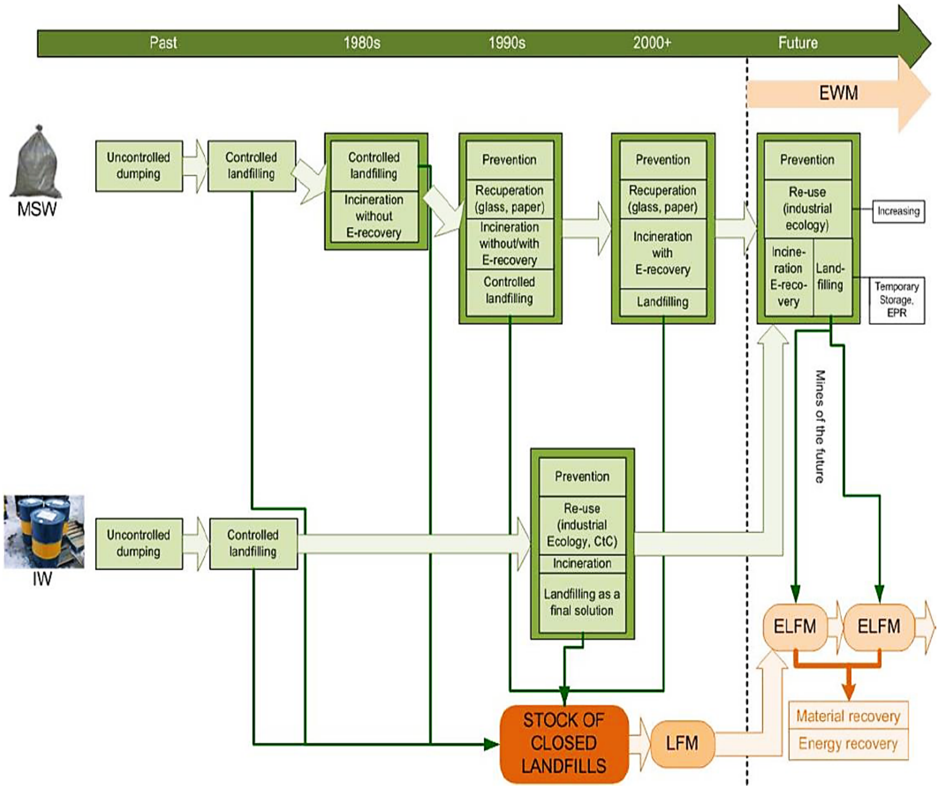


Figure 1-1 Schematic overview of the historic and future evolution of waste management (Jones et al. 2010, Danthurebandara, 2015)

In USA 136 million tons of waste (52.6%) of the total generated waste was landfilled in 2014 (US EPA, 2016). The major concerning factors about landfills are; (1) the environmental contaminations, (2) space and (3) post closure care challenges.

Last century's landfills have still high emission potential after 50 years, even though post closure monitoring period for closed landfills are 30 years. Therefore, they need longer term post-operation monitoring period (Sormunen, 2013). In 1990s, strict proclamation was enforced to the landfills to reduce environmental contamination and public health threats. Landfilling (without material recovery) has become problematic due to the monitoring as per regulation, proper management, and large space consumption. Moreover, waste management has been progressed to emphasis more strongly on the 3R concept which are reduce, reuse and recycle (Danthurebandara, 2015). Therefore, landfill mining has become popular in aspects of environmental protection, air spaces recovery and reuse of the historic landfilled wastes.

1.2 Problem statement

It has become crucial to conduct environmental evaluation of significant projects with the worldwide growing interests for environmental protection (Frändegård et al., 2013). Likewise, for a full-scale landfill mining project, it is mandatory to assess the environmental impact for evaluating the feasibility of the project which would facilitate to get permits from the regulatory agencies as well. One of the most effective tool to assess that is the Life Cycle Assessment (LCA). Moreover, generally a significant amount of financial investment is involved with any mining project which demands for accurate investigation of insight of profitability of the mining project for final decision of the project initiation. A popular approach to the assessment of the financial feasibility is cost-benefit analysis. However, the literature related to landfill mining is insufficient due to the variability and innovative nature of the mining concept. Few Life Cycle Assessment studies were conducted on the landfill mining mainly focusing on the valorisation of the mined materials with waste-to-energy facility, mining operational options, and end-use management options of mining (Danthurebandara et al., 2015, Gusca et al., 2014, Jain et al., 2014). And few studies were performed on the cost-benefit analysis of landfill mining (Zhou et al., 2014, Vossen et al., 2011, Rosendal et al., 2009). Therefore, there are very limited studies which were performed on the feasibility of landfill mining broadly for both environmental and economic aspects considering the scope of recycling of the mined materials as well. Therefore, it is important to conduct a feasibility analysis comprehensively on a specific landfill mining project considering its environmental impacts, financial scopes and recycle potential of the historic landfilled wastes.

1.3 Research objectives

The main objective of the current research is to evaluate the environmental and economic feasibility of landfill mining project of cell-0 of the City of Denton landfill. The material recovery from the mining of the landfill can make both financial profit and environmental benefit by replacing the virgin materials. And each landfill mining project is unique in aspects of location, market condition and operational considerations. Therefore, it necessary to investigate the feasibility of this landfill mining project in details. For this purpose, life cycle assessment and cost-benefit analysis considering the reuse potential of the mined waste materials were conducted to fulfill to the following objectives:

1. To evaluate the environmental feasibility of the landfill mining project of the City of Denton landfill, Texas.

2. To investigate the financial feasibility of landfill mining project of the City of Denton landfill, Texas.

3. To assess the environmental impact of recycling the mined waste materials specially the scope of the mined papers and plastics.

1.4 Thesis outline

The overall thesis is organized in the following chapters:

Chapter 1 includes the overall introduction along with the problem statement and objective of the study.

Chapter 2 presents a literature review on landfill, characteristics of landfilled wastes, landfill emissions, landfill mining, history, purpose and general process of landfill mining, material recovery potential from landfill mining, environmental and economic feasibility of landfill mining, concept of cost-benefit analysis and life cycle assessment and the implementation of LCA on landfill mining projects.

Chapter 3 describes the implemented methodologies and considerations to fulfill the research objectives. It includes the description of the different scenarios considered for the feasibility study for both in life cycle assessment and cost-benefit analysis.

Chapter 4 mainly focuses on the results obtained from the individual life cycle assessments and cost-benefit analyses of different scenarios and comparative analyses of the scenarios.

Chapter 5 summarizes the results and main conclusions obtained from this study along with the recommendations for future work.

Chapter 2

Literature Review

2.1 Landfill

A landfill is an engineering method of final disposal of waste into land having soil layers in between of the waste layers. Krook et al., 2012 defined landfill as a large area of land or an excavated site which is designed to receive wastes. Including United States in many regions of the world landfilling practice has been the common way to store waste at minimum cost. According to Danthurebandara (2015), a modern landfill is an engineered method for waste disposal into protected or specially constructed on land surface or in excavations into land surface. Landfill location, design, operation and monitoring are designed to ensure compliance with federal regulations (USEPA). Although in United States the waste recycling rate has increased significantly during last decades, among the waste management practices landfilling is still the most popular and most practiced method. US Air Quality Bureau (2010) defined closed landfill as a landfill where municipal solid wastes will no longer be placed. At present, in DFW and North Texas area there are more than 40 (forty) Municipal solid waste landfills (Samir. S., 2011).

2.1.1 Classification of landfills

According to US Environmental Protection Agency (EPA), a modern landfill is well engineered facility which is designed for receiving a specific types of wastes, municipal solid waste (MSW), construction and demolition debris (C&D) and hazardous waste. The landfills are classified according to the regulation principal of the Resource Conservation and Recovery Act (40 CFR Part 258 in Federal regulations 1991). Subtitle D landfills include the following:

- Municipal Solid Waste Landfills (MSWLFs) – Specifically designed to receive household waste, as well as other types of nonhazardous wastes.

- Bioreactor Landfills – A type of MSWLF that operates to rapidly transform and degrade organic waste
- Industrial Waste Landfill – Designed to collect commercial and institutional (i.e. industrial waste), which is often a significant portion of solid waste, even in small cities and suburbs.
- Construction and Demolition (C&D) Debris Landfill – A type of industrial waste landfill designed exclusively for construction and demolition materials, which consists of the debris generated during the construction, renovation and demolition of buildings, roads and bridges. C&D materials often contain bulky, heavy materials, such as concrete, wood, metals, glass and salvaged building components
- Coal Combustion Residual (CCR) landfills – An industrial waste landfill used to manage and dispose of coal combustion residuals (CCRs or coal ash)

Whereas, Subtitle C landfills including the following:

- Hazardous Waste Landfills - Facilities used specifically for the disposal of hazardous waste. These landfills are not used for the disposal of solid waste.

2.2 Characteristics of land-filled municipal solid wastes

According to the US EPA, Municipal solid waste (MSW) is the waste collected through community sanitation services. Municipal solid waste is denoted as trash or garbage which are discarded every day after use such as, food residuals, clothing, newspapers, bottles, paint, product packaging, furniture, appliances, grass clippings and batteries generated from households, institutions like schools, hospitals, and businesses. The MSW can be waste components of different categories such as including paper products, glass, metal, plastics, rubber and leather, textiles, wood, food wastes, yard trimmings, and miscellaneous inorganic wastes (Alam. Z., 2016). The municipal solid waste which was disposed earlier is defined as the landfilled waste. There characteristics of landfilled wastes depend on the location, community, type of landfill, depth of filling, age of waste, moisture content etc. Many studies have been conducted to determine these waste characteristic parameters of MSW. It is difficult to determine the characteristics of the MSW due to the following reasons as mentioned by Samir (2011) and Manassero et.al (1997):

- It is difficult to obtain samples of large enough size to be representative of in situ condition
- There are no generally accepted sampling procedure for waste materials
- The properties of waste materials change drastically with time
- The level of training and education of the personnel on site may be not high enough to deal with all necessary basic interpretations and understanding of the measurements, and
- Municipal solid waste is inherently heterogeneous and variable among different geographical locations

2.2.1 Physical composition of MSW

The physical composition of waste shows the type and proportions (commonly weight basic percentages) of waste components present in the waste stream (Samir. S. 2011). Jain, P., et al, 2013 estimated the physical composition of reclaimed materials (including the final cover soil) from unlined cells of the Perdido landfill in Escambia County which is shown in Figure 2-1. Reclaimed soil was included predominantly as the aim of the study was more likely to estimate the air space gain from the reclamation of the landfill cell.

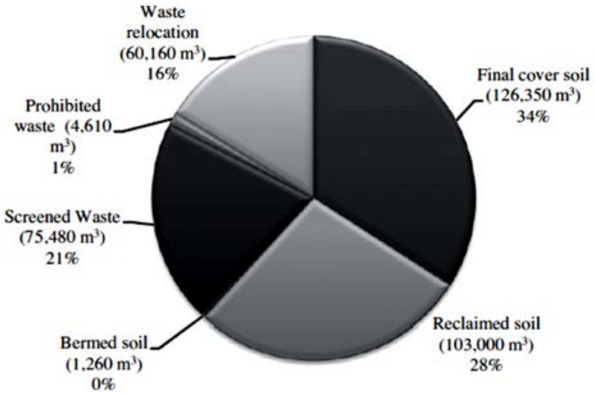


Figure 2-1 Distribution of various constituents of the mined material (Jain, P., et al, 2013)

Samir, S. 2011 determined MSW waste composition of a 25 years old conventional cell (named as Cell 1590) of City of Denton. Solid waste samples were collected from 2 boreholes (B70 and B72) by using Hydraulic Drill Rig. Six samples were collected from each borehole starting at 10 ft depth and then at every 10 ft interval up to 60 ft. the wastes were separated manually into paper, plastic, food waste, leather & textile, wood & yard waste, metals, glass, styrofoam and sponge, others (soil & fines), and construction debris. The waste components and the average waste composition found from two borings are presented in Figure 2-2 and Figure 2-3 respectively.

Figure 2-2 Average Composition of Landfilled Waste (Samir, 2011)

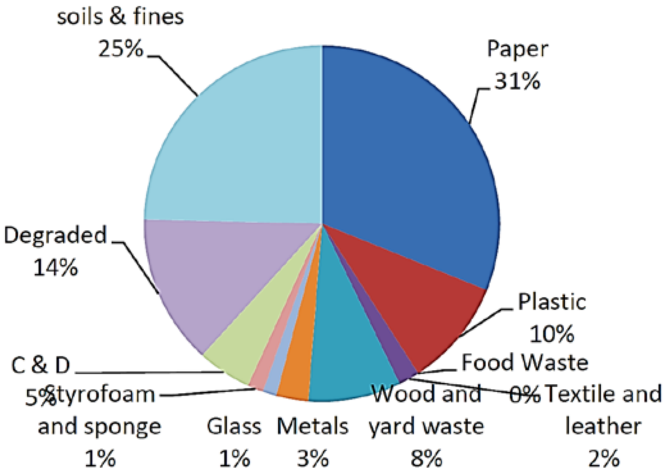


Figure 2-3 Waste components (Samir, 2011)

Another study on waste characterization of same study area was conducted by Koganti, 2015. The waste was collected from 3 boreholes in 2015 (BH-05 to BH-07) and separated manually into similar categories. The physical composition found by the study is shown in Figure 2-4.

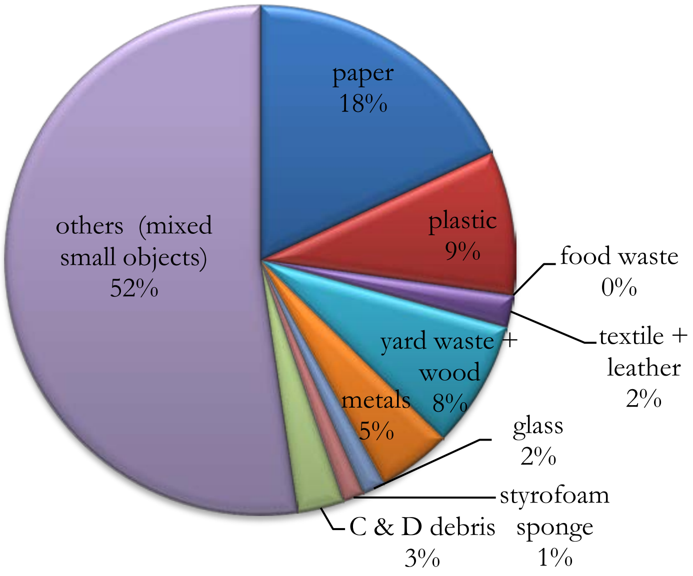


Figure 2-4 Physical Composition of mined wastes (Koganti, 2015)

2.2.2 Unit weight of MSW

Unit weight of MSW is an important characteristics of MSW for waste stability, landfill capacity and waste recovery. The unit weight depends on depth of filling, composition of wastes, compaction of wastes and type of waste. Unit weight of MSW found by many researchers are enlisted in Table 2-1.

Table 2-1 Comparison of unit weight of MSW samples (Koganti, 2015)

Reference	Unit Weight (pcf)	conditions	Remarks
Gabr & Valero (1995)	47.08 to 52.18	14 to 30 years old waste	
Reddy et.al (2009)	37.46 to 38.41	Working face	Orchard Hills Landfill
Vesilind et. al (2002)	23.3	Collection Truck	
	25.93 to 62.96	Landfilled (with cover soil)	
Yousuf & Rahman (2207)	14.36	Wet season	Dhaka City, Bangladesh
Landva & Clark	43.27 to 103		Canada
Chenet.al(2009)	31.82 to 95.46	Increases with depth	China
Hanet.al(2006)	62.4	Average	Sand town Landfill, Delaware
Cell0(2014)	66.12	Average	Cityof Denton Landfill
Cell0(2015)	86.32	Average	City of Denton Landfill
Cell2(2014)	50.47	Average	City of Denton Landfill
Cell3(2015)	80.62	Average	City of Denton Landfill
FreshWaste	59.76	Average	City of Denton Landfill

2.1.1 Volatile Organic Content (VOC) of MSW

The volatile organic content represents the degradability of MSW. With the VOC test, the quality of the landfilled wastes can be determined in aspects of decomposition of waste and gas generation potential. Samir, S. conducted VOC test on the waste samples collected from cell-0 of city of Denton Landfill. Two samples were collected named boring 70 and boring 72. Based on the test results, average volatile solids (VS) of all landfilled samples was determined to be 63.1%. It means there is 63.1% organic content which is degradable and the wastes may decompose resulting in producing landfill gas.

Table 2-2 Organic content of landfilled MSW (Samir, 2011)

10	**Boring70@ depth,ft**	**Year**	**Age, Year**	**VS (%)**	**Borehole**	**Boring72@ depth,ft**	**Year**	**Age, Year**	**VS (%)**
B-70	10	2001	9	85.79	B-72	10	2001	9	5
	20	1997	13	45.3		20	1999	11	20.2
	30	1994	16	59.28		30	1997	13	42.61
	40	1991	19	86.84		40	1994	16	83.9
	50	1988	22	82.57		50	1991	19	77.69
	60	1985	25	73.95		60	1989	21	82.8
	Average			72.29		Average			61.44
	Standard Deviation			16.73					34.45
	Maximum			86.84		Maximum			83.9
	Minimum			45.3		Minimum			20.2
Average=63.08									

2.2 Landfill emissions

Landfill gas and leachate are the major emissions of landfills along with wind-blown litter, vermin and insects which are known as the minor emissions (Danthurebandara, 2015). The landfill ecosystem is quite varied due to the heterogeneous nature of waste, the diversity of landfill operating characteristics and influence by environmental conditions such as temperature, pH, the presence of toxins, moisture content and the oxidation reduction potential (Danthurebandara, 2015).

2.2.1 Landfill gas

According to USEPA (2015), in context of carbon flows within a landfill system, carbon entering the landfill can have one of several fates: exit as CH4, exit as CO2, exit as volatile organic compounds (VOCs), exit dissolved in leachate, or remain stored in the landfill. Methane emissions from landfills are reported to vary from 0.0004 to 4000 g-CH4/m2/day (Bogner et al., 1997b). The biodegradable portion of the Municipal Solid Wastes (MSW) decomposes and is transformed into landfill gas and/or leachate eventually. The phases of gas generation from the landfill discussed in the following (Bove, R. 2006):

1. Aerobic decomposition. In this phase, wastes are digested by bacteria, in the presence of air. Heat is produced, while O2 is consumed for CO2 production. The time frame, depending on specific conditions, ranges from months to one year.

2. Acidogenic. In this phase, anaerobic conditions are established. As results, H2, CO2, H2O and organic acids are produced. Because of the anaerobic conditions, the energy release rate is low. Because of acid formation, the leachate pH can drop below 5.

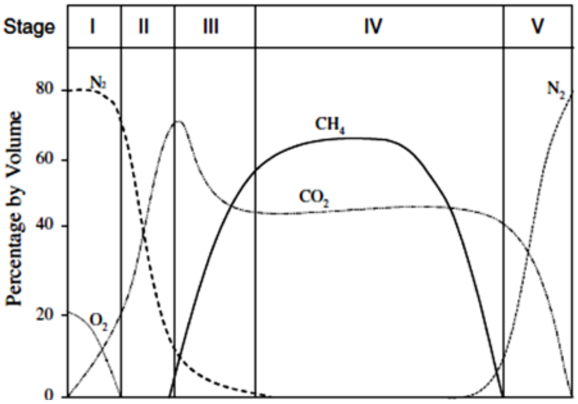


Figure 2-5 Landfill gas composition during the five phases (Bove, R. 2006)

3. Acetogenesis. In this phase, the oxidation of acids and alcohols to acetic acids plus CO2 and H2 takes place. The chemical oxygen demand (COD) noticeably increases due to the dissolution of acids and the leachate.

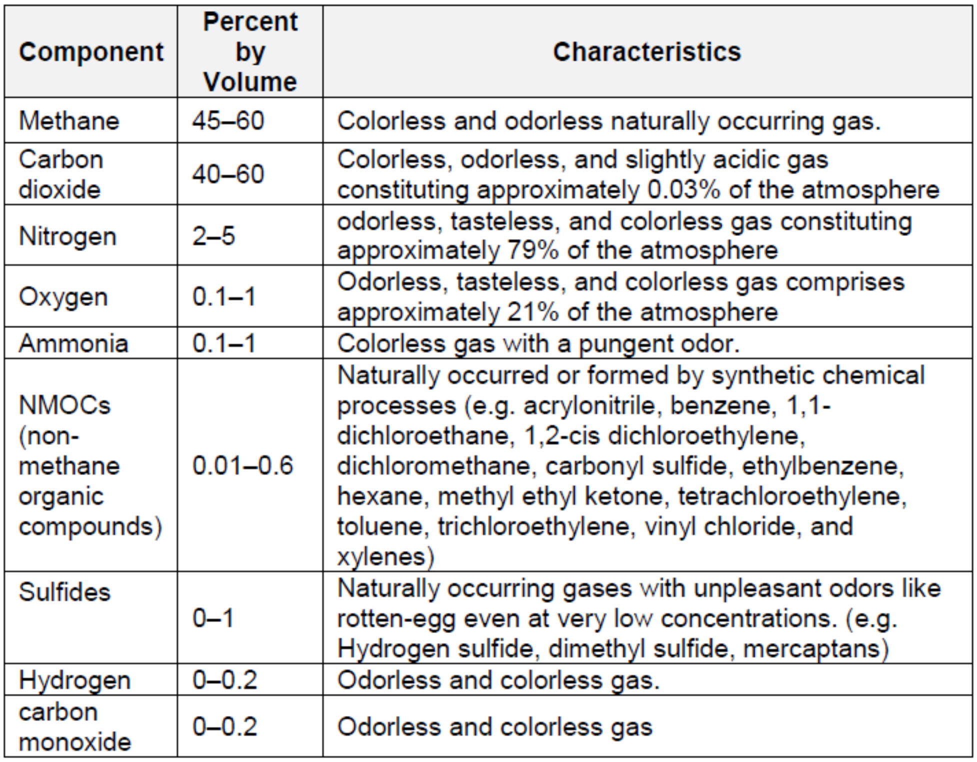
4. Methanogenesis. Products of acetogensis are converted to methane and CO2, and H2 is consumed. The methane content depends on the available substrates.

5. Maturation. Because of substrate depletion, gas production drops-off.

The quantity and timing of CH4 emissions released from the landfill depends upon three factors: (1) how much of the original material decays into CH4, (2) how readily the material decays under different landfill moisture conditions, and (3) landfill gas collection practices (USEPA, 2015). Landfills emit 1.3 tons equivalent CO2 per tons of landfilled waste without any gas collection system while this value cuts down to 0.6 when the landfill gas is used to produce electricity (Cherubini et al. 2009). A Life Cycle Assessment performed by Damgaard, et al. (2011) revealed that landfills are one of the main contributors for global warming when they are not facilitated with proper gas collection technologies.

The organic or degradable fraction of MSW includes paper, food waste, textiles and leathers, and yard trimmings and wood. Landfill gas comprises of methane, carbon dioxides and water together with some traces of other gases (Sapkota, A., 2017). The typical landfill gas components in percentage are shown below in Table 2-3.

Table 2-3 Typical landfill gas components (Tchobanoglous et. al, 1993, Sapkota, A, 2017)



Component	Percent by Volume	Characteristics
Methane	45–60	Colorless and odorless naturally occurring gas.
Carbon dioxide	40–60	Colorless, odorless, and slightly acidic gas constituting approximately 0.03% of the atmosphere
Nitrogen	2–5	odorless, tasteless, and colorless gas constituting approximately 79% of the atmosphere
Oxygen	0.1–1	Odorless, tasteless, and colorless gas comprises approximately 21% of the atmosphere
Ammonia	0.1–1	Colorless gas with a pungent odor.
NMOCs (non-methane organic compounds)	0.01–0.6	Naturally occurred or formed by synthetic chemical processes (e.g. acrylonitrile, benzene, 1,1-dichloroethane, 1,2-cis dichloroethylene, dichloromethane, carbonyl sulfide, ethylbenzene, hexane, methyl ethyl ketone, tetrachloroethylene, toluene, trichloroethylene, vinyl chloride, and xylenes)
Sulfides	0–1	Naturally occurring gases with unpleasant odors like rotten-egg even at very low concentrations. (e.g. Hydrogen sulfide, dimethyl sulfide, mercaptans)
Hydrogen	0–0.2	Odorless and colorless gas.
carbon monoxide	0–0.2	Odorless and colorless gas

In many landfills there is no available gas collection system in their facility, thus allowing free movement of methane from the landfill envelope to the surface. Even with presence of gas collection system in a landfill, the efficiency of the landfill gas recovery remains uncertain and the uncollected LFG might still migrate from the landfill envelope. A major part of escaping LFG travels upward; however, only a fraction the migrating gas is oxidized in the cover and the rest is emitted to the atmosphere. These emitting gases increase the global warming potential by entrapping the heat in the atmosphere (Samir, 2014).

For emission reduction Methane has become a target due to its higher effectiveness as a greenhouse gas (Samir, 2014). Landfills have been reported to be a major source of greenhouse gas emissions (USEPA, 2005). Municipal solid waste (MSW) landfills are the third-largest source of human-related methane emissions in the United States, accounting for approximately 15.4 percent of these emissions in 2015. Landfill gas (LFG) is a natural byproduct of the decomposition of organic material in landfills. Methane is a potent greenhouse gas 28 to 36 times more effective than CO2 at trapping heat in the atmosphere over a 100-year period due to its ability to retain infrared radiation (USEPA, 2015). Stern and Kaufmann (1996) stated that approximately 12% of worldwide methane emissions are caused by the decomposition of waste within landfills (Samir, 2014). According to USEPA (1990-2015) stated that landfills are the third largest source of methane emissions in the United States, with 18% of total methane emissions originating from landfills (Figure 2-6).

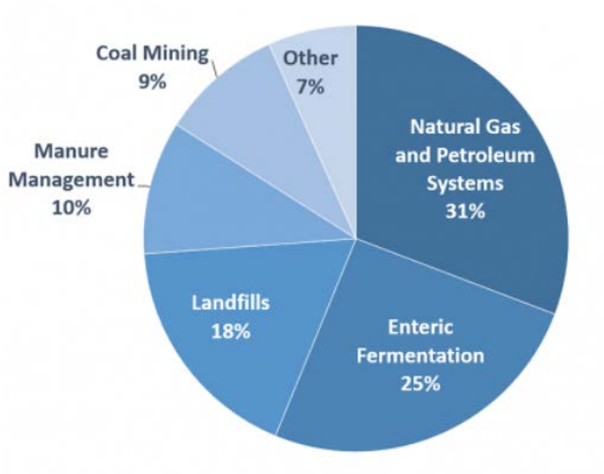


Figure 2-6 U.S. Methane Emissions (2015), By Sources Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2015.

2.2.2 Leachate

Leachate is defined as any liquid percolating through the wastes being either confined or leaching from the landfill. When the leachate flows through the wastes it takes the suspended and soluble materials with it which are originated due to the waste decomposition. The organic contents or the organic strength of leachate is normally measured in terms of biochemical oxygen demand (BOD), chemical oxygen demand (COD), or total organic carbon (TOC) (Crowley et al. 2003, Danthurebandara, 2015). The characteristics of leachate depends on the composition of the waste, waste age, precipitation rates, site hydrology, compaction, cover design, sampling procedures and interaction of leachate with the environment and landfill design and operation (Danthurebandara, 2015). The leachate composition revealed by Vesilind et al. (2002) are shown in Table 2-4.

Table 2-4 Leachate composition in different phases of landfill stabilization (Vesilind et al. 2002)

Parameter	PhaseII	PhaseIII	PhaseIV	PhaseV
COD(mg/l)	480-18000	1500-71000	580-9760	31-900
Total volatile acids (mg/l as acetic acid)	100-3000	3000-18800	250-4000	0
Ammonia(mg/l-N)	120-125	2-1030	6-430	6-430
pH	6.7	4.7-7.7	6.3-8.8	7.1-8.8
Conductivity(µS/cm)	2450-3310	1600-17100	2900-7700	1400-4500

2.3 Landfill mining

Municipal solid waste (MSW) landfill reclamation or landfill mining is the process of excavation of materials which were disposed previously (Jain, 2012). Krook et al. (2012) defined landfill mining as a process for extracting materials or other solid natural resources from waste materials which have been disposed of by burying them in the ground. Landfill mining was initiated in Tel Aviv, Israel in 1953 as a way to obtain fertilizers for orchards (Savage et al. 1993). Due to the concern for regaining further waste storage capacities of landfill, further landfill mining projects have been evolved in the United States as a strategy to gain landfill space (Kruse, 2015).

2.3.1 History of Landfill mining

The first projects in the US were started in Naples, Florida (1986-1992) and Edinburgh, New York (1988). Both of the projects were incorporated for avoiding and reducing closure costs as well as the environmental footprint of the landfills (US-EPA, 1997). In addition to the contamination concerns in the Naples project resource recovery strategies were also designed and followed as (Kruse, 2015): i) recover landfill cover material, ii) using combustible waste as fuel for a close by waste-to-energy facility and iii) recover recyclable materials. In US, four landfill mining projects were executed by 1990 including Florida (Naples) and New York (Edinburg) which are in Connecticut (Thompson) and New Hampshire (Bethlehem) (Lee and Jones (1990) cited in Kurian et al. (2003b) and Ortner et al. (2014). Strange (2010) cited in Ortner et al. (2014); Guerriero (1996); Strange (2010) cited in Ortner et al. (2014). The practice of landfill mining was prompted in US in 1990s directly or indirectly due to the strict legislation regarding final closure and post closure monitoring management, difficulty in getting permissions for new landfills (Krook et al., 2012, Spencer, 1990; Richard et al., 1996a; 1996b).

In Europe, the first pilot project was conducted in Germany (Burghof) in 1993 which aimed to recover landfill space (Rettenberger et al., 1995 cited in Kruse, 2015). Consequently other projects were followed in Germany which were motivated by hazard prevention (Hölzle, 2010 cited in Kruse, 2015). In Italy (Sardinia) and Sweden (Filbona), the first landfill mining project was introduced by in 1994 aiming to reduce the risks for poor installation and space storage with expanding cities (Cossu et al., 1996 cited in Kruse, 2015). Though few landfill mining projects were practiced in Europe and US, but due to regulation restrictions, there is no large scale mining projects till now. Few pilot projects were initiated in few regions of the world. The locations were Germany (Hogland 2002), the Netherlands (Van der Zee et al. 2004), and Finland (Kaartinen et al. 2013). In United Kingdom some pilot scale projects were conducted (Hayward-Higham 2008 cited in Gaitanarou et al., 2014) which did not prosper, although designed and were finally abandoned (Gaitanarou et al., 2014). There is not much information about the mining projects of worldwide. Few projects were conducted in Asian region as well such as in India (Kurian et al. 2003; Hogland et al. 2005) and China (Zhao et al. 2007; Lou et al. 2009 cited in Gaitanarou et al., 2014) due to the issues of vast population related to landfilling (Gaitanarouet al., 2014).

2.3.2 Purpose of landfill mining

There are numerous reasons behind landfill mining projects but mostly they are dominated by the local issues and contamination problems. Resource recovery was seldom the driver of LFM in the past, but has recently gained more importance (Kruse, 2015). A law passed in Germany in 2005 forbidding only relocation of an old landfill without recovering resources from the stored contents. In Bavaria subsidized efforts were implemented to explore old landfills and the materials stored therein. These incentives and policies have headed to flourish landfill mining activities in 2007 and 2008 (Bockreis and Knapp, 2011 cited in Kruse, 2015).

LFM projects have been carried out throughout the world during the last 50 years with different purposes such as (Reno Sam, 2009, Hogland, 2002):

- Conservation of landfill space
- Reduction in landfill area
- Expanding landfill lifetime
- Elimination of a potential source of contamination
- Mitigation of an existing contaminated source
- Energy recovery
- Recycling of recovered materials
- Reduction in management system costs (aftercare costs)
- Site re-development

2.3.3 Enhanced landfill mining

Landfill mining has been redefined as Enhanced Landfill Mining (ELFM) when the primary motto is to recover resources from old landfills. Danthurebandara (2015) defined it as an innovative concept developed to reintroduce historic waste streams present in the landfills to the material cycle either as energy or as materials. According to Geysen et al., (2013), the goal of enhanced landfill mining is not only stabilizing the waste stream but also valorizing them into either materials or energy. Additionally, ELFM contributes to reduce the environmental and social impacts of landfills and regain land space as well Danthurebandara (2015). The objective of this work was to investigate the environmental and economic performance of this ELFM concept. ELFM has become popular in Flanders, Belgium, where research and pilot studies have led to a series of publications (Geysen et al., 2009; Jones et al. 2012; Bosmans et al., 2013; Quaghebeur, et al.,2013; Van Passel et al.,2013).

2.3.4 General process of landfill mining

Traditional landfill mining consists of excavation, processing, treatment and/or recycling of deposited materials (Frändegård et al. 2013). According to IWCS (2009), landfill mining consists of three basic operations:

- Excavating waste
- Processing the excavated material, and
- Managing the excavated or processed material.

Novel ELFM comprises of the same activities but broader attention is given to the valorization of all types of waste streams such as waste present in the landfill and even the waste produced during processing of the landfilled waste (Danthurebandara, 2015). A general outline of the landfill mining process is shown in Figure 2-7, Figure 2-8 and Figure 2-9 which are proposed by Danthurebandara (2015), IWCS 2009 and Jain et al. (2014).

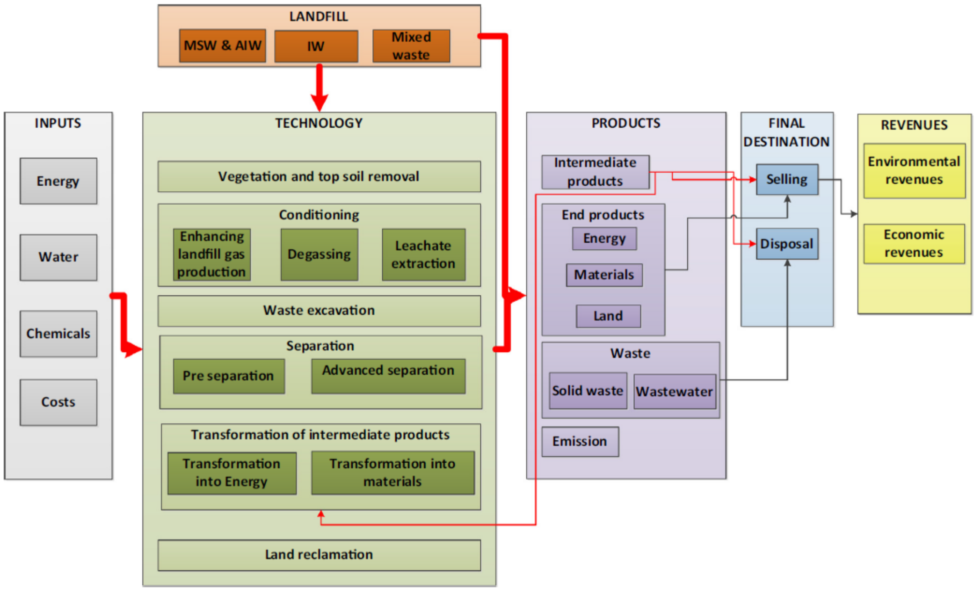


Figure 2-7 General process flow of ELFM (Danthurebandara, 2015)

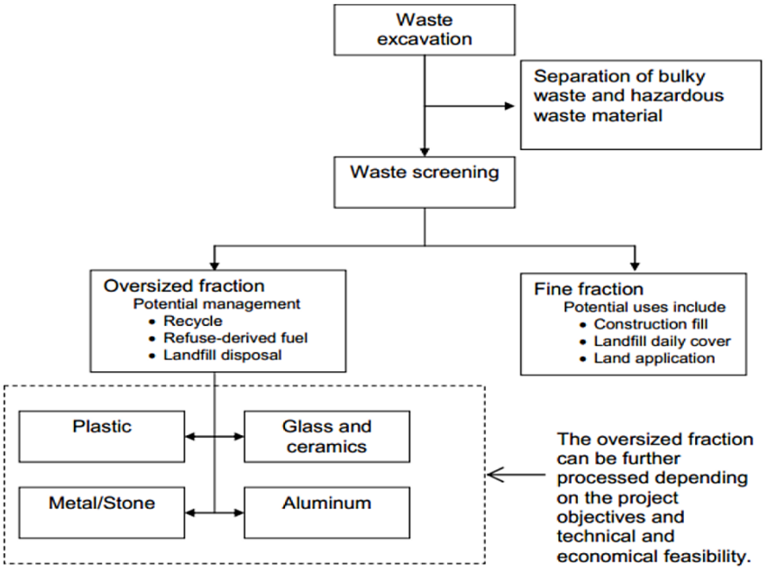


Figure 2-8 Landfill mining process (reproduced from IWCS 2009)

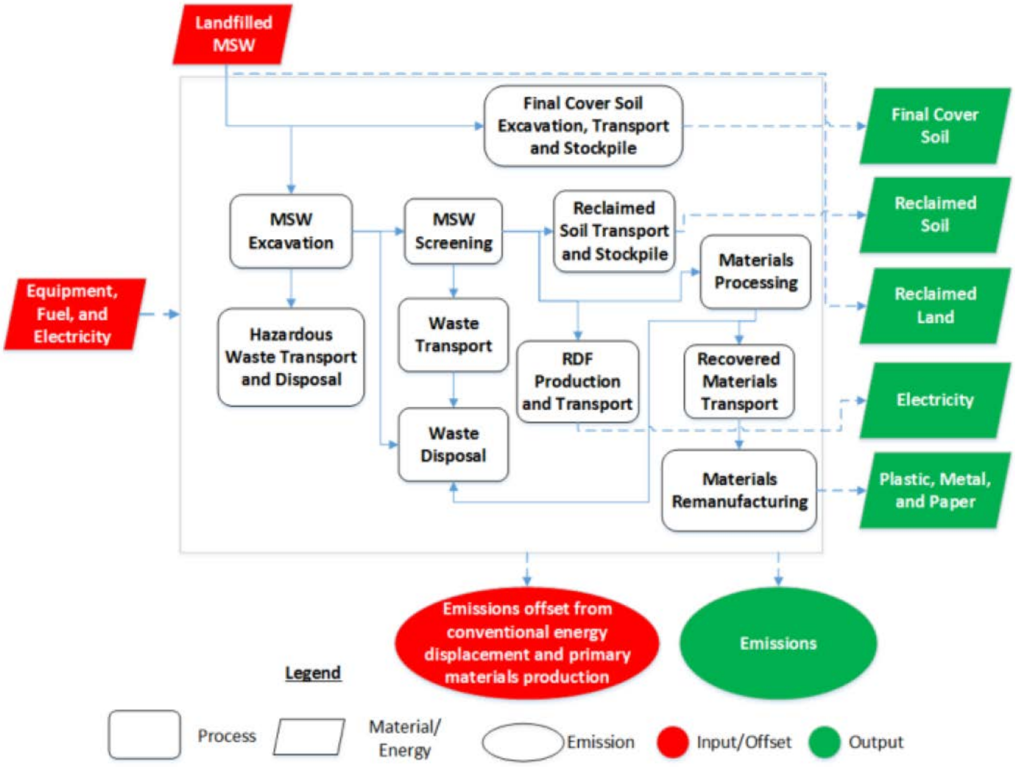


Figure 2-9 Generalized landfill mining process flow diagram (Jain et al., 2014)

2.3.5 Resource recovery from landfill mining

The beneficial aspects regarding material recovery of LFM significantly depend on (a) the objectives of the project, e.g. closure, remediation, new landfill, (b) site-specific landfill characteristics, e.g. material disposed, waste decomposition, burial practices, age and depth of fill, and (c) local economics, e.g. value of land, cost of closure materials, and monitoring (Rosendal, 2009) as well as on post-closure costs, danger of contamination, already installed liner system and demand for land (Bockreis et al. 2011). According to Rosendal (2009), in specific circumstances material recovery focuses on ferrous metals, aluminum, plastic, glass as well as fine organic and inorganic material if they represent significant volume for recovery. Vossen et al. (2011) studied on European landfills focusing on the examination of the technical and financial feasibility of landfill mining by recovering raw materials and (rare) metals comparing the partial (separation steps up to metal recovery) and complete separation of the materials. A profit of $3.4 million and $2.1 million or a return on investment of 10.7 % and 16.2% were gained in the complete separation and partial separation scenario respectively after selling the recovered materials in local market price rate. According to Rosendal^b (2009), in Denmark, in pursuance of Environmental Project, metals for an estimated value of €26.66 – 66.66/ton excavated shredder residue can be reclaimed. In Collier county LFM project in 1988, it was believed that the dumped materials worth about $25 millions. The recovered soil as well as plastics, glass, ferrous and non-ferrous metals and rubber were planned to sell to recycling companies (Spencer, 1990). In 2009, in the Perdido Landfill reclamation project, approximately 230,600 in-place m^3 of net airspace was recovered due to beneficial use of the recovered final cover soil and reclaimed soil as intermediate and daily cover soil, respectively (Jain et al., 2012). The reclamation cost was estimated to be $8.33 per in-place m3 airspace. Over $9 million revenue was estimated from airspace. The use of the final cover soil and reclaimed soil as intermediate and daily cover soil avoided the use of materials from outside the existing landfill footprint (such as virgin soil) as daily and intermediate covers. The recovery and beneficial use of the final cover soil, berm soil, and reclaimed soil. The recycled products markets are highly demanding, and potential investors are more interested in improving markets and then base their business model development on a mature market (Gaitanarou et al. 2014). In the optimal case, the additional benefits from material recovery may compensate the total costs of mining and may generate a return on investment of 10 to 20% which may lead the mining project to become financially profitable (Vossen et al. 2011). The extent of material recovery depend on the market condition, the processing companies demand, quality of the materials reclaimed and available technologies.

2.3.5.1 Plastics

Global plastics demand was 233.75 million tons in 2013 and is expected to reach 334.83 million tons by 2020, growing at a CAGR of 5.3% from 2014 to 2020. Central & South America is expected to be the fastest growing regional market for plastics, at an estimated CAGR of 6.3% from 2014 to 2020. North America plastic demand is expected to grow at an estimated CAGR of 4.3% from 2014 to 2020 (CISION, 2015). Worldwide polymer production was estimated to be 260 million metric tons per annum in the year 2007 for all polymers including thermoplastics, thermoset plastics, adhesives and coatings, but not synthetic fibers (Plastics Europe 2008b). For more than 50 years, global production of plastic has continued to rise. Some 299 million tons of plastics were produced in 2013, representing a 3.9 percent increase over 2012's output. With a market driven by consumerism and convenience, along with the comparatively low price of plastic materials, demand for plastic is growing. Recovery and recycling, however, remain insufficient, and millions of tons of plastics end up in landfills (Gourmelon, 2015).

The production of plastic uses around eight percent of the world's oil production (EcoWatch, 2014). About 4 percent of the petroleum consumed worldwide each year is used to make plastic, and another 4 percent is used to power plastic manufacturing processes (Worldwatch, 2017). Therefore, in near future the plastic production using natural resources would not be possible further due to the resource depletion which urges for recycling the plastics. In the United States, only 9 percent of post-consumer plastic (2.8 million tons) was recycled in 2012. The remaining 32 million tons was discarded. According to the United Nations Environmental Program, between 22 percent and 43 percent of the plastic used worldwide is disposed of in landfills, where its resources are wasted, the material takes up valuable space, and it blights communities. Recovering plastic from the waste stream for recycling or for combustion for energy generation has the potential to minimize these problems (Worldwatch, 2017). Recycling plastics minimizes the amount of plastic being taken to the ever diminishing landfill sites. Recycling plastics provides a sustainable source of raw materials to the manufacturing industry. The process of manufacturing plastic using natural raw materials is expensive, time and energy consuming compared to the recycling process. If plastics are recycled to produce product which would otherwise be made from new (virgin) polymer, this will directly reduce oil usage and emissions of greenhouse gases for production of the virgin polymer (less the emissions owing to the recycling activities themselves) (Hopewell et al., 2009).

A suitable plastic product using recycled plastics is Recycled plastic pin (RPP). It is used other states (Missouri, Iowa) as a cost effective solution for slope stabilization compared to conventional techniques (Loehr and Bowders, 2007, Khan, 2013). The recycled plastic pin, which is commercially known as, recycled plastic lumber are produced using post-consumer waste plastic, has been proposed as an acceptable material for use in the construction of docks, piers and bulkheads. Based on environmental and life cycle cost analysis (LCCA), the recycled plastic pin (RPP) is under serious consideration as structural materials for marine and waterfront application. A typical RPP is composed of High Density Polyethylene, HDPE (55% – 70%), Low Density Polyethylene, LDPE (5% -10%), Polystyrene, PS (2% – 10%), Polypropylene, PP (2% - 7%), Polyethylene- terephthalate, PET (1%-5%), and varying amounts of additives i.e. sawdust, fly ash (0%-5%) (McLaren, M. G., 1995, Khan, 2013). The manufacturing process of plastic lumber differs according to available technologies. According to Bedford technology, the processes include extrusion, dyeing, vacuum sizing, cooling, profile puller and sawing.

2.3.5.2 Paper

Ongmongkolkul et al. (2001) conducted a life cycle assessment of a paperboard box produced from virgin pulp and old corrugated box in Thailand. They found that the box can be used more than once and if the box use is doubled, the production of new box can be avoided and environmental impacts from almost all processes in the life cycle of box can be avoided. The double use of box could reduce most environmental impacts by 50% compared with the reference. Landfilling/recycling rate was found to affect the environmental impacts vary significantly and if the degree of landfilling is high (e.g. 60%), landfilling is the main source of most environmental impacts (Figure 2-10). Similar study was conducted by Denison (1997) to assess the environmental impacts throughout the life cycle (from cradle to grave) of different grades of newsprints manufactured from virgin papers and recycled papers along with the disposal criteria of the product at the end of life. It was found from the study that that the manufacturing energy consumption was the dominating impact. Moreover For all aspects, the reduction in total manufacturing energy consumption from recycled paper rather than virgin materials was much larger than the increase in energy required for collecting the recycled materials. In aspect of virgin materials it was found that, to make 1 ton of pulp for paper production, 2 tons as many as 3.5 tons of trees must be harvested. Another study of life cycle assessment was done by Côté (2009) for paperboard production from virgin materials and different stages of the paperboard was compared. It was found that the most impacts are induced by the box production (Figure 2-11).

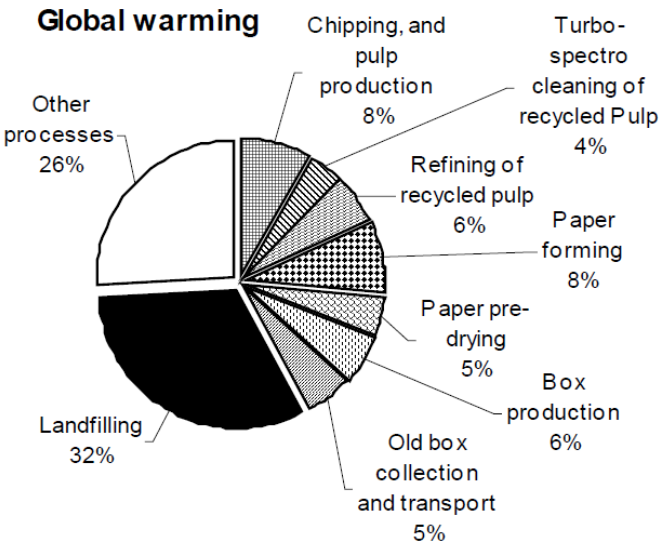


Figure 2-10 Sources of environmental impacts and energy use for life cycle of the corrugated box (Ongmongkolkul et al., 2001)

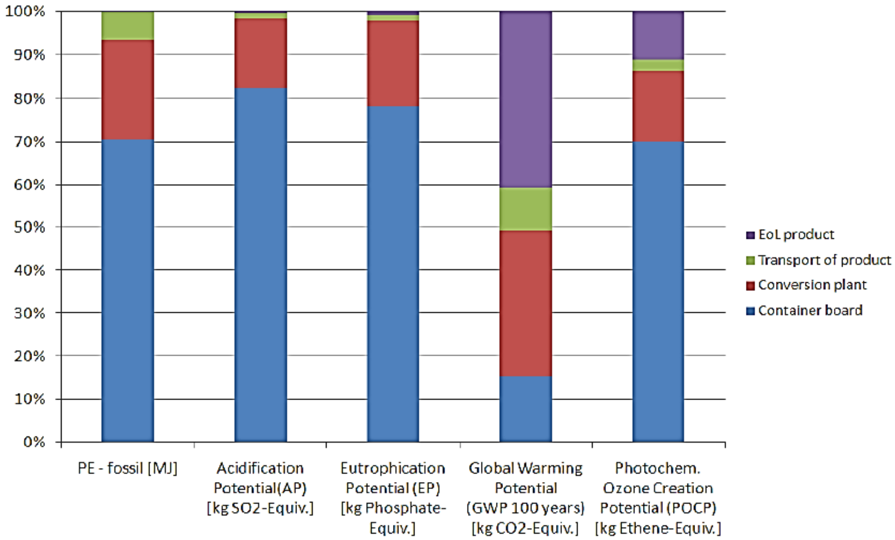


Figure 2-11 Share of different life cycle stages for a corrugated box (Côté, 2009)

2.3.6 Economic and environmental feasibility of landfill mining

Danthurebandara (2015) assessed the environmental and economic feasibility of ELFM in REMO landfill, Flanders, Belgium for three types of wastes (i) municipal solid waste and assimilated industrial waste (MSW & AIW), (ii) industrial waste (IW), and (iii) mixed waste (which is applicable when the landfilled waste cannot be distinguished clearly either as MSW & AIW or IW). The variety of possible choices were analyzed for several processes (Fiigure 2-12). Each of these scenarios contained the general processes ELFM. The scenarios were differentiated between (i) the waste type (MSW versus IW), (ii) the applied separation technology (depending on the characteristics of the excavated waste), (iii) the thermal treatment technology for RDF and (iv) the valorization route of the thermal treatment (Plasma gasification) residues. The goal of this LCA study is to evaluate the environmental impacts of the valorization of landfilled waste in the context of ELFM. The methodology was in accordance with the International Standards for LCA (ISO14040, 2006; ISO14044, 2006). SimaPro 7 was used as the LCA software tool with ReCiPe midpoint method for setting up the LCA model.

The results showed that, none of the waste types or processes has the highest or lowest environmental score for all impact categories (Figure 2-13). In this case study, the impact categories related to climate change are always influenced adversely by ELFM, while human toxicity, particulate matter formation, natural land transformation, metal depletion and fossil depletion impact categories are positively affected.

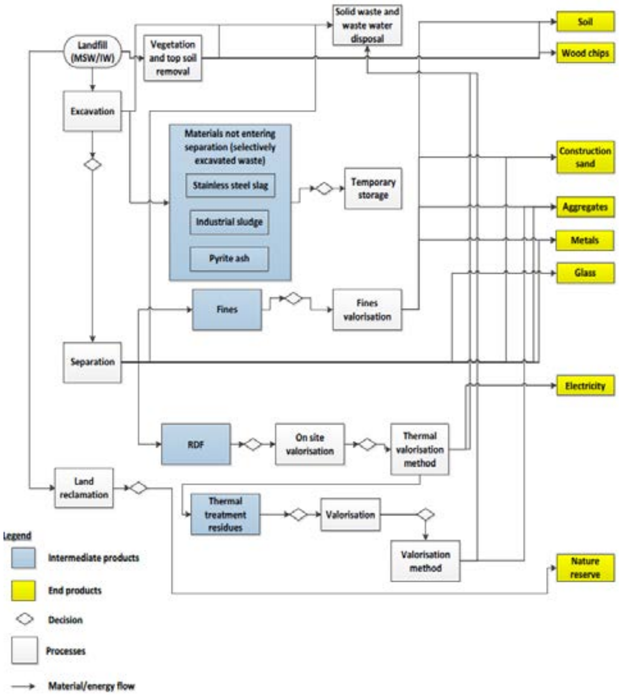


Figure 2-12 Overview of the ELFM processes of REMO landfill (Danthurebandara, 2015)

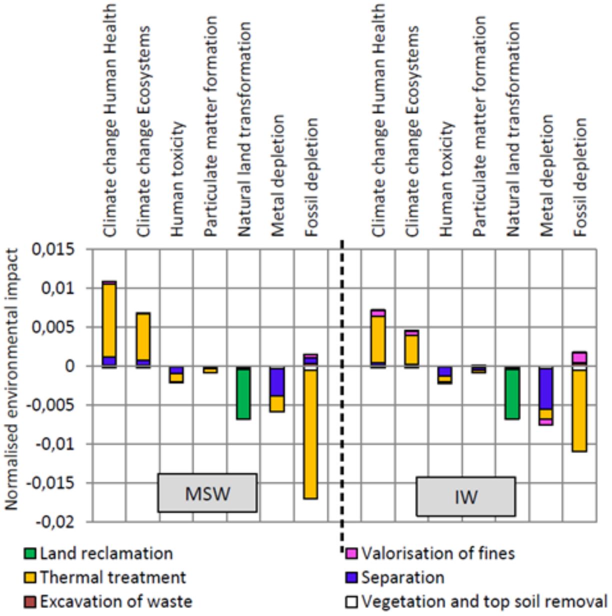


Figure 2-13 Normalized environmental profile of valorization of 1 ton of MSW/IW (Danthurebandara, 2015)

It was also found that, the environmental impact (both benefits and burdens) of valorization of total waste (IW + MSW) in all impact categories is highly significant compared to the Do-nothing scenario (Figure 2-14). However, the level of this impact differs depending on the type and phase or average age of the landfill. This suggests that the actual situation of the landfill is important in decision making in ELFM.

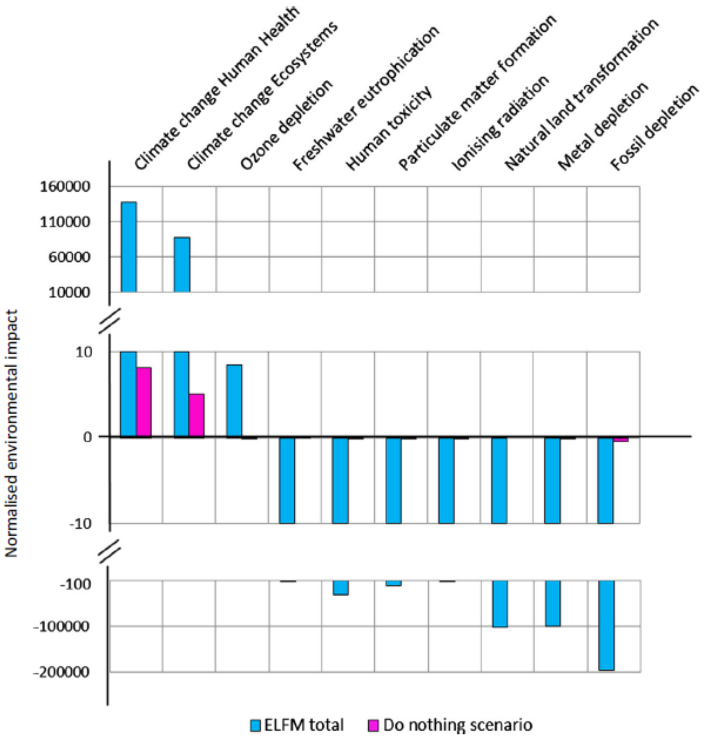
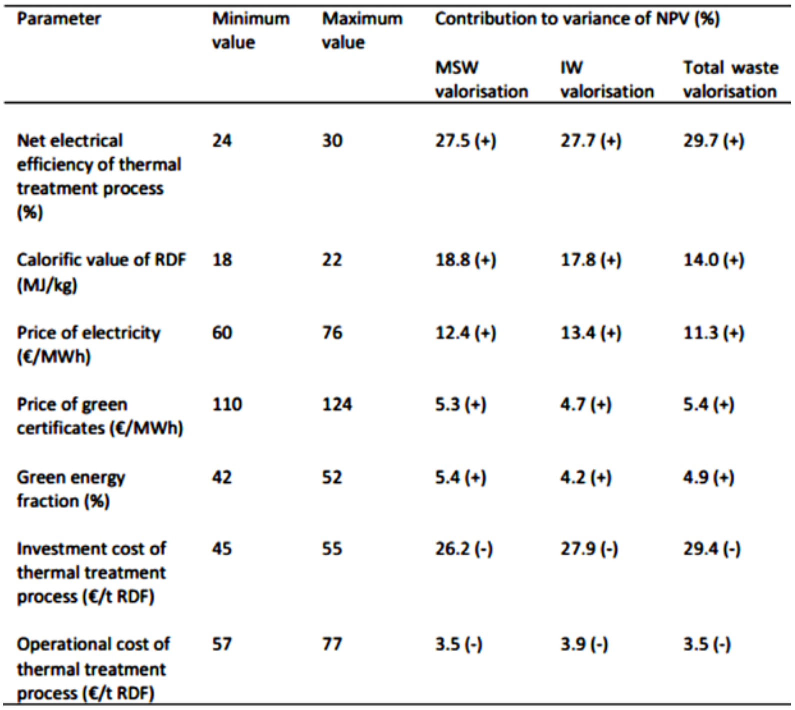


Figure 2-14 Normalized environmental profile of valorization of total waste present in the landfill compared to Do-nothing scenario (Danthurebandara, 2015)

For economic analysis LCC model was implemented by Danthurebandara (2015) for economic analysis of the REMO landfill. Detailed cash flow with all relevant investment costs, operational costs and revenues for 20 years of period were incorporated while building up the cash flow. NPV was used as economic indicator with 15% discount factor similar as the study done by Passel et al., (2013) and to identify the uncertainties of the assumptions, a Monte Carlo simulation approach was used (shown in Table 2-5).

Table 2-5 Net Present Value sensitivity analysis using Monte Carlo (Danthurebandara, 2015)



Parameter	**Minimum value**	**Maximum value**	**Contribution to variance of NPV (%)**		
			MSW valorisation	**IW valorisation**	**Total waste valorisation**
Net electrical efficiency of thermal treatment process (%)	**24**	**30**	**27.5 (+)**	**27.7 (+)**	**29.7 (+)**
Calorific value of RDF (MJ/kg)	**18**	**22**	**18.8 (+)**	**17.8 (+)**	**14.0 (+)**
Price of electricity (€/MWh)	**60**	**76**	**12.4 (+)**	**13.4 (+)**	**11.3 (+)**
Price of green certificates (€/MWh)	**110**	**124**	**5.3 (+)**	**4.7 (+)**	**5.4 (+)**
Green energy fraction (%)	**42**	**52**	**5.4 (+)**	**4.2 (+)**	**4.9 (+)**
Investment cost of thermal treatment process (€/t RDF)	**45**	**55**	**26.2 (-)**	**27.9 (-)**	**29.4 (-)**
Operational cost of thermal treatment process (€/t RDF)	**57**	**77**	**3.5 (-)**	**3.9 (-)**	**3.5 (-)**

2.3.7 Cost-Benefit analysis

The assessment of economic feasibility is very crucial issue for making decisions regarding a landfill mining project, but only few studies have focused on the economic issue of landfill mining (Zhou et al., 2014). Vossen et al. (2011), Zhou et al. (2014), Eilrich et al. (2003), Rosendal et al. (2009) and few more researchers conducted the cost benefit analysis of landfill mining projects. The US-EPA (1997) developed a framework for assessing the potential economic benefits and the capital and operational costs of landfill mining projects (Zhou et al., 2014). Van der Zee et al. (2004) conducted study on economic analysis combining cost-benefit analysis (CBA) and multi criteria analysis (MCA) to make decision on landfill mining projects considering market condition and opportunities. Van Passel et al. (2013) conducted cost benefit analysis considering the costs of landfill mining including excavation, sorting and pre-treatment, incineration and contingency, and the benefits including waste to material (WtM), waste to energy (WtE) and land reclamation. (Zhou et al., 2014) considered capital cost, rental or purchase of equipment, construction or expansion of materials handling facilities, operational cost, waste processing cost including excavation, screening and sorting, transportation cost of materials and final waste disposal cost as cost indicator in the CBA study (Figure 2-15).

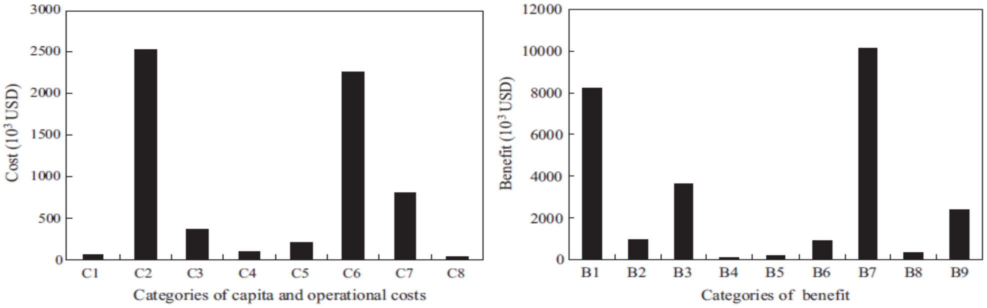


Figure 2-15 Different categories of costs and benefits of landfill mining (Zhou et al., 2014)

Whereas, as benefit elements land and space remediation, airspaces, recyclable materials recovery (soil type material as organic fertilizer and substrate, stones as construction materials, metals and glass), energy recovery (producing residue fuels (RDFs), heat and electricity generation from waste plastics) and avoidance cost of post-closure care (leachate management and treatment and landfill gas emission monitoring) were included (Figure 2-13). Where, C1: site preparation; C2: rental excavation & hauling equipment; C3: rental screening & sorting equipment; C4: construction of materials handling facilities; C5: pre-activity research; C6: waste processing; C7: material transportation; C8: final disposal). Different categories of benefits of landfill mining (B1: benefit of regained lands; B2: benefit of recovered air-spaces; B3: recycling soil-like materials; B4: recycling stones and construction waste; B5: recycling metals and glasses; B6: producing RDFs; B7: generating electricity by incineration; B8: avoidance of leachate collection and treatment; B9: avoidance of landfill gas emission. Based on land reclamation and energy recovery four scenarios were designed which are scenario 1 (MAX), occupied land of the old landfill is reclaimed for urban and industrial development and the material with high calorific value is incinerated and then generated electricity; and total maximum benefit might be obtained in this scenario, scenario 2 (MID-1), the air-space of the old landfill is recovered to be used as new landfill cell after landfill mining, and the material with high calorific value is incinerated and then generated electricity, scenario 3 (MID-2), occupied land of the old landfill is reclaimed for urban and industrial development and the material with high calorific value is used as the raw material for producing RDFs and scenario 4 (MIN), the air-space of the old landfill is recovered to be used as new landfill cell after landfill mining, and the material with high calorific value is used as the raw material for producing RDFs. The results are shown in Figure 2-16.

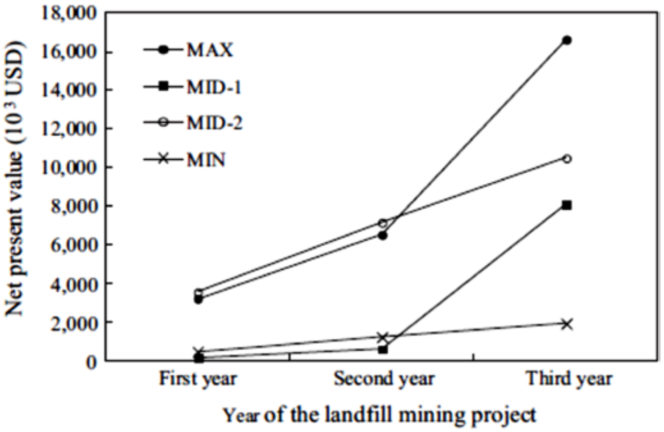


Figure 2-16 Net present value for different project years under different scenarios (Zhou et al., 2014)

Many other previous studies followed useful methodologies likewise, but the CBA is a location and available facility specific which urge for separate study for different landfill mining projects.

2.3.7.1 Net present value (NPV)

The net present value (NPV) or net present worth (NPW) is a measurement of the profitability of an undertaking; any investment or project. It is calculated subtracting the present values of cash outflows (including initial cost) from the present values of cash inflows over a time period. The formula for NPV is-

$$NPV = \sum_{t=0}^{n} \frac{B_t - C_t}{(1 + i_s)^t}$$

Where, where NPV is net present value; t is the year; B_t is the total benefit of the t year; Ct is the total cost of the t year; n is the calculated duration of the project in years; and is the social discount rate. NPV greater than zero means that the project will result in a positive benefit compared with current expectations (social discount rate); NPV equals zero means that the project will just meet expectations; NPV less than zero means that the benefits are lower than expected. NPV was used as economic indicator by Danthurebandara (2015), Van Passel et al. (2013), Zhou et al. (2014) for their economic analysis.

2.3.8 Life Cycle Assessment (LCA)

According to PRéConsultants (2016), '*LCA is a tool for quantifying the environmental performance of products taking into account the complete life cycle, starting from the production of raw materials to the final disposal of the products, including material recycling if needed*'. The United States Environmental Protection Agency (USEPA) considers life cycle assessment (LCA) as one of the markers on the way to sustainability. According to USEPA, '*LCA is a technique to assess the environmental aspects and potential impacts associated with a product or process by compiling an inventory of relevant energy and material inputs and environmental releases, evaluating the potential environmental impacts associated with identified inputs and releases, and by interpreting the results in order to make a more informed decision*.' It can assess the environmental impacts of any process or activity or product covering whole life cycle from cradle to grave including final disposal or recycling of the process or activity or product.

The most important applications for an LCA are (PRéConsultants, 2016):

- Identification of improvement opportunities through identifying environmental hot spots in the life cycle of a product.
- Analysis of the contribution of the life cycle stages to the overall environmental load, usually with the objective of prioritizing improvements on products or processes.
- Comparison between products for internal or external communication, and as a basis for environmental product declarations.

- The basis for standardized metrics and the identification of Key Performance Indicators used in companies for life cycle management and decision support.

According to ISO 14044, ‘*LCA addresses the environmental aspects and potential environmental impacts2) (e.g. use of resources and environmental consequences of releases) throughout a product's life cycle from raw material acquisition through production, use, end-of-life treatment, recycling and final disposal (i.e. cradle-to-grave)*.’

The methodological framework of LCA consists of four phases (ISO, 2006; PRéConsultants, 2016):

1. Goal and scope definition phase,
2. Inventory analysis phase,
3. Impact assessment phase, and
4. Interpretation phase

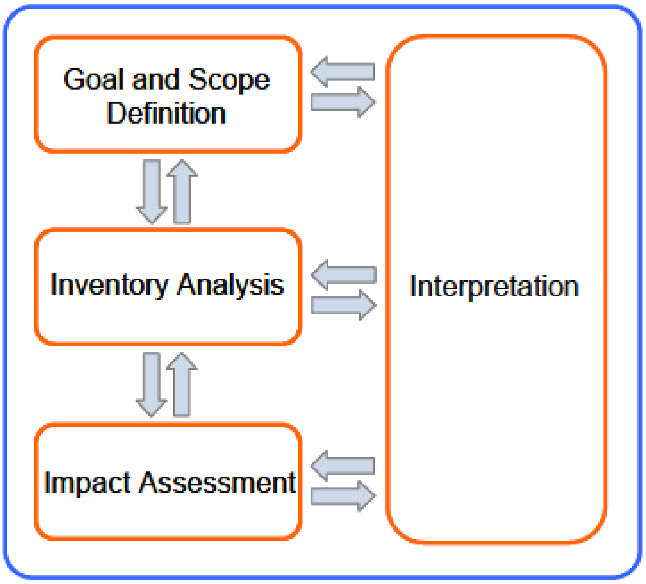


Figure 2-17 The methodological framework for LCA (ISO, 2006a)

1. Goal and scope definition

Defining the goal includes determining the reason for carrying out the LCA study, the intended audience, and the intended application while defining the scope involves setting the system boundaries and the level of detail (Lehtinen et al. 2011). For example, in the landfill mining feasibility study conducted by Danthurebandara et al. (2015a), the goal was defined as ‘To evaluate the environmental impacts of the valorisation of landfilled waste in the context of ELFM’ and to compare the ELFM with no mining scenario the system boundary was set as shown in Figure 2-18.

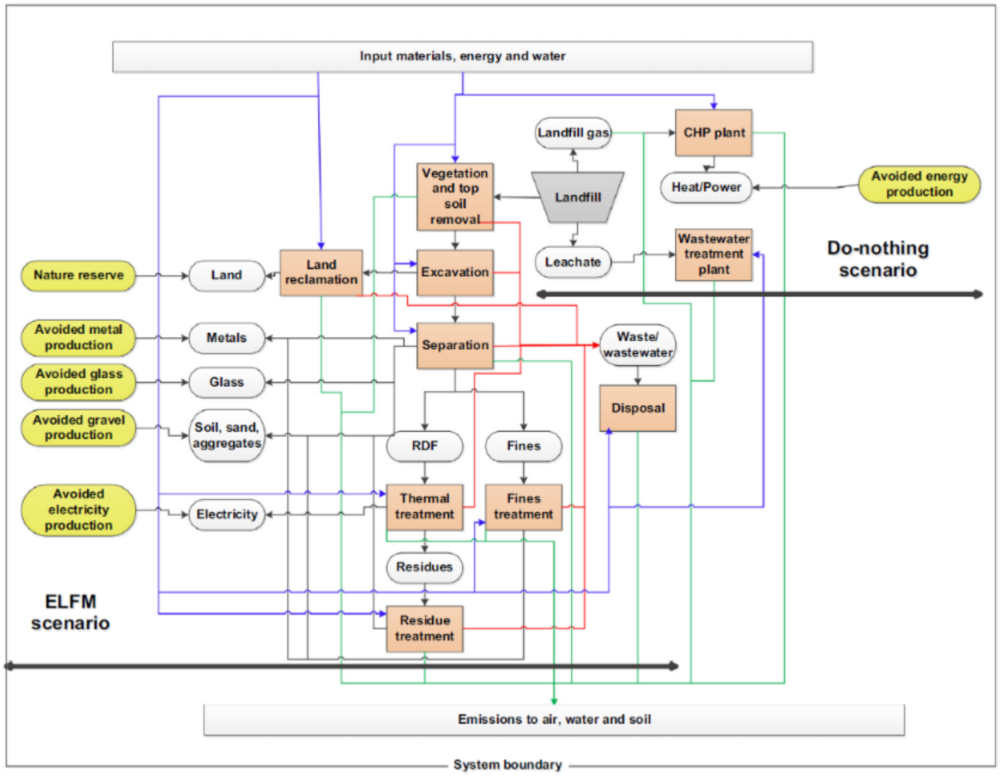


Figure 2-18 System boundary of ELFM and Do-nothing scenarios (Danthurebandara, 2015)

2. Inventory analysis

The second phase of the LCA, the life cycle inventory analysis (LCI) phase, deals with collecting the necessary data to meet the objectives of the LCA study by inventorying the input and output data of the studied system. Possible data sources include for example measurements on the production site, existing databases and bibliographic research (Lehtinen et al. 2011).

3. Impact assessment

The purpose of the third phase of LCA, life cycle impact assessment (LCIA), is to convert the LCI results into the related environmental impacts – effects on natural resource use, natural environment and human health (Lehtinen et al. 2011). There are many methodologies for LCA which differs due to the impact categories or environmental indicator focuses. SimaPro contains a number of impact assessment methods, which are used to calculate impact assessment results. Few methodologies of impact assessment in SimaPro are enlisted here (PRéConsultants, 2014):

- CML-IA
- Ecological Scarcity 2013
- EDIP 2003
- EPD 2013
- EPS 2000
- IMPACT 2002
- ReCiPe
- ILCD 2011 MIDPOINT+
- BEES
- TRACI 2.1
- Single issues

Among these, the BEES and TRACI 2.1 are North American method. The rests are European methods. BEES combines a partial life cycle assessment and life cycle cost for building and construction materials into one tool. TRACI is denoted by the Tool for the Reduction and Assessment of Chemical and other environmental Impacts (TRACI) which is a stand-alone computer program developed by the U.S. Environmental Protection Agency specifically for the US using input parameters consistent with US locations. TRACI facilitates the characterization of environmental stressors that have potential effects, including ozone depletion, global warming, acidification, eutrophication, tropospheric ozone (smog) formation, eco-toxicity, human health criteria related effects, human health cancer effects, human health non-cancer effects, fossil fuel depletion, and land-use effects. TRACI was originally designed for use with life-cycle assessment (LCA), but it is expected to find wider application in the future. TRACI is a midpoint oriented life cycle impact assessment methodology.

4. Interpretation

The final phase of the LCA procedure is a life cycle interpretation, where the results are summarized and discussed to provide a basis for conclusions, recommendations and decision making, depending on the goal and scope definition (Lehtinen et al. 2011).

2.3.8.1 Structure of methods in SimaPro

The basic structure of impact assessment methods in SimaPro includes Characterization, Damage assessment, Normalization, Weighting.

- Characterization

The substances that contribute to impact category are multiplied by a characterization factor that shows relative contribution of the substances. For example, the characterization factor for CO_2 in the Climate change impact category can be equal to

1, while the characterization factor of methane can be 25. This means the release of 1 kg methane causes the same amount of climate change as 25 kg CO_2. The total result is expressed as impact category indicators (PRéConsultants, 2014). An example of interpretation of LCA results in the form of characterization is as Figure 2-19 found by Danthurebandara, et al. (2015).

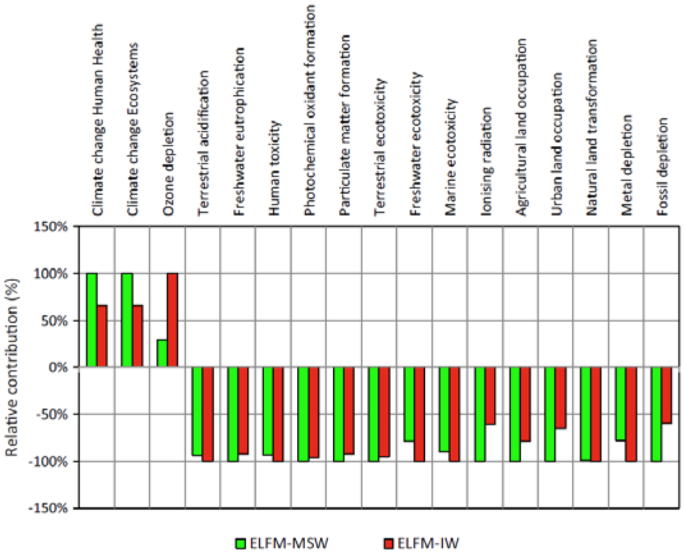


Figure 2-19 Interpretation of characterization results in Recipe method (Danthurebandara, et al., 2015)

- Damage assessment

Damage assessment is a relatively new step in impact assessment. It is added to make use of 'endpoint methods', such as the Eco-indicator 99 and the EPS2000 method. The purpose of damage assessment is to combine a number of impact category indicators into a damage category (also called area of protection) (PRéConsultants, 2014).

- Normalization

Many methods allow the impact category indicator results to be compared by a reference (or normal) value. This mean that the impact category is divided by the reference. A commonly used reference is the average yearly environmental load in a country or continent, divided by the number of inhabitants. After normalization the impact category indicators all have the same unit, which makes it easier to compare them. Normalization can be applied on both characterization and damage assessment results (PRéConsultants, 2014). An example of interpretation of LCA results in the form of characterization is as Figure 2-20 found by Danthurebandara, et al. (2015).

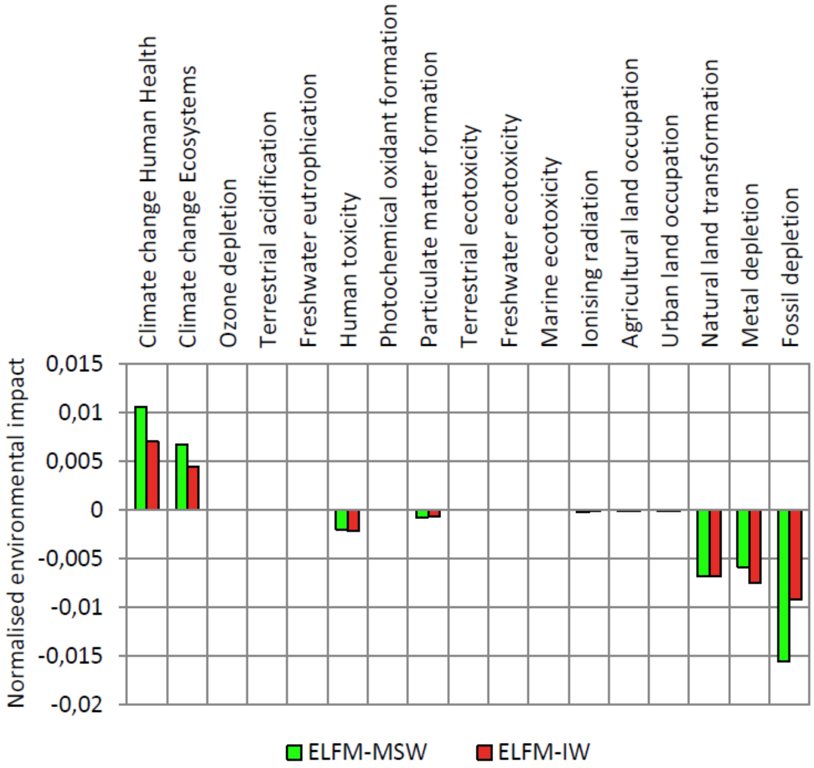


Figure 2-20 normalized environmental profile of valorization of 1 ton of MSW/IW (Danthurebandara, et al., 2015)

- Weighting

Some methods allow weighting across impact categories. This means the impact (or damage) category indicator results are multiplied by weighting factors, and are added to create a total or single score. Weighting can be applied on normalized or non-normalized scores, as some methods like EPS do not have a normalization step.

2.3.8.2 The History of Life Cycle Assessment (LCA)

Life Cycle Assessment (LCA) was introduced in the late 1960s to early 1970s. The first implementation of LCA can be tracked back to 1969, which was done out by Coca-Cola for the evaluation of the resource consumption and emissions associated with beverage containers to assess the feasibility of replacing disposable plastic containers with returnable glass bottles (Fan, 2014). This study is considered recognized as one of the first studies of LCA and recognized for basis for life cycle inventory analysis (Environmental Protection Agency, 1993). More companies in the United States and Europe started similar life cycle inventory analyses in 1970s. For example, the Japan Nomura Research Institute, multinational food packaging and processing company, conducted a packaging LCA study for Tetra Pak in 1975 (Imura, et al., 1997); and after that Franklin Associates performed an LCA for soft-drink containers for Goodyear (Franklin Associates Inc., 1978). In this period the studies commonly used the energy analysis method (quantification method of resource use and environmental release), which was known as the Resource and Environmental Profile Analysis (REPA). This method was used more during late 1970s to the mid-1980s with the emergence of the global problem of solid waste (Fan, 2014). And later on some consultant companies in Europe and the United States further developed this method for a range of waste management purposes. Similar method was also developed by some European researchers (as represented by Ian Boustead, United Kingdom) which is also called as

‘Eco-balance’ (based on the balance of energy vs. mass, coupled with an ecological test). After the late 1980’s, due to global awareness of sustainable development and environmental protection, the LCA studies was in boom. To develop a unified specification of LCA, in 1989, the Dutch National Living, Planning and the Environment Ministry first proposed a product-oriented environmental policy instead of the traditional terminal environmental control policy which covered the all aspects of a product life cycle including the consumption and disposal phases. The Society of Environmental Toxicology and Chemistry (SETAC) hosted the International LCA Seminar for the first time in 1990 and the specifications of LCA were officially recognized. A unified regulation was finally determined in 1993 at the Portugal Sesimbra Seminar, and the final name was officially designated as the Life Cycle Assessment (LCA) (SETAC, 1993). Still today, LCA methodology is being researched and developed. Now, SETAC and the International Organization for Standardization (ISO) are actively promoting the international standards for the LCA methodology. ISO has made LCA one of the most important steps of the ISO14000 environmental management system. In June 1993, ISO formally founded the Environmental Management Standards Technical Committee (TC-207), which was responsible for the standardization of the environmental management system. The TC-207 Technical Committee reserved 10 standards numbers (ISO14040-ISO14049) for LCA in the ISO14000 series of environmental management standards (Saunders, 1996; Fan, 2014). With a growing interest in environmental concerns around the globe, the environmental evaluation of large-scale projects has become an increasingly important issue. For instance, it is often necessary to conduct study for a landfill mining project to be able to demonstrate the environmental impacts in order to obtain permits from the government. A common way of conducting such an evaluation is to use an analytical measure called Life Cycle Assessment (LCA).

2.3.8.3 LCA studies in Landfill mining

In landfill mining, there are very few studies which were conducted using LCA. Gusca et al. (2014) performed comparative life cycle assessment of landfill mining process to compare between on-site and off-site waste sorting during mining operation for the landfill of city of Riga in Latvia. The results showed that waste sorting at the landfill site succeeds in minimizing the effects to the environment by 28% more than sorting of waste at the centralized plant. Jain et al. (2014) presented Life Cycle Assessment of the end-use management options for mined materials of an unlined cell of the Perdido Landfill, USA. Three scenarios were assessed in the study which were no-mining, mining with waste relocation and mining with material recovery using an off-site waste-to-energy facility. The recovery of metal components from landfilled waste was found to have the greatest benefit across nearly all impact categories evaluated, while emissions associated with heavy equipment to mine the waste itself were found to be negligible compared to the benefits that mining provided. Feasibility study of Remo landfill mining in Belgium conducted by Danthurebandara et al. (2015) found that improvements in the electrical efficiency of thermal treatment process, the calorific value of refuse derived fuel and recovery efficiencies of different waste fractions lead the performance of ELFM towards an environmentally sustainable and economically feasible direction comparing with the no mining scenario. Again possible basic scenarios have been built up between the different waste type (MSW & AIW versus IW), the separation process that could be applied (wet separation versus dry separation) and the valorization route of the thermal treatment residues (geo-polymer production versus blended cement production). Industrial waste was found to deliver net environmental benefit in all scenarios, while valorization of MSW gives a net benefit only in scenarios including geo-polymer production. However, the valorization of all waste present in the landfill yields a net environmental benefit for all suggested scenarios comparing with no-mining.

2.3.8.4 LCA limitations

According to Lehtinen et al. (2011), '*limitations of LCA are related to the insufficient transparency of the results, which can hinder the utilization of existing studies as a source of information and in comparisons. Moreover, LCA does not take into account the social and economic impacts during the life cycle of a product (even though the life cycle approach and its methodologies can also be applied to these aspects).*'

Chapter 3

Methodology

3.1 Introduction

The aim of the study was to evaluate the environmental and economic feasibility of enhanced landfill mining. The existing condition of the landfill was compared with mining with material recovery and mining with waste relocation cases.

In the environmental feasibility study, the impact of recycling and reuse of mined materials instead of virgin materials was assessed additionally. A detail life cycle assessment was conducted on the production of plastic product and paperboard from mined materials comparing with the virgin material products.

The economic analysis involved cost-benefit analysis of the mining project. Similar to the environmental analysis three scenarios were compared in order to assess the economic feasibility of enhanced landfill mining.

This chapter presents the methodology for life cycle assessment and cost-benefit analysis along with the assumptions and considerations of this study.

3.2 Study Area

The study area is the City of Denton Landfill which is located on south eastern side of Denton. The landfill is owned and operated by City of Denton and it follows operational rules cited in the 30 TAC 330 subchapters D, which is provided by the Texas Administration Code. The average temperature of Denton is 64.85℉. It is about 6.1 miles from the center of the city which is 11 mins drive. The aerial view of the landfill is shown in Figure 3-1.

Figure 3-1 City of Denton landfill

The City of Denton Landfill was built in 1983. The Denton landfill received its permit to start accepting waste on March 7, 1983 (permit number of 1590). Cell 1590 was pre subtitle-D. The permit was modified the permit number changed to 1590A. Initially the landfill started with 32 acres and then expanded in 1998. The expanded landfill covers a total of 252 acres, with 152 acres for waste and 100 acres for offices, buffer zone, compost and extra rented land. At present there are six cells in the landfill and the former cell is considered as cell zero or cell 1590 A which is shown in Figure 3-2. City of Denton landfill currently receives approximately 550 tons of MSW a day with 80% of the waste commercial and 20% residential. The landfill is a type I landfill which means that it is a standard landfill for the disposal of municipal solid waste (MSW). In 2016, the landfill got authorized permit from Texas Commission on Environmental Quality (TCEQ) to conduct landfill mining of cell 1590 in accordance with Title 30 Texas Administration Code 305.70 (1) and 330.605.

Figure 3-2 Aerial view of Cell 1590 A (cell 0) (photo courtesy: City of Denton)

3.3 Life Cycle Assessment

Life Cycle Assessment (LCA) is a tool for quantifying the environmental performance of products taking into account the complete life cycle, starting from the production of raw materials to the final disposal of the products, including material recycling if needed (PRéConsultants, 2016). The LCA methodology consists of 4 phases: goal and scope definition, life cycle inventory (LCI) analysis, impact assessment and interpretation (ISO14040, ISO14044). The study followed the international standard for Life Cycle Assessment (ISO 14040, 14044) methodology. The goal, scope, life cycle inventory and system boundaries for the study along with the data source are discussed in the following sections

3.3.1 LCA model

The LCA model has been developed in SimaPro 8 using TRACI 2.1 (version 1.02) method among other North American methodologies. Default normalization factors were used based on US 2008 data. Data inventory was developed into the system from Ecoinvent 3.0 default database and US based database along with field investigation and questionnaire surveys. TRACI 2.1 is a midpoint oriented life cycle impact assessment methodology which facilitates the characterization of environmental stressors that have potential effects, including (i) ozone depletion (ii) global warming (iii) acidification (iv) eutrophication (v) tropospheric ozone (smog) formation (vi) eco-toxicity (vii) human health cancer effects (viii) human health non-cancer effects (ix) fossil fuel depletion and (x) land-use effects (PRéConsultants, 2015).

3.3.2 Goal and scope

The goal of this LCA study is to evaluate the environmental impacts of landfill mining (ELFM) comparing with existing condition of landfill. The study includes the valorization of mined wastes to replace the virgin materials. Additionally, environmental impact of production of plastic product (plastic lumber) and paper product (paperboard) with recycled (mined) and virgin materials; plastics and papers respectively to assess the energy saving potential of reusing mined materials instead of using virgin materials.

Functional unit of the LCA is 1 ton of landfilled wastes (municipal solid waste). From excavation of 1 ton landfilled waste to the processing of recovered materials and disposal of unrecovered materials are included in the study. For the LCA of recycling of mined plastics functional unit has been chosen as 1 ton of plastic product. Likewise, for LCA of mined papers the functional unit is 1 paperboard box or 1 kg of paper product.

3.3.3 System boundary

System boundary is the interface between a product system and the environment or other product systems (ISO 14040). For a life cycle assessment study it is very important to specify the boundary of the consideration of the study. All related processes, emissions, sub activities within the boundary need to show clearly. The landfill construction, collection of wastes are not included in the scope of the study.

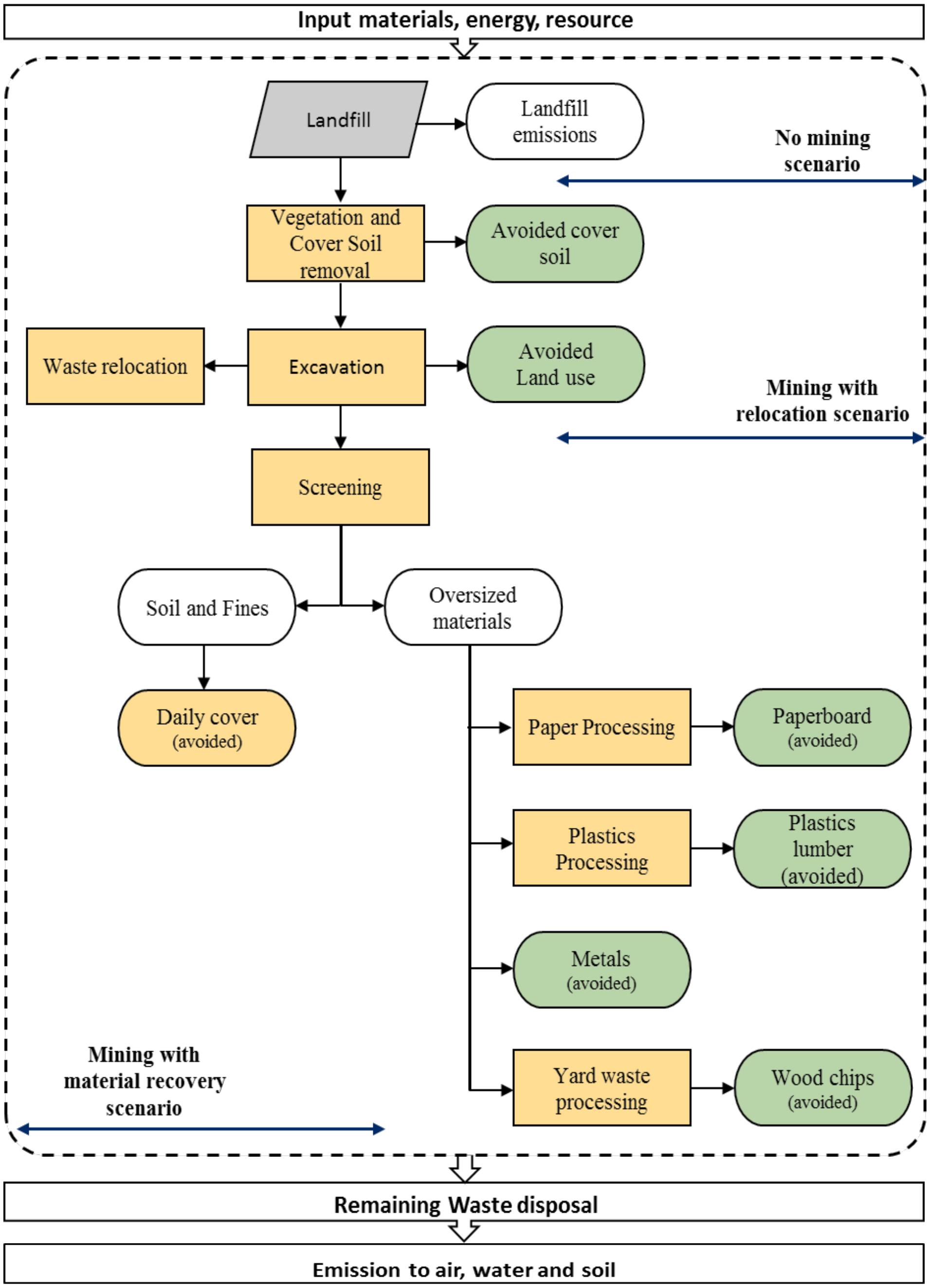


Figure 3-3 LCA System boundary

The common activities for the landfill mining involve vegetative and top soil removal, waste excavation, relocation or further processing of the reclaimed materials. In the study three scenarios were considered. Those are no mining or existing condition of the landfill, mining with relocation of wastes and mining with material recovery. In the last scenario in addition to the other activities processing of the excavated materials such as separation, transforming into intermediate products, land reclamation and final disposal of the wastes were taken into consideration. The considerations of each scenario are described in the following sections. The system boundary of the LCA study including all scenarios are shown Figure 3-3.

3.3.4 Data Inventory

For each unit process that is included within the system boundary, qualitative and quantitative data need to be collected for inclusion in the inventory. The procedures used for data collection may vary depending on the scope, unit process or intended application of the study (ISO 14040). In the study data were collected through questionnaire survey in study area landfill personnel, different manufacturing companies, through data collection from previous studies on same study area or similar projects and with judgmental assumptions to some extents. The general data used in the study regarding mining operations are enlisted in Table 3-1.

Table 3-1 General Data used in this Study

Activities/criteria		source
dust control		
Spraying rate of water (t/m2)	0.01	Danthurebandara M. el al., 2015
Amount of water (lb) for 1 ton wastes	0.718	Danthurebandara M. el al., 2015
top soil removal		
Excavation amount of cover soil/ton waste	0.203	present study
Excavation volume for top soil removal for 1	3.862	present study
Unit wt. of cover soil (pcf)	105	case study
Unit wt. of wastes (pcf)	86	case study
Diesel consumption of excavators (kg/m3 top	0.131	Ecoinvent database (version 3)
Vegetation density (t/m2)	0.01	Danthurebandara M. el al., 2015
Vegetation (lb) for 1 ton of waste	0.718	present study
Diesel for grinding wastes (L/t waste)	1.3	Dimitris P. et al.,2004
Top soil transport (tkm)	8	assumption
Waste Excavation		
Diesel consumption of excavators (kg/m3	0.131	Ecoinvent database (version 3)
Separation		
electricity consumption (kWh/t waste)	35	Danthurebandara M. el al., 2015

3.3.5 Scenario considerations

Three scenarios were modeled to assess the feasibility of landfill mining in accordance to the environmental impacts of 1 ton of the mined MSW wastes of a 25 years old unlined landfill. 1 ton of MSW was selected to be consistent in the all three scenarios. All emissions, activities regarding the scenarios are accounted for 1 ton of MSW wastes. The excavated wastes management alternatives involve relocation of the excavated wastes, processing of the materials to transform into new products. Again to determine whether the mining is beneficial over existing condition of the landfill, the mining alternatives were compared with the no mining or do nothing scenario. Therefore, the baseline scenario is ‘do-nothing’ or ‘no mining’ scenario (scenario 1), the other two scenarios are ‘Landfill mining with relocation on lined cell’ (scenario 2) and ‘Mining with material recovery’ (scenario 3) scenario. The scenarios are discussed in the following sections.

3.3.5.1 Scenario 1: No Mining

The baseline scenario is the current condition of the landfill which means to keep it as it is now with conventional cover which is prone to landfill gas emissions to the environment. It considers the existing impact of the landfill if no mining activates would take place.

For a conventional landfill the main concerns are the landfill gas and leachate emission to environment. Whereas, the produced gas from the existing landfill acts as beneficial parameter if it is collected and utilized for electricity generation. As the landfill cell is a dry tomb, there is very less potential of production of enough gas to convert into electricity. According to field investigation and questionnaire survey, there is no groundwater contamination from of the landfill. The emission to water from leachate is considered to be managed as required by corresponding regulatory framework ensuring adequate periodic monitoring and maintenance. So, for the considered landfill, the main environmental impact to the environment is induced from the landfill gas emission. Fugitive emissions measurement was conducted by Samir (2014) on the same location (cell 0 of City of Denton landfill) with portable flame ionization detector (FID) and static flux chamber technique in more than 1000 points on the landfill during each investigation. Methane emissions were found to vary from 0 ppm to 47 ppm for the investigation period (from December 2012 to January 2014). The measurement was conducted both in the slope and flat surface of the landfill. The average emission found in the study was 3.25 ppm or 0.8 g.ch4m-2day-1. According to gas generation prediction by Samir (2011) on this conventional landfill cell, the dry tomb may generate gas approximately up to next 50 years. So it was considered in ‘do nothing’ that the 30 years old MSW would continue to decompose in the unlined cell and continue emitting landfill gas for next 50 years.

3.3.5.2 Scenario 2: Mining with waste relocation

In USA the most common objective of landfill mining projects was to relocate waste from an unlined landfill unit to an adjacent lined unit. The excavated waste was typically directly disposed of in the lined cell without further processing for the recovery of any constituents (e.g., soil, metals) (FDEP, 2009). In this scenario after top soil and vegetative cover removal the waste was excavated, transported and deposited on existing lined cell of the landfill which represents the majority of the mining projects. As the management (type, gas generation potential, way of handling the generated gas etc.) of the new lined cell is uncertain, the system boundary of this scenario is considered up to the waste relocation phase as shown in Figure 3-3.

3.3.5.3 Scenario 3: Mining with materials recovery

In addition to the air space recovery the benefit in landfill mining projects depends on the extent of recycling or recovering materials to use further by processing the materials into intermediate products. In this scenario, in excess of the mining activities as scenario 2, the mined wastes are processed to separate reclaimed soil and other wastes as per composition shown in Figure 3-4, the recyclable materials are reprocessed to convert them into new products. Plastics, papers, soil and fines, metals and yard wastes are considered to be recycled to great extent. The rest are disposed to landfill again. There are about 52% soil and fines in the composition. Potential reuse options for the recovered soil include use as daily and intermediate landfill cover material (uses inside the landfill) and as construction fill (uses outside the landfill) (US EPA, 1997). The reclaimed cover soil and soil like fines found after separation process are considered to be used as further cover soil or daily cover soil for the existing cells.

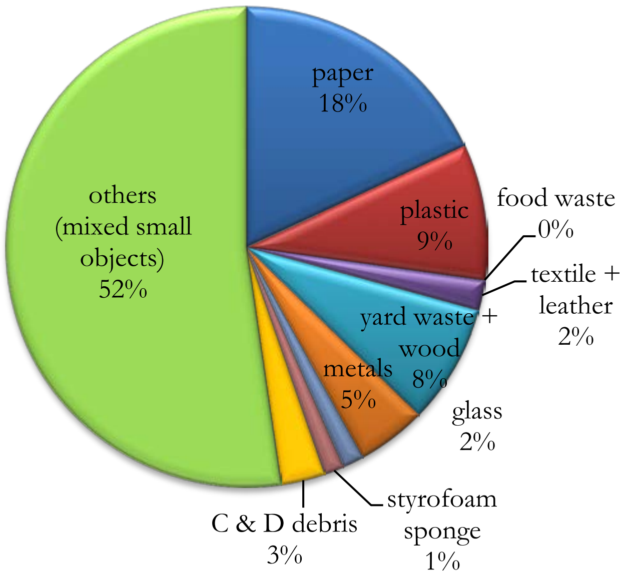


Figure 3-4 Physical Composition of mined wastes (Koganti, K., 2015)

Among the recovered materials, only the manufacturing of plastics and paper products which are plastic pin and cardboard box respectively, are considered. The yard wastes are considered to be chipped and used as the wood chips and the metals are assumed to be sold as scrap metals. Other waste components are assumed to be disposed into the other cells of the landfill. Therefore, 90% of each recoverable materials are assumed to be recycled and reused further in this manner. The system boundary for this scenario is shown in Figure 3-3.

3.3.6 Recycling of mined waste components

Among the recoverable mined materials metals are considered as replacement of iron scrap which was in the SimaPro inventory. Yard waste processing to wood chips and the replaced product (wood chips) was also taken from database. The soil like materials were assumed to be a replacement of the equivalent excavated soil. The plastics and papers were considered to be processed into new product which are explained in the following sections.

3.3.6.1 Plastic recycling

The production of plastic uses around eight percent of the world's oil production (Sormunen, K. 2013). So, in near future the plastic production using natural resources would not be possible further due to the resource depletion which urges for recycling the plastics. Due to lack of recovery millions of tons of plastics end up in landfills. Therefore, the plastics of the last decades which end up in landfills would be a potential source of plastics. According to the waste composition of the study area plastics are about 40% of the waste volume and 9% of weight of wastes. So, recycling of plastics would add up more space gain. It is necessary to assess the impact of recycling the mined plastics by processing into new product. Therefore, the mined plastics are assumed processed to make plastic lumber in the study.

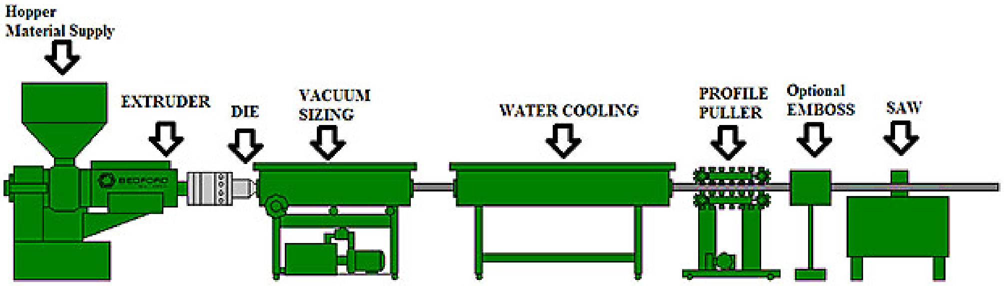
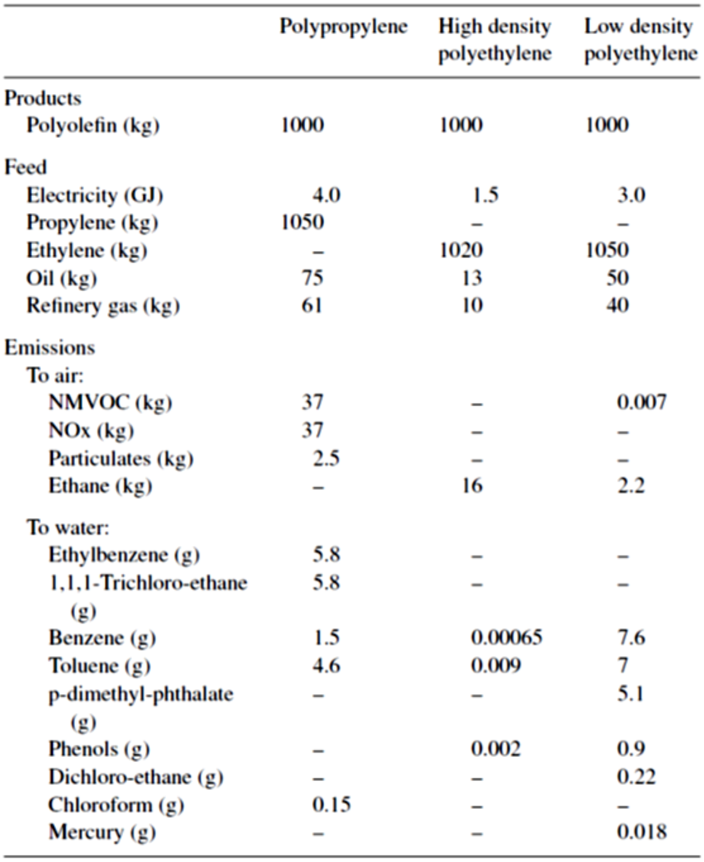


Figure 3-5 Processes involved in Plastic Lumber production (source: BEDFORD Technology)

The goal of the LCA was to assess the energy saving potential of reusing mined plastics to produce 1 ton of plastic lumber instead of using virgin plastics. The environmental impact of manufacturing 1 ton plastic product (40 plastic lumbers each weighing 50 lbs.) from these mined plastics is compared with manufacturing from virgin plastics to assess the energy saving potential of the mined plastics. According to manufacturing company each ton of plastic lumber would need 16,000 milk jugs. The data inventory was collected from literature, manufacturing companies and Ecoinvent 3.0 database. The system boundary for these two scenarios are presented in Figure 3-6 and Figure 3-7. The process flow considered for lumber production for the study is shown in system boundary. The main differences between these two cases are collection and processing of raw materials for plastic lumber production. Typical composition (80%HDPE, 10%LDPE, 5%PP and 5%glass fiber) of plastic lumber was considered for the study. For raw material transportation same hauling distance was considered for both of the cases. The production procedure and properties of the lumber were followed according to the information given by Bedford Technology as shown in Figure 3-5.

The cleaning, contamination and emission to water and air need to be considered for using the mined plastic. The data of input, materials, emissions to air, water for processing mined plastics before further using as raw materials were taken from Ecoinvent 3.0 database and mined sample properties. The inventory for HDPE, LDPE, PP polyolefin production was considered as used in the LCA of Frischknecht and Suter (1996) (Table 3-2) and K.G. Harding et al. (2007). The input data for lumber manufacturing processes such as extrusion, thermoforming, sawing etc. are taken from Ecoinvent 3 database. The mined plastic reclamation data was taken from the LCA analysis of landfill mining which is described previously.

Table 3-2 Values for polyolefin production as used in the LCA of Frischknecht



	Polypropylene	High density polyethylene	Low density polyethylene
Products			
Polyolefin (kg)	1000	1000	1000
Feed			
Electricity (GJ)	4.0	1.5	3.0
Propylene (kg)	1050	–	–
Ethylene (kg)	–	1020	1050
Oil (kg)	75	13	50
Refinery gas (kg)	61	10	40
Emissions			
To air:			
NMVOC (kg)	37	–	0.007
NOx (kg)	37	–	–
Particulates (kg)	2.5	–	–
Ethane (kg)	–	16	2.2
To water:			
Ethylbenzene (g)	5.8	–	–
1,1,1-Trichloro-ethane (g)	5.8	–	–
Benzene (g)	1.5	0.00065	7.6
Toluene (g)	4.6	0.009	7
p-dimethyl-phthalate (g)	–	–	5.1
Phenols (g)	–	0.002	0.9
Dichloro-ethane (g)	–	–	0.22
Chloroform (g)	0.15	–	–
Mercury (g)	–	–	0.018

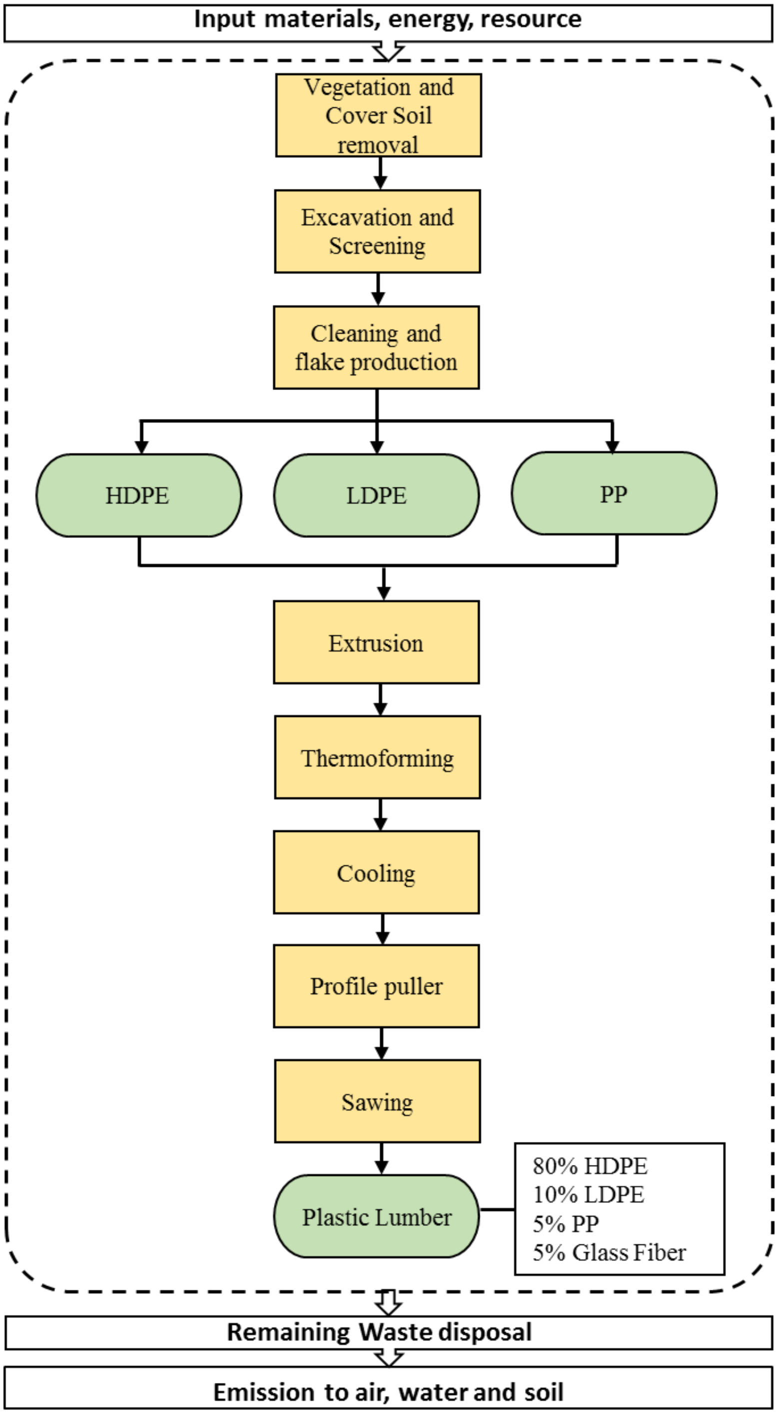


Figure 3-6 System boundary for lumber manufacture from mined plastics

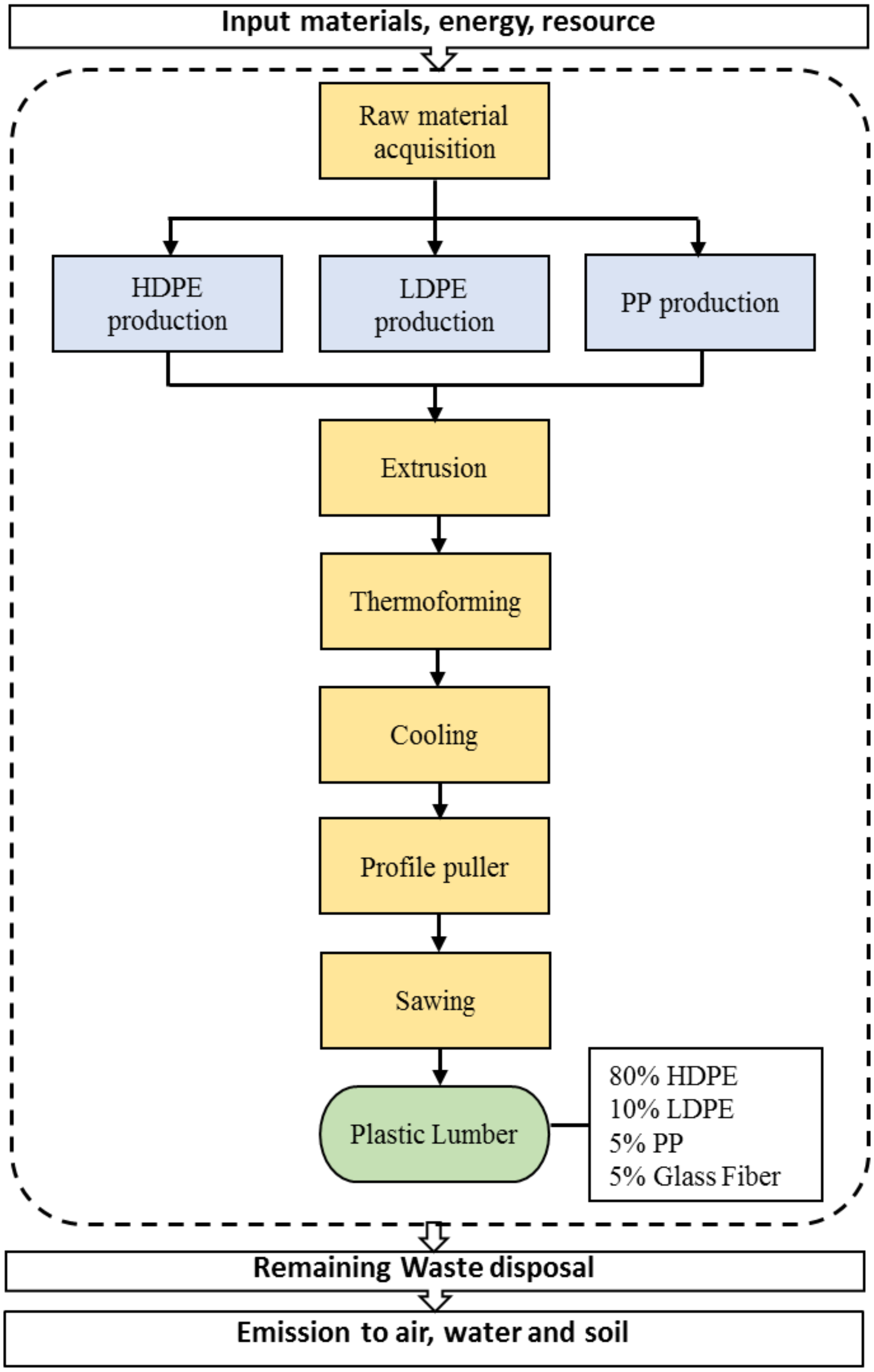


Figure 3-7 System boundary for lumber manufacture from virgin plastics

3.3.6.1 Paper recycling

According to USEPA 2012, paper and paperboard made are the major component of MSW generated (27.4 percent). The paper is categorized as medium degradable material by many researchers due to its constituting moderate lignin percentages. According to the waste composition of the cell 0 paper content is about 18% by weight and the paper category includes of all kinds of papers like cardboard packaging, newspaper, magazines, office papers, etc. The sampling done on the cell 0 in 2011 revealed that in the landfilled waste composition the paper content was very high. The paper content increased after 30 ft. depth to a percentage of 31% and the papers were relatively fresh compared to the earlier researches on landfilled waste. The sample of the paper quality collected from cell 0 is shown in Figure 3-8 which was collected from 50 ft. down. It shows that the paper is not decomposed at all and can be recycled and reused further. So, it is necessary to assess the impact of recycling the mined papers by processing into new product. Therefore, the mined papers are assumed processed to make paperboard or corrugated box in the study.

Figure 3-8 Reclaimed paper sample from cell 0 (source: TCEQ website)

The goal of the LCA was to assess the energy saving potential of reusing mined papers to produce 1 corrugated box weighing 1 kilograms, instead of using papers found from virgin material acquisition. The environmental impact of manufacturing 1 kg paper product (1 corrugated box or paperboard weighing 1 kg) from these mined plastics is compared with manufacturing from virgin plastics to assess the energy saving potential of the mined plastics. The data inventory was collected from literature, manufacturing companies and Ecoinvent 3.0 database. The system boundary for these two scenarios are presented in Figure 3-9 and Figure 3-10. The main differences between these two cases are raw materials paperboard production, such as for production with virgin materials the major raw material is tree (pine or eucalyptus tree) and land use of the tree. For the mined samples contamination is a major matter of concern. The data of input, materials, emissions to air, water for processing mined papers before further using as raw materials were taken from Ecoinvent 3.0 database and mined sample properties. The data inventory for paperboard production from recycled materials are considered as LCA inventory of Ongmongkolkul A., et al. (2001) and Suwansaard M. (2006). Whereas, the data inventory for paperboard production from virgin materials are considered similar to the LCA inventory used by Côté W. (2009) and Suwansaard M. (2006). The process flows involved in the production of paperboard are considered from the previous studies on corrugated box manufacture and manufacture company information. The system boundary for corrugated box production from mined raw materials and virgin materials are shown in Figure 3-9 and Figure 3-10.

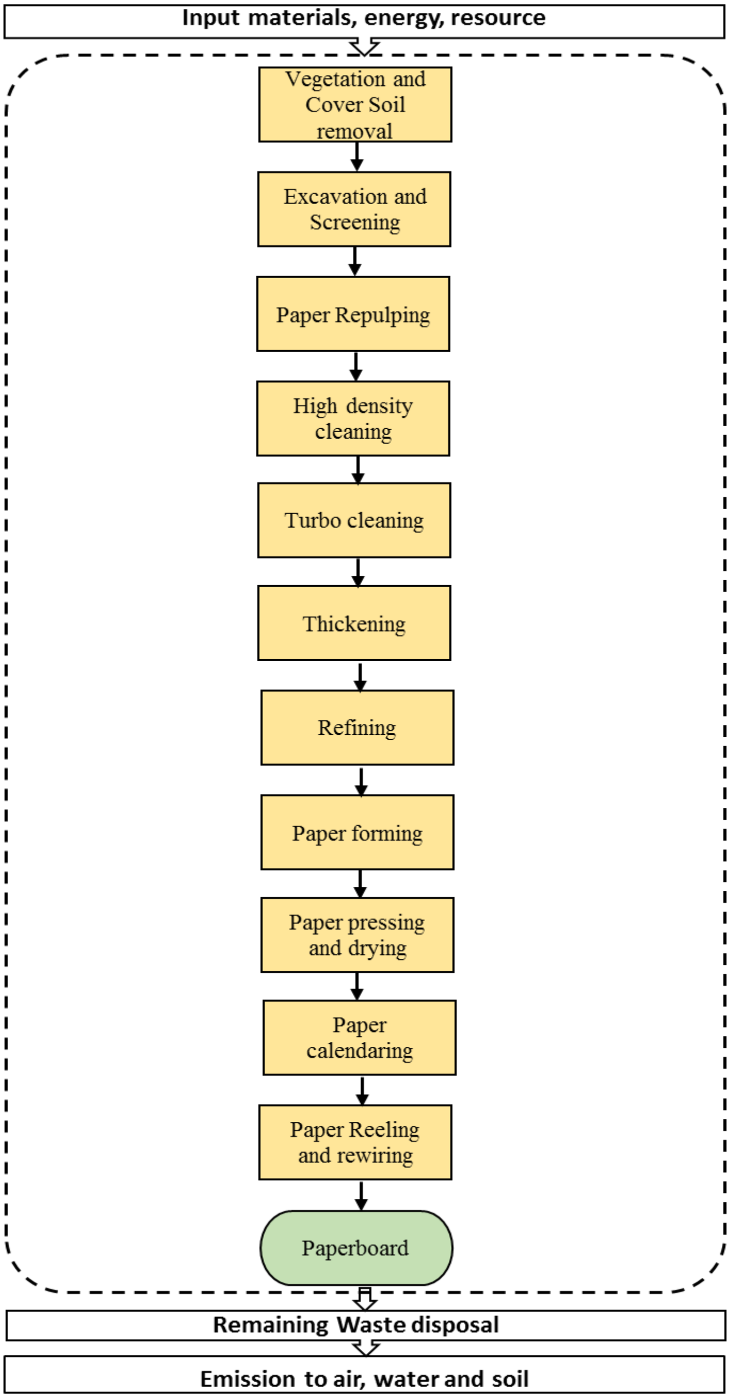


Figure 3-9 System boundary for paperboard manufacture from mined papers

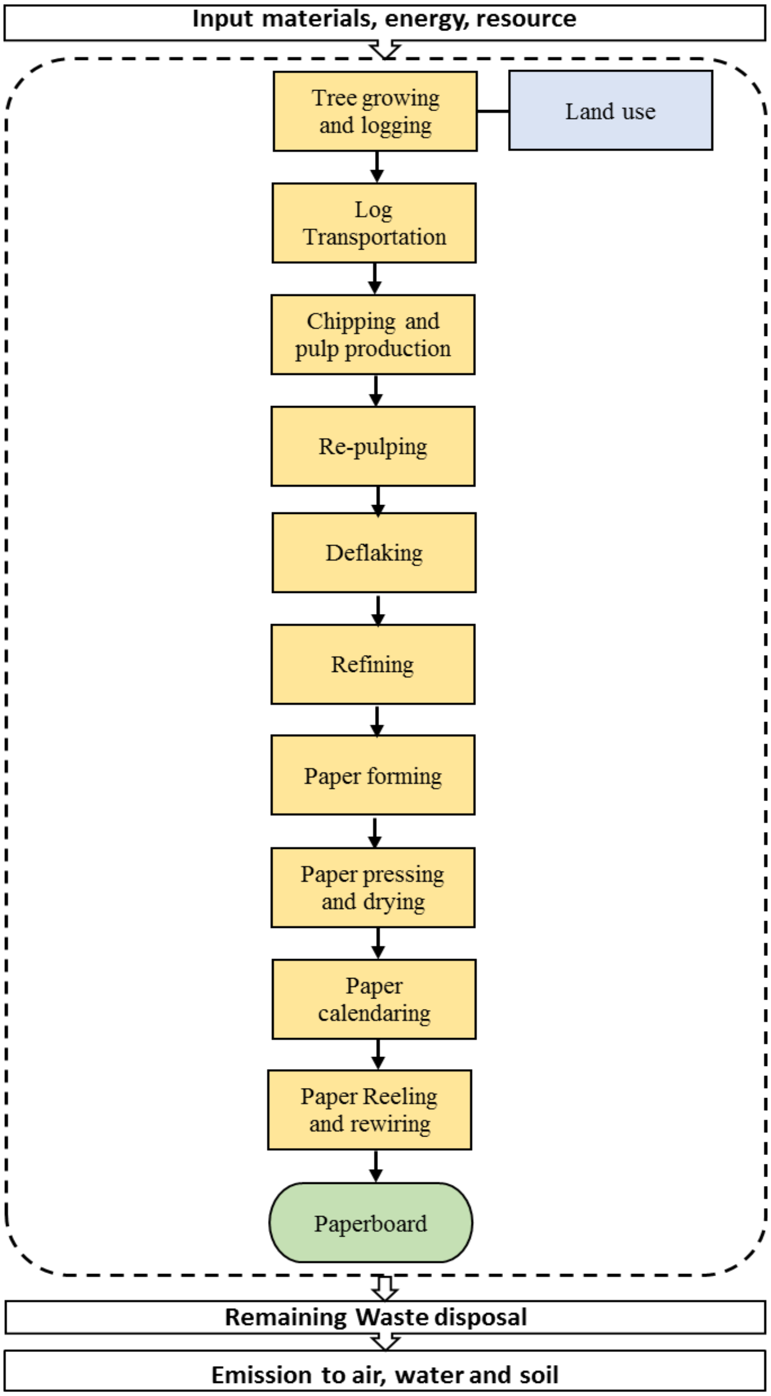


Figure 3-10 System boundary for paperboard manufacture from virgin papers

3.4 Cost-Benefit Analysis

Landfill mining combines the concepts of material recycling and sustainable waste management system. It can be defined as a technique of excavating a landfill in conventional process to recover metals, glass, plastics, soils and land resource etc. (Morelli, 1990). USEPA (1997) defined it as landfill reclamation which is used to expand landfill capacity and avoid high cost of acquiring additional land. Reclamation costs are often offset by the sale or use of recovered materials, such as recyclables, soil and waste. Other important benefits may include avoided liability through site remediation, reductions in closure costs, and reclamation of land for other uses. It is necessary to perform an economic analysis of landfill mining project comparing with existing condition of landfill to identify its viability. This study aims to conduct cost-benefit analysis to assess the economic feasibility of mining of cell 0 (1590 A) of City of Denton Landfill.

The cost-benefit elements regarding mining and material recovery were selected as per study landfill authority, previous mining projects experiences, USEPA (1997), economic analyses done by C.Zhou et al. (2015), Danthurebandara (2015) et al. (2015), S.Van Passel et al. (2013).

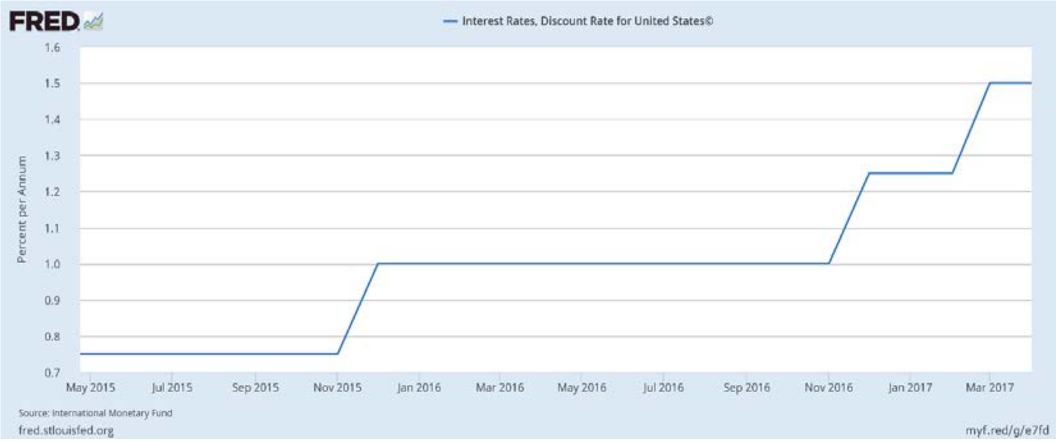
3.4.1 Economic indicator

The indicator of net present value (NPV) was adopted to evaluate the economic feasibility of the project. Net Present Value (NPV) is the difference between the present value of cash inflows and the present value of cash outflows. NPV is used in capital budgeting to analyze the profitability of a projected investment or project.

The formula for NPV is shown as follows:

$$NPV = \sum_{t=0}^{n} \frac{B_t - C_t}{(1 + i_s)^{\mathrm{t}}}$$

Where, where NPV is net present value; t is the year; Bt is the total benefit of the t year; Ct is the total cost of the t year; n is the calculated duration of the project in years; and is is the social discount rate, which is 1.5% till April’2017 (updated value taken from FRED economic data) for United States (Figure 3-11). NPV greater than zero means that the project will result in a positive benefit compared with current expectations (social discount rate); NPV equals zero means that the project will just meet expectations; NPV less than zero means that the benefits are lower than expected.



Source: International Monetary Fund

Figure 3-11 Annual Discount rate (FRED economic data)

The Figure 3-11 shows the monthly discount rate of United States. For the study the recent month discount rate was selected and used for the whole project duration. The project is planned to last for 10 years. The NPV of each year was calculated to determine the economic benefit of the project each year. Again NPVs of different scenarios were also compared each year to assess the feasibility of landfill mining.

3.4.2 Scenario considerations

The scenarios for economic analysis was kept similar to the environmental analysis which are ‘No mining’, ‘Mining with relocation’ and ‘Mining with material recovery.

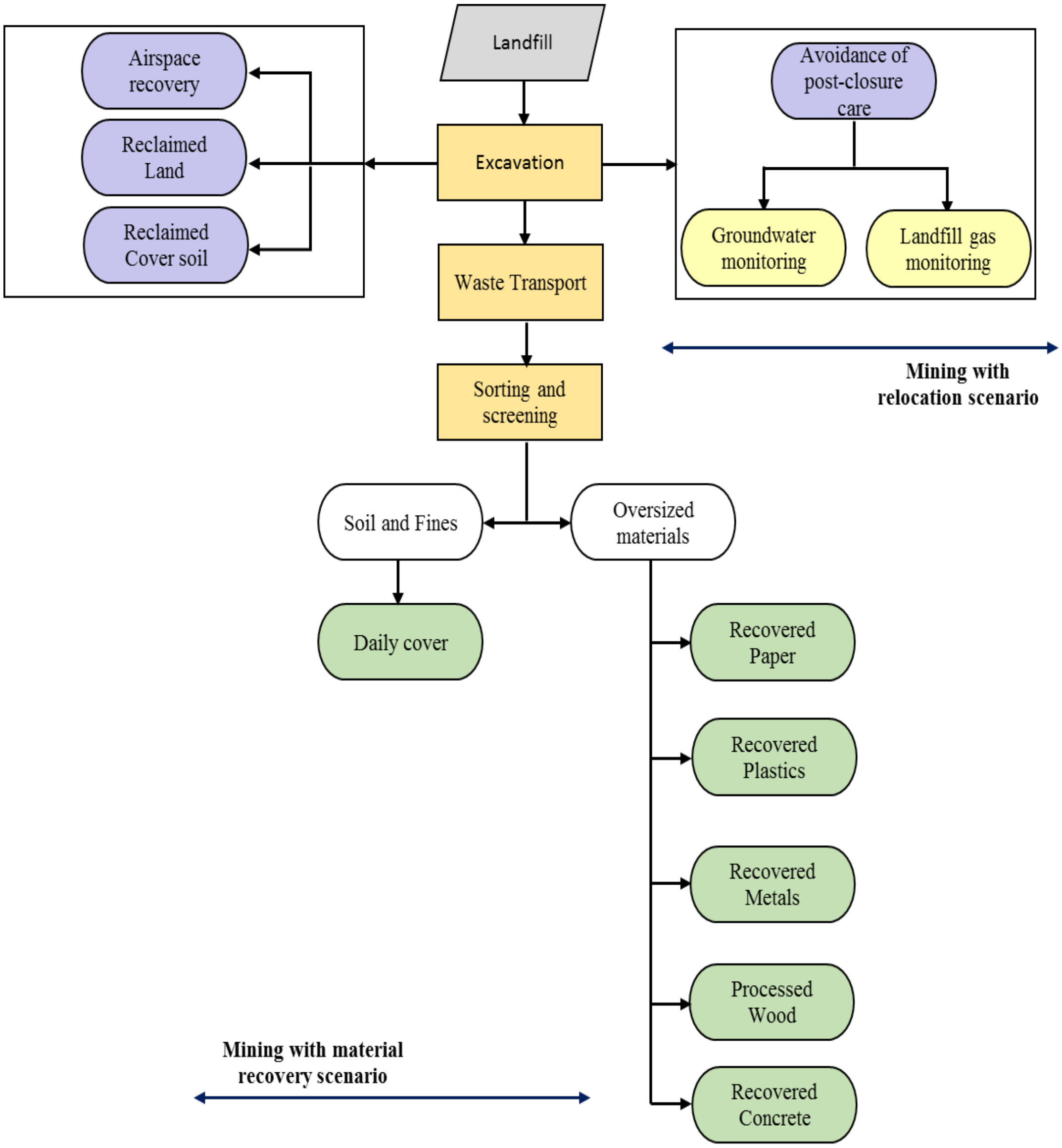


Figure 3-12 Framework of landfill mining scenarios in cost benefit analysis

As the project timeline is planned to be 10 years, the scenarios were also designed accordingly. The mining scenario framework for cost benefit analysis is shown in Figure 3-12. The considerations for the scenarios are described in the following sections.

3.4.2.1 Scenario 1: No Mining

If the landfill is kept as it is now (no mining), it would be needed to monitor the groundwater and landfill gas according to the regulatory guideline. The related cost of the groundwater monitoring are leachate management, pipe purchase and repair and administrative cost. The costs regarding gas monitoring includes equipment and administrative costs. The data of the cost of monitoring was collected from the authority of City of Denton landfill. No benefit element was considered for no-mining scenario. The cost elements which are considered for the study are-

1. Landfill gas monitoring cost for 30 years
2. Groundwater monitoring cost for 30 years
3. Administrative, accessories and equipment costs for monitoring

3.4.2.2 Scenario 2: Mining with waste relocation

In this scenario the framework of landfill mining processes considered are excavation of landfill reclaiming the air spaces and cover soil. The excavation saving due to the mining activity was also taken into consideration. In this scenario it was assumed that no materials will be recovered and sort out to further reuse. Therefore, the wastes were considered to be relocated or re-landfilled in the existing lined cells of the landfill which induced re-landfilling costs for the scenario. In total 2.6 million cubic yards of MSW would be excavated and relocated. The airspace of reclaimed cell was counted as benefit as the re-landfilling cost of 100% materials was included in cost elements. The overview of the activities are shown in Figure 3-3. Nine indicators of costs and five indicators of benefits were taken into consideration in the scenario. The cost and benefit elements for this scenario are enlisted in Table 3-3. The list of equipment considered for this scenario in the context of mining activities are provided in Table 3-4.

Table 3-3 Cost-benefit element for scenario 2

Costs			Benefits		
Equipment cost	-	Purchase of equipment	Land reclamation	-	Benefit from reclaimed land value
Administrative cost	-	Personnel and labor	Avoided cost of post monitoring care	- -	Avoidance of leachate management Avoidance of landfill gas monitoring Employee payment, equipment and accessories
Maintenance and Miscellaneous cost	- - - - - - - - - - -	Materials and supplies Fuel Insurance Outside contract services Transfer costs Maintenance and repair Franchise fee Miscellaneous Equipment maintenance Other operations Debt service			

Table 3-4 List of equipment for scenario 2

No.	Equipment name	Purpose
1	Track Loader	Cover handling, stockpiling
2	Conveyors	Transfer wastes
3	Excavator	Digging
4	Roll-Off Truck	Trash loading
5	Articulated Dump Truck	Cover soil handling
6	Wheel Loader	Stockpiling
7	Hydraulic Generator	Power supply
8	Vocational Syle Truck	Materials hauling
9	100 Yard Trailer	Materials/wastes transfer
10	100 Yard Trailer	Materials/wastes transfer

3.4.2.3 Scenario 3: Mining with material recovery

In this scenario the mined waste components were considered to be recovered and sold after the excavation and waste screening. The recoverable materials were considered based on the information from the project authorities. The benefits from soils and fines were calculated on the basis of equivalent amount of soil excavation expense. According to the project plan the concrete, metals, plastics, papers would be sold to the vendors to further processing into products. And the wood or yard wastes would be grinded and sold as processes wood or wood chips.

Table 3-5 Cost-benefit elements of scenario 3

Costs		Benefits	
Equipment cost	- Purchase of equipment	Land and space reclamation	- Benefit of recovered airspaces - Benefit from reclaimed land value
Administrative cost	- Personnel and labor	Soil recovery	- Benefits of recovered cover soil
Maintenance and Miscellaneous cost	- Materials and supplies - Fuel - Insurance - Outside contract services - Transfer costs - Maintenance and repair - Franchise fee - Miscellaneous - Equipment maintenance - Other operations - Debt service	Avoided cost of post monitoring care	- Avoidance of leachate management - Avoidance of landfill gas monitoring - Employee payment, equipment and accessories

The materials assumed to be replaced for this scenario along with the recovery percentages are shown in Table 3-6. For being conservative in materials recovery design in the project, a total of 75% materials are considered to be recycled and reused after mining. Few materials are considered to be reused and few are processed and recycled as mentioned earlier. The price of the materials are taken as per the solid waste service group of the City of Denton landfill.

Table 3-6 Recovered materials

Recovered Materials	USD Per Ton	Composition %	Individual Material Recovery %
Cardboard (OCC)	$ 75.00	9.0%	60.0%
Mixed Paper	$ 50.00	9.0%	25.0%
Mixed Metal	$ 130.00	5.0%	50.0%
Aluminum Metal	$ 975.00	2.0%	50.0%
Concrete	$ 10.00	3.0%	90.0%
Processed wood	$ 5.00	8.0%	70.0%
plastics	$ 3.00	9.0%	100.0%
Rolled Paper - Tetra Pak	$ 100.00	-	100.0%
Bulky Recoverable materials	$ 35.00	-	100.0%

The overview of the scenario framework is shown in Figure 3-3. The avoided gas monitoring includes the equipment and employee payments. The avoided groundwater monitoring includes the employee payments and pipe purchase costs. Ten indicators of costs and six indicators of benefits were taken into consideration in this scenario. The cost and benefit elements assigned in this scenario are shown in Table 3-5. The list of equipment considered for this scenario in the context of mining activities are provided in Table 3-6. As materials are considered to be recycled, more equipment for sorting and separating the materials are also included for this case. The equipment list is taken from the solid waste service group of the City of Denton landfill.

Table 3-7 List of equipment for scenario 3

No.	Equipment name	Purpose
1	Splitter (SM 720K)	Waste separation
2	Track Loader	Cover handling, stockpiling
3	2 Deck Shaker	Waste separation
4	Sorting Station (SS 604EXT)	Waste separation
5	Grinder (DZ 750K)	Processing materials
6	Conveyors	Transfer wastes
7	Star Screen	Separation
8	Excavator	Digging
9	Roll-Off Truck	Trash loading
10	Articulated Dump Truck	Cover soil handling
11	Wheel Loader	Stockpiling
12	Hydraulic Generator	Power supply
13	Vocational Syle Truck	Materials hauling
14	100 Yard Trailer	Materials/wastes transfer
15	100 Yard Trailer	Materials/wastes transfer

Chapter 4

Results and Discussion

4.1 Comparison of physical composition of landfilled Municipal Solid Waste (MSW)

The average physical composition done by Koganti (2015) for cell 1590A of the city of Denton landfill shows that the non-degradable components and soil & fine percentage are approximately 63% of the composition. The composition shown Figure 4-1 indicates that major portion of waste is soil and degraded fines (52%). The main waste component other than soils and degraded fines are paper (18%) and plastics (9%).

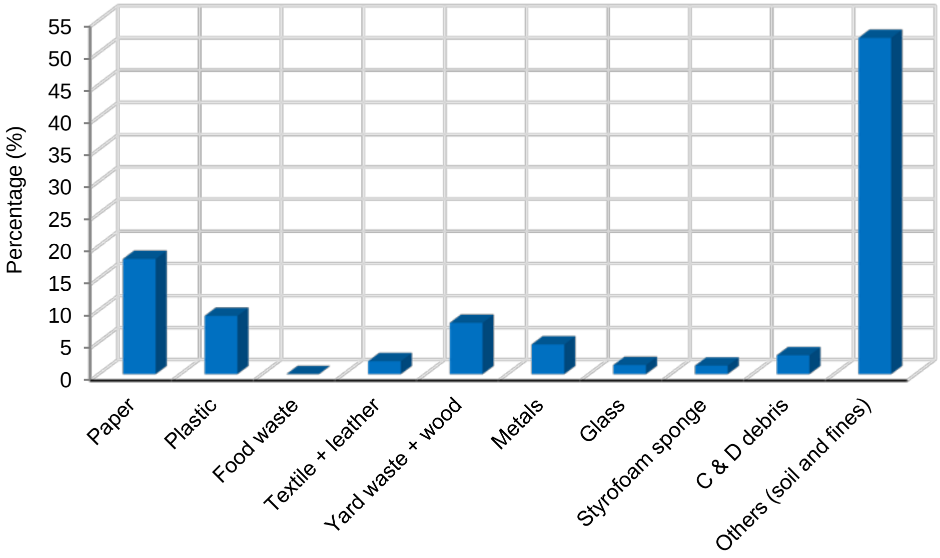


Figure 4-1 Average Physical waste composition (by weight)

The landfilled MSW composition (by weight) of waste samples of 2011 and 2015 of study cell which were conducted by Samir (2011) and Koganti (2015) are compared to characterize the waste degradation trend. The comparison is shown in Figure 4-2 which depicts that with time the amount of soil and fines are increasing due to the waste degradation.

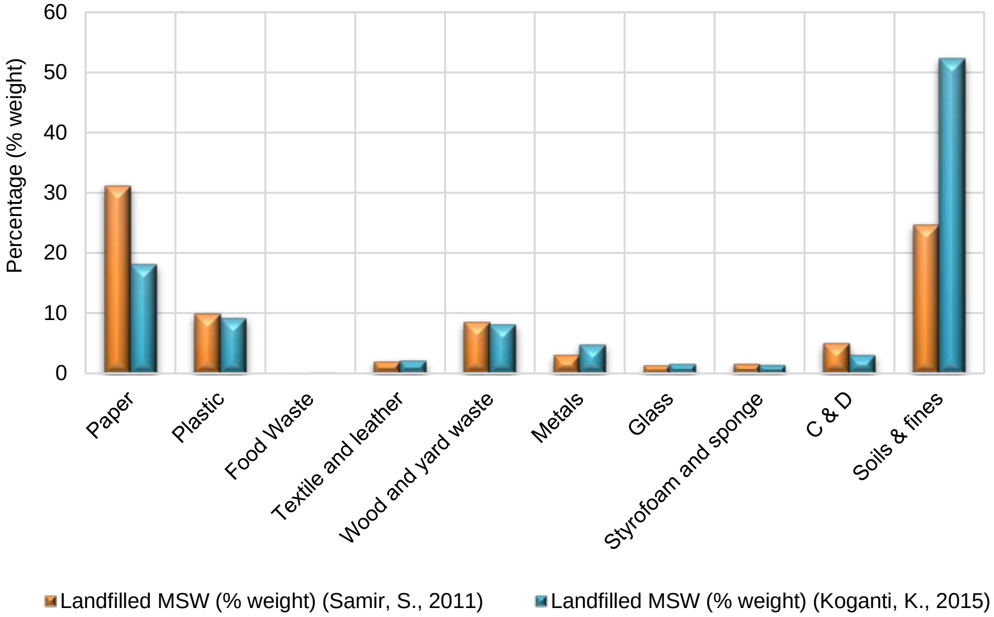


Figure 4-2 Waste composition (by weight) of landfilled waste samples of 2011 and 2015

To identify the major contributing waste component for landfill space occupation, it is important to determine the physical waste composition by volume of the landfilled wastes. From the weight basis composition of the study area the volume basis waste composition is estimated as per conversion factors of USEPA (2016) which is shown on Figure 4-3. The Figure shows that the main component of the mined wastes is plastics which is 40% of wastes. It means that 40% of landfill space is occupied by plastics which is good source of recyclable material for future use and larger air space can be reclaimed as well. The other major components are wood and yard wastes, soils and fines and papers which are 15%, 12% and 10% respectively of the wastes.

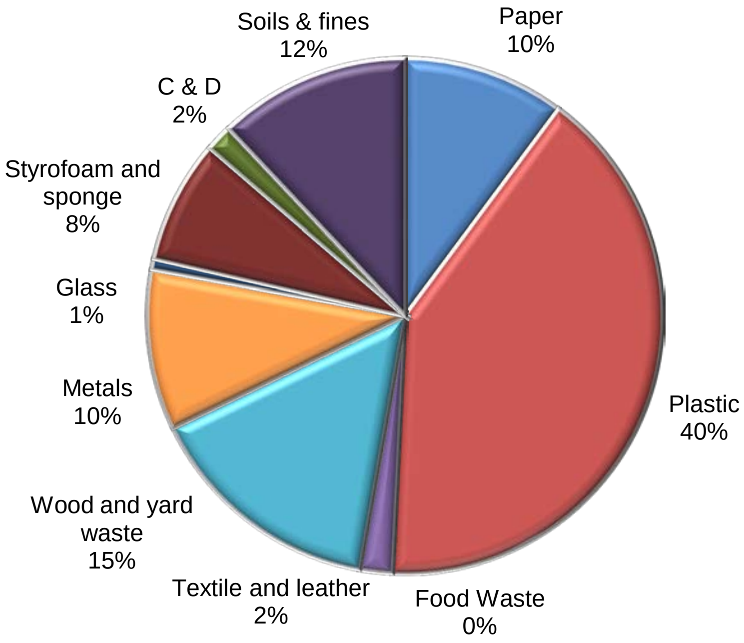


Figure 4-3 Average Physical waste composition (by volume)

Again the landfilled MSW compositions (by volume) of 2011 and 2015 are compared which is shown in Figure 4-4. Figure 4-4 illustrates that with time the degradation of wastes is increasing resulting the increase of the soil and fines and degraded components by weight. Whereas the plastics, glass and papers are almost in same percentages. Again it is clear that the plastics, papers and yard wastes are occupying the landfill space mostly. For instance, plastics and papers are occupying about 40% and 10 to 15% of the landfill space among the landfilled waste. These non-degradable portion can be recycled after mined wastes reclamation.

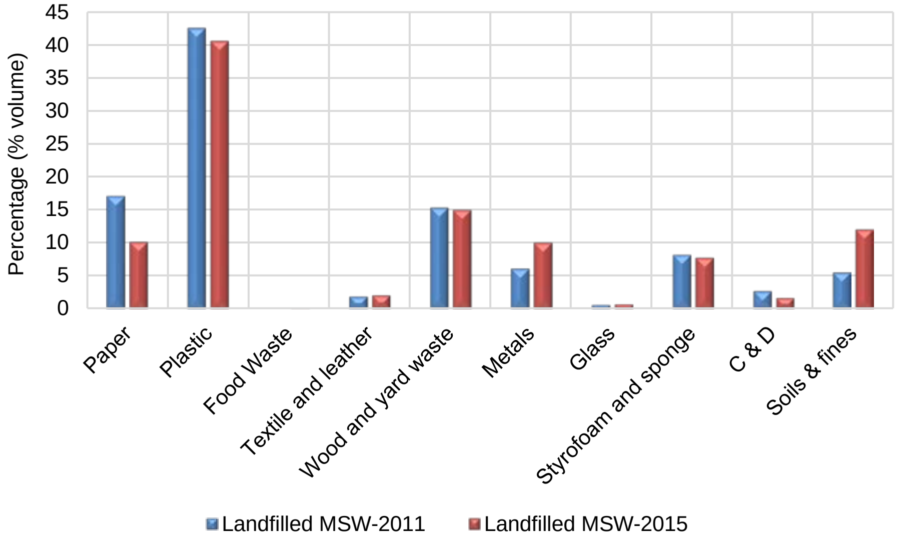


Figure 4-4 Waste composition (by volume) of landfilled waste samples of 2011 and 2015

4.2 Environmental feasibility of Landfill mining

Three scenarios were modeled to assess the feasibility of landfill mining in accordance to the environmental impacts of 1 ton of the mined MSW wastes of a 30 years old unlined landfill. 1 ton of MSW was selected as functional unit for the analysis in order to be consistent in all the three scenarios. The excavated wastes management alternatives involve relocation of the excavated wastes or processing of the recyclable materials to transform into new products. Therefore, the focus is to assess the environmental impact assessment of 1 ton of MSW comparing with other management alternatives such as No Mining, mining with relocation of the wastes on lined cell. All emissions, activities regarding the scenarios are accounted for 1 ton of MSW wastes.

The LCA model is developed to assess the environmental impact of the associated processes for all impact categories, using TRACI 2.1 (version 1.02) method, including ozone depletion, global warming, smog, acidification, eutrophication, carcinogenics, non-carcinogenics, respiratory effects, eco-toxicity, and fossil fuel depletion. The emissions are represented by the model default normalization factors to assess the relative impact of the individual impact categories. The impact category which shows significant impact, is further evaluated further details for better understanding of the impact of the dominant activity of a scenario. In the life cycle assessment results the positive sign indicates the environmental burden and negative sign shows the environmental benefits. All the environmental impact results are based on the valorization of 1 ton of municipal solid wastes.

4.2.1 Basic mining processes

The common landfill mining activities are top soil and vegetative cover removal, excavation, waste transportation, dust control, land reclamation. The wastes are either further screened, processed and reused or relocated into other existing cells. A comparative study was conducted on the basic mining processes only, to have preliminary idea about dominating activities among the others in aspect of the environmental impacts.

4.2.1.1 Basic mining activities with resource recovery

In this case, basic activities of mining considered are mining activities are cover soil removal, excavation, waste transportation, dust control, waste screening including material recovery and land reclamation. The recovered material processing and intermediate product production are not considered for this analysis. The waste disposal scenario was not included for this analysis of impact assessment of basic mining activities.

The normalized environmental impacts of the activities for 1 ton of MSW are shown in Figure 4-5, which depicts that the dominating activities are the waste screening and the top soil removal and transportation of top soil. The waste screening induced environmental benefits due to the recovery of metals, soils and fines, plastics, papers and yard wastes from the landfill mining resulting in environmental credit in eco-toxicity and carcinogenic impact categories.

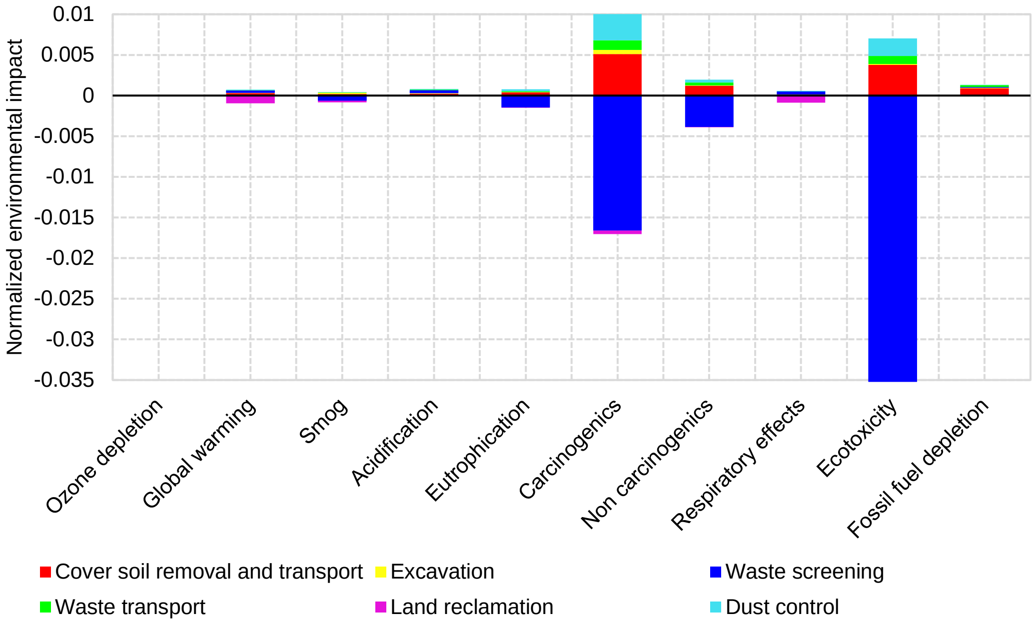


Figure 4-5 Normalized environmental impact of basic mining activities

To understand the relative contribution of the activities on the basic mining process, each impact category was set into 100% which is illustrated in Figure 4-6. It is also showing that the waste screening activity is the major activity which is important in the mining scenario. From the Figure 4-6, it is also clear that the land reclamation is contributing positively due to the land recovery from the mining. As it was found earlier, the top soil removal activity is inducing environmental burden significantly.

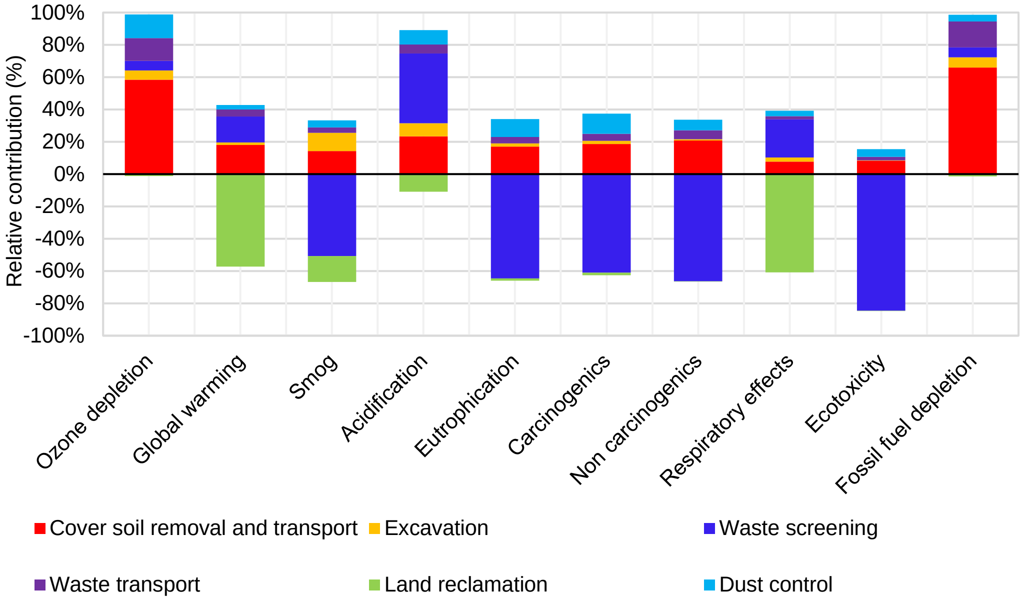


Figure 4-6 Relative contribution of the activities of mining

4.2.1.2 Basic Mining activities with waste relocation

In the basic mining process, if the wastes are relocated into the existing landfill cells rather than screening and recovering the waste materials the environmental impact would be different. The waste disposal was not included in this analysis. The environmental impacts of the activities of mining with relocation of wastes are shown in the Figure 4-7. The environmental impact should be more than the previous case.

The relative contribution of the mining with relocation is illustrated in Figure 4-8. Here the only environmental benefit is induced by the land reclamation after the mining activities. If the land after mining is gained it avoids the environmental impacts of acquisition activities of another piece of land.

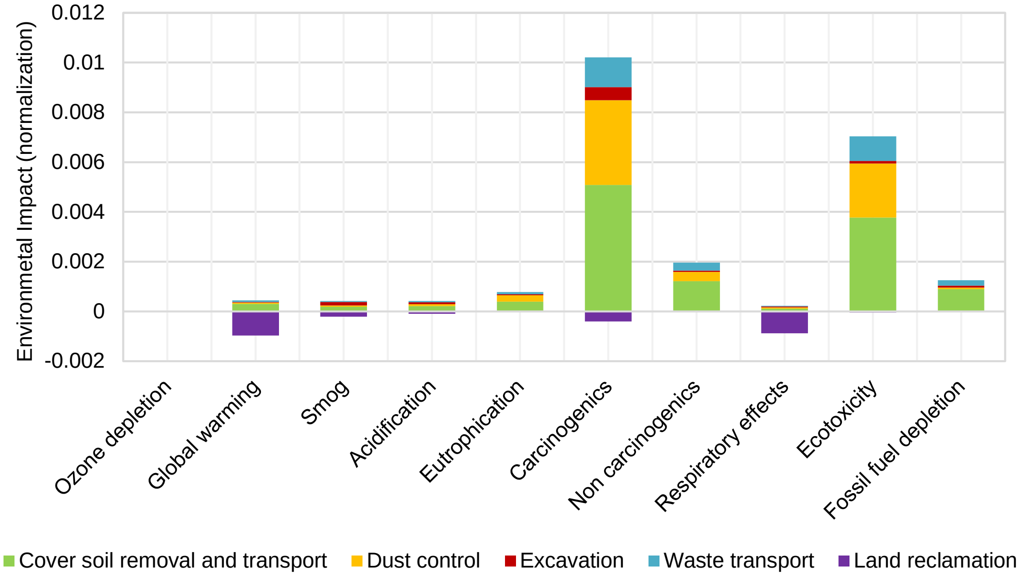


Figure 4-7 Mining activities with waste relocation

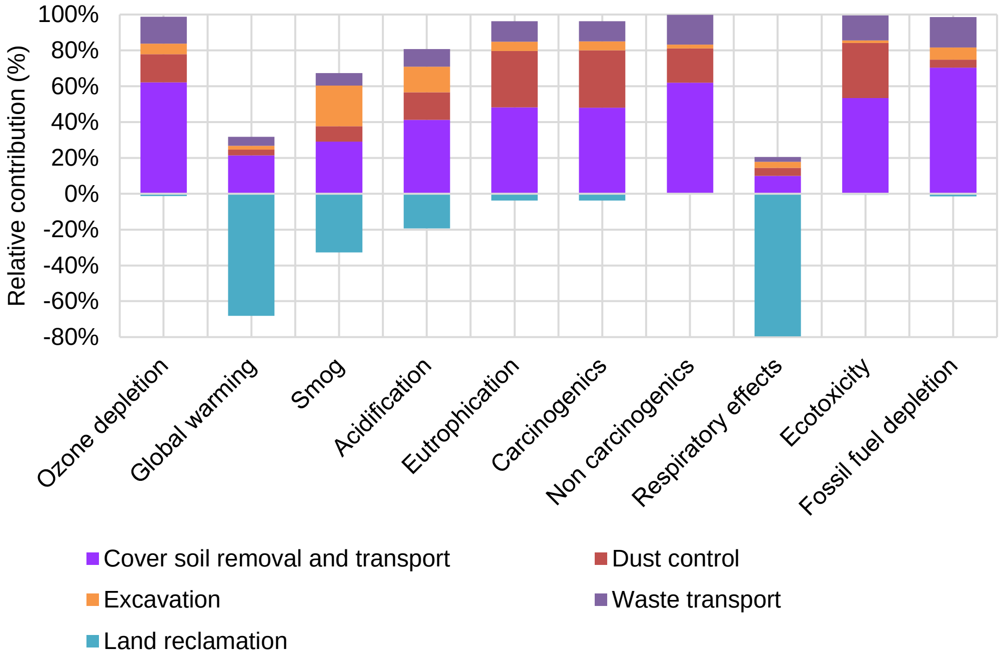


Figure 4-8 Relative contribution of the process wise analysis of mining with relocation

Danthurebandara et al. (2015) conducted study on the feasibility of ELFM for 1 ton of MSW and 1 ton of industrial wastes and assessed the contribution of different processes of mining activities. The assessment and relative contribution of the process found by the study is shown in Figure 4-9. In the study in addition to the common mining activities, thermal treatment was also included which contributed to environmental benefits for both the MSW and industrial wastes due to the electricity generation from the thermal treatment. In the current study the thermal treatment option was not included in the options of valorization. Rather than the thermal treatment, they found the separation and land reclamation as major benefit to environment which is similar to the current study. Likewise the current study the recovery of recyclable materials credited to the benefits in their study as well.

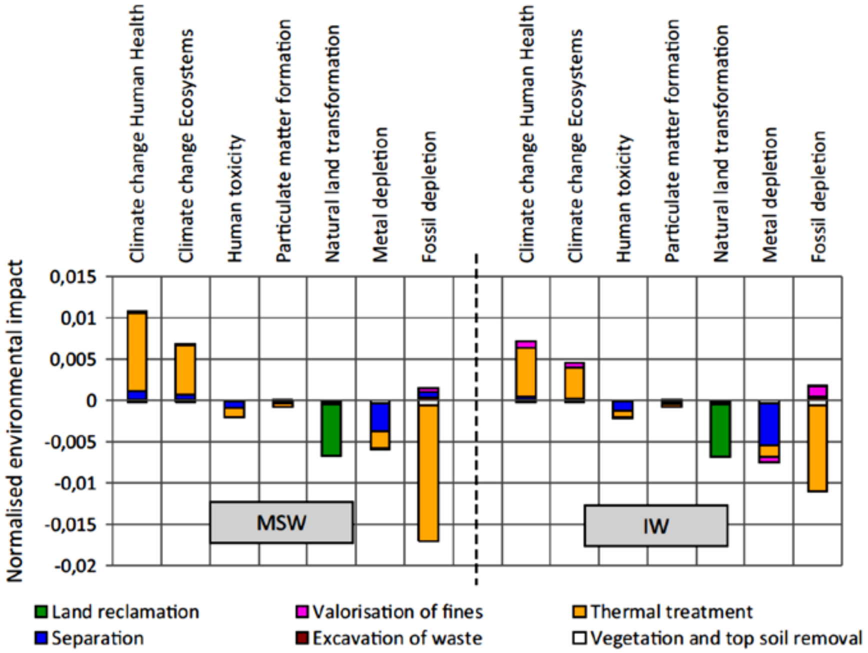


Figure 4-9 Contribution of different ELFM processes-normalised environmental profile of valorisation of 1 tonne of MSW/IW (basic scenario) (Danthurebandara et al., 2015) Maheshi D, et al.2015)

4.2.2 Comparison between the basic mining processes

The environmental impact comparison between these two basic mining activities (with waste recovery and without the processing of the recovered materials) is depicted in Figure 4-10. It can be easily seen that the mining with relocation is inducing much higher emissions and environmental burdens than the mining with resource relocation. The material recovery from the former scenario induced credit to environmental benefits.

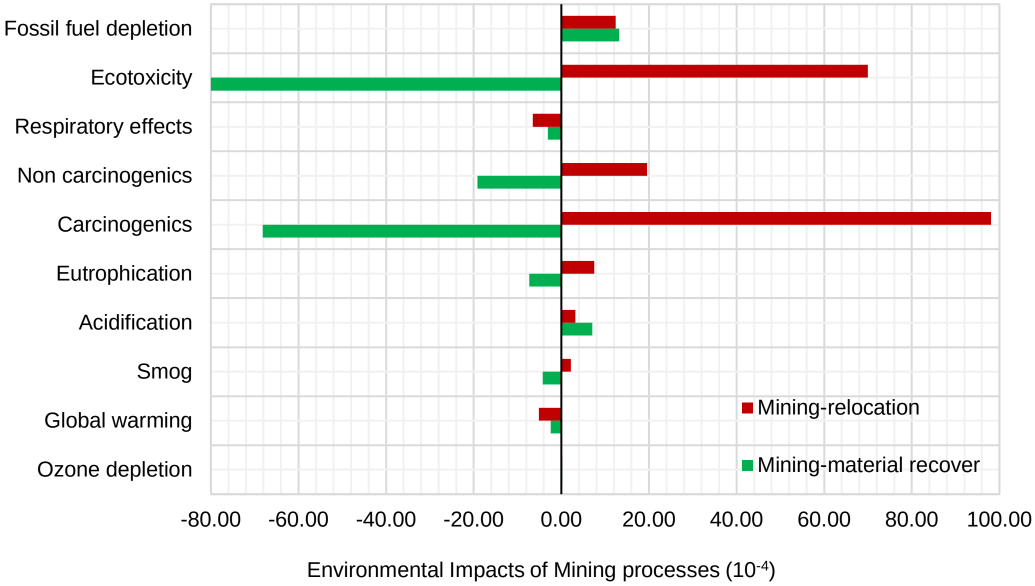


Figure 4-10 Comparison between the process wise analysis mining activities

To understand the relative impact of these scenarios on any impact categories, the comparative relative contributions are illustrated in Figure 4-11. As previous, the scenario with material recovery depicts more environmental benefits than the other one.

A details analysis is further needed to include the material processing, material recycling and waste relocation activities into these scenarios which is done in the next sections of the study.

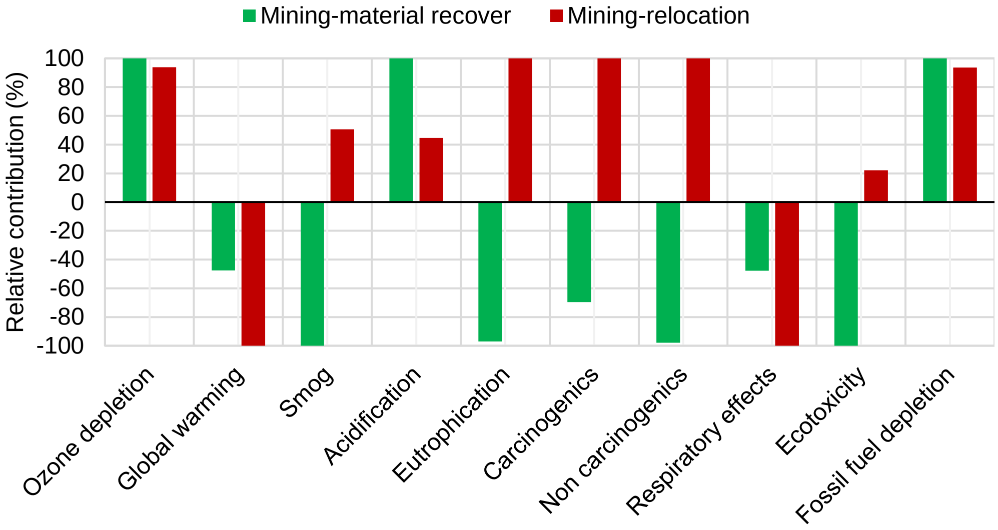


Figure 4-11 Comparison of Relative contribution

4.2.3 Scenario wise environmental impacts analysis

4.2.3.1 No-mining (Scenario 1)

This is the basic scenario which is the existing condition of the landfill. It is also called no mining scenario. In this scenario the activities are related to the emissions such as ground water emissions, gas emission from the top cover of the landfill due to the decomposition of the municipal solid waste of landfill which were there for last 30 years. As mentioned earlier that the gas generation curve showed decreased trend which may induce due to this landfill being a dry tomb rather than the leachate being recirculated. The gas generation calculation was based on the prediction with 50% collection efficiency for more 50 years from 1 ton of landfill wastes. Figure 4-12 presents the normalized environmental profile for scenario 1 for a functional unit of 1 ton of MSW. The normalized impact results are also shown in Table 4-1.

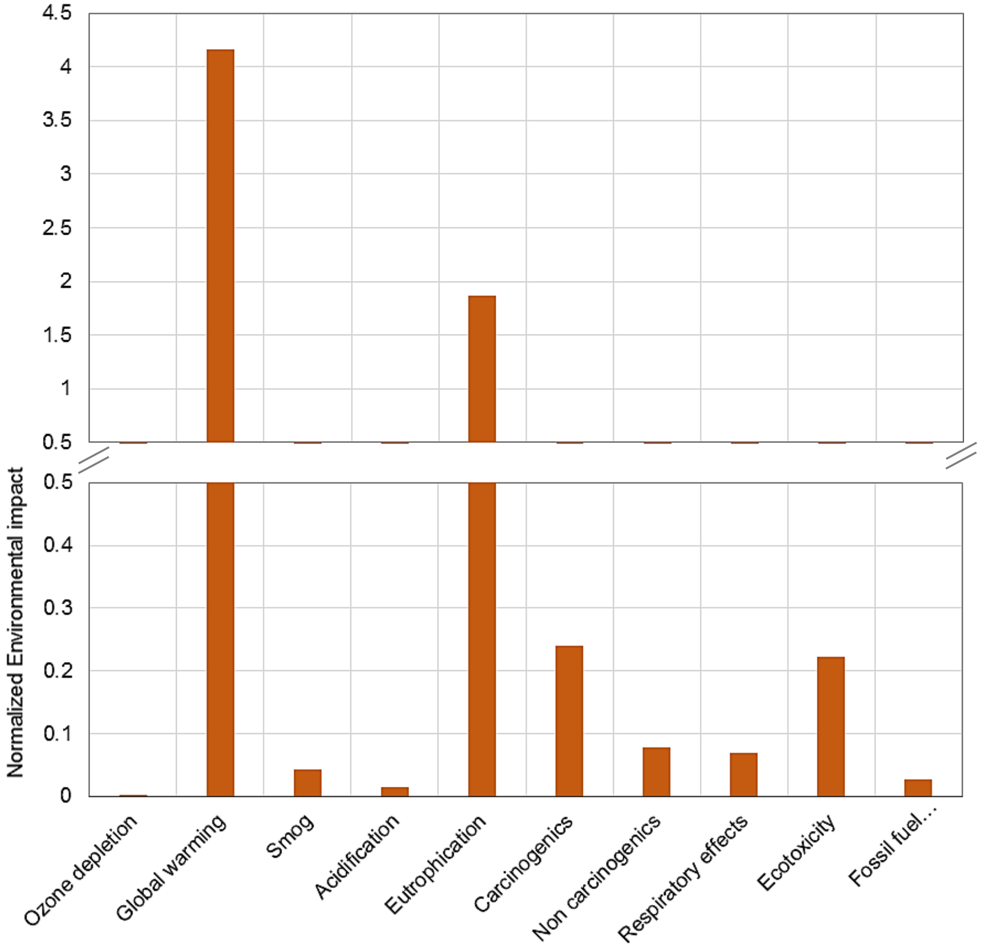


Figure 4-12 Normalized environmental profile of scenario 1 for 1 ton of MSW (scenario 1)

Figure 4-12 indicates that in normalization the contribution of global warming and eutrophication impacts are very crucial. The scenario yields environmental burden in global warming impact category due to the air emissions from the landfill gas.

The characterized environmental impact results of scenario 1 are provided in Table 4-2. In Figure 4-12 the process flow network for this scenario is illustrated in network pattern. The red color indicates the environmental burden, whereas the green color mean it is inducing environmental benefit. From the figure it is prominent that the emission from top cover is affecting the environment adversely. The characterization impact results of the scenario 1 are provided in Table 4-2. It indicates that the global warming is the dominating impact category among the others.

Table 4-1 Contribution of processes of scenario 1 (Normalization results)

Impact category	**Total**
Ozone depletion	0.000314375
Global warming	4.159636434
Smog	0.042236637
Acidification	0.015106914
Eutrophication	1.863353781
Carcinogenics	0.240180708
Non carcinogenics	0.077177972
Respiratory effects	0.069648867
Eco-toxicity	0.221757169
Fossil fuel depletion	0.026457937

Table 4-2 Environmental Profile of scenario 1 (Characterization results)

Impact category	**Unit**	**Total**
Ozone depletion	kg CFC-11 eq	5.07057E-05
Global warming	kg CO2 eq	100717.5892
Smog	kg O3 eq	58.82539984
Acidification	kg SO2 eq	1.373355842
Eutrophication	kg N eq	40.24522205
Carcinogenics	CTUh	1.21882E-05
Non carcinogenics	CTUh	8.10693E-05
Respiratory effects	kg PM2.5 eq	1.690506481
Ecotoxicity	CTUe	2450.355461
Fossil fuel depletion	MJ surplus	456.9591878

The impact components of the categories are presented in Figure 4-13. The environmental burdens are expressed as positive values and environmental benefits are expressed as negative values. Figure 4.13 shows that the equivalent CO_2 emission due to the global warming is the major emissions from this scenario. The energy due to fossil

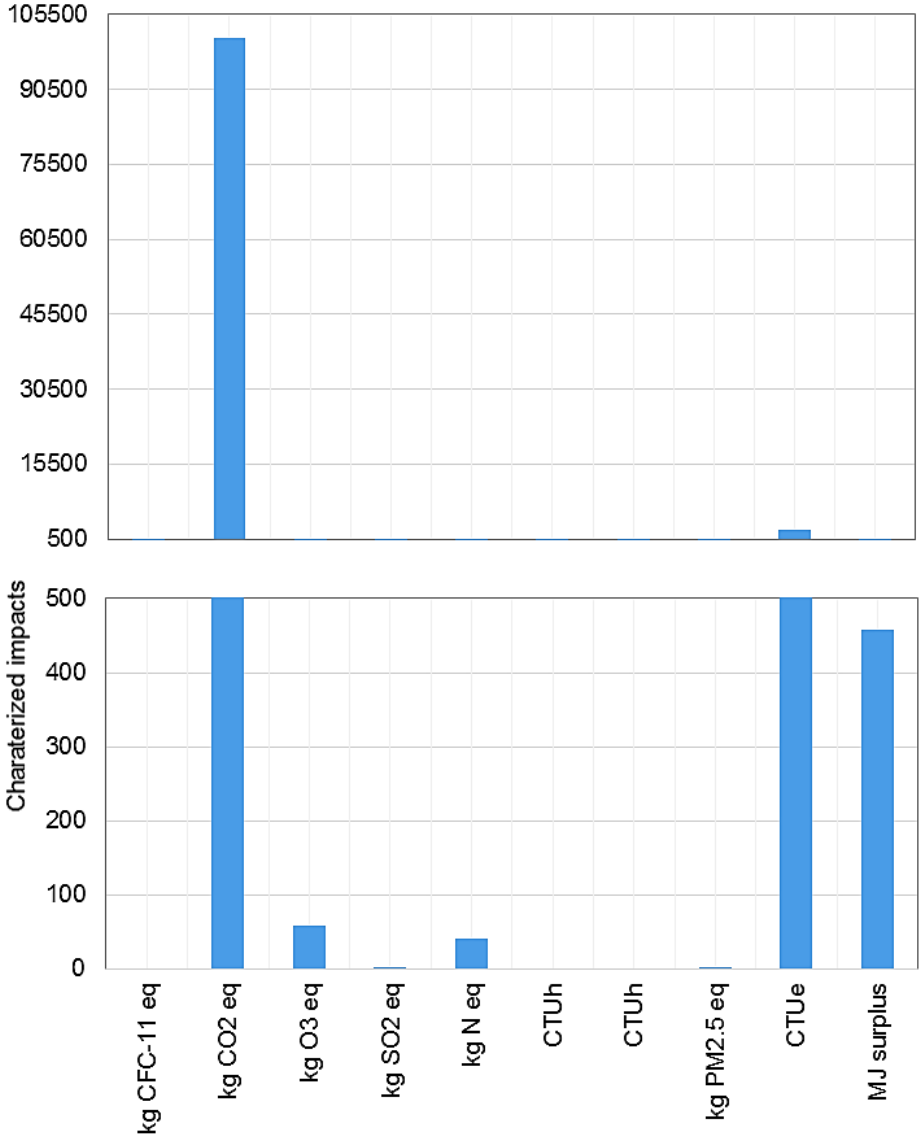


Figure 4-13 Environmental impact components of scenario 1

fuel depletion and the CTUe due to eco-toxicity are also contributing significantly in this case. The gas emissions from the top cover of the landfill and the maintenance of the landfill cell would be the major source of these emissions in this scenario 1.

The impact of each process on each impact category can be found from SimaPro through a network flow diagram. The percentage of contribution of each interrelation process can be depicted from the diagram. For instance, in figure 4-14 the impact

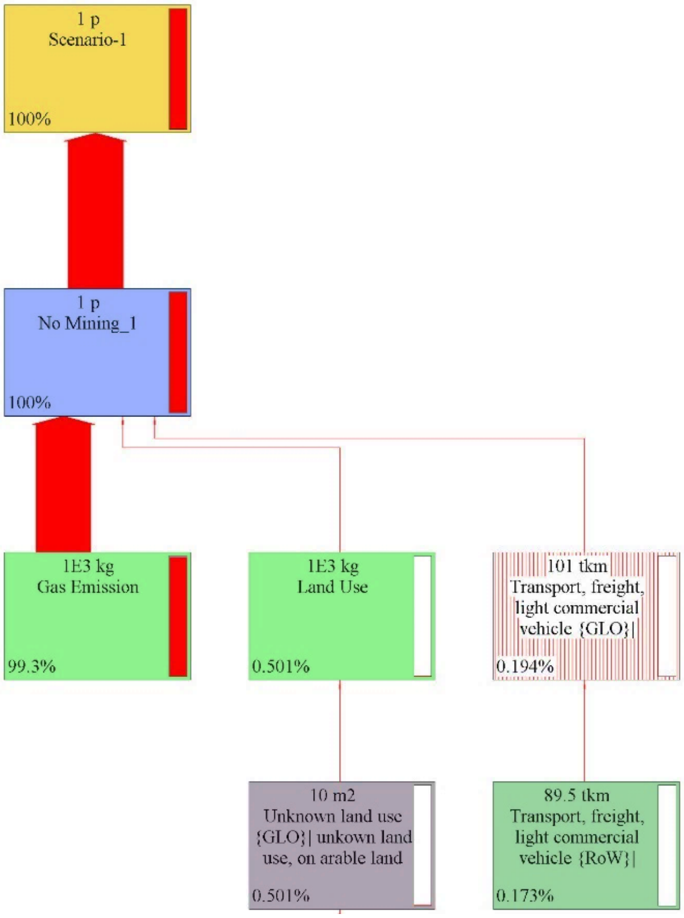


Figure 4-14 Process flow network diagram for global warming indicator (impact cut off at 0.16%)

percentages of the processes on global warming impact category is provided. Commonly in output, all the processes in network analysis can be found. But due to visual ease, the network diagram of impacts at cut off of 0.16% is shown in this Figure which means the processes which have contribution more than 0.16% are shown in the Figure. The rest processes have less impacts than this cut off values (not shown in Figure 4-14).

It is clear from Figure 5.14 that, the gas emissions from the landfill is mostly responsible for the impacts of scenario 1.

4.2.3.2 Mining with relocation (Scenario 2)

The second scenario of the study is landfill mining scenario with waste relocation. In this scenario including the basic mining activities, the mined materials are considered to be relocated into other existing cells and the recovered top soil and recovered fines are considered to be recycled and used as daily cover of landfill. In many landfill mining projects this condition prevailed due to the excavation of unlined cells, regulation legislations etc.

The characterization and normalized results of the life cycle assessment of the scenario 2 is provided in Table 4-3. To assess the relative contribution of the waste components on the environmental impact of this scenario Figure 4-15 is presented which shows that soils and fines are the dominating waste component. This was obvious as the MSW of this case study consists of mostly soils and fines. Figure 4-15 is symbolizing the waste composition likewise.

Table 4-3 LCA results of scenario 2

Impact category	Normalized	Unit	Characterized
Ozone depletion	0.00767	kg CFC-11 eq	0.001237
Global warming	0.19178	kg CO2 eq	4643.6203
Smog	0.37004	kg O3 eq	515.3751
Acidification	0.42087	kg SO2 eq	38.2606
Eutrophication	1.77054	kg N eq	38.2407
Carcinogenics	12.55038	CTUh	0.0006369
Non carcinogenics	10.23878	CTUh	0.010755
Respiratory effects	0.12715	kg PM2.5 eq	3.086168
Ecotoxicity	152.04445	CTUe	1680049.147
Fossil fuel depletion	0.63579	MJ surplus	10980.7748

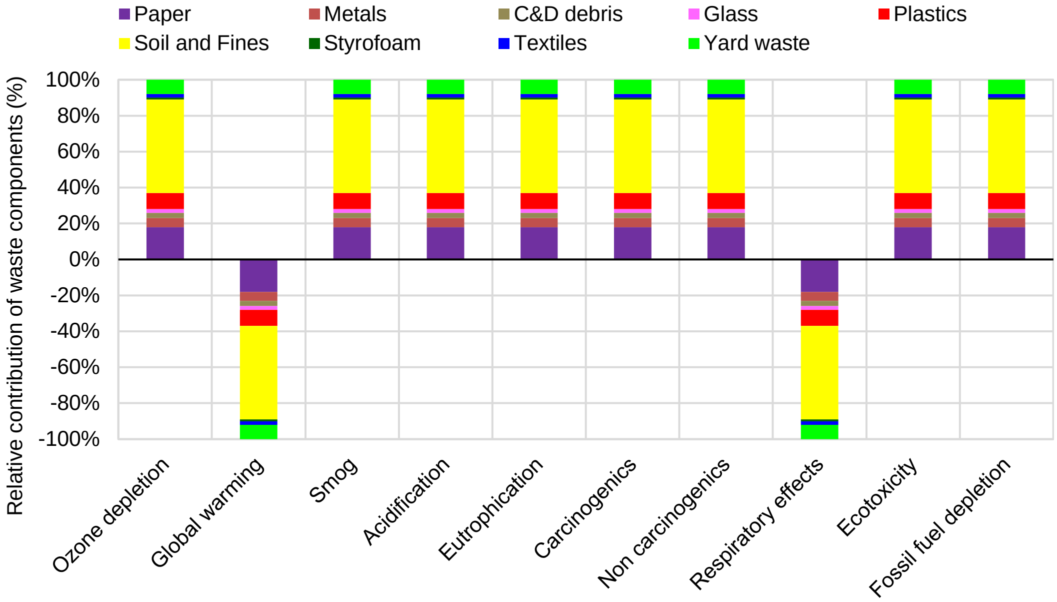


Figure 4-15 Contribution of waste components on scenario 2

The environmental impact of scenario 2 is illustrated in Figure 4-16, which shows that the environmental burden is significant in carcinogenic, non-carcinogenic and eco-toxicity categories.

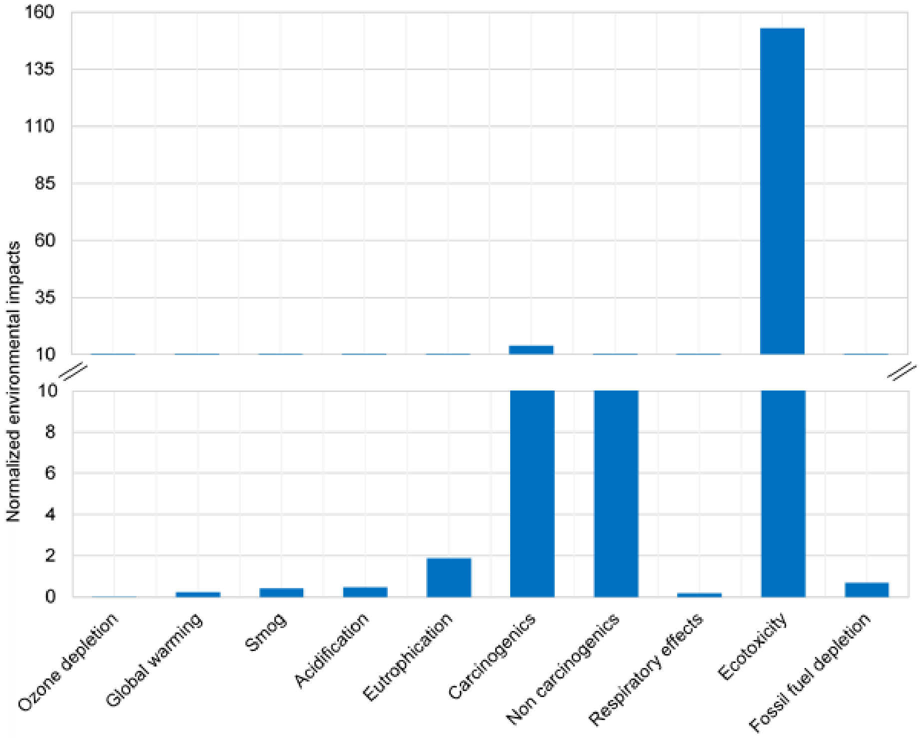


Figure 4-16 Environmental impact of Scenario 2 (normalized results)

The nitrogen and trace amounts of toxic substances contribute to toxicity to humans and ecology. The most important contributions to eco-toxicity from waste treatment systems come from toxic metals and persistent organic pollutants.

In a life cycle assessment, the disposal scenario is a major component which may also be named as waste scenario. In this scenario, after the mining activities the wastes are considered to be landfilled. The re-landfilling is considered in the waste scenario of this scenario. The impact of each process on each impact category can be found from Simapro through a network flow diagram.

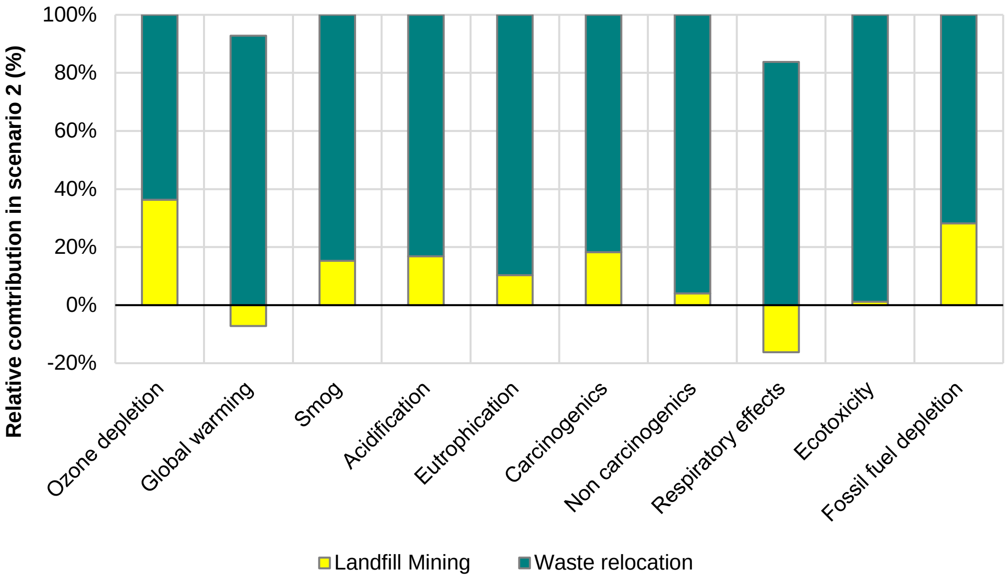


Figure 4-17 Relative contribution of processes within scenario 2

The percentage of contribution of each interrelation process can be depicted from the diagram. In Figure 4-17 the impact percentages of the processes on global warming impact category is provided.

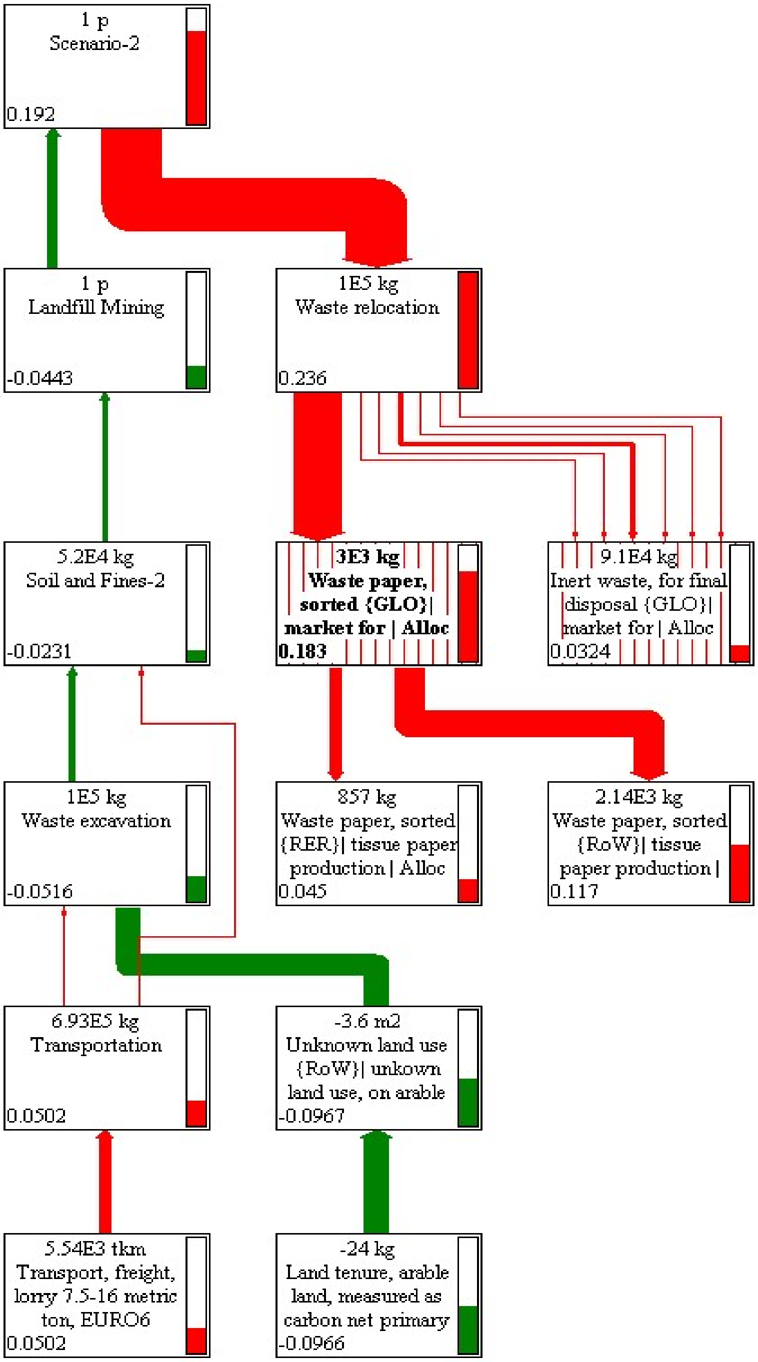


Figure 4-18 Normalized global warming impact flow for scenario 2 (cut-off at 15%)

Commonly in output, all the processes in network analysis can be found. But due to visual ease, the network diagram of impacts at cut off of 15% is shown in this Figure which means the processes which have contribution more than 15% are shown in this Figure. The rest processes have less impacts than this cut off values (not shown in Figure 4-18). The green color indicates the environmental benefits and red color indicates the burdens. It is noticeable from the Figure 4-17 that the land reclamation after mining of landfill credited in environmental benefits. Whereas it is clear that the waste relocation or disposal of the excavated materials induced larger emissions than the mining activities. The similar result can be seen in the Figure 4-18 where the relative contribution of the processes are plotted.

4.2.3.3 Mining with material recovery (Scenario 3)

The last scenario of the study is landfill mining with resource recovery. In this scenario including the basic mining activities, the processing of mined materials into intermediate or final products are also considered. The recoverable materials from landfill mining are papers, plastics, yard waste (woods), soil and fines and metals which are more than 90% of the wastes. The recovered top soil and recovered fines are considered to be recycled and used as daily cover of landfill. The soil and fines are considered to be used as daily cover soil, yard wastes are considered to be chipped and used as the wood chips and the metals are assumed to be sold as scrap metals. The plastics are considered to be used as raw materials for plastic pin production and papers as raw materials for cardboard box production. The emissions and production of intermediate products are considered for 1 ton of product and 1 ton of MSW mining. The disposal scenario was also included which is waste relocation for this scenario.

Other waste components are assumed to be disposed into the other cells of the landfill. Therefore, more than 90% recovered materials from landfill mining are considered to be recycled and reused further in this manner.

The analysis result of life cycle assessment of scenario 3 is provided in Table 4-4. The normalized impacts are presented in Figure 4-19 which shows that in all impact categories, the scenario has environmental benefits due to the recycling of the recovered materials.

Table 4-4 Environmental impacts of scenario 3

Impact category	Environmental impacts (characterization)		Environmental impacts (Normalization)
	Unit	Total	Total
Ozone depletion	kg CFC-11 eq	-0.002334524	-0.014474049
Global warming	kg CO2 eq	-20210.61986	-0.8346986
Smog	kg O3 eq	-1193.498523	-0.856931939
Acidification	kg SO2 eq	-75.42579138	-0.829683705
Eutrophication	kg N eq	3.340961811	0.154686532
Carcinogenics	CTUh	-0.000650726	-12.82321105
Non carcinogenics	CTUh	-0.003937615	-3.748609637
Respiratory effects	kg PM2.5 eq	-23.49412786	-0.967958068
Ecotoxicity	CTUe	-174476.051	-15.79008261
Fossil fuel depletion	MJ surplus	-91673.71046	-5.307907836

Eco-toxicity is found to be the major impact category among all. The avoided products found after the recycling is the major reason of the environmental benefits as if the new product would not be produced then those products would need to be manufactured with virgin materials which would need lots of processes for material acquisition, processing etc.

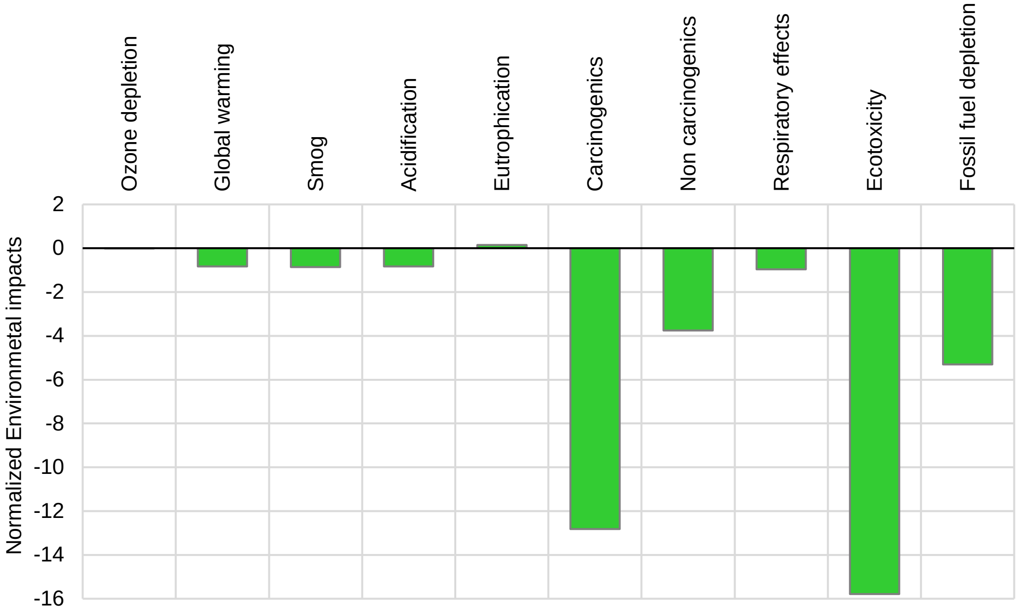


Figure 4-19 Normalized environmental impacts of scenario 3

In this scenario, after mining activities waste components are considered to be processed, reused or redisposed into landfill as inert landfill wastes. The relative impact contribution of processes are illustrated through flow network diagram (impacts of more than 5%) and relative contrition manner as shown in Figure 4-20 and Figure 4-21 respectively. It is found that the waste processing and recycling along with re-landfilling influenced beneficially in this scenario. As example, the mined plastics are converted into new products which is replacing the production of the same product from virgin materials. In Figure 4-20, the plastic product production from mined materials is found to be taken as burden (red color) to the scenario and the avoided processes for production from virgin materials are found as benefits (green color). In Figure 4-21, it is again found that the recycling processing is contributing environmental benefits and the other activities are crediting environmental burdens.

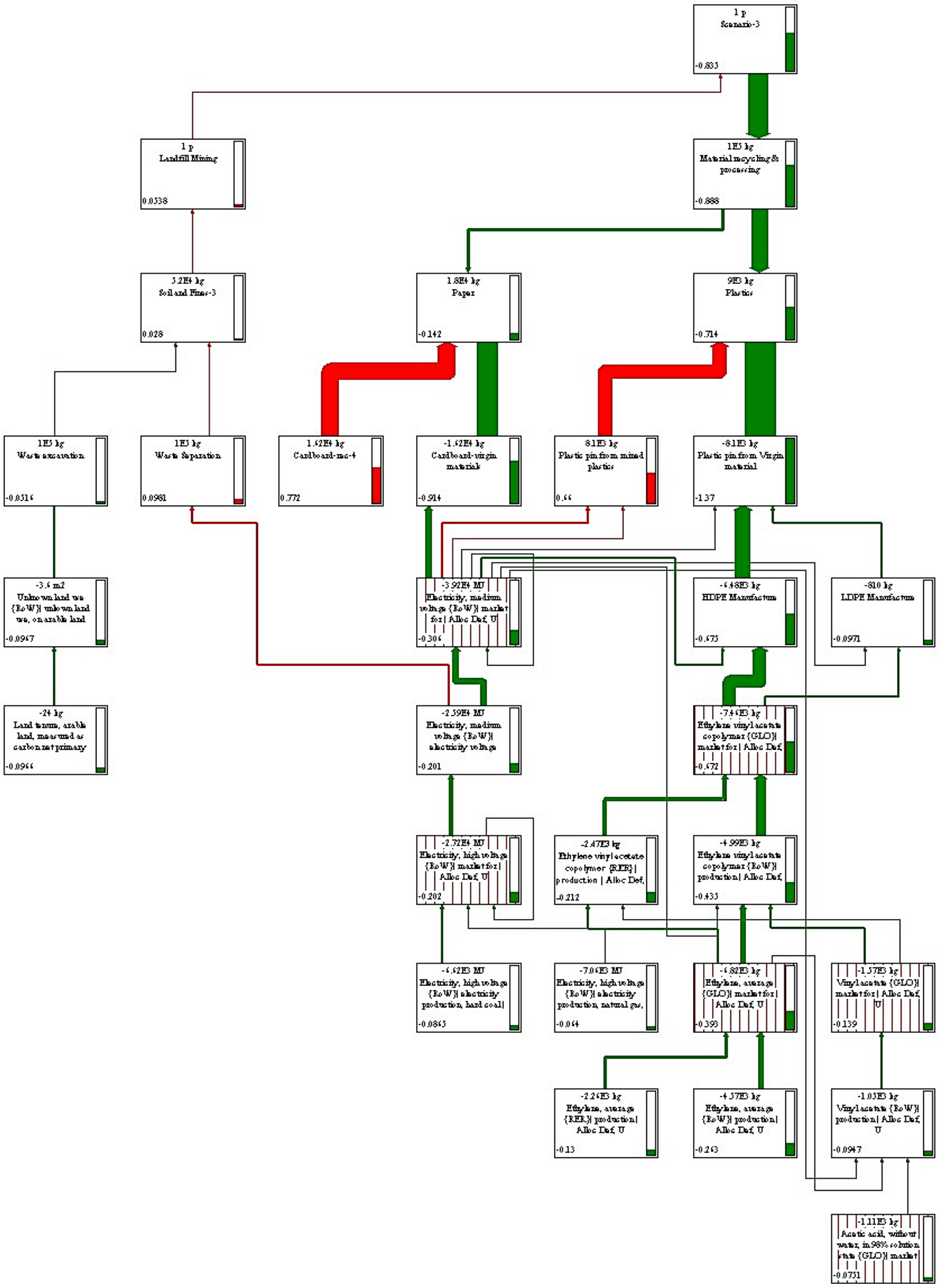


Figure 4-20 Normalized global warming impact flow for scenario 3 (cut-off at 5%)

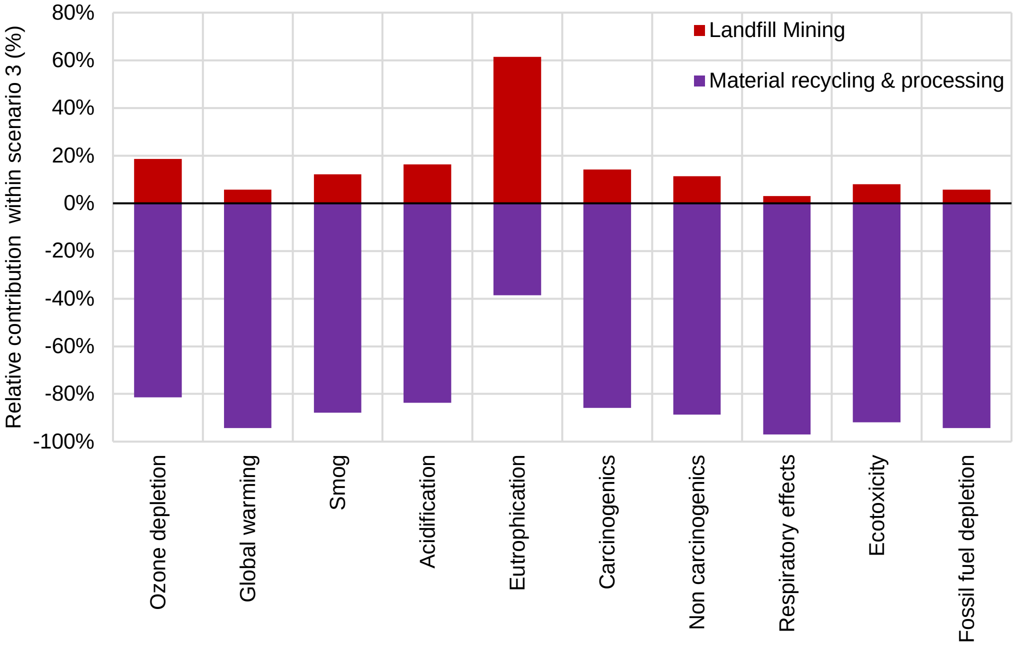


Figure 4-21 Relative contribution within scenario 3

4.2.4 Life Cycle Assessment of intermediate product processing

4.2.4.1 Recycling of mined plastics

The recovered plastics from the landfill can be a source of raw materials to the manufacturing industry such as plastic pin or plastic lumber production industry. The mined plastics can be processed and reused further which would be a sustainable solution with respect to the energy consumption, expense and emissions induced by production from the scratch. Two individual LCA models were created and analyzed to assess the energy saving potential of reusing mined plastic instead of virgin plastics. The system boundary and process flow of plastic lumber manufacture are described in chapter 3. The emissions to air, water from mined plastic plastics were also taken into account in this regard. The disposal scenario of the product is also included in the analysis. The functional unit of the analysis was 1 ton plastic product which is equivalent to 40 plastic pins or plastic lumbers.

Table 4-5 Comparative normalized results of plastic pin production

Impact category	Plastic Pin Manufactured	Plastic Pin manufactured
Ozone depletion	0.234893838	0.213595924
Global warming	1.36678393	16.70313134
Smog	6.234999418	19.69688963
Acidification	12.3474015	24.36672948
Eutrophication	48.92669937	60.58985127
Carcinogenics	111.3731498	291.2717336
Non carcinogenics	48.98096356	66.68075449
Respiratory effects	7.150130972	11.57211987
Ecotoxicity	121.2933105	217.2078946
Fossil fuel depletion	-33.7232641	71.86853026

To compare different categories with each other, the normalization was performed in North American level (PRéConsultants, 2010). The normalized results of plastic pin production from mined and virgin materials are provided in Table 4-5, which is also illustrated in Figure 4-22. It shows that plastic pin manufactured from recycled plastic (mined plastics) has significantly lower environmental impacts than that of manufacturing from virgin materials. In aspect of global warming impact category, the impact of production from virgin materials is more than 2 times of the impact of production from mined plastics. In both cases, the major impact induced in eco-toxicity and carcinogenic categories.

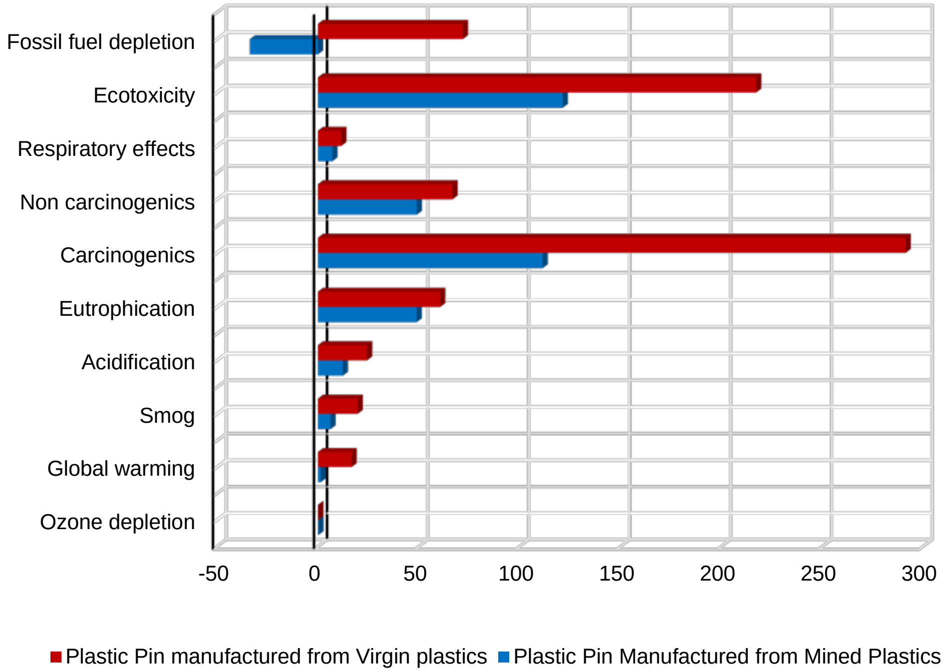


Figure 4-23 Comparison of normalized impacts for plastic lumber production from mined and virgin plastics

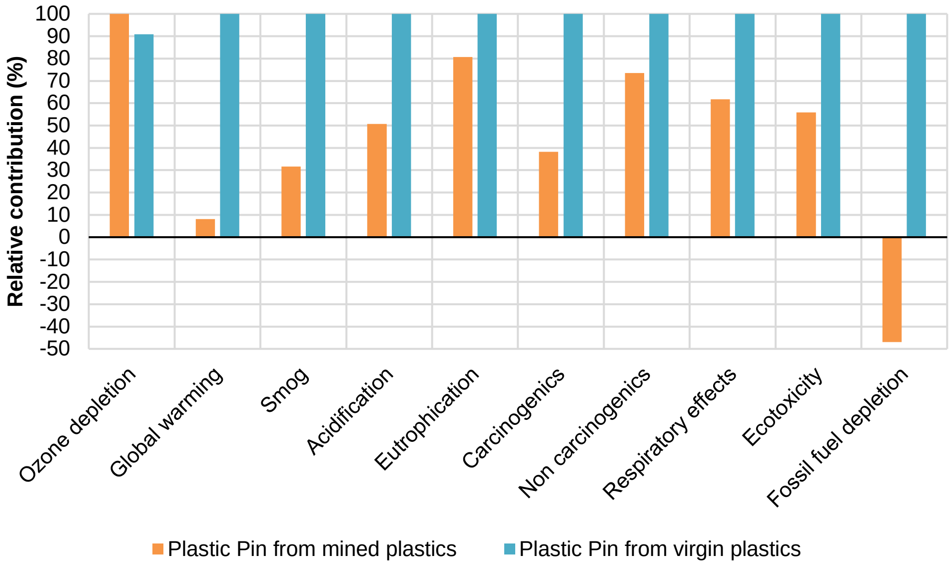


Figure 4-22 Comparison of relative contribution of two LCA models

The relative contribution of the two scenario are presented in Figure 4-23 which shows that in all the impact categories specially in fossil fuel depletion category, the plastic pin manufacture from virgin products has higher impact than the other.

Table 4-6 Comparative characterized results of plastic pin production

Impact category	Unit	Plastic Pin Manufactured from Mined Plastics	Plastic Pin manufactured from Virgin plastics
Ozone depletion	kg CFC-11 eq	0.037886103	0.034450956
Global warming	kg CO2 eq	33094.04189	404434.173
Smog	kg O3 eq	8683.843201	27432.99391
Acidification	kg SO2 eq	1122.491045	2215.157226
Eutrophication	kg N eq	1056.732168	1308.636096
Carcinogenics	CTUh	0.005651738	0.014780865
Non carcinogenics	CTUh	0.051450592	0.070042809
Respiratory effects	kg PM2.5 eq	173.5468683	280.8766959
Ecotoxicity	CTUe	1340257.575	2400087.233
Fossil fuel depletion	MJ surplus	-582439.7945	1241252.682

The characterized environmental result of the comparison of plastic pin production from virgin materials and mined plastics are presented in Table 4-6. It shows that 1 ton of plastic product from recycled plastic materials reduce more than 90% of GHG gas emissions than virgin materials. With 1 ton of plastics, about 40 plastic pins of 50 lb. each can be produced which means that 40 pins can reduce about 0.4 million kg equivalent CO2 which worth of removing about 85 thousand cars from road per year. Also, it can save 1.8 million MJ energy if it is manufactured from mined plastics instead of virgin plastics. Similar results were found by other researchers. Shen et al. (2010), Arena et al. (2003) concluded that the recycling of PET can reduce GHG emissions almost by 90%. PET recycling required 93% less crude oil than the production of virgin PET. The study by Morris (2005) suggests that the recycling of plastics requires approximately 95% less energy than the production of virgin plastics. Therefore, recycling of the mined plastics promotes less energy consumption and environmental impacts which proved the recycling scenario as environmentally beneficial concept.

4.2.4.2 Recycling of mined papers

The mined papers can be processed and converted into intermediate product as cardboard box or corrugated box. The production processes of the cardboard box out of the mined papers and virgin material were considered in the study. Separate life cycle assessments along with the disposal scenarios of both cases were conducted and the environmental impacts are compared to assess the feasibility of recycling the mined papers to convert into new products. The system boundaries and assumptions for both studies are explained in chapter 3.

Table 4-7 Results of environmental impacts (normalized)

Impact category	Cardboard from mined materials	Cardboard from virgin materials
Ozone depletion	5.04347E-07	1.60707E-06
Global warming	5.05944E-06	5.80239E-05
Smog	1.96059E-05	6.48272E-05
Acidification	2.30351E-05	8.80672E-05
Eutrophication	-2.70064E-05	0.000149544
Carcinogenics	-0.000614149	0.000738372
Non carcinogenics	-0.000305968	0.000148692
Respiratory effects	-1.951E-05	5.4721E-05
Ecotoxicity	-0.000847661	0.000536988
Fossil fuel depletion	-1.23791E-06	0.000133387

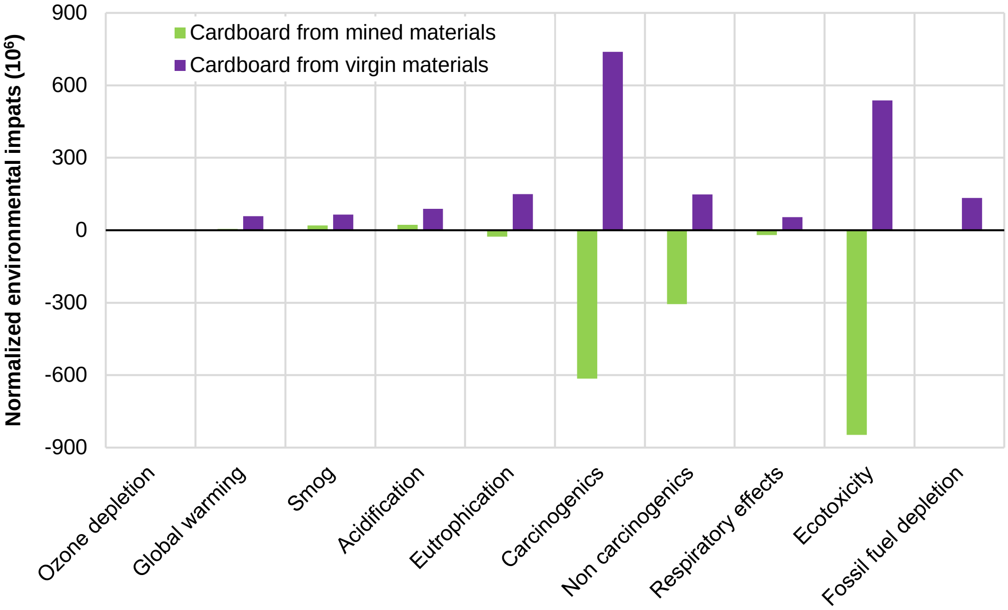


Figure 4-24 Comparison of normalized environmental impacts

To compare different categories with each other, the normalization was performed in North American level (PRéConsultants, 2010). The environmental impact results in normalized pattern are presented in Table 4-7 and Figure 4-24. It can concluded from the results that the paper product production has more adverse impact in case of virgin raw materials rather than the recycled plastics. Due to recycling of papers the cardboard production credits environmental benefits as it avoiding the raw material acquisition from the cradle. Eco-toxicity and carcinogenic are the major influencing categories in this analysis. For better understanding of the relative impact of the two scenarios, characterization results as well as relative contribution results are provided in Table 4-8 and Figure 4-25.

Table 4-8 Results of environmental impacts (relative)

Impact category	Unit	Cardboard from mined materials	Cardboard from virgin materials
Ozone depletion	kg CFC-11	8.13463E-08	2.59205E-07
Global warming	kg CO2 eq	0.122504601	1.404937786
Smog	kg O3 eq	0.027306217	0.090288635
Acidification	kg SO2 eq	0.002094102	0.008006113
Eutrophication	kg N eq	-0.000583291	0.003229886
Carcinogenics	CTUh	-3.11656E-08	3.74694E-08
Non carcinogenics	CTUh	-3.21395E-07	1.56189E-07
Respiratory effects	kg PM2.5	-0.000473544	0.00132818
Ecotoxicity	CTUe	-9.366418639	5.933573218
Fossil fuel depletion	MJ surplus	-0.02138014	2.303747207

The characterized result shows that the recycling scenario is found to be more environmentally feasible than the other one. 1 kg paper product manufactured from mined materials reduce more than 90% equivalent CO2 emissions than virgin materials

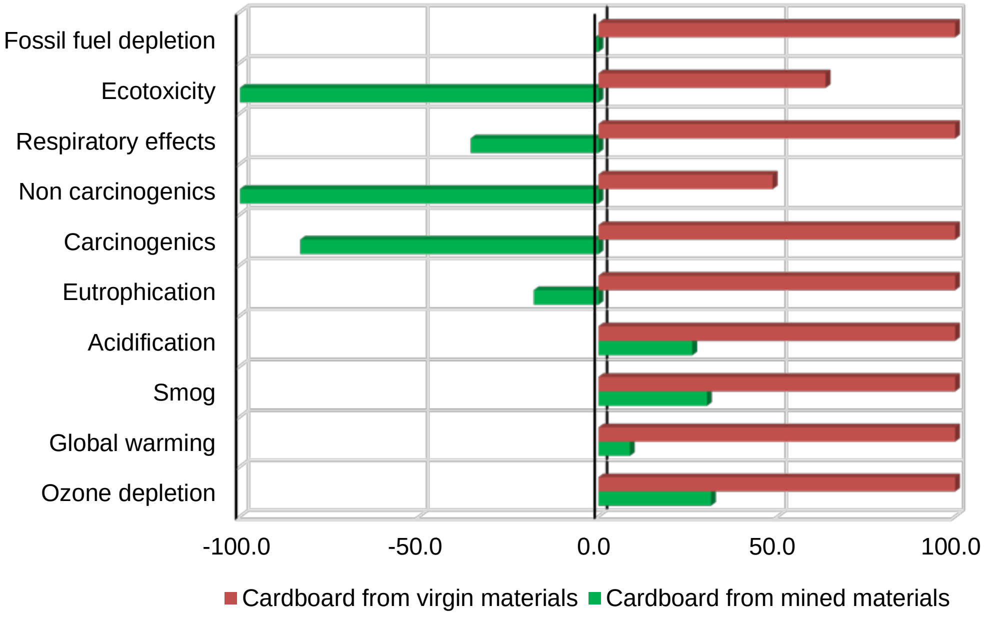


Figure 4-25 Relative contribution of characterized environmental impact

which is about 1.3 kg of equivalent CO2. For 1 kg weigh one corrugated box, about 2.3 MJ less energy would be consumed by using the recycled mined papers instead of virgin materials. However, extensive processing involved with the cardboard manufacture, the energy consumption by the recycling scenario is high. Different combination of recycled and raw materials should be analyzed for optimized and more energy effective recycling of the papers.

4.2.5 Comparison of environmental impacts between three scenarios

The environmental impact of the scenarios are assessed individually. To compare different categories with each other, the normalization was performed in North American level (PRé Consultants, 2010).

Table 4-9 Environmental impacts of three scenarios

Impact category	Normalized Impacts			Characterized Impacts			
	Scenario 1	Scenario 2	Scenario 3	Unit	Scenario 1	Scenario 2	Scenario 3
Ozone depletion	0.00031	0.00767	-0.01447	kg CFC-11 eq	5.07E-05	0.00124	-0.00233
Global warming	4.15964	0.19178	-0.8347	kg CO_2 eq	1.00E5	4643.62	-20210.6
Smog	0.04224	0.37004	-0.85693	kg O3 eq	58.8254	515.375	-1193.5
Acidification	0.01511	0.42087	-0.82968	kg SO2 eq	1.37336	38.2606	-75.4258
Eutrophication	1.86335	1.77054	0.15469	kg N eq	40.2452	38.2407	3.34096
Carcinogenics	0.24018	12.5504	-12.8232	CTUh	1.22E-05	0.00064	-0.00065
Non carcinogenics	0.07718	10.2388	-3.74861	CTUh	8.11E-05	0.01076	-0.00394
Respiratory effects	0.06965	0.12715	-0.96796	kg PM2.5 eq	1.69051	3.08617	-23.4941
Eco-toxicity	0.22176	152.0444	-15.7901	CTUe	2450.36	1680049	-174476
Fossil fuel depletion	0.02646	0.635787	-5.30791	MJ surplus	456.959	10980.77	-91673.7

The impacts in characterization manner is also found from the analysis. The comparative results of the environmental impacts are shown in Table 4-9. All the environmental impact results are based on the calculations for 1 ton of municipal solid wastes. This functional unit is chosen for simplification of calculation and better understanding of results.

4.2.5.1 Comparison of environmental impacts between scenario 1 and scenario 2

The environmental impacts of no mining (scenario 1) and mining with relocation (scenario 2) is assessed and compared to assess the feasibility of landfill mining. The comparison of normalized environmental impacts for valorization of 1 ton of MSW is shown in Figure 4-26. The impact of scenario 1 was very less than the mining with relocation scenario.

In scenario 2, mining with relocation, in addition to the landfill mining processes the relocation or re-landfilling to other existing cells are also included which induced more burdens to the environment. Moreover, there are no material recovery in this scenario which would reduce the impact. Though from land reclamation and top soil reuse there are some benefits to the environment as shown earlier, the impacts from other processes and waste disposal to landfill as inert material of the landfill suppress those benefits resulting to high emissions and impacts.

Whereas, in no mining scenario or scenario 1, the impact is lower in most cases compared to scenario 2 due to lower gas generation and emissions and small low contaminations to environment. Danthurebandara (2015) found that the overall environmental impacts of no mining scenario was ignorable in many categories. But in their study the electricity generation from cogeneration heat and power plant, found to be contributing significantly in no mining scenario. Moreover the soil recovery from the top cover were not considered to be reused as daily cover. In the current study the top soil is considered to be reused and due to less gas generation efficiency the electricity generation option was not considered. These are possible reason of the no mining scenario to be not as ignorable compared to scenario 2 as it was found in previous study. From this life cycle assessment the scenario 2, mining with relocating the wastes doesn't seem to be feasible compared to scenario 1 that is no mining scenario.

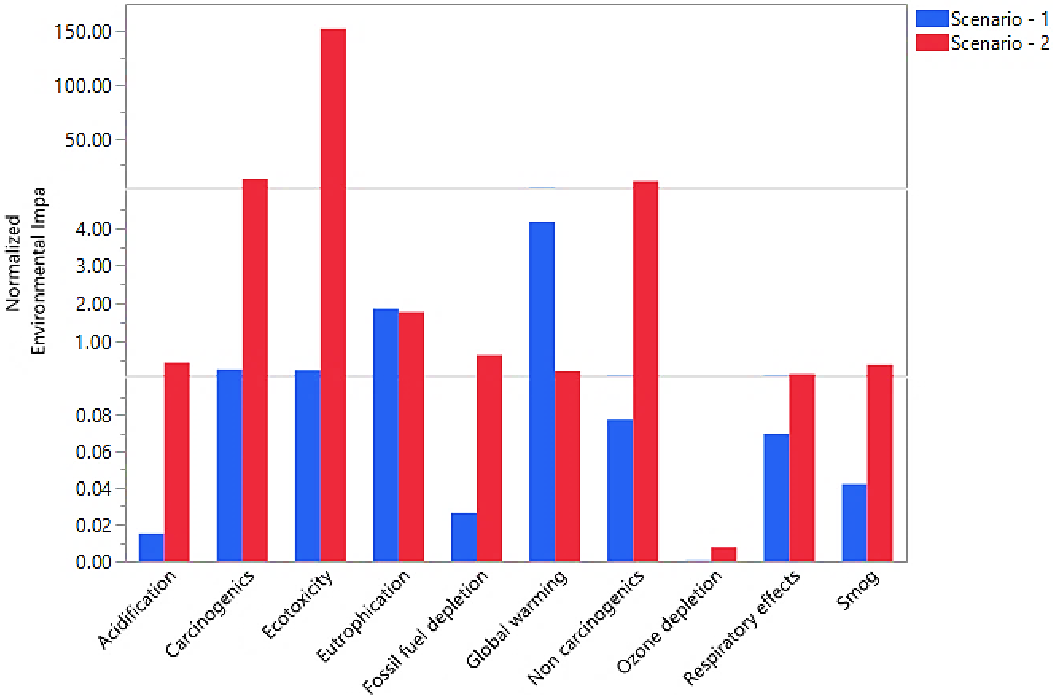


Figure 4-26 Normalized environmental impacts of scenario 1 and 2 in valorization of 1 ton of MSW

4.2.5.2 Comparison of environmental impacts between scenario 2 and scenario 3

The environmental impacts of two mining scenarios which are mining with relocation (scenario 2) and mining with material recovery (scenario 3) are compared to identify the more feasible option among the waste management alternatives after mining. The comparative environmental impacts of scenario 2 and scenario 3 in normalization aspect is shown in Figure 4-27.

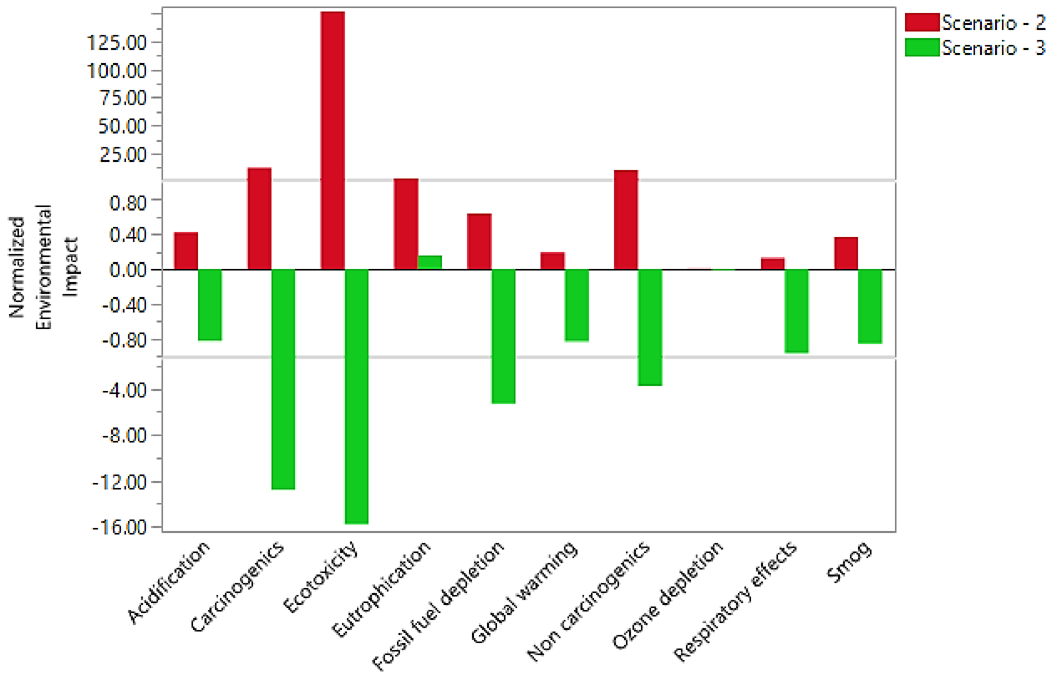


Figure 4-27 Normalized environmental impacts of scenario 2 and 3 in valorization of 1 ton of MSW

According to Figure 4-27, the material recovery from landfill mining is predominantly beneficial than the mining with relocation scenario. Benefits from land reclamation after mining activities and reuse of recovered top soil are considered in both cases. As mentioned earlier, in the disposal scenario the reclaimed wastes are assumed to be re-located in scenario 2, whereas the recyclable wastes are considered to be processed and reused in scenario 3. According to the composition of the wastes of the study area, 95% wastes are recoverable. Among the recyclable materials 90% materials are considered to be recovered and reused. Overall 85% materials are considered to be recovered and reused in this scenario. The rest are considered to be re-landfilled as inert landfill wastes. Figure 4-27 shows that the mining with relocating wastes is inducing much environmental impacts than the material recovery option. In all the impact categories, the later scenario has benefits except the eutrophication which may due to the nitrogen and phosphate emissions from material processing. The major impact category is found to be eco-toxicity and carcinogenics. Therefore, it can be concluded from this analysis that among the mining scenarios of the study mining with material recovery is beneficial and viable option comparing to mining with relocation.

4.2.5.3 Comparison of environmental impacts between scenario 1 and scenario 3

Whenever the landfill mining is planned to transformed from conceptual phase to implementation phase, it is necessary to know whether the landfill mining is feasible and beneficial compared to no mining scenario (Danthurebandara et al., 2015). The comparison of the environmental impacts between no mining and mining with material recovery is given in Figure 4-28.

In scenario 1, the major impact category is global warming, whereas in scenario 3 it is eco-toxicity. Due to material processing and recovery such as metal recovery as scrap metal, yard wastes as wood chips, plastics as of plastic lumber, papers as cardboard box, soil and fines as daily cover soil; induced environmental credit which can be seen to impact in fossil fuel depletion category in Figure 4-28.

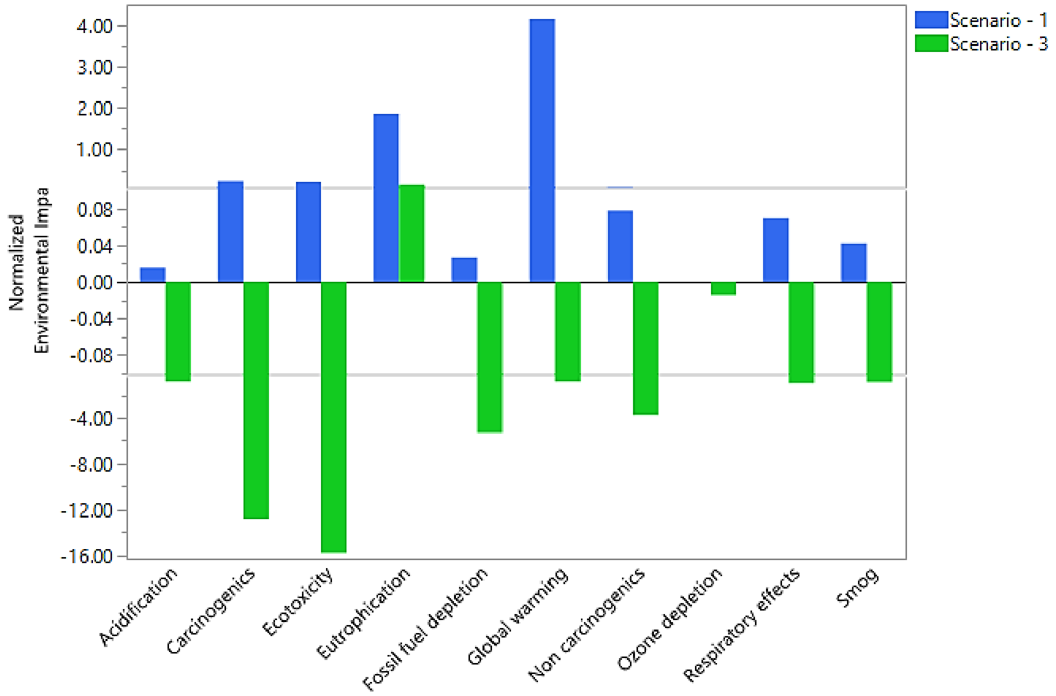


Figure 4-28 Normalized environmental impacts of scenario 2 and 3 in valorization of 1 ton of MSW

Danthurebandara et al. (2015) compared landfill mining with no mining scenario for valorization of total wastes (8.2 million MSW) of the landfill. In Figure 4-29 results indicate that due to the metal, sand, aggregates, soil recovery and energy recovery from thermal treatment, mining scenario seemed to have environmental impacts. Whereas, due to less gas generation and well maintained landfill, electricity generation from landfill gas induced comparatively less burdens as it was expected. This study isn't comparable to present study as the methodologies and considerations are different.

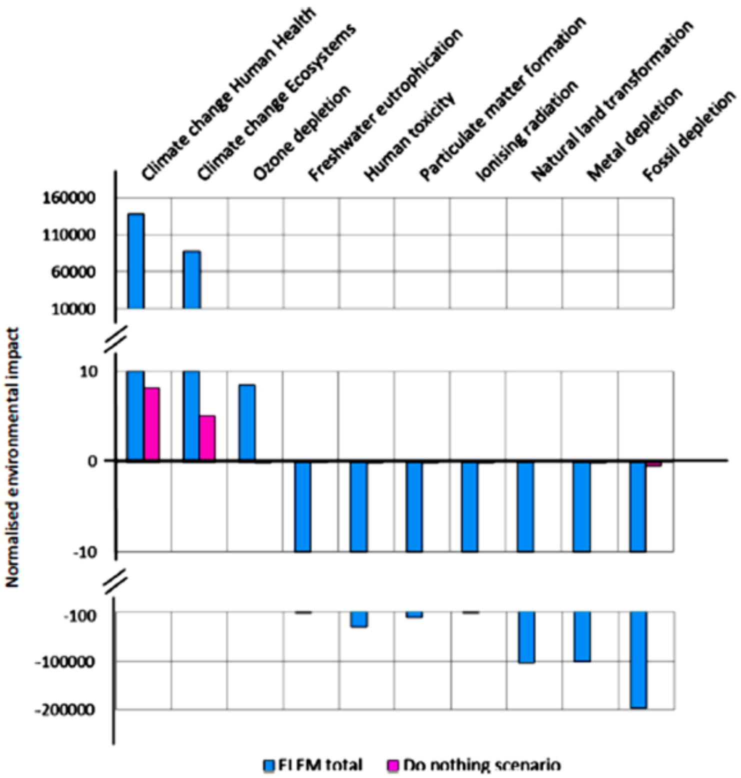


Figure 4-29 Normalized environmental profile for total wastes in landfill compared to do nothing scenario (Danthurebandara et al. 2015)

4.2.5.4 Comparison between scenario 1, scenario 2 and scenario 3

The comparison of normalized environmental profile of 1 ton of MSW among the three scenarios is presented in Figure 4-30. In this overall comparison aspects, the major impact categories are global warming, fossil fuel depletion, eco-toxicity, eutrophication and carcinogenics and which are shown in details to compare the scenarios on major impact category basis.

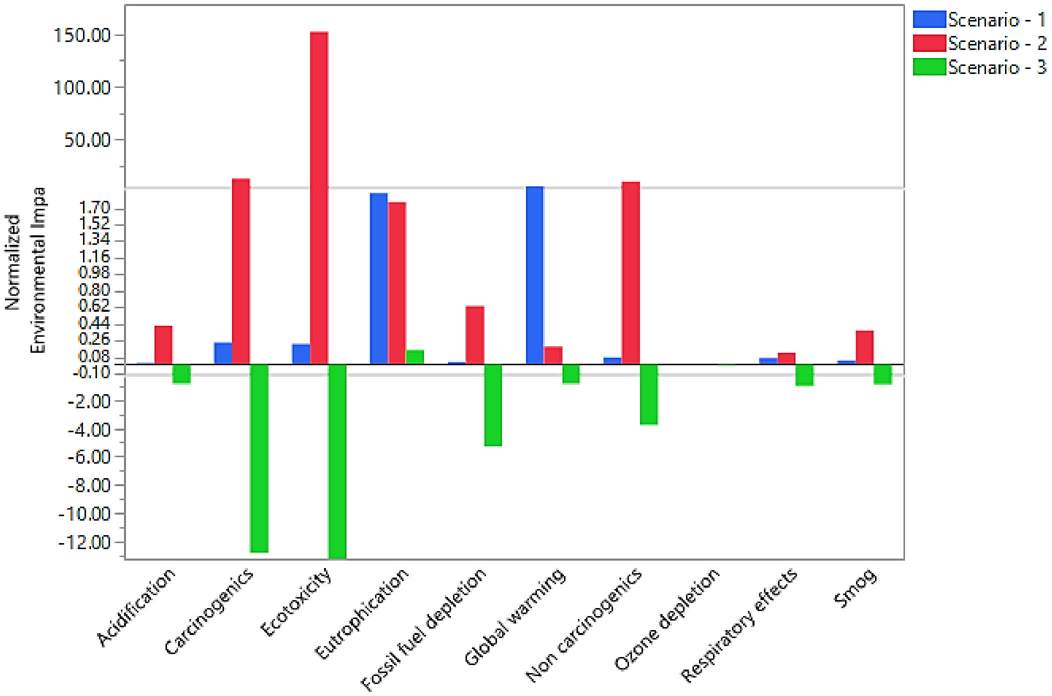


Figure 4-30 Comparison of normalization profile among three scenario of 1 ton MSW

The impact on global warming impact category can be directly linked with the equivalent CO_2 emissions. As expected, the baseline scenario has the greatest global warming potential which is more than two times of the mining scenario. The negative emissions represent the emission offsets by the activities. Here, scenario 3 is crediting environmental benefits by about 0.1 million kg of equivalent CO_2 which worth of removing about 21 thousand cars from road per year

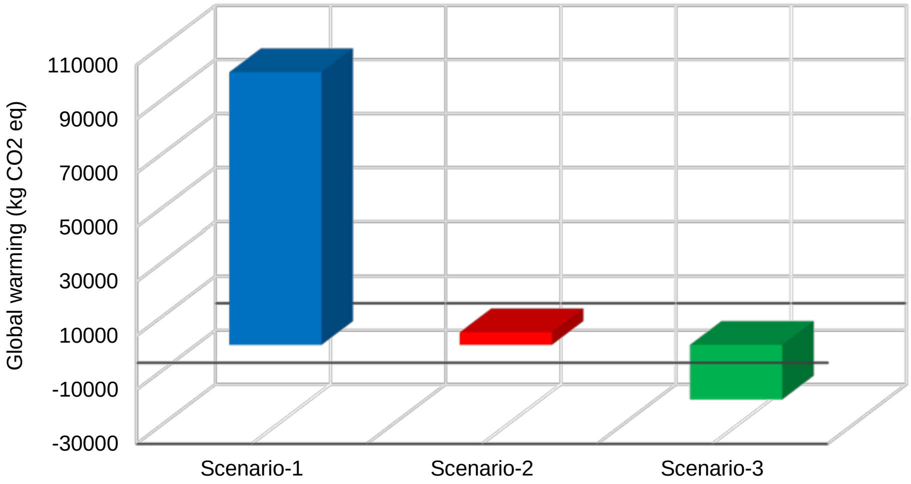


Figure 4-31 Impact assessment of three scenarios on global warming impact category

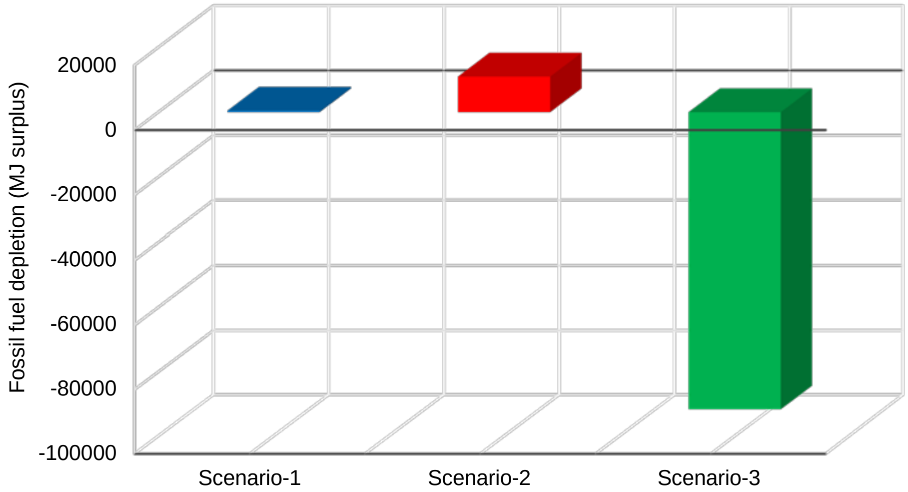


Figure 4-32 Impact assessment of three scenarios on fossil fuel depletion impact category

As shown in Figure 4-32, in fossil fuel impact category, scenario 3 is inducing more benefits than the others due to the recovery of metals, plastics, yard wastes, papers etc. which saved energy because of using the recycled materials rather than the virgin materials.

The eco-toxicity impacts are greater in scenario 2 than the others as shown in Figure 4-33. Eco-toxicity impact associated with soil occurs due to discharge of process water or wastes from land application of reclaimed soil. Due to the relocation of wastes in scenario 2 the eco-toxicity impacts are much higher than others. And due to metal recovery and reuse in the manufacturing process scenario 3 induced entire benefits.

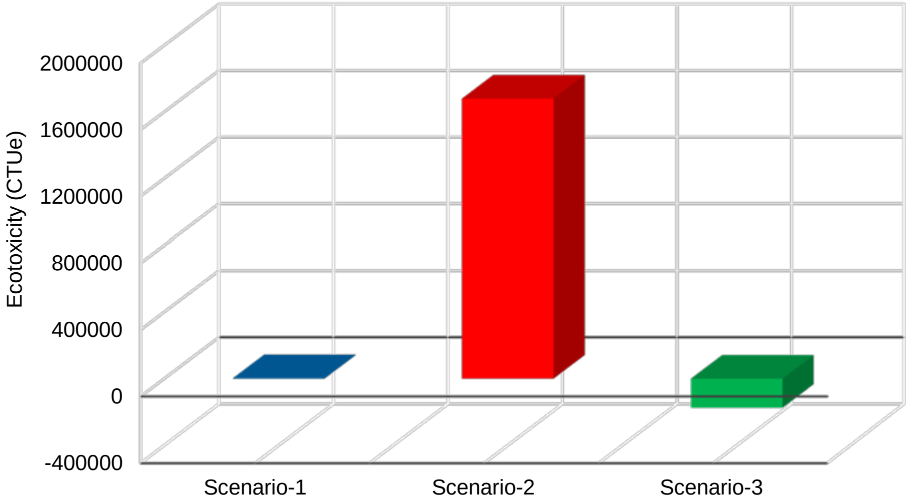


Figure 4-33 Impact assessment of three scenarios on Eco-toxicity impact category

Nitrogen and phosphorus are macronutrients which are responsible for eutrophication process. The main sources of P-emissions are municipal waste water treatment plants and agriculture. The main sources of N-emissions in waste treatment systems are incineration and transportation processes emitting NOx (Christensen T. 2010). Due to the higher transportation, emission to water in scenario 1 and 2 there is more impacts in eutrophication than the scenario 3.

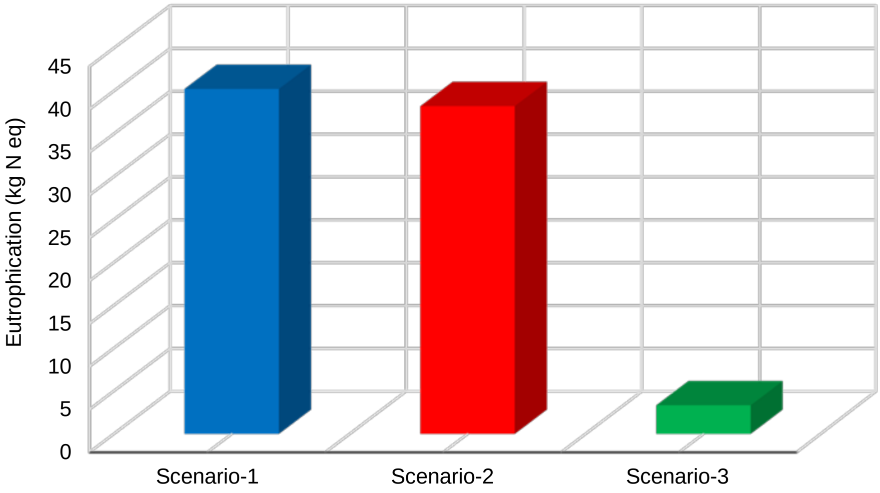


Figure 4-34 Impact assessment of three scenarios on Eutrophication impact category

Carcinogenics and non carcinogenics are a category of human toxicity impact in broad aspect. Major source of Carcinogenics is waste treatment activities comes from exposure to particles from waste incineration and transportation and exposure to toxic metals and persistent organic pollutants like dioxins and furans. Toxic impacts on human beings exposed in the environment occur through inhalation with air, ingestion with food and water after contact with polluted surfaces (Christensen T., 2010, Humbert S. et al, 2012). Due to transportation and toxic elements from inert waste induced impact for scenario 2 the most.

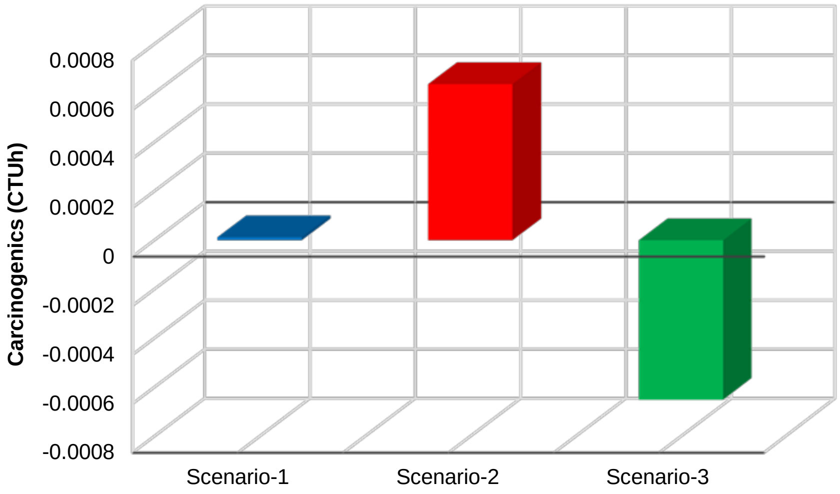


Figure 4-35 Impact assessment of three scenarios on carcinogenics

Jain P. et al. (2014) conducted study on sustainable management of waste materials after landfill mining. The no mining and mining with different waste management criteria were analyzed and compared for major impact categories as shown in Figure 4-36 where the emissions are based on 1 million ton of MSW. In the study no mining scenario induced higher global warming potential after the relocation scenario. In case of human toxicity, material recovery scenario was found to be most beneficial scenario which is likewise the present study.

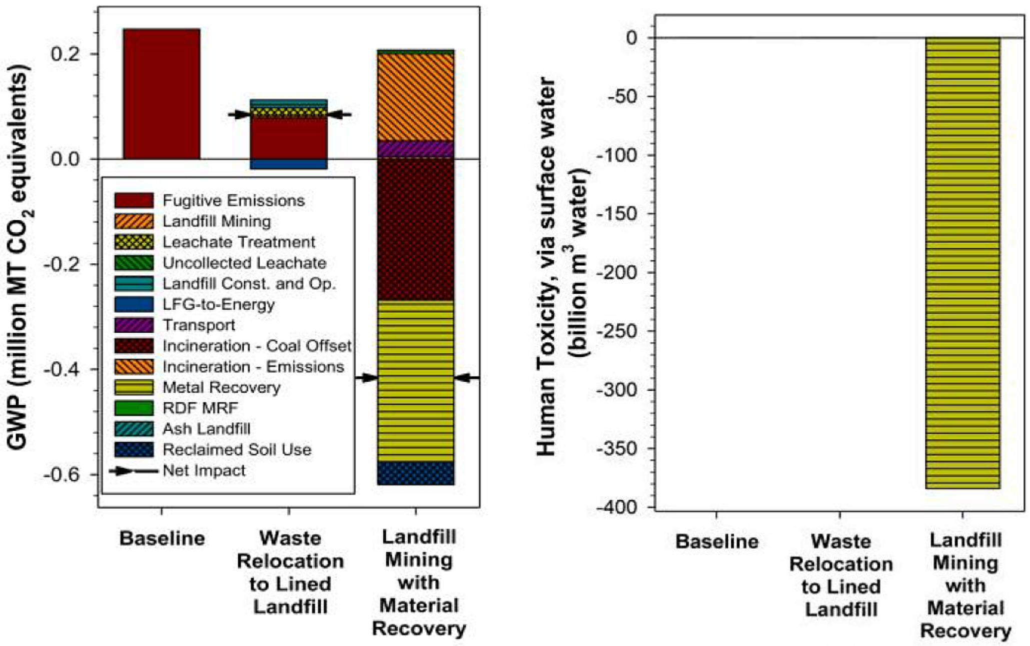


Figure 4-36 LCA for different landfill mining materials management scenarios for global warming and human toxicity (Jain P. et al. 2014)

Lastly, the main challenge in landfill mining is the recuperation of materials from the project for making it beneficial. According to the life cycle assessment results for different scenarios it can be concluded that the landfill mining is environmentally feasible and a good viable waste management solution among the studied alternatives if the landfilled materials would be reclaimed, processed, reused to some extent replacing the virgin materials acquisition. Landfill mining aiming to only relocation of the waste proved to be a burden to environment in the circumstances of the current study considerations. Again further study required considering more details scenario analysis and comparing more alternatives in this regards.

4.3 Economic Feasibility of Landfill Mining

For environmental feasibility assessment, Cost-Benefit Analysis (CBA) approach was adopted in the study. Three scenarios were considered same as the environmental analysis. The scenarios are ‘no-mining’, ‘mining with relocation’ and ‘mining with material recovery’. The cost-benefit analysis was conducted for 10 years of the mining project. The benefits and NPV of each year was determined to evaluate the feasibility of the project.

4.3.1 No-mining (Scenario 1)

According to USEPA (2005), the post-closure care includes two primary tasks which are groundwater monitoring and maintaining waste containment systems. The post-closure period normally lasts for 30 years after the date closure is completed but may be modified (e.g., extended or shortened) by the Resource Conservation and Recovery Act (RCRA). So, if the landfill is kept as it is, it must be protected with final cover followed by monitored for groundwater and landfill gas emission during the post closure care period. Therefore, the related costs of this no mining option are the closure costs and post-closure care costs. There is barely any revenue element associated with the no mining option. The cost elements for this scenario is presented in Table 4-10.

Table 4-10 Cost Elements for scenario 1

Cost elements	**USD (in millions)**
Post-closure cost	$ 11.27
Closure cost	$ 4.80
Total cost	**$ 16.07**

4.3.2 Mining with relocation (Scenario 2)

In this scenario, the expense categories include broadly the administrative, equipment and maintenance costs. Whereas, the revenue elements consist of land value, avoided closure and post-closure care costs. In the first fiscal year the expense and revenues were considered for three months with 60 working days and in the rest years working days were considered to be 240 days. The results of the cost-benefit analysis for the scenario are provided in Table 4-11, Figure 4-38 and Figure 4-39.

Table 4-11 Cost-benefit elements of Scenario 2

Cost Elements	**USD (in millions)**									
	Project Fiscal year									
	1	2	3	4	5	6	7	8	9	10
Administrative	0.16	0.51	0.52	0.44	0.45	0.47	0.48	0.49	0.51	0.52
Equipment	0.44	0.44	0.44	0.44	0.28	0.06	0.06	0.06	0.02	-
Maintenance and Miscellaneous	0.91	2.11	2.19	2.39	2.61	2.64	2.69	2.18	2.19	2.1
Total cost	**1.50**	**3.05**	**3.15**	**3.26**	**3.34**	**3.17**	**3.23**	**2.73**	**2.71**	**2.62**
*Other revenues**	0.16	1.89	1.89	1.9	1.9	1.9	1.9	1.9	1.9	1.9
Total revenue	**0.16**	**1.89**	**1.89**	**1.9**	**1.9**	**1.9**	**1.9**	**1.9**	**1.9**	**1.9**
Net Benefit	**-1.3**	**-1.2**	**-1.3**	**-1.4**	**-1.4**	**-1.3**	**-1.33**	**-0.83**	**-0.8**	**-0.7**
NPV ***(i= 1.5%)***	**-1.3**	**-1.1**	**-1.2**	**-1.3**	**-1.3**	**-1.2**	**-1.2**	**-0.8**	**-0.7**	**-0.6**

*(land value, closure and post-closure monitoring)

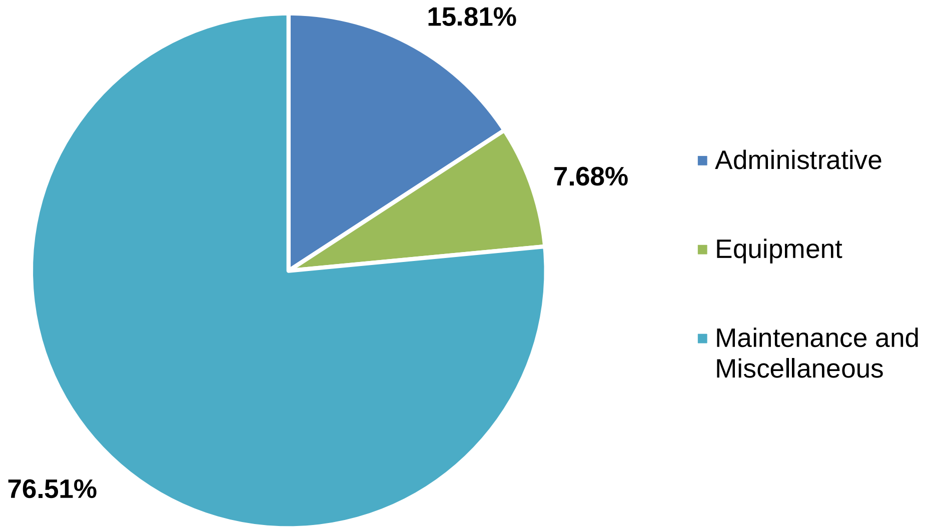


Figure 4-38 Cost elements of scenario 2

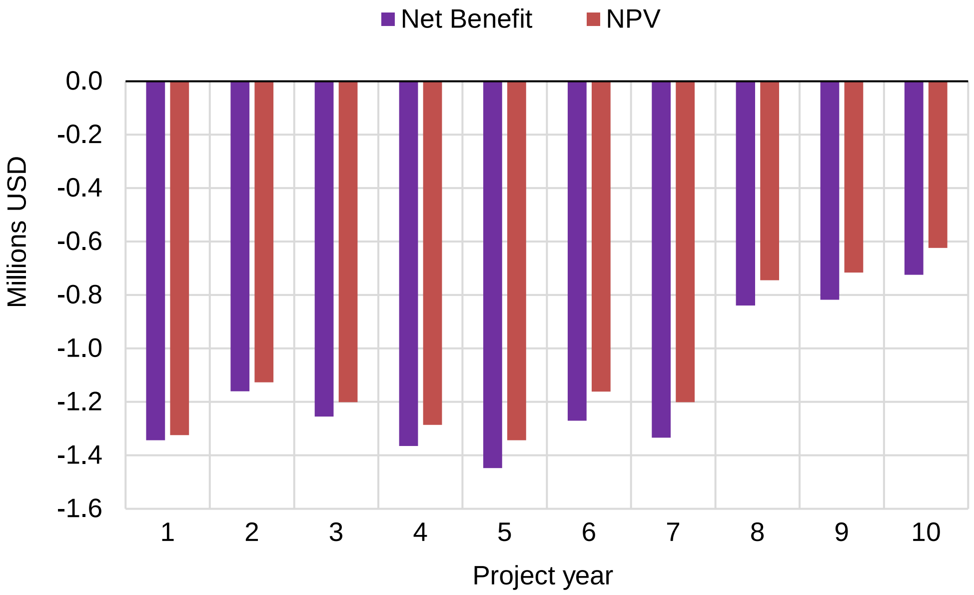


Figure 4-37 Net benefit and NPVs for scenario 2

Among the cost elements the major costs are induced from maintenance and miscellaneous costs which can be seen in Figure 4-37. The net present value (NPV) was considered as the economic indicator in this cost-benefit analysis. In all fiscal years the net benefits and NPVs are found to be less than zero as shown in Table 4-11 and Figure 4-38, which means the project would not be feasible if the scenario 2 is adopted. As there is no revenues from materials, soil recovery and air space recovery as well in this scenario, the project was found to be unprofitable.

4.3.3 Mining with material recovery (Scenario 3)

In this scenario, the cost-benefit components were included considering the materials recovery after landfill mining in addition to the mining activities considered in scenario 2. Similar to scenario 2, the expense categories include broadly the administrative, equipment and maintenance costs. Whereas, the revenue elements consist of revenue from material recovery, soil recovery, air space recovery, land value, avoided closure and post-closure care costs. In the first fiscal year the expense and revenues were considered for three months with 60 working days and in the rest years working days were considered to be 240 days. The cost-benefit results for the scenario are shown in are provided in Table 4-12.

Table 4-12 Cost-benefit elements of Scenario 3

Cost Elements	**USD (in millions)**									
	Project Fiscal year									
	1	2	3	4	5	6	7	8	9	10
Administrative	0.16	0.51	0.52	0.44	0.45	0.46	0.48	0.49	0.51	0.52
Equipment	0.71	0.44	0.44	0.44	0.28	0.06	0.06	0.06	0.02	-
Maintenance and Miscellaneous	0.91	2.11	2.19	2.39	2.61	2.64	2.69	2.18	2.19	2.10
Total cost	**1.78**	**3.05**	**3.15**	**3.26**	**3.34**	**3.16**	**3.23**	**2.73**	**2.71**	**2.62**
Material Recovery	0.35	1.35	1.35	1.35	1.35	1.35	1.35	1.35	1.35	1.35
Soil Recovery	0.01	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04
Airspace recovery	0.35	4.21	4.22	4.22	4.22	4.22	4.22	4.22	4.22	4.22
*Other revenues**	0.16	1.89	1.89	1.89	1.89	1.89	1.89	1.89	1.89	1.89
Total revenue	**0.87**	**7.49**	**7.50**	**7.51**	**7.51**	**7.51**	**7.51**	**7.51**	**7.51**	**7.51**
Net Benefit	**-0.90**	**4.164**	**4.08**	**3.97**	**3.89**	**4.07**	**4.00**	**4.5**	**4.72**	**4.89**
NPV (i= 1.5%)	**-0.89**	**4.04**	**3.9**	**3.742**	**3.61**	**3.72**	**3.61**	**3.99**	**4.13**	**4.21**

*(land value, closure and post-closure monitoring)

The results showed that, considering the scenario 3 the net benefit and NPV is greater than zero except in the first year of the project. Therefore, project would be in challenging phase in first year of mining, after that the project would be profitable to a great extent as shown in Figure 4-41 and Table 4-12. The cost and benefit elements of the scenario are presented in Figure 4-39 and Figure 4-40 respectively. The maintenance cost is found to be major costs of the scenario. Whereas, the benefit from airspace recovery is found to be most influencing revenue in this case. The project benefit and

NPV was found to be higher in the last few years due to the reduction of equipment costs and increase in associated other benefits.

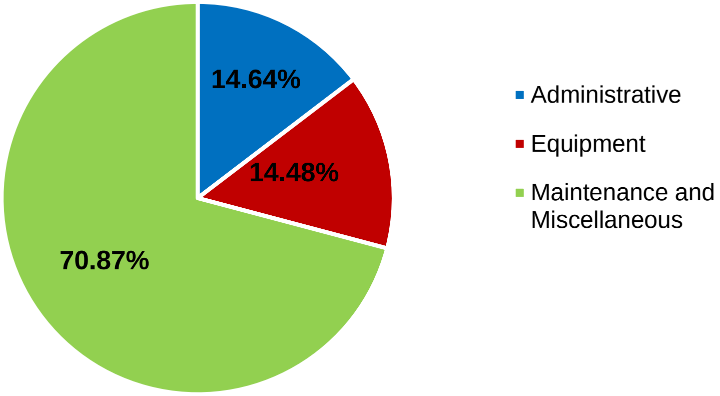


Figure 4-39 Cost elements of scenario 3

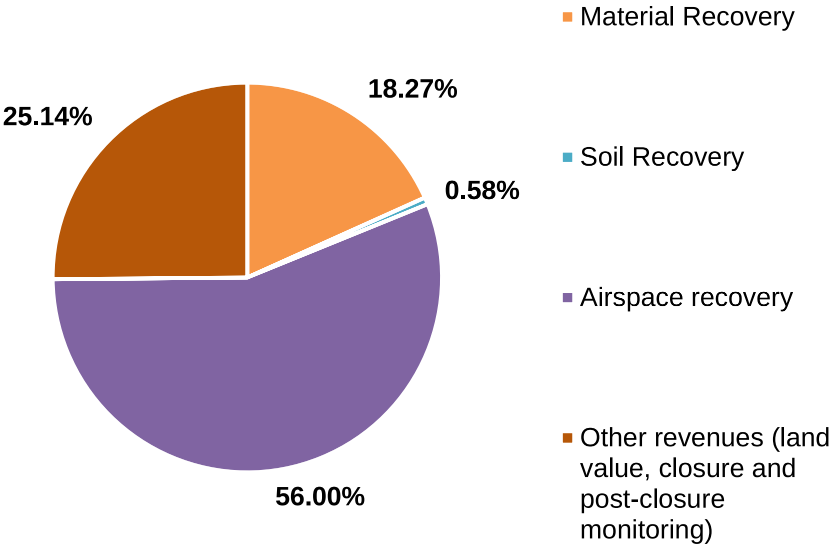


Figure 4-40 Benefit elements of scenario 3

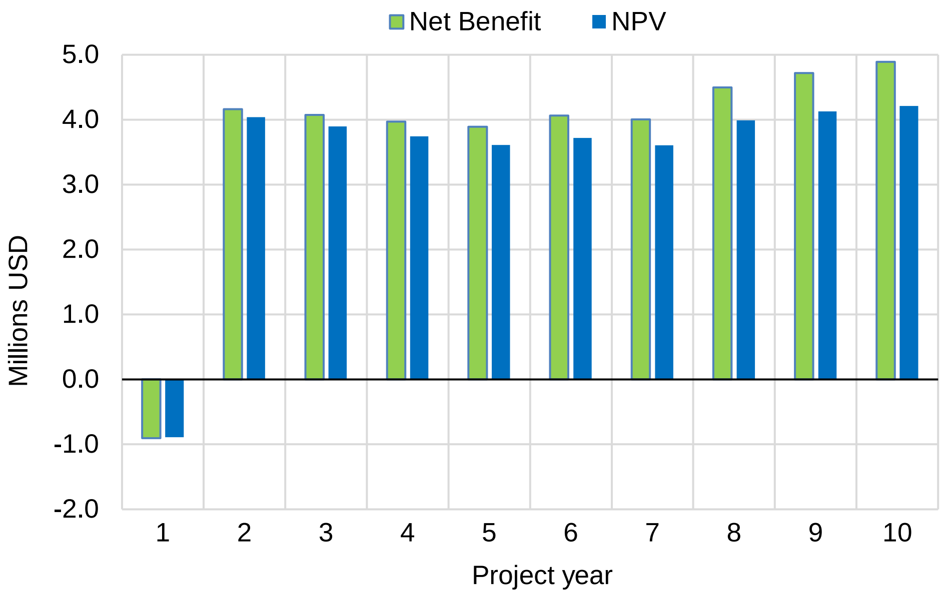


Figure 4-41 Net benefit and NPV of scenario 3

4.3.3 Comparison between cost-benefit analysis of three scenarios

The comparison among the three mining scenarios are given in Table 4-13. It is clear that the no mining scenario is not feasible as per cost-benefit analysis. Consequently, among the mining alternatives highest net benefit of $37.37 million is found in the 'mining with material recovery' scenario. Whereas, in the 'mining with relocation' scenario the induced cost is suppressing the benefits resulting in net loss of $11.56 million in the project which can be seen in Figure 4-42 as well.

Table 4-13 Comparison between three scenarios

Elements	**No Mining**	**Mining with relocation**	**Mining with material recovery**
Total Cost (in Millions)	$ 11.27	$ 28.76	$ 31.05
Total Benefit (in Millions)	$ -	$ 17.20	$ 68.42
Total Net Benefit (in Millions)	$ (11.27)	$ (11.56)	$ 37.37
Total NPV (i= 1.5%)	-	$ (10.727)	$ 34.06
B/C	0	0.60	2.20

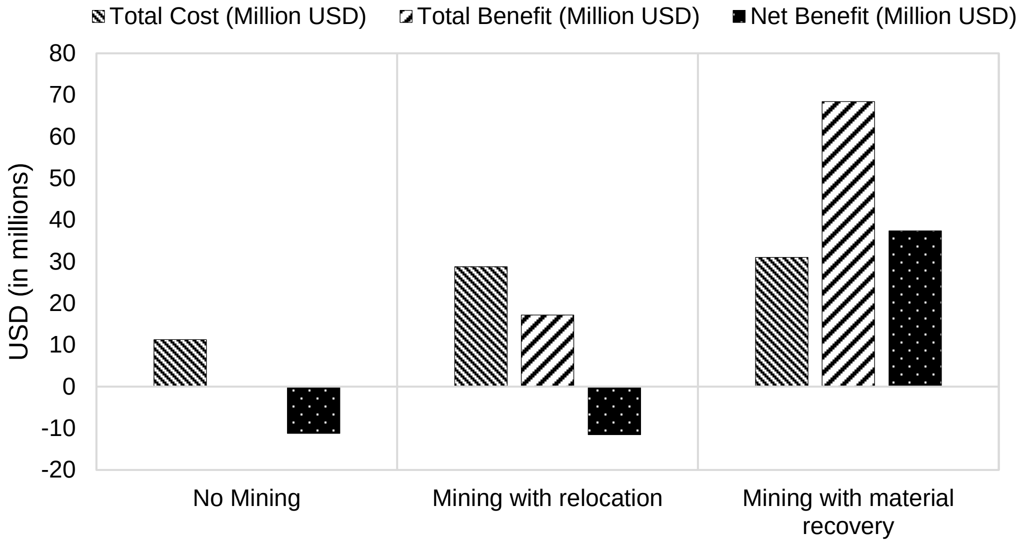


Figure 4-42 Comparison between different scenarios

The comparison of the economic indicators of the study, benefit to cost ratio and net present value (NPV), for different scenarios are depicted in Figure 4-43 and Figure 4-44. In aspects of the Benefit-cost ratio, only in the 'mining with material recovery' scenario the benefit to cost ratio was found to greater than one which was 2.20, the benefit is more than two times of the costs of the project. In scenario 1 and scenario 2 the B/C ratio was 0 and 0.6 respectively which means they are not feasible in this regards. Similar results were found for another economic indicator, net present value (NPV), as well. The NPV of the scenario 3 was found to be $34.1 million with discount rate of 1.5%, which is a good standpoint for the decision makers to accept this scenario as strongly feasible in economic aspect.

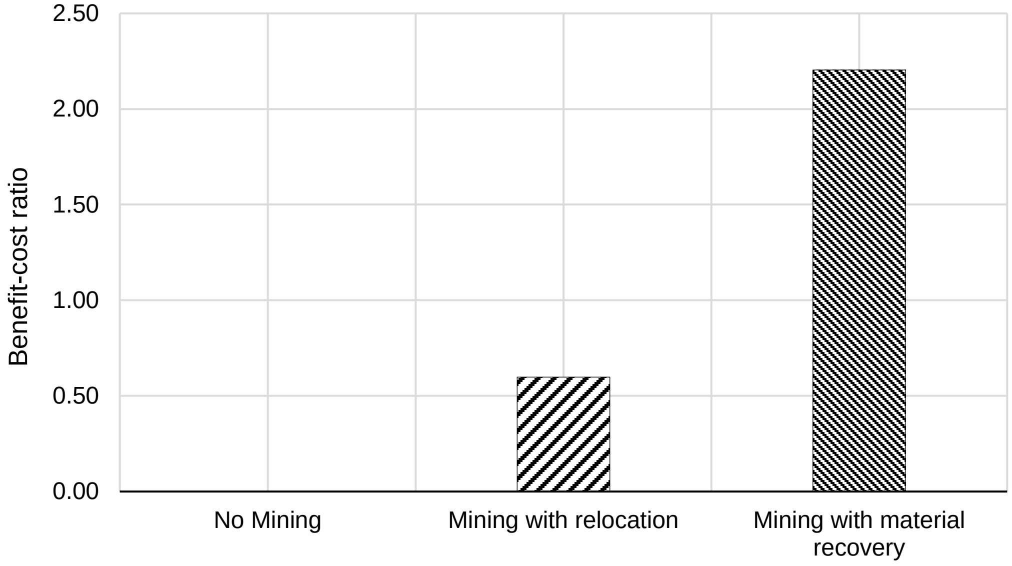


Figure 4-43 Benefit-cost ratio for different scenarios

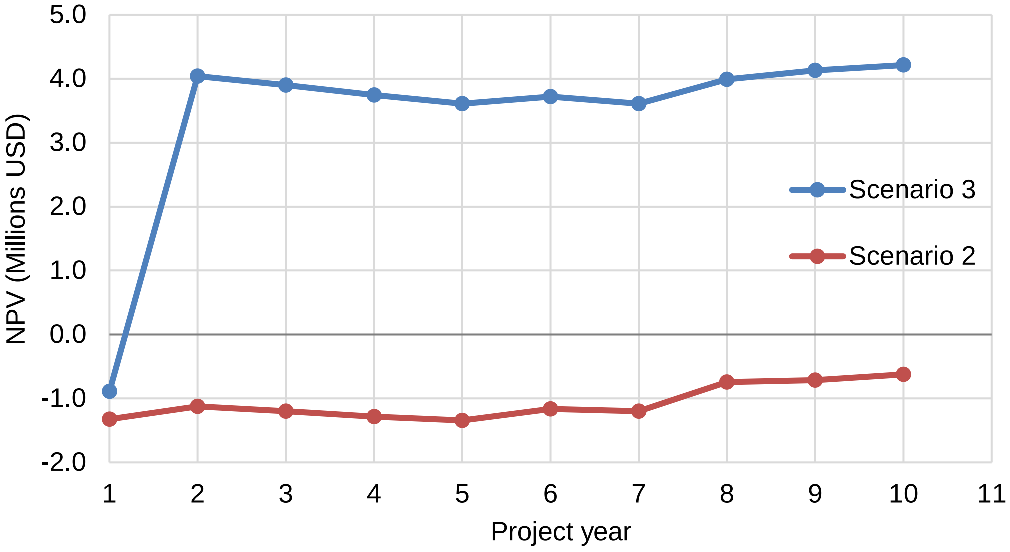


Figure 4-44 NPV for mining scenarios

Therefore, according to the cost benefit analysis along with the economic indicators, mining with material recovery is found to be the most feasible option among all the scenarios in the project perspective. The mining with only relocation was not found to be feasible in this study. The combination of the other options in landfill mining may be analyzed for further assessment of project feasibility in economic criteria.

Chapter 5

Conclusions and Recommendation

5.1 Summary and conclusion

This study focuses on environmental and economic feasibility of landfill mining for the City of Denton Landfill (Texas). Environmental feasibility has been assessed with Life Cycle Assessment (LCA) tool and economic feasibility has been conducted with the cost-benefit analysis (CBA) approach including Net Present Value (NPV) and benefit-cost ratio as economic indicator. The analyses were based on the data provided by the solid waste service group of the city of Denton Landfill. The environmental impact of recycling and reusing of mined materials instead of virgin materials was also assessed using the LCA tool, SimaPro 8 with TRACI 2.1 (version 1.02) methodology, to evaluate the energy saving potential of reusing mined materials. A detailed life cycle assessment was conducted on the plastic product (plastic pin/lumber) and paper product (paperboard) which were also compared with the production with virgin materials for 1 ton of functional unit of the product. Details cost benefit analysis is performed for each year of the landfill mining project considering all the cost and benefit elements. Three different scenarios are considered for both environmental and economic analysis which are; a) no mining, b) mining with relocation and c) mining with material recovery. In case of no mining scenario closure and post closure cost were considered as cost elements and no tangible benefit is considered. Administrative expenses, purchasing equipment and maintenance expenditure are considered as cost elements for mining with relocation scenario and benefits are calculated from avoided closure, post-closure cost and reclaimed land value. In case of mining with recovery scenario, cost elements are similar to the previous one and material recovery, soil recovery, land value, avoided closure and post closure costs are considered as benefit elements. Summary of this present study is presented below.

1. The City of Denton landfill is a type I landfill, which got authorized permit from Texas Commission on Environmental Quality (TCEQ) in 2016 to conduct landfill mining of cell 1590A in accordance with Title 30 Texas Administration Code 305.70 (1) and 330.605.
2. The LCA model has been developed in SimaPro 8 using TRACI 2.1 (version 1.02) method among other North American methodologies. Default normalization factors were used based on US 2008 data. Data inventory was developed into the system from Ecoinvent 3.0 default database and US based database along with field investigation and questionnaire surveys. Environmental stressors including (i) ozone depletion (ii) global warming (iii) acidification (iv) eutrophication (v) tropospheric ozone (smog) formation (vi) eco-toxicity (vii) human health cancer effects (viii) human health non-cancer effects (ix) fossil fuel depletion and (x) land-use effects are considered for life cycle analysis.
3. In the study, data were collected through questionnaire survey in study area landfill personnel, different manufacturing companies, through data collection from previous studies on same study area or similar projects and with judgmental assumptions to some extents.
4. Three scenarios were modeled to assess the feasibility of landfill mining in accordance to the environmental impacts of 1 ton of the mined MSW wastes of a 30 years old unlined landfill. The baseline scenario is ‘do-nothing’ or ‘no mining’ scenario (scenario 1), the other two scenarios are ‘Landfill mining with relocation on lined cell’ (scenario 2) and ‘Mining with material recovery’ (scenario 3) scenario. System boundary is developed considering all the scenarios which includes energy use, sub activities and product obtained from different processes.

5. For the Life Cycle Assessment study, among the recoverable mined materials, metals are considered as replacement of iron scrap, yard waste is considered to be processed to wood chips which would be a replacement of wood chips product. These replaced products were taken from LCA database. The soil like materials were assumed to be a replacement of the equivalent excavated soil. The plastics and papers were considered to be processed into new products which are plastic lumber and paperboard respectively. These products were assessed considering the cradle-to-grave boundary of the products.
6. The cost-benefit elements regarding mining and material recovery were selected as per the information from study landfill solid waste service group, previous mining projects experiences, USEPA (1997), economic analyses done by C.Zhou et al. (2015), Danthurebandara (2015) et al. (2015), S.Van Passel et al. (2013).
7. As the project timeline is planned to be 10 years, the scenarios were also designed accordingly. For the first year the working days are considered as 3 months and for the rest of the years as 240 days. The indicator of net present value (NPV) and benefit to cost ratio were adopted to evaluate the economic feasibility of the project.
8. The boring log information in cell 1590A of the city of Denton landfill revealed that the major portion of waste is soil and degraded fines (52%), paper (18%), plastics (9%) and metals (5%) which are potential recoverable materials of landfill mining in this case.
9. The normalized environmental impacts of the activities for 1 ton of MSW depicts that the dominating activities among the landfill mining operations are the waste screening and the top soil removal and transportation of top soil.

10. The waste screening induced environmental benefits due to the recovery of metals, soils and fines, plastics, papers and yard wastes from the landfill mining resulting in environmental credit in eco-toxicity and carcinogenic impact categories
11. Landfill gas emission from top cover is crediting to the global warming impact category mostly in case of scenario 1.
12. In scenario 2, the environmental burden is significant in carcinogenic, non-carcinogenic and eco-toxicity categories. The most important contributions to eco-toxicity from waste treatment systems come from toxic metals and persistent organic pollutants.
13. In scenario 3, the major impact categories were found to be ecotoxicity, carcinogenics and fossil fuel depletion. The material processing and recycling was found to be contributing environmental benefits.
14. Plastic pin manufactured from recycled plastic (mined plastics) has significantly lower environmental impacts than that of manufacturing from virgin materials. 1 ton of plastics, about 40 plastic pins of 50 lbs. each can be produced which means that 40 pins can reduce about 0.4 million kg equivalent CO_2 which worth of removing about 85 thousand cars from road per year. Also, it can save 1.8 million MJ energy if it is manufactured from mined plastics instead of virgin plastics.
15. 1 ton of paper product manufactured from mined materials can reduce about 2400 MJ energy consumption and lessen more than 90% equivalent CO_2 emissions than virgin materials which is about 1300 kg equivalent CO_2 that is worth of removing 276 cars from road per year.
16. According to the life cycle assessment results for different scenarios, it can be concluded that the landfill mining is environmentally feasible and a good viable waste management solution among the studied alternatives if the landfilled materials would

be reclaimed, processed, reused to some extent replacing the virgin materials acquisition. Landfill mining aiming to only relocation of the waste and no-mining condition has been proved to be a burden to environment in the circumstances of the current study considerations. It was found that the landfill mining with resource recovery (scenario 3) is crediting environmental benefits by about 0.1 million kg of equivalent CO_2 comparing with no mining scenario which worth of removing about 21 thousand cars from road per year.

17. No-mining scenario is not feasible as per cost-benefit analysis. Consequently, among the mining alternatives highest net benefit of $37.37 million is found in the 'mining with material recovery' scenario. Whereas, in the 'mining with relocation' scenario the induced cost is suppressing the benefits resulting in net loss of $11.56 million.
18. In no-mining and mining with relocation scenario, the Benefit to cost (B/C) ratio was 0 and 0.6 respectively which means they are not feasible in this regards. Whereas, in scenario 3 the B/C ratio was found to be 2.20. Similar results were found for another economic indicator, net present value (NPV), as well. The NPV of the scenario 3 was found to be $34.1 million with discount rate of 1.5%, which is a good standpoint for the decision makers to accept this scenario as strongly feasible in economic aspect for this case study.

5.2 Recommendations for future studies

Based on the findings of this study and literature review following recommendations are suggested for further research:

1. Further research needs to be done assessing the comparison between more operational alternatives of landfill mining for this case study area.

2. A further sensitivity analysis, such as Monte Carlo simulation, is required to assess the reliability and uncertainty of the assumptions and data of the present study.
3. In present study the environmental and economic analysis were conducted as the feasibility study of the study area. A further details study need to be performed after and during the landfill mining execution for more accurate assessments and justification of the current study.
4. A study may be conducted for the quality assessment of the mined materials to evaluate the scope of further recycling.
5. A further study may be conducted considering more details of system boundaries along with more comprehensive parameters with detailed real field data.
6. Further studies may be performed assessing the other valorization options of the recoverable materials rather recycling which may be incineration, new product processing with the mined materials.

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