THE UNIVERSITY
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ECO-COSTING OF BUILDING CONSTRUCTION WASTES

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by

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ABSTRACT

The construction industry is one of the key industries within the world economy. Construction creates many activities from the extraction of raw material for its products until the disposal of waste at the end-of-life of the materials. Along the life cycle of the construction, the activities may produce waste and emission, thus creating environmental problem. Managing construction waste material could generate a significant impact to environment and as a result this will pose problem on public health and safety of the existing environment. This research aims to develop an estimating eco-costs model based on relationship between eco-costing and environmental impact of construction waste. The impact pathway approach is used during the development of eco-costs model which involved three main phases which are; (i.) Life Cycle Assessment (LCA) processes, (ii.) monetary valuation of the impact of waste and it disposal option, and (iii.) developing the model to estimate eco-cost for the construction material wastes. LCA methodology is used to evaluate the environmental impact of construction waste disposal options i.e. final disposal, recycling and sorting plant for the nine identified environmental indicators namely global warming, acidification, euthrophication, winter smog, summer smog, heavy metal, ozone layer depletion, carcinogen and energy resource. Whilst, monetary evaluation for this research is based on the marginal damage cost extracted from the secondary data obtained from DEFRA. The eco-costs models for the construction waste disposal option estimation are presented in the form of graphs and mathematical algorithms. Beneficiaries of the model will be among the parties that involve in the construction industry in order to choose the Best Practicable Environmental Option (BPEO) of construction waste disposal option toward the achievement of sustainable construction.

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INTRODUCTION

1.1. Introduction

Sustainable Development is not just about the environment, but includes the economy and society as well. The Earth Summit, Rio de Janeiro in 1992, organised by the United Nations Conference on Environment and Development (UNCED) was seen as a milestone in the history of sustainable development. Agenda 21, the outcome of the summit is known as a blueprint on how to make development socially, economically and environmentally sustainable in the 21st century.

The Brundtland Report gave the most popular definition of sustainable development. The report has defined the sustainable development as (United Nations 1987.):

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

One of the key themes of 'sustainable development' is managing waste (Williams, 1998). Sustainable waste management encourages the generation of less waste, the re-use, recycling and recovery of waste that is produced. Waste is something for which we have no further use and which we wish to get rid of. It can be solid or liquid, and includes waste products arising from our way of life. Waste is generated by all sorts of means and comes from many different sources including domestic and municipal consumption of goods, manufacturing, construction, sewage treatment, agriculture and the generation and disposal of hazardous substances. Waste includes paper, plastics, glass, metals, foods, chemicals, oils, bricks, wood, soil, and effluent (DETR, 2000).

Similarly with other major industries, construction waste comprises a large proportion of the total waste in many cities in the world, thus creating environmental problems. One significant impact expected to occur during the execution of construction site processes is that of construction waste materials. Basically, construction waste refers to solid waste containing no liquids and hazardous substances, largely inert waste, resulting from the process of construction of the structures (Chen, Li et al. 2002). Indiscriminate disposal of waste materials not only creates problems of aesthetics but also provides habitats for disease, leaching toxic matter into the ground and aquatic system and creating potential fire hazards. As a result this will pose problems for public health and safety of the existing environment.

Fishbein (1998) reported that construction site waste is estimated to be as much as 30 percent of the weight of total materials on site; despite some success in recent years to increase recycling, most construction and demolition (C&D) waste ends up in landfills. In a city, where the land is scarce, the amount of space taken up by landfills will create problems for the state and local government. Gavilan and Bernold (1994) and Craven, Okraglik et al. (1994) described lack of waste management as one of the main causes of the waste generation.

According to the Environmental Protection Agency (EPA), The United State of America (USA), in 1996 C&D contributed almost 136 million tons of waste, which is equivalent to £2.8 per population per day. In 1998, an average of 7030 tonnes of C&D waste was disposed in landfills in Hong Kong. In an assessment made by the European Union (EU), C&D accounts for about 25 percent of the waste flow in Europe (Giglio 2002). Meanwhile, Department for Environment, Food & Rural Affairs – DEFRA (2006) reported that the UK produced 32 percent of C&D waste from approximately 335 million tonnes of total annual waste in 2004. The demolition of buildings leads to large amounts of construction and demolition waste (Seemann, Schultmann F. et al. 2002). It was more than half the municipal waste stream and demolition debris was found to be the most significant contributor with 48 percent of the C&D waste stream (Goldstein 1999).

Therefore, a comprehensive understanding of the issues of construction waste impact on the environment is required and should be considered during the planning stage of construction. Furthermore, it could be incorporated with the need of the bidding process in order to maintain the sustainable environment and construction (Fishbein 1998). In addition, it can enhance a builder's operation and the image of the entire building industry. Hence the study will propose a framework for assessing eco-costs of waste from building sites, where the eco-costing topic will be discussed in detailed in CHAPTER 5. The framework consists of waste identification, determination of eco-indicators and pricing the effect.

The research aim is to establish a relationship between eco-costing and the environmental impact of construction waste. This relationship is presented in the form of algorithms and graphs for construction waste eco-costing estimation. The developed model can be used as a guideline for the new developments to identify options for construction waste disposal (i.e. reuse, recycling, and disposal) and plan a strategy in minimising the amount of construction waste going to the final disposal (landfill, incineration). By minimising harmful impacts to the environment, it will not only be able to save money by reducing waste-related costs, but it will help to improve the performance in achieving global sustainable development which is among the current main agenda in the construction industry.

1.2. Theoretical Background

The increase in population and the growth of the economy are some of the elements that make construction activities become more dynamic. This means much more pressure on material resources and greater strain on the landfill capacity to take up waste. Construction waste is reported to be up to as much as 30 percent of the total amount of purchased construction material. This indicates that contractors have to make some allowance for the cost of waste disposal. This may lead to a huge impact on the environment from emission released from the waste especially to the surrounding areas.

Tackling such waste will not only involve the internal costs (direct costs) by the first party that created the waste, but it will also generate external costs (hidden costs) that need to be borne by the society i.e. eco-cost. Minimizing the waste generation will protect the environment and enhance the reputation of the construction industry among the potential customers including developers, environmental officers and planners. In order to minimise waste generation, development of a methodology to estimate eco-costing of construction waste is proposed within this thesis.

The concept of eco-costing has been used by some researchers to estimate impact value in monetary form. Vogtländer (2001) utilised the eco-cost concept to express the ecological burden of products or services in his

Eco-costs Value Ratio (EVR) model. The EVR model assesses sustainability of products and services by indicating the value/costs ratio. Low EVR score indicates that the product is fit for use within a future sustainable society (Jonge 2005). Hur, Lim et al. (2003) then used the EVR principle to evaluate eco-efficiencies for recycling methods of plastics wastes. Tseng, Hsu et al. (2005) also suggested that eco-costs should be incorporated into a decision-making tool for the assessment of eco-efficiency of any industries.

Kumaran, Ong et al. (2001) defined direct and indirect costs of the environmental impacts caused by the product in its entire life cycle as eco-costs and had included the eco-costs element to calculate total costs of products. The eco-costs include eight eco-cost elements, namely cost of effluent/waste treatment, cost of effluent/waste control, cost of waste disposal, cost of implementation of environmental management systems, costs of eco-taxes, costs of rehabilitation (in case of environmental accidents), cost savings of renewable energy utilization, and cost savings of recycling and reuse strategies. Whereas Huisman (2003) had used the eco-cost concepts to develop a model called the quotes for environmentally weighted recyclability (QWERTY). QWERTY is used to determine environmentally weighted recycling scores rather than weight-based recycling scores.

The environmental impact associated with buildings is as much an issue as financial cost in their construction and use (Ofori 1992). In the early nineties, impact assessment of the building was encompassed in the assessment of energy with regard to the release of carbon dioxide (CO_2) emissions in construction and building used (Treloar 1994; Treloar 1998; Pullen 2000). But Hájek (2002) valued the impact by means of the specific target behaviour of construction products (e.g. cost, self-weight, thermal resistance, acoustic characteristics, cultural aspects, etc.), embodied CO2 (from a global point of view), the value of embodied SO2 (from a regional point of view) and the total embodied energy. Hájek (2002) defined total environmental impact as the total eco-cost in evaluating environment-based optimisation which is a process targeting reduction of the negative environmental impact of product for civil engineering structures (buildings, bridges etc.). The importance of the evaluating eco-costing in construction was also highlighted by Corinaldesi, Giuggiolini et al. (2002) in evaluating the use of rubble from building demolition as replacement material in mortar. The authors suggested that the calculation of total cost of mortar should be incorporated with the eco-cost of the aggregates. Meanwhile, Yahya and Boussabaine (2004) developed a framework to estimate the eco-costs of construction site activities. Eco-costs could also be used to estimate the impact assessment for end-of-life of construction waste disposal option for the development of waste prevention goals in construction site waste plan and management.

1.3. Statement of Problem

Construction waste management aims to reduce the amount of construction waste going to landfill - thereby minimising harmful impacts on the environment. The lack of detailed information relating to quantifying the effect of waste generation and disposal construction waste in the UK had worsened the scenario.

A survey by Symond (1999) is believed to be the most comprehensive research that has ever been carried out on C&D waste in the UK. Even though the research produced comprehensive statistical results of C&D waste, however no appropriate techniques exist at present to extract the eco-costing of construction and demolition waste. Therefore, it is the intention of this research to address this deficiency.

Beside to develop the eco-cost model, the new approach developed in this research would also provide the best waste disposal option for construction waste towards the achievement of sustainable construction. For the development of construction waste disposal eco-costs modelling, the following important justification is applied (Vogtländer 2001);

1. The need for a quantitative approach for assessing environmental burden

2. It is important that the strategies on sustainability will lead us in the right direction
3. Transition towards a sustainable society will be easier and therefore faster when the economy is brought in line with ecology.
4. It is important to keep the model as simple as possible to be able to explain the results to a large group of society in order to mobilise enough people to gain the required momentum for change

1.4. Research Objective

The aim of this project is to develop a methodology for estimating eco-costing of construction waste. The model is intended for use whether monitoring the performance of the sustainable construction or at a very early stage of planning by the parties involved in a construction project including contractors, developers, environmental officers and planners to choose the Best Practicable Environmental Option (BPEO) for their project.

The objectives of this research are as follows;

1. To investigate methods for assessing the impact of construction waste disposal

2. To determine the environmental indicator for the "life cycle impact assessment analysis" of a construction waste disposal
3. To determine the damage cost (external cost) for a related indicator in order to be used as a reference
4. To calculate the eco-cost for the identified indicators of each selected construction material waste disposal option.
5. To calculate total eco-costing of each selected material waste based on three waste disposal options (i.e. final disposal, sorting plant and recycling).
6. To develop an algorithm for eco-costing for material waste based on three disposal options.
7. To apply the developed model in quantifying the eco-costing of construction waste from real case studies.

1.5. Research Questions

In order to satisfy the objectives, the following questions need to be established;

1. What are the sources and cause of construction site waste?
2. How much waste is generated from construction sites?
3. What are the environmental impacts caused by construction waste?

4. What are the methods currently used to model the environmental impact of construction waste?
5. How are the methods identified in (4) analysed and interpreted?
6. Which waste disposal options could represent the Best Practicable Environmental Option (BPEO) of a construction waste disposal option?

1.6. Importance of Study

The research will focus on assessing the environmental impact of the construction waste before translating into eco-costing. Mathematical approaches to estimating eco-costs will be proposed for the environmental assessment of construction site waste disposal options. The impact from each waste disposal option is estimated before it can be translated into its monetary value. The proposed methodology will help to determine the BPEO for construction waste disposals.

As already stated in the research objectives, the findings of the study could be used in monitoring the performance of construction projects against sustainable thinking. It could also be implemented at very early stages of project planning to expedite the selection of BPEO by the parties involved in construction project, typically as part of the briefing process.

The beneficiaries from this research will be to those involved with the construction management and planning functions of construction projects such as architects and local authorities where a relatively simple framework would be employed regularly as feature of the general project management process. Local authority and environmental departments will benefit from the method, since it will allow them to assess and subsequently minimise the environmental impact of a construction projects that they procure. The contractor will also be able to respond in a flexible way since a quick method will be available in targeting waste prevention strategies and developing waste prevention goals. Building contractors may also find it very useful as a reference in preparing a tender for a project if the client requires them to include their waste management program in the tender. It could evaluate how each bidder would approach the management of waste, before any waste is generated or any waste removal occurs.

1.7. Methodology of Study

The methodology used for carrying out the research was carried out in three main stages as shown in Figure 1.1 and is summarised as follows;

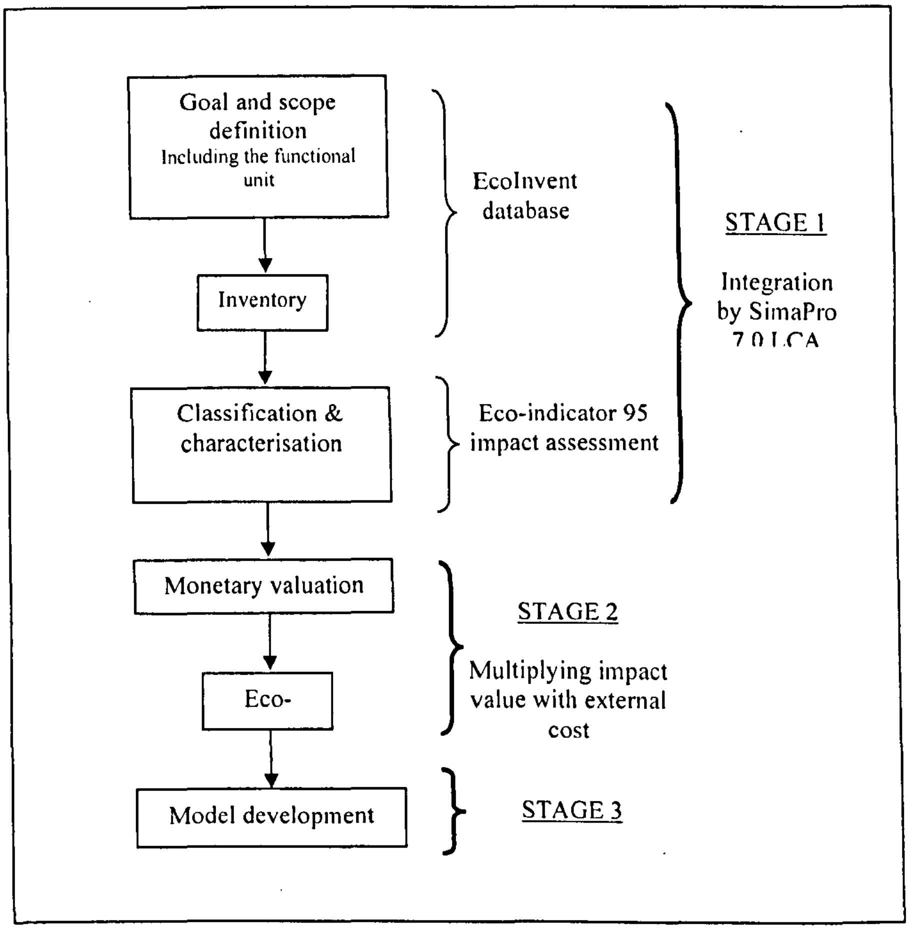

Figure 1.1: Methodology of the research

Discussion starts with explanation of the Life Cycle Assessment (LCA) methodology that has been used and the Impact Pathway Approach (IPA) that has been chosen to calculate emissions and monetary valuation of the waste. As the research adapts the ISO 14040 LCA methodology, discussion continues with the general issues of LCA, including the clarification of Life Cycle Impact Assessment (LCIA) processes based on the scope of research that has been established in the earliest chapter. In the next section, discussion continues with the explanation for the selection of environmental indicators, which is then followed by clarification of the method to evaluate the eco-costs from the LCIA results.

Goal and scope definition of this research is based on the inventory of disposal of construction material waste made by EcoInvent, a Swiss database. The database of the inventory was developed based on average data from the construction material waste disposal option throughout Western European Countries including the UK, whilst for assessing the environmental impact the Eco-indicator 95 model is used. Nine impact categories which are based on indicators in the Eco-indicator model are used as environmental indicators. In order to get impact values of the nine impact categories, integration of the EcoInvent database and the Eco-indicator 95 model is facilitated by using the SimaPro 7.0 LCA software as (STAGE 1). In STAGE 2, calculation of the environmental impacts in monetary terms (eco-cost) is determined based on the externalities secondary data of the scientific and economic studies by the Department for Environment, Food and Rural Affairs (DEFRA), UK (Guy Turner, David Handley et al. 2004) and ExternE (Externalities of Energy). From the calculated eco-costs results, the relationship between the quantities of construction waste with eco-cost is presented in a graphical form and the mathematical algorithm of the relationship is obtained for estimating total eco-costs of the construction material waste disposal option (STAGE 3). Detailed of the methodology will be discussed in CHAPTER 4.

1.8. Outline of the Thesis

The thesis consists of 9 chapters and the outlines of the chapters are presented as follows:

CHAPTER 1 provides a holistic overview of the research, including the background and the justification of the study as well as the objective of the research. The methodology of the research is also presented

CHAPTER 2 describes the basic understanding of construction waste especially waste generated by the construction industry. The source of impact by construction to the environment is also discussed.

CHAPTER 3 presents the background of the five most common materials used in the construction industry (i.e. bricks, concrete, metals, plasterboard, and wood). Discussion will include a brief introduction about their physical properties and application within the construction method. Their usage in the UK construction industry and the effects and consequences on the environment are also discussed.

CHAPTER 4 present the overall processes which have been carried out to determine and to develop an eco-costing model for the construction material waste. An in-depth explanation of the life cycle assessment (LCA) methodology and the Impact Pathway Approach (IPA) is made. The reasons for the selection of environmental indicators and how to develop the model are also discussed.

CHAPTER 5: explain the concept of eco-costing including the definition of eco-cost, general concepts of eco-cost and detailed explanation about "damage eco-cost" which is one of the important elements of the research. Discussion will also explain the damage eco-cost for every selected the environmental indicator used in the research

CHAPTER 6 presents the results of the ecological impact of the five common construction material waste forms i.e. brick, concrete, metal, plasterboard and wood and their impact based on a selected waste disposal option. The nine potential environmental indicators are global warming potential (GWP), acidification (AP), eutrophication (EP), winter smog (WS), heavy metal (HM) and energy resource potential (ER) are used for this purpose. The other three potential indicators that give less significant impacts are summer smog (SS), carcinogenic (CP) and ozone layer depletion (ODP).

CHAPTER 7: This chapter will discuss specifically the result of eco-cost of five common construction materials i.e. brick, concrete, metal, plasterboard and wood.

CHAPTER 8 describes the most important findings of the research. Mathematical models are developed to show the eco-costs of the waste of each disposal options.

CHAPTER 9 presents the conclusion of the thesis. Recommendations for future research are also identified.

Chapter 2

WASTE AND THE CONSTRUCTION INDUSTRY

2.1. Introduction

Construction is an industry that consumes a huge quantity and variety of material. Materials waste could be generated from a variety of materials that have been used. This chapter discusses issues related to construction material waste and the subsequent impact on the environment. The chapter starts with discussion on the definition of general waste, followed by a review of the key issues related to construction and demolition (C&D) waste. Discussion on the specific issues of construction waste is also presented. This includes the current waste management policies of some countries, current methods of disposal, and composition and impact of construction waste to the environment.

2.2. Definition and concept of Waste

Waste is generated by all sorts of means. Most waste comes from domestic and municipal consumption of goods, manufacturing, construction, sewage treatment, agriculture and the generation and disposal of hazardous substances. Waste includes paper, plastics, glass, metals, foods, chemicals, oils, bricks, wood, soil, and effluent. Formoso, Isatto et al. (1999) define waste as any losses produced by activities that generate direct or indirect costs but do not add any value to the product from the point of view of the client.

The more waste produced, the more waste needs to be disposed of. The production of consumables in the first place, and their disposal when used, uses up valuable natural resources and energy, processes which can impact upon the environment and in particular the atmosphere, through pollution. Sustainable waste management encourages the generation of less waste, the re-use of consumables, and the recycling and recovery of waste that is produced.

The Waste Strategy 2000 for England and Wales describes the policies concerning the recovery and disposal of waste. These policies are a requirement of all countries in the European Union (EU). The key objectives of the strategy are to reduce the risk of pollution from those wastes. The idea of 'sustainable development' has been incorporated into the themes of the Waste Strategy 2000. This requires countries within the EU to give careful consideration to the environmental impacts of waste disposal. The UK has implemented the EU strategy by developing the idea of a 'waste management hierarchy'. This encompasses the processes of reduction, re-use, recycling and recovery, in that order of priority as shown in Figure 2.1.

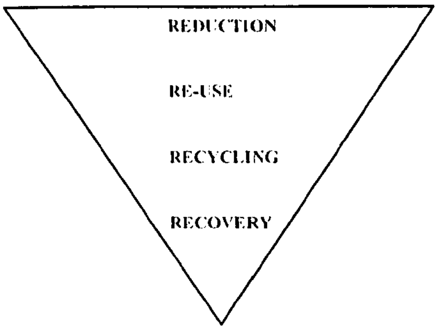

Figure 2.1: Triangle of 'waste management hierarchy'

The challenge now is to achieve the top of the hierarchy as the top is the priority option, while the bottom is the least desirable option

2.3. Construction and Demolition Waste (C&D)

Construction wastes are related to any wastes from the construction, remodelling and repairing of individual residences, commercial buildings, and other civil engineering structures. Any waste from razed buildings is normally defined as demolition waste (Huang, Lin et al. 2002). Construction and demolition (C&D) activity is one of the major waste contributors to the landfill sites. It has been classified as one of the major types of waste in the

European Waste Catalogue (EWC). The European Environment Agency (2001) has stated that total waste generation by European Union countries is about 1300 million tonnes per year, where C&D and manufacturing industries generate half of total waste. Figure 2.2 shows the percentage of total waste generation by sector from 1992 to 1997. In the year 2000, it is estimated that the total amount of C&D waste generation in Western Europe has reached 215 million tonnes with about 175 million tonnes coming from demolition work and another 40 million tonnes from construction (Bossink and Brouwers 1996). These figures indicate that the weight of generated demolition waste is more than twice the weight of generated construction waste.

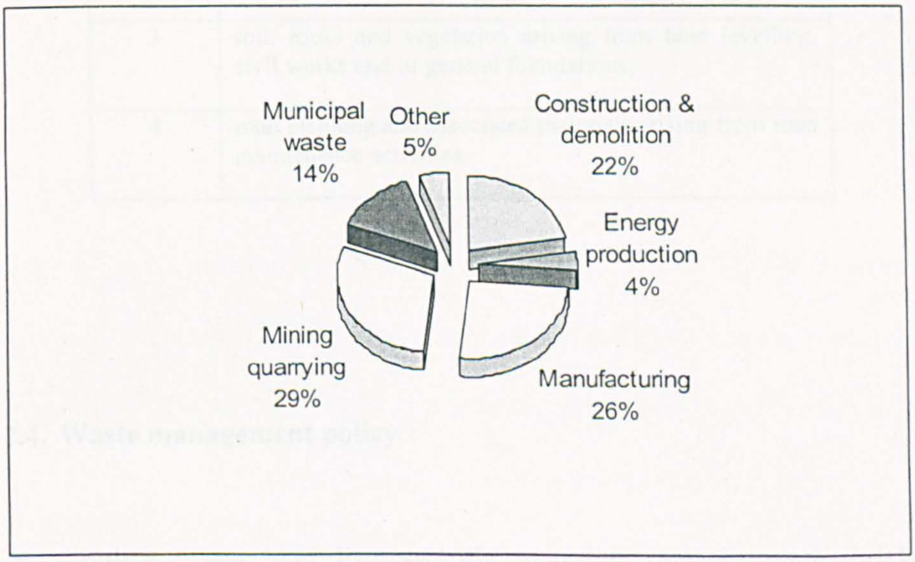

Figure 2.2: Total waste generation by sector EEA Countries 1992-1997 (Source: European Environment Agency, 2001)

Gavilan and Bernold (1994) classified the source of C&D wastes into six categories: design; procurement; handling of materials; operation; residual and other sources. In general, C&D can be classified depending on the nature of works, into five categories: roadwork material, excavated soil, demolition waste, site clearance waste and renovation waste (Poon, Yu et al. 2003). According to Symonds Group Ltd, 1999, the C&D most obvious categories are as shown in Table 2.1:

Table 2.1: Source of waste in construction industry

Category	Source
1	waste arising from the total or partial demolition of buildings and/or civil infrastructure;
2	waste arising from the construction of buildings and/or civil infrastructures;
3	soil, rocks and vegetation arising from land levelling, civil works and/or general foundations;
4	road planning and associated materials arising from road maintenance activities.

2.4. Waste management policy

A complete waste plan lists specific materials (e.g. concrete, bricks, plasterboard, metals, wood, etc.) and identifies amounts to be targeted for reduction, salvage, reuse, or recycling. The addition of a timeline makes it possible to identify when in the construction process specific materials will be generated from the building activities (for example, rubble from demolition or packaging from interior finishing). By means of this process, waste prevention goals can be set for the project, along with goals for specific materials and arrangements for storage, shipping, or reuse. Incorporating the goal of waste prevention into the project's specifications can bring the client one step closer to reducing the amount of C&D waste going to landfill (Fishbein 1998).

Every government has their specific policy on handling C&D waste. For example, the Hong Kong government has introduced a policy called *two-tier policy* in order to conserve landfill space (Poon, Yu et al. 2003). The first tier includes the restriction to the amount of C&D waste deposited at the landfill. Only C&D waste that contains more than 20 percent inert material by volume or 30 percent by weight cannot be disposed in landfill and C&D waste producers are encouraged to adopt waste sorting before disposal. In the second tier, an economic incentive is introduced on which a landfill charging system under the "Polluter-Pays-Principle" will be imposed. In this system, waste producers will need to pay 50 percent of land filling cost and subsequently it will increase in the next stages.

In the United States, the New York City waste management plan managed to reduce as much as 8 percent waste. Concurrent with this reduction, the city council requires contractors to prepare a waste plan during the bidding process; it could evaluate how each bidder would approach the management of waste, before any waste is generated or any waste removal occurs. The plan could be subjected to review by the architect and by city officials responsible for the project, and it could be used in targeting waste prevention strategies and developing waste prevention goals.

Statistics in 1999 show that the amount of 'core' C&D waste produced by the Member State of Europe was around 180 million tonnes each year.. In 1999 only about 28 percent of this figure were re-used or recycled as shown in Table 2.2. But DEFRA (2006) reported that approximately 107 million tonnes was produced by this sector in 2004 in England, which was significantly increased from about 69 million tonnes in 1999 to about 107 million tonnes in 2004. The proportion of C&D waste recycled had increased from 35 per cent to 50 per cent over this period.

'Core' C&D waste is essentially a mix of material obtained when a building or piece of civil engineering infrastructure is demolished excluding road planning, excavated soil, external utility and service connections (drainage pipes, water, gas and electricity) and surface vegetation. The figure of C&D waste could be double the total amount each year if these parts of works are taken in account (Symonds Group Ltd

1999). Five Member States (Germany, UK, France Italy and Spain) account for around 80 percent of the total 'core' C&D wastes.

Table 2.2: Amount of 'core' C&D waste produced by the Member States of Europe in 1999

Member State	Core C&DW arisings (million tonnes, rounded)	% Re-used or recycled	% Incinerated or Landfilled
UK	30	45	55
France	24	15	85
Italy	20	9	91
Spain	13	<5	>95
Netherlands	11	90	10
Belgium	7	87	13
Austria	5	41	59
Portugal	3	<5	>95
Denmark	3	81	19
Greece	2	<5	>95
Sweden	2	21	79
Finland	1	45	55
Germany	59	17	83
Ireland	1	<5	>95
Luxembourg	0	N/a	N/a
EU in total	180	28	72

In the UK steps are already being taken by the government to control C&D wastes. Following the above scenario, the UK government through the Department of Environment, Transport and the Regions (DETR) with the support by the National Assembly for Wales has carried out the most comprehensive survey of the production, recovery and disposal of C&D waste. This is the first of its kind to be conducted in the UK and was undertaken by Symonds Group Ltd for the period of 1999 until 2000. The aim of the study was to provide regional and national estimates of the amounts of C&D waste re-used, recycled and disposed of in England and Wales.

In response to the demands of the Landfill Directive as well as the other European Directive, the UK government has produced a National Waste Strategy 2000. This was set out in order to view the future of waste management in England and Wales. Every year, England and Wales produce approximately 400 million tonnes of waste comprising of industrial, commercial and municipal waste (DETR 2000). The quantity of these wastes produced in 1998/99 is shown in Table 2.3

Table 2.3: Waste production in England and Wales 1998/99

Waste	**Landfill**	**Recovery**	**Recycling/ composting**
Industrial waste (excluding C&D waste)	44%	48%	44%
Commercial waste	68%	28%	24%
Municipal waste	78%	21%	12%

Source: Waste Strategy 2000

2.5. Current method of C&D Disposal

In 1995, the UK generated 70 million tonnes of C&D waste (EEA, 2001) and approximately 27.4 million tonnes (51.2 percent of total annual C&D wastes) of C&D waste in UK are disposed directly to landfill (Lawson, 2001). Although the tonnage of waste landfilled has increased from about 26 million tonnes in 1999 to 29 million tonnes in 2004, but the proportion of construction and demolition waste sent to landfill has fallen from 37 percent to 32 percent, (DEFRA, 2006).

Meanwhile, in the Netherlands the absolute annual amount of C&D waste is 14,000,000 and the share of this industry in the total amount of waste produced is 26 percent (Bossink and Brouwers 1996). This percentage agrees with the results of several studies in other countries especially in Europe. Figure 2.4 depicts waste generation in Europe by sector and country in 1995.

Waste from construction activities in the US is also enormous. Estimated figures of current C&D waste created annually is over 145 million metric tonnes compared to about 136 million metric tonnes in 1998. This figure comprises about one-third of the total materials being landfilled. From the total of C&D waste stream in the US, 92 percent is attributed to demolition activities and another 8 percent is from construction activities (Kibert 2002).

Table 2.4: Waste generation in Europe by sector and country in 1995 (in 1000 tonnes) - Source: European Environment Agency, 2001

Country	Construction & demolition	Energy & gas	Manufacturing	Mining	Other	Municipal waste	Total
Austria	6400	775	14284		201	4110	25770
Belgium	7718	1135	13359	398	1256	5007	28864
Denmark	3427	1775	2736		845	2826	11609
Finland	8000	3000	15400	15000	300	2100	43800
France	24000		101000	75000		35600	235600
Germany	131645	25310	65119	67813		48715	338602
Greece	3400	7000	2905	3900		3600	20805
Ireland	1520.	353	3781	2200	774	1848	10476
Italy	14311	1330	22208		42500	25780	106129
Luxembourg	1499				189	299	1987
Netherlands	13650	1410	19970	326		8716	44072
Portugal	3200	392	418	472	84	3500	8066
Spain	115		13800	70000	380	14914	99209
Sweden	1500	600	13990	47000		3200	66290
United kingdom	70000	13000	56000	82000	15000	29000	265000
EU 15	290385	56080	344970	364100	61529	189215	1287922
Iceland	-		9		30	150	189
Liechtenstein	-						-
Norway	3578		3288	7600		2722	17188
EEA area	293963	56080	348267	371700	61559	192087	1323656

In Australia, (Craven, Okraglik et al. 1994) said C&D activity is likely to generate approximately 20-30 percent of all waste entering Australia's landfills; this conclusion is based on the results of three studies at several landfill sites in Melbourne and Perth. Mincks (1994) reported that a percentage of 20 percent of the solid-waste stream in the United States consists of C&D waste. Some research reports an even higher level than Mincks (1994), for example 23 percent found by Apotheker (1990), 24 percent by Peng, Scorpio et al. (1997) and 29 percent by Rogoff and Williams (1994). On the other hand, smaller percentages were found in Germany and Finland. From Germany a percentage of 19 percent is reported (Brooks, Adams et al. 1994); and C&D waste was found to be 13-

15 percent of the waste disposed of at the landfill in the Helsinki, Finland, metropolitan area (Heino 1994).

C&D waste is a complex issue and can arise from a range of different origins or site types as defined in Table 2.5 below:

Table 2.5 : Various origins and site types of C&D waste

Site types for C&D waste	**Description**
"Demolish and clear" sites	Sites with structures or infrastructure to be demolished, but on which no new construction is planned in the short term
"Demolish, clear and build" sites	Sites with structures or infrastructure to be demolished prior to the erection of new ones
"Renovation sites	Sites where the interior fittings are to be removed or replaced
"Greenfield" building sites	Undeveloped sites on which new structures or infrastructures are to be erected
"Road build sites	Sites where a new road is to be constructed on a green field or rubble free base
"Road refurbishment" sites	Sites where an existing road is to be resurfaced or substantially rebuilt

Source: (Symonds Group Ltd 1999)

2.6. The composition of construction and demolition (C&D) waste

Construction and demolition waste represent a large part of total waste generation. Most material waste has a high potential for recycling and it is important to know the composition of this type of waste. European countries commonly refer to the European Waste Catalogue (EWC) in managing the statistics on waste in order to improve the efficiency of waste management activities. EWC is a list of waste types and each of it is assigned with a unique code to describe the type of process, industry or sector from which a waste type arises. Major headings of EWC list consist of twenty major types of waste as shown in Table 2.6 and C&D waste is classified under group waste code 17

Table 2.6: Construction and demolition waste in the European Waste Catalogue (Including Road Construction)

Waste Code	Description
17 01	concrete, bricks, tiles, ceramics and gypsum based materials
17 02	wood, glass and plastic
17 03	asphalt, tar and tarred products
17 04	metals (including their alloys)
17 05	soil and dredging spoil
17 06	insulation materials
17 07	mixed construction and demolition waste

The waste from construction site activities will vary from one site to another depending on the type of project and its design. It is proven, as shown in the literature review above, that project and material specification contribute to a large extent to waste generation. For example, building construction activities involve several construction activities that can be broadly grouped as land clearing, road and sewer, substructure work (excavation and foundation work), superstructure (framing), internal carcassing and service installation (wiring, plumbing, insulation, drywall), finishing work (paint, exterior finishing and roofing), energising phase prior to handling; landscaping and completion of external works. These may involve many parties like main contractors, sub-contractors and statutory undertakers. Each of these activities have a high potential to generate waste from materials such as soil, contaminated soil, wood, metal, concrete, plastics, waste solvents, gypsum, plasterboard, cardboard, boxes, paint solvents, brick, masonry, vinyl, asphalt shingles and tiles as shown in Figure 2.3.

2.7. Classifying of building products

Buildings have a wide variety of constituent parts and are assembled from a wide array of components that can be generally divided into five general categories. Each of these categories of building components has an influence on the potential for reuse and recycling at the end of the building's useful life and the quantity of waste generated during site assembly. The scenarios can be seen in Table 2.7.

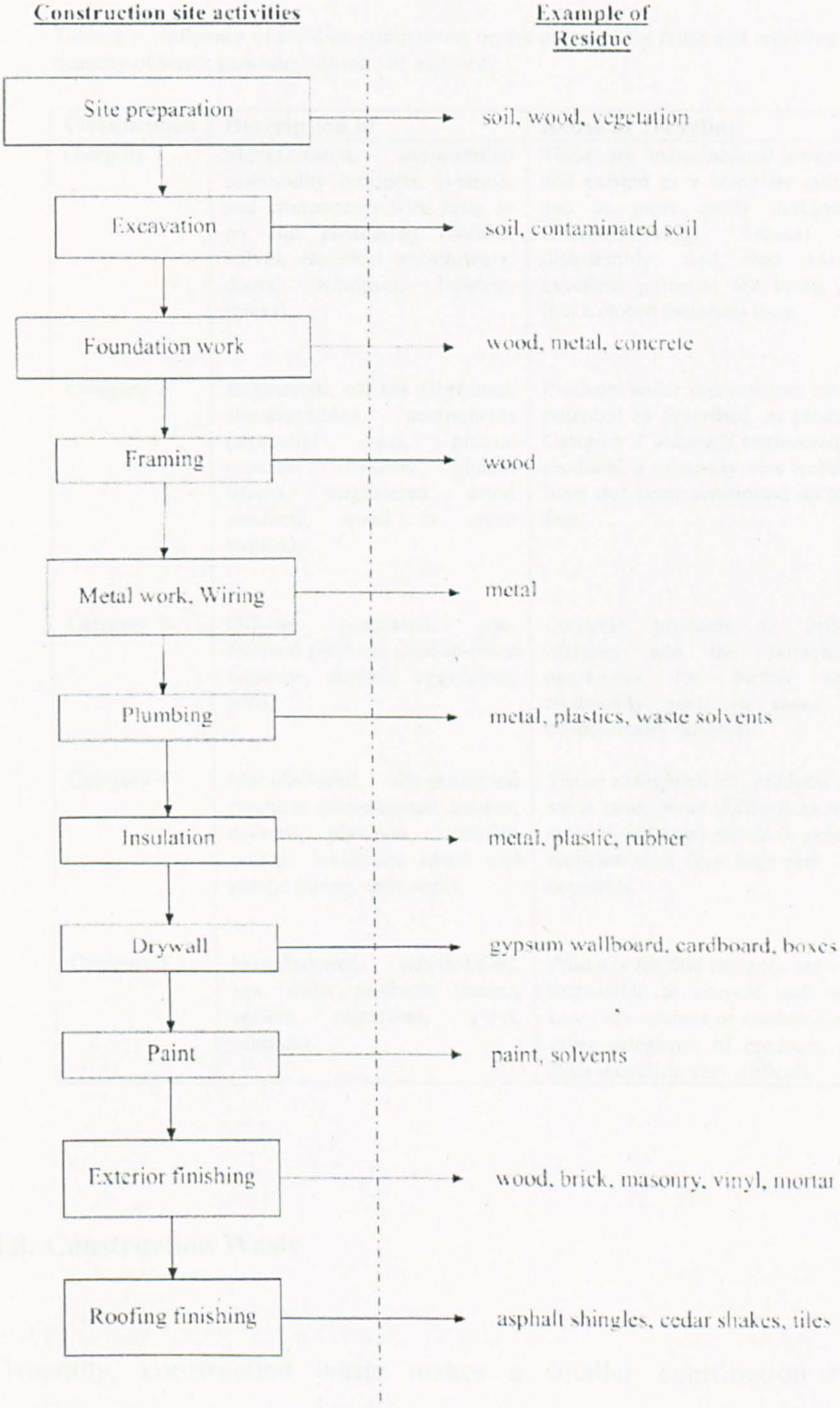

Figure 2.3: Waste from potential building site activities [Source: (Yahya and Boussabaine 2006)]

Table 2.7: Influence of building components on the potential for reuse and recycling and the quantity of waste generated during site assembly

Classification	Description of	Reuse or recycling
Category 1	Manufactured, site-installed commodity products, systems, and components with little or no site processing (boilers, valves, electrical transformers, doors, windows, lighting, bricks)	These are manufactured components and existed as a complete system. It can be more easily designed for remanufacturing, reuse, and disassembly, and thus have an excellent potential for being placed into a closed materials loop.
Category 2	Engineered, off-site fabricated, site-assembled components (structural steel, precast concrete elements, glulam beams, engineered wood products, wood or metal trusses);	Products under this category have also potential as described, as products in Category 1 although engineered wood products, a relatively new technology, have not been scrutinised as to their fate.
Category 3	Off-site processed, site-finished products (cast-in-place concrete, asphalt, aggregates, soil);	Concrete products fit into this category and the extraction of aggregates for further use is technically and, in many cases, economically feasible.
Category 4	Manufactured, site-processed products (dimensional lumber, drywall, plywood, electrical wiring, insulation, metal and plastic piping, ductwork);	These categories of products are in some cases more difficult to reuse or recycle, although metals in general are recycled at a very high rate in most countries.
Category 5	Manufactured, site-installed, low mass products (paints, sealers, varnishes, glues, mastics).	Products for this category are virtually impossible to recycle and in many cases are sources of contamination for other categories of products, making their recycling very difficult.

2.8. Construction Waste

Generally, construction waste makes a smaller contribution to the generation of C&D waste than demolition waste. It could be in the form of solid, liquid, gas or a combination of all of these materials. Waste from the construction activities has the following characteristics:

1. Construction site waste might consist of materials that contain high levels of contamination, which are very hard to recycle (Brooks, Adams et al. 1994). The best example of contamination may be from asbestos-based material, such as insulations, as stated in EEC Directive 91/689 (1991) (Fatta, Papadopoulos et al. 2003)
2. The prevention of construction waste is preferable to the recycling of demolition waste "at the end of the pipeline".
3. Construction waste may contain a relatively large amount of chemical waste, i.e. materials that have a toxicity or flammability characteristic as classified in EEC Directive 91/689 (1991) (Fatta, Papadopoulos et al. 2003).
4. The cost reduction caused by preventing the generation of construction waste is of direct benefit for most construction industry stakeholders.

Some studies have been conducted in Brazil to determine the waste rates for construction materials on site. According to Pinto and Agopayan (1994), experimental studies pointed out that the waste rate in the Brazilian construction industry is as high as 20-30 percent of the weight of total materials on site. Hamassaki and Neto (1994) conclude on the basis of research in the south region of Brazil that 25 percent of construction materials are wasted during construction operations. Finally, Formoso et al. (1993) estimated the amount of construction waste generated in Brazil to be as much as 20 percent of all materials delivered to site.

Waste can occur at any stage because of not only construction activities but also external factors such as theft and vandalism. These external influences are likely to influence the statistics on construction waste. It is not clear whether the reported amounts account for these external factors. A second critical note is that the waste rates in Brazil may not be directly comparable to those from other countries in consequence of differences in used construction techniques, work procedures, and common practices. At any rate, the amount of construction materials wasted on site cannot be neglected. Although some residual level of construction waste seems unavoidable, the potential cost reduction by preventing generation of construction waste on site is substantial and can be an incentive for participants in construction projects to put efforts in minimizing construction waste (Boussink and Browers, 1996).

Boussink and Browers (1996) reported the percentages of generated waste during construction operations for specific materials. The results showed that there is an enormous variation in waste percentages between different construction materials in a study. A waste percentage of 1 percent is found for concrete and 50 percent for mortar. The differences in waste percentages for a specific construction material between the three studies in most cases are small. For instance, Pinto (1989) [cited in Boussink and Browers (1996)] and Pinto and Agopayan (1994) found a waste percentage for sand equal to 28 percent; Soibelman et al. (1994), a percentage of 31 percent. The percentages agree with each other to a fairly high degree.

Gavilan and Bernold (1994) and Craven, Okraglik et al. (1994) described the main causes of waste generation which, among other things, include error in contract document, changes to design, ordering error, accident, lack of site control and lack of waste management, damage during transportation and off cuts from cutting materials to length. However, Chen (2002) emphasised that construction waste is still beyond control because of these three factors, construction firms are reluctant to adopt low-waste technique as it is expensive to use, design coordination has a major impact of waste generation and on-site construction waste proliferates. The last participant to be involved in any building project, the contractor, is confronted with the positive and the negative environmental effects of many of the activities of the previous stages of the project. But reduction of construction waste is not only the responsibility of the construction company.

2.9. Impact of Construction on the Environment

The construction industry has a significant impact on the environment. Boussabaine and Kirkham (2004) classified environmental impact in two main categories i.e. atmospheric and resources related. Atmospheric impact includes the green house effect and ozone layer depletion while resources impact includes contamination of air, water and earth. The impact of construction on the environment could occur across a broad spectrum of its activities loosely grouped into off-site, on-site and operational activities as illustrated in Figure 2.4.

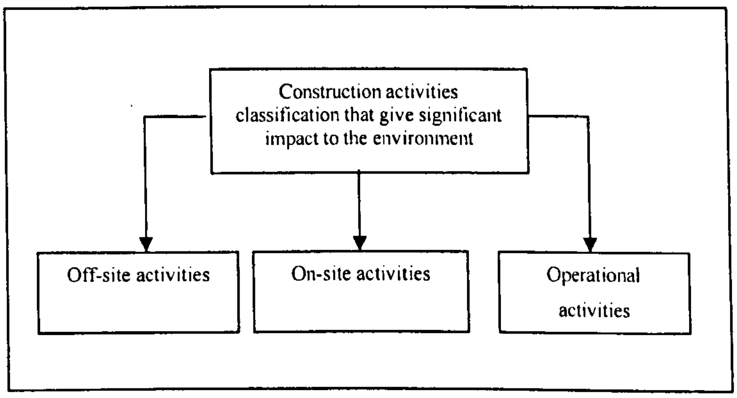

Figure 2.4: Classification of construction activities that give significant impact to the environment.

Off-site activities include mining and manufacturing of materials and components, transport of materials and components, land acquisition, project definition and design. The impact on the environment can be significant in the following areas (Uher 1999):

1. Consumption of renewable and non-renewable resources such as minerals, water and timber for building materials and components. This may also lead to the loss of bio-diversity;
2. Pollution of air, water and land from manufacturing and transportation;
3. Committing land for a new facility may lead to deforestation, loss of agricultural land, expansion of urban areas with associated transport and social problems, more demand for water, electricity and other services, and loss of bio-diversity;
4. Decisions about project goals influence design, construction and operation of the facility in areas of resource usage, quality of indoor environment, traffic issues, recycling, waste management, maintenance and life of the facility as well as social environment

On-site activities from which the impact could be found in the areas of air, water and ground pollution include consumption of resources in building the facility, traffic problems related to site activities, generation of construction waste, absence of recycling of construction materials and components, and loss of bio-diversity.

Those areas associated with operating the asset and include maintenance and future demolition/deconstruction of assets will be categorised as operational activities. These activities may significantly impact on the environment in areas such as energy and water consumption, pollution of air, water and ground, traffics problems caused by the physical presence of the facility and in- and out-flow of its occupants, generation of waste (sewerage, drainage and garbage) and indoor air quality.

Chapter 3

OVERVIEW ON THE SELECTED CONSTRUCTION MATERIALS

3.1. Introduction

The construction industry uses a huge number of material types. The type of materials range from raw materials like sand, aggregates, soil and water to production materials like bricks, cement, plasterboard, metals (steel and iron), wood, concrete, cement and plaster. Due to the broad types of construction material, the discussion in this chapter will only focus on the five most common materials that are mostly used in the construction industry i.e. bricks, concrete, metals, plasterboard, and wood. For every material, the discussion will start with a brief introduction into their physical properties. This will then be followed by a description of their usage in the UK construction industry. The effects and consequences on the environment will also be discussed.

3.2. Brick as a Construction Material

Bricks are widely used in the built environment and have been used in construction for thousands of years especially in building works. Since at least 5000 years ago when man discovered the strength and durability of brick, the technique of making bricks has improved from *drying mud in the sun* to the *fired in kiln* (The Brick Development Association 1974; Handisyde and Haseltine 1976; Woodforde 1976).

Generally, there are three main types of bricks on the market namely *facing, engineering* and *common* brick. The three types of brick are based on the production technique shown in Table 3.1 (Brick Development Association 2006). Demands for bricks in the built environment are still huge especially for facing brick. Within the market served by the brick industries in the UK are housing, commercial buildings, civil engineering works and repair and maintenance work. Their durability and natural aesthetic value make bricks attractive to the construction sector despite the existence of other optional materials like concrete and steel. In addition, in-service performance of bricks is longer if compared to the concrete and steel. In general the size of a brick in the UK is 8.5 x 4 x 2.5 inches (215 x 102.5 x 65 millimetres).

Table 3.1: Types of brick by production technique

Type of brick	Production technique	Production process
Facing brick	Soft mud process	A free-flowing claymix with up to 30% moisture content is thrown into mould-boxed either by hand or machine then dried and fired. Brick product is in the form of a soft irregular and attractive appearance
Engineering brick	Extrusion process/wirecut	Clay is forced by an auger through a lubricated die to form a continuous column of stiff clay which can be 'faced' by roll-texturing, sand-blasting and pigment spraying to produce a range of textures and other aesthetic effects. The column is cut into bricks using tightly strung steel wires, hence the alternative name 'wirecut'.
Common brick	Pressing	Semi-dry clay is pressed into a mould box to produce a brick which is regular in size and shape with square edges.

3.2.1. Brick in UK Construction Industry

Since the demise of the common brick and its replacement by concrete and plasterboard in construction, the decline of new built houses, and the trend of building small houses and flats caused the consumption of bricks to decline (British Geological Survey 2005). However, it is reported that the production of brick is more stable nowadays due to demand from its principal markets such as new housing development, commercial buildings and repair and maintenance. It is now expected to maintain its current level in the foreseeable future (Brick Development Association 2006). The three principal markets shared the proportion of 7 million tonnes in recent years with the percentage of 60 percent, 20 percent, 20 percent (British Geological Survey 2005). It was also reported that the annual economic contribution of the brick industry in the UK is estimated at approximately

£670 million, where £500 million of which are from brick production (Brick Development Association 2006). Table 3.2 shows the cost breakdown value of heavy clay construction products in 2001.

Table 3.2: Value of UK production of heavy clay construction products in 2001

Clay product	**Production value (£'000)**
Clay building bricks	506,104
Clay roofing tiles	48,263
Clay flooring blocks	4,483
Clay pipes	18,285
Other clay construction products	54,542
Total	**631,677**

Source: National Statistic, UK

3.2.2. Brick and the Environment

Approximately 3 tonnes of clay or shale are needed to produce 1000 bricks. As the principal materials used in the production of bricks is clay, brick production with 95 percent clay consumption emerged as the highest usage of extracted clay compared to other heavy clay construction products i.e. clay roofing tiles, clay flooring blocks and clay pipes as shown in Table 2. The annual consumption of clay in the UK is estimated at around 8 million tonnes (Brick Development Association 2006).

As many other forms of production, brick production requires input of resources, whereby this can give some degree of negative impact on the environment. The impact includes the extraction of clay, energy consumption, emissions, and noise. It is reported that brick production has a large impact on the environment as a result of energy use and carbon emission. Brick production is energy intensive with the annual energy consumption at approximately 5.4 Terawatt per hour - Twh (Brick Development Association 2006).

The impact also will occur at the end-of-life of the brick. The impacts could also be generated during the dismantling processes, sorting processes and disposal processes. Perhaps the impacts may occur during the recycling processes. Among the impacts are energy consumption and emission from activities like dismantling, transportation and other equipment. Table 3.3 shows an example of energy impact by specific diesel consumption during the dismantling of bricks in C&D at their end-of-life cycle (Doka 2003).

Table 3.3: Specific diesel consumption for bricks

Process	**Unit**	**Brick wall**
Tearing with hydraulic devices	h/m3	0.0707
Diesel consumption	MJ/m3	57.50
Material density	kg/m3	1600
Specific diesel consumption	**MJ/kg**	**0.0359**

3.3. Concrete as a Construction Material

Concrete is one of the most important and widely use materials in construction. It is used mainly for the structures of building construction such as foundations, columns and floors. Generally, concrete is a manmade hardened rocklike mass made from a mixture of aggregates, cement and water. Aggregates are generally divided into two groups: fine (i.e. sand) and coarse (i.e. gravel or crushed stone). The majority of concrete used in the construction nowadays are in the form of ready-mix produced from the batching plant and accounts for nearly three-quarters of all concrete (Portland Cement Association).There are currently 1200 ready-mix concrete plants in the UK, producing 23.5 million cubic metres of concrete per year (Sealey, Hill et al. 2001)

Concrete is classified according to its density as shown in Table 3.4 (Kellenberger, Kunniger et al. 2004). In general, one cubic metre of concrete has a mass of around 2400 kilograms consisting of around 80 per cent of aggregate, 12 per cent cement and 8 per cent water and small quantities of chemical admixture. The purpose of adding admixtures to the concrete mixture are to improve the concrete performance. Typical concrete mixes are proportioned by absolute weight and some of the mixes can be shown in Table 3.5 (Portland Cement Association).

Table 3.4: Classification of concrete

Class of concrete	Density of concrete
Lightweight concrete class1	≤ 1,885 kg/m3
Lightweight concrete class 2	≤ 2,000 kg/m3
Normal-weight concrete	≤ 2,800 kg/m3
Heavyweight concrete	> 2,800 kg/m3

Table 3.5: Typical mix of concrete use in construction

	Cement	Water	Air	Fine agg.	Coarse agg.
Mix I	15%	18%	8%	28%	31%
Mix II	7%	14%	4%	24%	51%
Mix III	15%	21%	3%	30%	31%
Mix IV	7%	16%	1/2%	25-1/2%	51%

3.3.1. Concrete in the UK Construction Industry

Concrete was used extensively as an alternative to brickwork in house construction since the 1920s (Harrison, Mullin et al. 2005). General concrete productions include site-mixed, pre-cast, ready-mixed and reinforced concrete. Harrison, Mullin et al. 2005 also reported that, from the total of about 1.5 million non-traditional houses built in the UK up to mid-1970s, approximately 450,000 used in-situ concrete construction and more than 175,000 other used pre-cast concrete. The UK pre-cast concrete industry produces over 35 million tonnes of products annually for the construction sector, worth an estimated £2 billion (British Precast).

Ready-mixed concrete is also widely used in construction especially for bulk construction, i.e. commercial buildings, industrial buildings, housing, hospitals and schools. Ready-mixed concrete usage per capita in UK has been reported at around 60 percent of that of its other European neighbour (Les Parrott 2002). Annually, more than 100 million tonnes with the sales amounting to about £5 billion of concrete is used in the UK (The Concrete Centre).

3.3.2. Concrete and the Environment

Concrete is brittle but a durable and inert type of construction material. It is very versatile, non-toxic and can easily be found almost everywhere, because concrete has been used widely in construction especially in urban areas. In the UK, the market of cement and concrete is very huge as it represents approximately 10 percent of all construction activities in the UK (Glass 2001). A project conducted by the Concrete Industry Alliance (CIA) produced an environmental report on the UK concrete industry. The CIA defined eight environmental effects from the source of concrete including aggregated cement, pulverised fuel ash, ground granulated blast-furnace slag, reinforcement, aggregated and concrete production, generation of electricity and its use and transportation.

Consumption of concrete in the built environment is large. It was also reported that concrete was becoming second only to water as the most consumed substance on Earth, with almost one tonne of concrete being used for each human every year (British Cement Association 2003). As with many other construction materials, the use of concrete will have an impact on the environment, especially if the material is used in very large quantities. As the concrete production accounts approximately one third of the UK mineral extraction, the subsequent environmental impact of concrete was reported as ranging from 0.1 percent to 4.0 percent of UK totals (Shear 2002).

The British Cement Association in their response to the government strategy toward sustainable development stated that 2.6 percent of UK carbon dioxide was produced from the manufacture of concrete (Parrott 2002; British Cement Association 2003). The indication was based on 10 indicators including land used, water used, energy, CO2, SOx, NOx, CO, dust, metals and waste. Figure 3.1 indicates the average proportion of the UK's environmental impact related to the built environment and construction material in relation to cement and concrete production. The figures have shown that the embodied environmental impact cause by concrete and cement manufacturing was far lower if compared to building in-use and transport to the UK's environmental performance, where 50 percent of UK emission of CO2 is related to the occupancy of the existing building. The percentage of CO2 emission released by concrete manufacturing was also the lowest if compared to other sectors such as the transport, industry, domestic and services (Shear 2002) as shown in Figure 3.2.

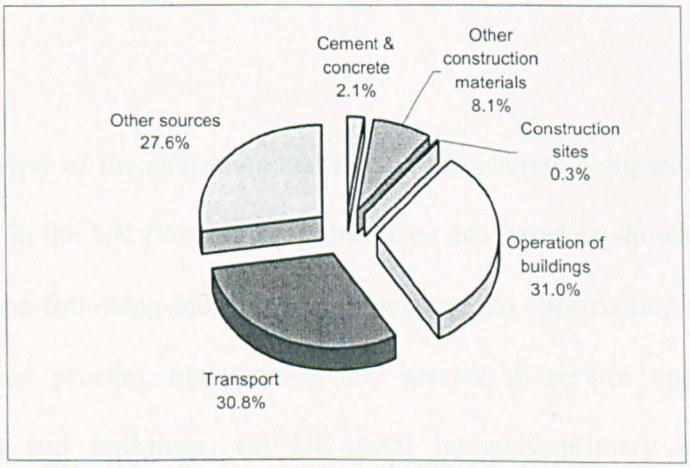

Figure 3.1: Average percentage of related environmental impacts in relation to built environment and construction material compared to cement and concrete production

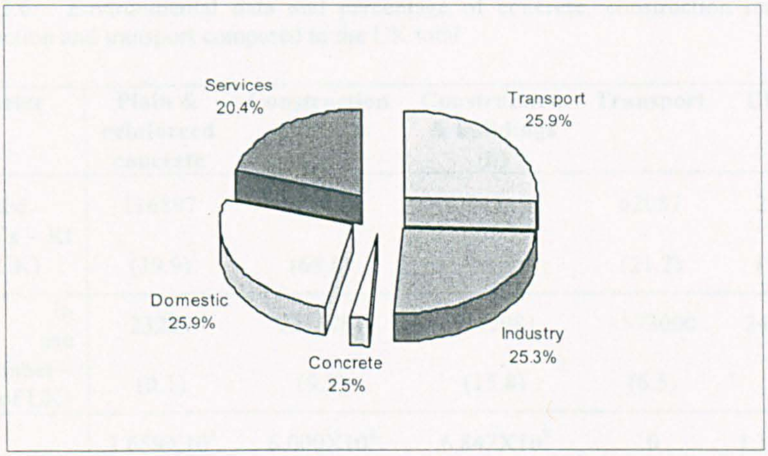

Figure 3.2: The percentage of CO2 emission released by concrete manufacturing, transport, industry, domestic and services

A broad view of the environmental impact of concrete compared to other processes in the UK (Parrott 2002) has been estimated as shown in Table 3.6 with the following indication; (a) concrete, (b) construction materials, construction process, maintenance and service in service operation of dwellings and buildings, (c) UK total includes primary energy of electricity.

Table 3.6: Environmental data and percentage of concrete, construction materials, construction and transport compared to the UK total

Parameter	**Plain & reinforced concrete**	**Construction materials (a)**	**Construction & buildings (b)**	**Transport**	**UK total (c)**
Extracted minerals – Kt	116897	201715	201715	62087	293000
(% of UK)	(39.9)	(68.8)	(68.8)	(21.2)	(100.0)
Land in active use excl. timber – ha (% of UK)	23224	2215781	3812981	1573000	24200000
	(0.1)	(9.2)	(15.8)	(6.5)	100.0
Water consumption – m3	$1.659X10^{8}$	$6.000X10^{8}$	$6.847X10^{9}$	0	$1.170X10^{10}$
(% of UK)	(1.4)	(5.1)	(58.5)	(0.0)	(100)
Energy (c) – TJ Primary	65708	347056	4480504	2370870	9433646
(% of UK)	(0.7)	(3.7)	(47.5)	(25.1)	(100)
CO2 emission to air – Kt	14587	39829	262700	134271	557700
(% of UK)	(2.6)	(7.1)	(47.1)	(24.1)	(100)
SO2 emission to air – Kt	34.9	161.9	820.8	62.0	1258.0
(% of UK)	(2.8)	(12.9)	(65.2)	(4.9)	(100)
NOx emission to air – Kt	77.5	247.2	854.8	1011.1	1806.6
(% of UK)	(4.3)	(13.7)	(47.3)	(56.0)	(100)
CO emission to air – Kt	36.3	104.4	606.8	3458.6	4311.3
(% of UK)	(0.8)	(2.4)	(14.1)	(80.2)	(100)
PM10 emission to air – Kt	6778	20956	84004	44757	196927
(% of UK)	(3.4)	(10.6)	(42.7)	(22.7)	(100)
Heavy metals emission to air –t	61	619	902	477	1780
(% of UK)	(3.4)	(34.8)	(50.7)	(26.8)	(100)
Waste to land – Kt	8027	12000	154000	7000	424000
(% of UK)	(1.9)	(2.8)	(36.3)	(1.7)	(100)

It is clearly shown that the processing of concrete itself (i.e. from extraction, land use, water consumption, energy consumption, emissions, and waste) has a less significant impact on the environment in contrast with other construction activities. In term of wastes, concrete waste is classified as an inert waste. It does not contain any harmful effect when in place. It was also reported that concrete requires no toxic protective treatment to prevent it from deterioration based preservative like volatile organic compound - VOC (Glass 2001). But similar to brick, impacts like energy consumption and emissions might occur during transportation, sorting and disposal processes.

3.4. Metal as a Construction Material

Metals have been mined extensively for many years in the majority of construction facilities. The metals used for everyday objects have usually been subjected to a number of different processing techniques such as heating, coating with non-metallic substances, alloying with other metals and reacting with chemicals (Wasteonline 2005). Metals are generally classified as either *ferrous* or *non-ferrous* as shown in Table 3.7. Ferrous metals are the ones most widely used compared to non-ferrous metals.

Table 3.7: Classification of metal

Classification of metal	**Types of metal**
Ferrous	Iron, steel.
Non-ferrous	Aluminium, copper, lead, mercury, nickel, tin and zinc.

Metal production in the UK, in particular steel, is a major industry. The nation steelworks use almost 7 million tonnes of secondary metal a year in making about 18 million tonnes of new steel. The British Metals Federation estimated that between 4.5 million and 5 million tonnes of this secondary material is provided by the recycling industry (Wasteonline 2005).

3.4.1. Fabricated Metal Products Used in Construction in The UK

Metals in the form of fabricated metal products (FMP) are among the most important resources in the construction industries. Approximately 3.94Mt of fabricated metal products have been used in the UK in 1998 (The Steel Construction Institute 2005). Steel is a type of FMP that has been extensively used compared to other types of FMP, especially for major building and civil engineering structures. For many years, steel has been a commonly recycled material throughout the world. Efficiently managing and recycling used steel products is important to maximize the utility of this commodity. The usage of fabricated metal products in 1998 is presented in Table 3.8 and illustrated in Figure 3.3 and Figure 3.4.

Table 3.8: Primary uses of fabricated metal products in the UK construction industry (Smith, Kersey et al. 2003)

Material	Product	Uses
Steel	Structural sections	Structural frames, lintels, staircases, lift supports and runners
	Plate	Gussets, structural frames
	Structural hollow sections	Structural frames
	Sheet piling	Coffer dams, trenching, formwork
	Thin sheet	Roof and external wall cladding, eaves, verge and ridge details, lintels, formwork, stair treads and risers, radiators.
	Reinforcement bars - mild steel, high tensile	Reinforced concrete
	Reinforcement mesh	Reinforcement slabs and walls
	Light sections	Suspended ceiling support, partition frames, lintels, conduit ducts, handrails and banisters, fence posts.
	Steel bars - general	Post and pre-tensioning bars
	Steel tubes	Structural sections
	Prefabricated structural sections	Large structures - football stadiums, bridges etc, pylons, lattice masts, steel towers, scaffolding towers
	Manufactured and formed sheet	Hangers, connectors, lintels, urinals, baths, WCs, wall and roof cladding, eaves, verge and ridge details, permanent formwork conduit trays, ducting, doors
	Small sections	Window and door frames
	Specialist components	Boilers, calorifiers, fans, pumps, air-conditioning units, control panels, compressors
	Small components	Ironmongery, locks, hinges, nails, screws, bolts, nuts, wall ties
	Miscellaneous	Wire, fencing mesh, chain, cable, light fittings.
Stainless steel	Structural sections	Staircases
	Thin sheet	Roof and wall cladding, eaves, verge and ridge details, valley lintels
	Miscellaneous	Wall ties
	Steel tubes	Services
Iron	Pipes	Rainwater down pipes, underground drainage
	Formed	Gutters, manhole covers
	Specialist products	Bollards, litter bins etc.
Aluminium	Structural sections	Structural columns and beams
	Thin sheet	Wall and roof coverings, eaves, verge and ridge details, radiators, stair treads and risers.
	Light sections	Window and door frames, partitioning frames, suspended ceiling support.
	Sheet	Wall and roof claddings, eaves, verge and ridge details.
	Small sections	Window and door frames.
	Specialist components	Fans, pumps, mechanical parts, equipment casings.
	Miscellaneous.	Ironmongery, lighting, foil (vapour barriers etc), trim.
Copper and brass	Thin sheet	Roof and wall coverings, flashings.
	Steel tubes	Pipes for services.
	Small components	Ironmongery, locks, hinges, nails, screws, bolts, nuts, wall ties.
	Manufactured and formed	Valves and fittings.
	Specialist components	Wiring in motors, transformers etc.
	Miscellaneous.	Ironmongery, hinges, locks, electrical fittings, leaded lights.
Lead	Thin sheet	Flashings.
	Miscellaneous	Leaded lights
Zinc	Galvanising	Various.
	Sheet	Flashings.
	Miscellaneous	Component of some paints, solder, leaded lights.
Titanium	Miscellaneous	Component of some paints.
Tin	Miscellaneous	Solder
Beryllium	Miscellaneous	Springs.

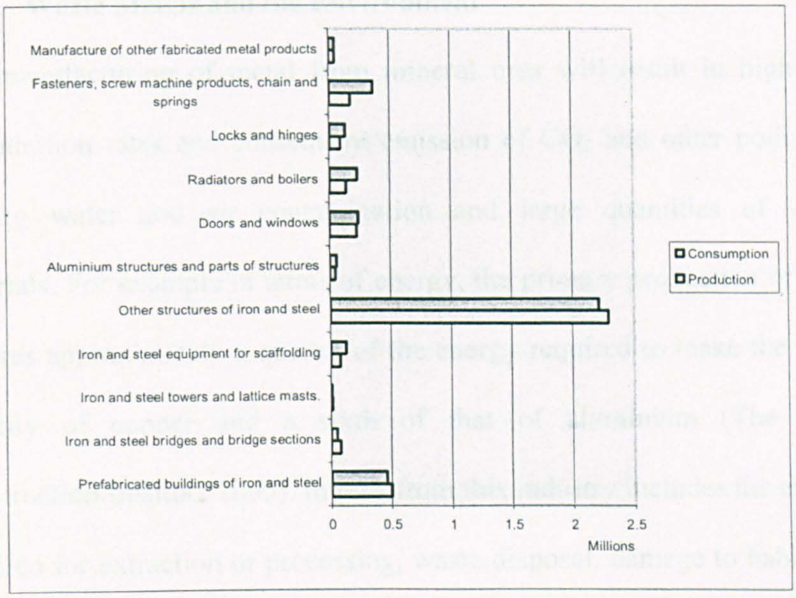

Figure 3.3: Total consumption of fabricated metal products in the UK in 1998 (tonnes)

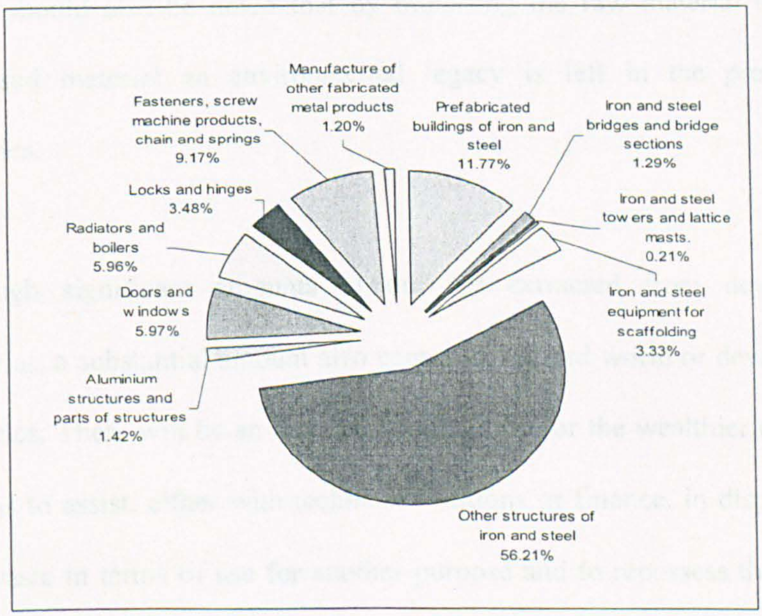

Figure 3.4: Consumption of fabricated metal products in the UK in 1998

3.4.2. Waste Metals and the Environment

The manufacturing of metal from mineral ores will result in high fuel consumption rates and consequent emission of CO_2 and other pollutants causing water and air contamination and large quantities of waste materials. For example in terms of energy, the primary production of steel requires approximately a quarter of the energy required to make the same quantity of copper and a sixth of that of aluminium (The Steel Construction Institute 2005). Impact from this industry includes the energy required for extraction or processing, waste disposal, damage to habitat as well as noise and dust. However, since the UK imports a high proportion of ore from overseas, there is the added environmental burden of transport. But it should also be noted that by importing the raw material or part processed material an environmental legacy is left in the providing countries.

Although significant amounts of ore are extracted from developed countries, a substantial amount also comes from third world or developing countries. There will be an increasing obligation for the wealthier end use nations to assist, either with technical solutions or finance, in disposal of this waste in terms of use for another purpose and to repossess the waste covered areas caused by previous extraction and processing. Even though the recycling of metals policy is well developed, consideration of sufficient recycling products will take place in the immediate future to meet demand. Hence, the primary production is still needed. The last option in waste hierarchy, metals that find their ways into landfill are potential polluters as they may corrode and there is the possibility of metals leaching into the groundwater. When it is impossible, or undesirable, to extend the life of buildings through adaptation or refurbishment, and therefore demolition becomes unavoidable, it is important that end-of-life impacts are minimised. Principally this involves minimising waste and ensuring that materials are recovered, recycled and reused.

Like many other construction wastes, metal waste is classified as controlled waste. The Waste Management Licensing Regulations 1994 (SI 1994/1056) require businesses dealing with controlled wastes to hold a Waste Management Licence. However, many potential sources of metal-related pollution still occur in some places like unlicensed metal scrap yards, resulting in the soil or water course contamination.

3.4.3. Waste Metals in the Construction Industry

Metal, especially in the form of steel, is used in a wide range of manufactured goods, including construction materials. Large quantities of steel and other ferrous metals are found in construction materials and transportation products, such as automobiles, locomotives, and ships

(Environmental Protection Agency 2005). Although the majority of scrap metal is from other industrial activities like off-cuts from metal processing, the dismantling of industrial plants, railway track and ship-breaking yard (Wasteonline 2005), metals from construction industry contribute considerable amounts of waste as well. This is shown in Table 3.9 and Table 3.10.

Table 3.9: Type and quantity of waste generated during various UK construction projects (in m^3 of waste)

Waste type	**Office construction (mean of 2 projects)**	**Residential construction (mean of 6 projects)**	**Road construction (mean of 3 projects)**
Ceramics	2.64	25.82	0.00
Concrete	26.57	37.56	15.10
Electrical equipment	91.37	54.14	0.00
Furniture	9.63	15.58	0.00
Inert	1.15	105.24	15.83
Insulation	591.60	334.29	0.00
Metals	547.59	153.85	0.00
Miscellaneous	391.65	581.22	0.00
Packaging	577.00	414.66	0.00
Plaster/cement	293.65	779.42	0.00
Plastics	141.35	189.83	0.00
Timber	923.73	465.15	0.00
Liquids and Oils	0.00	0.29	0.00
Hazardous	4.85	0.04	5.08

Table 3.10: "Typical" construction waste estimated for a 2,000ft^2 house in the United States (Smart Growth 2005)

Material	**Weight (in pounds)**	**Volume (in cubic yards)***
Solid Sawn Wood	1,600	6
Engineered Wood	1,400	5
Drywall	2,000	5
Cardboard (OCC)	600	20
Metals	150	1
Vinyl (PVC)**	150	1
Masonry***	1,000	1
Hazardous materials	50	-
Other	1,050	11
Total	8,000	50

*Volumes are highly variable due to compressibility and captured air space in waste materials.
**Assuming three sides of exterior clad in vinyl siding.
***Assuming a brick veneer on home's front facade.

3.4.4. The Environmental Impact of Metal Waste

Metals have an impact on the environment because they are extremely toxic. There are well-documented events involving metal contamination, for example at Minimata Bay in Japan, mercury-contaminated fish were responsible for poisoning 18,000 people, resulting in 700 deaths (Wasteonline 2005).

Metal waste that is exposed to the elements will break down over time and the metals can be released into the soil in the form of metal salts. These metal salts will be washed by rainwater into rivers where they can be taken up by aquatic organisms and have a detrimental impact on the environment. Metal waste disposed of in landfill sites not only takes up valuable landfill space but also produces a noxious leachate during the breakdown of material which eventually finds its way into the environment (Wasteonline 2005).

Due to regulations that prevent metal waste from construction to enter the landfill site, the impact from metal waste may be generated mainly from other activities related to the transportation of waste to the sorting plant and recycling sites as well as the use of energy from up-stream activities like the production of electricity and fuel.

3.5. Plasterboards as Construction Material

Plasterboard (also known as drywall or wallboard or gypsum board) is made either from natural or synthetic gypsum processed into a board and usually faced with a paper covering (Waste & Resources Action Programme (WRAP) 2006). In England, gypsum rock is mined at three main points: in Sussex, Lincolnshire, and Yorkshire. Natural gypsum or calcium sulphate dihydrate consists of 70 percent calcium sulphate and 21 percent water by weight. Synthetic Gypsum is produced synthetically as a by-product of a number of industrial processes as follows (Waste & Resources Action Programme (WRAP) 2006).

- Flue-gas desulphurisation (FGD) of power station emissions - the largest production method of gypsum used in plasterboard manufacture.
- Titanogypsum – a by-product from the manufacture of titanium dioxide (a whitening agent used in many products from paint to toothpaste).
- Phosphogypsum – a by-product from the manufacture of phosphoric acid and phosphate-based fertilisers.
- Fluorogypsum – a by-product from the manufacture of hydrofluoric acid, used in a number of industries including the manufacture of electronic components.

The main use of plasterboard in construction is in the interior cladding material such as partitions, external wall lining and ceiling. Plasterboard is normally used during the finishing of the interior wall and ceiling as an alternative to traditional plastering work. As gypsum is an excellent fire barrier (Jang and Townsend 2001), it is used as a main fire resistant material in plasterboard for interior use in the building, besides acting as an insulation from noise and heat for the building.

3.5.1. Plaster Products Used in the UK

Plasterboard is the most common material for construction of interior walls and ceilings. It is made primarily from gypsum sandwiched between two sheets of covering paper. The use of plaster product including plasterboards has increased every year. This can be shown in the Table 3.11 below.

Table 3.11: United Kingdom plaster products net supply

Year	UK net supply (m^2)
2001	241,045,660
2002	252,024,024
2003	298,443,246
2004	357,216,607

Source: National Statistic of the UK (2004) (British Geological Survey 2006)

The trend of construction works that uses prefabricated building materials to reduce on-site building time makes the growth rate of plasterboard higher (Entec UK 2006). The summary of UK gypsum manufacture is shown in Table 3.12

Table 3.12: Summary of UK gypsum manufacture in the UK (Entec UK 2006)

Product	**Quantity of gypsum product manufactured (tonne)**		
	2003	**2004**	**2005**
Bagged plaster	1,073,675	1,164,318	1,190,863
Plasterboard	2,091,065	2,223,736	2,347,622
Coving	25,661	23,750	22,055
Glass reinforcement gypsum (GRG)	36,211	35,290	37,588
Total	**3,226,612**	**3,447,093**	**3,598,129**

Smith, Kersey and Griffiths (2003) reported that the total sale of cement, concrete, and plaster products in construction in 1998 was 24.88Mt. The total UK manufacturers' sale of plasterboard in 2004 was £501 million (British Geological Survey 2006). The main use of cement, concrete, and plaster products in construction in 1998 is shown in Table 3.13.

3.5.2. Plasterboard Waste and Its Environment Impact

Plasterboard waste is considered to be among the highest components of construction waste. It is estimated that between 20-30 percent of material waste on London projects is plasterboard. The main material of plasterboard is gypsum. Approximately 3 million tonnes of gypsum was produced in 2000 in the UK (Entec UK 2006). Industrial consumption of gypsum in the UK is dominated by the production of plaster products such as plasterboard and plaster. The British Geological Survey (2006) estimated the consumption was approximately 2.0 tonnes and 1.0 tonne respectively as shown in Figure 3.5.

Table 3.13: The uses of cement, concrete, and plaster products in construction in the UK (Smith R.A., Kersey J.R. et al. 2003)

Material	**Uses**
Cement clinker	Ground and mixed with gypsum and other materials to produce cement.
Cement	Used in production of mortar, fibre cement products, ready mixed concrete, cement constructional products. Cement is also used on construction sites mixed with gravel and sand to produce concrete *in situ*.
Lime	Used in the production of glass, as an additive in pigments and paints, soil stabilisation, rendering, asphalt additive and mortar production.
Plaster	Used in the plastering of external and internal walls to prepare them for paint or wallpapering.
Building blocks and bricks of cement	Used for the construction of external and internal walls for commercial and residential buildings.
Tiles, flagstones and other similar article of cement	Used for walling and flooring in buildings.
Pipe of cement, concrete or artificial stone	Used for water supply, drainage and sewarage.
Prefabricated buildings of cement	Prefabricated buildings such as sheds, garages, greenhouses, conservatories, holiday homes or industrial plant room including complete buildings fully assembled ready for use, complete buildings unassembled and incomplete buildings.
Plaster products for constructional purposes	Mainly consists of plasterboard which is used in the construction of walls and ceilings in buildings.
Ready-mixed concrete	Used for construction of buildings in-situ on construction sites e.g. floors, blocks.
Factory made mortars	Used as a bedding or adhesive between stone, brick and other materials used in masonry construction.
Fibre cement	Used to manufacture external and internal lining panels/boards and pipes.
Articles of plaster or compositions based on plaster	Ornamental articles for use as decoration in building domestic and commercial buildings.

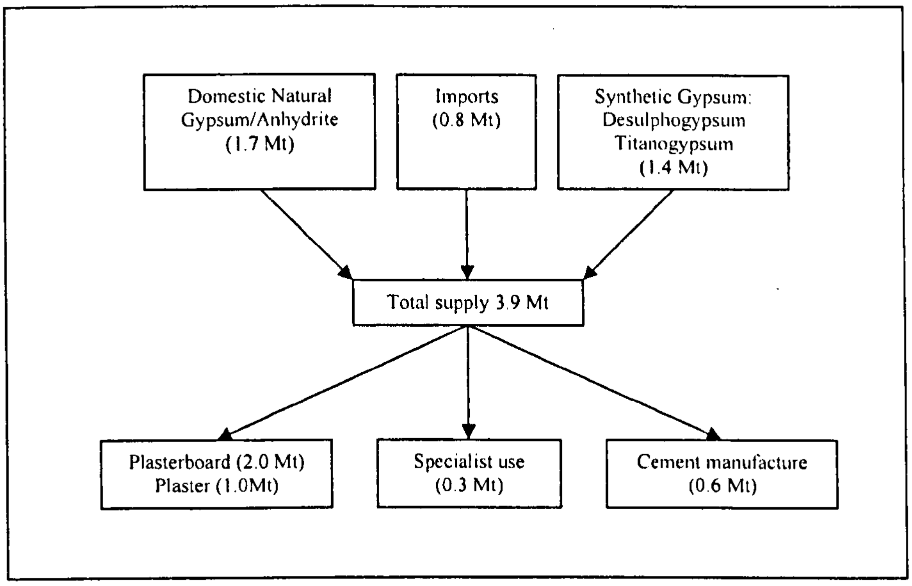

Figure 3.5: Gypsum supply chain in the UK (British Geological Survey 2006)

Gypsum is processed into a board and usually faced with a paper covering (Waste & Resources Action Programme (WRAP) 2006). In 1998, the UK consumed approximately 4.3 million tonnes of gypsum and this was estimated to represent nearly 16 percent of the quarry products used in the construction (Smith, Kersey et al. 2003). This can be shown in Figure 3.6

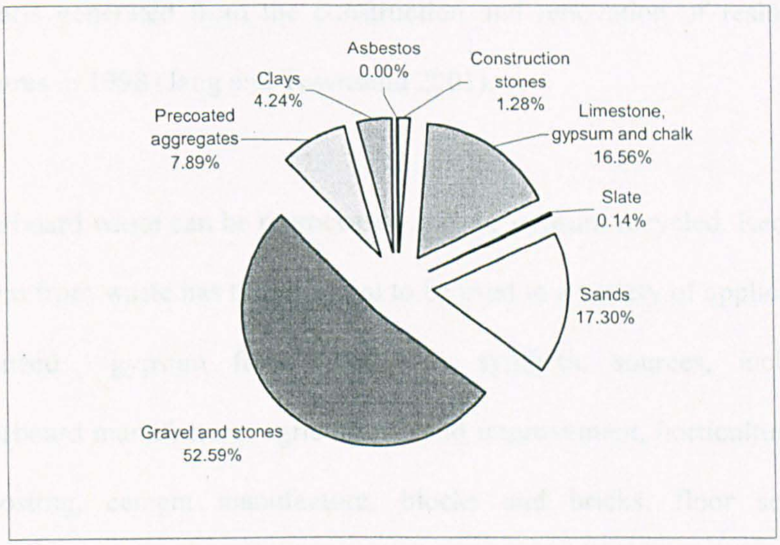

Figure 3.6: Percentage of quarry products used in construction in the UK (Smith, Kersey et al. 2003)

Traditionally, the majority of plasterboard waste has been landfilled. It is reported that approximately 3 million tonnes of plasterboard are used in construction in the UK each year (Waste & Resources Action Programme (WRAP) 2006). Approximately 360 million m^2 of plasterboard was used in UK construction in 2004, of which 40 million m^2 was net imports (Entec UK 2006). The Waste & Resources Action Programme, UK (WRAP) reported that it is estimated that some 300,000 tonnes of waste plasterboard are generated each year from new construction activity (largely as offcuts) and range between 500,000 tonnes to more than 1 million tones per year for demolition and refurbishment works. In the US, plasterboard accounts for between 21 percent and 27 percent of the mass of debris generated from the construction and renovation of residential structures in 1998 (Jang and Townsend 2001).

Plasterboard waste can be reprocessed and the gypsum recycled. Recycled gypsum from waste has the potential to be used in a variety of applications that need gypsum from natural or synthetic sources, including plasterboard manufacture, agricultural land improvement, horticulture and composting, cement manufacture, blocks and bricks, floor screeds, ceramics and mouldings, miscellaneous minor uses (Marvin 2000; Waste & Resources Action Programme (WRAP) 2006).

As gypsum is extracted from its rock, the operation of extraction in the quarries involves mechanical operations that create impacts from noise, vibration and dust to the surrounding areas. In some degree, the movement of the traffic for transportation of the materials also generates an unwelcome feeling to the surrounding area.

Gypsum represents the main component of plasterboard. The composition of plasterboard waste consists of a large amount of gypsum. Even though gypsum from plasterboard is classified as non-hazardous non-inert waste, the presence of sulphate raises some concern in term of threatening the environment especially if the waste goes to the landfill sites. Sulphate can cause a cathartic effect in humans when present in excessive amounts in water supplies (Sawyer and McCarty 1978; Jang and Townsend 2001). Sulphate also has aesthetic effects (taste, odour, and colour) in drinking waster (Jang and Townsend 2001). Before July 2005 plasterboard wastes had been classified as a non-hazardous inert waste by the EU Landfill Directive and able to be co-disposed of with other wastes. However, after a new revision, it was reclassified as non-hazardous non-inert waste. This was due to the high sulphate content in the gypsum (Waste & Resources Action Programme (WRAP) 2006).

Ninety-five percent of new construction plasterboard waste can be recovered and turned into new plasterboard (Marvin 2000). The purity of gypsum used in recycled plasterboard manufacturing is important before it to enter the reprocessing stage. Marvin (2000) recommended that the economic feasibility of recycling plasterboard depends heavily upon the costs of transportation and tipping fees (plasterboard is a dense, heavy material that is hard to compact making transportation difficult and expensive). In general the steps of reprocessing (recycling) the plasterboard waste from construction sites include (Marvin 2000):

1. Separate plasterboard from other construction waste. The plasterboard must be kept dry and clean in order to guarantee meeting specifications

2. Transport the plasterboard to a transfer station or store until a large enough quantity has been generated to make transport to the recycling facility economical
3. Transport to the recycling facility
4. In the recycling plant the gypsum is separated from the paper (the paper must be removed because it is viewed as a contaminant)
5. Run the scrap plasterboard through a magnet to remove nails and other metal contaminants
6. Shred or chip gypsum
7. Combine with raw gypsum to form new gypsum plasterboard or other gypsum products.

3.6. Wood as a Construction Material

On average the United Kingdom consumes approximately 47.1 million cubic metres of wood per year (see Table 3.14). It is mainly used in housing and civil engineering, furniture, railway ties (sleepers), poles and reinforcement for mining (Werner, Althaus et al. 2003). On the other hand, Magin (2001) reported that about half the wood used in the UK is consumed as timber or panel products and half as paper and paperboard. It is also reported that sawn softwood is the largest product group.

Table 3.14: United Kingdom wood consumption

Year	Consumption (million of cubic meters)
1995	46.2
1996	47.2
1997	48.8
1998	47.4
1999	46.3
2000	48.2
2001	49.4
2002	47.3
2003	44.9
2004	45.0

Source: Forestry Commission, UK (2005)(Forestry Commission 2005)

3.6.1. Wood Used in the UK Construction Industry

Generally, timber is a highly demanded resource in the construction industry. Wood is utilised in many forms. Today wood is still one of the leading construction materials (Werner, Althaus et al. 2003). Smith, Kersey et al. 2003 reported 9.24Mt of wood resource use by this sector in 1998 for the UK. Table 3.15 and Figure 3.7 have shown that construction is by far the largest consumer of wood and wood-based products in the UK timber industry.

Table 3.15 Fraction of sawn timber consumed by sectors (based on studies in the early 199s by Friends of Earth)

Sector	% of sawn timber consumption
Construction	39%
Joinery	11%
Packaging/pallets	11%
Fencing	6%
DIY	16%
Other	11%

Source Magin (2001)

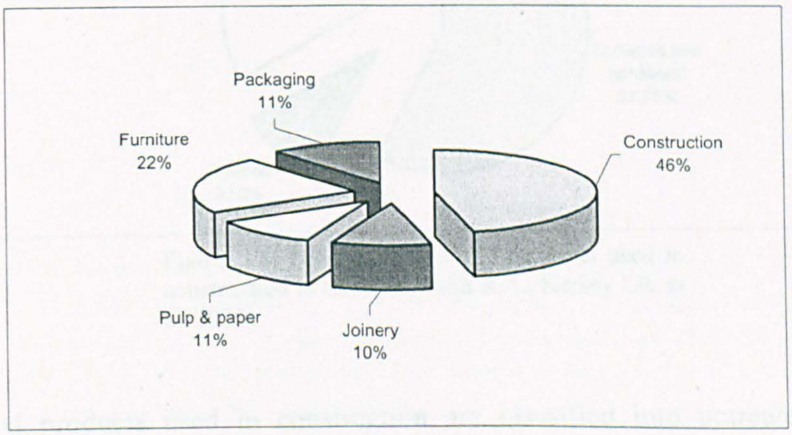

Figure 3.7: The fraction of timber flow by the UK sector in 2002 (Biffaward 2005)

Studies had also shown that the consumption of sawn timber in the construction sector had increased by 7 percent i.e. from 39 percent in early 1990s to 46 percent in 2002. Wood based products are among the most common materials in construction. Even today wood is still one of the leading construction materials (Werner, Althaus et al. 2003). Its products have been used in a variety of construction work especially in building work. Distribution of wood products and use in construction in the UK are shown in Figure 3.8 and Table 3.16.

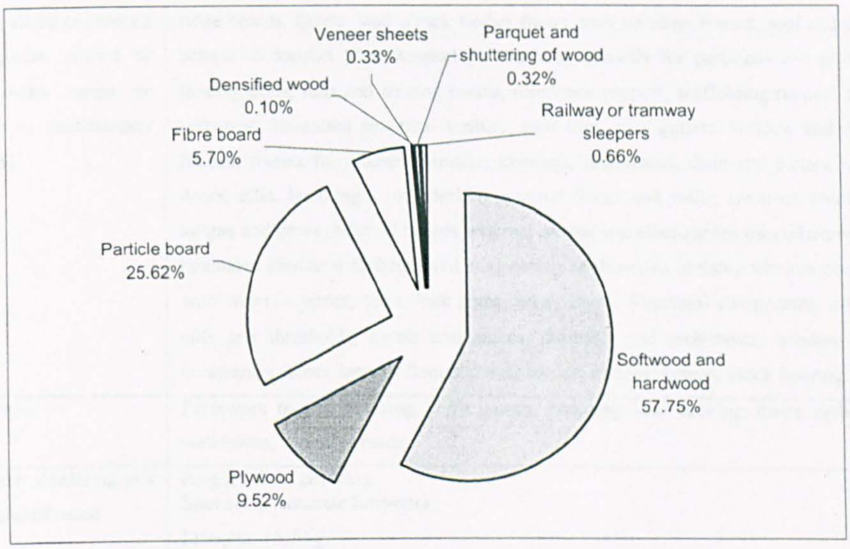

Figure 3.8: Percentage of wood products used in construction in the UK (Smith R.A., Kersey J.R. et al. 2003)

Wood products used in construction are classified into untreated and treated wood. Untreated woods are mainly used for inner building applications. While treated woods are used for outdoor applications and any other application exposed to decay or wet conditions and to resist from the risk of insect attack. Properly treated wood can have 5 to 10 times the service life of untreated wood (Forintek Canada Corporation and Canada Wood Council 2005).

Table 3.16: Uses of wood products in construction in the UK (Smith R.A., Kersey J.R. et al. 2003)

Material	*Uses*
Railway sleepers	Reclaimed railway sleepers are used mainly in landscaping
Softwood or hardwood sawn, sliced or chipped lengthwise, planed or in blocks, strips or frieze or continuously shaped	White softwood: structural timber - floor joists, ceiling joists, rafters, trusses, purlins, ridge boards, lintels, wall plates, timber frame, stud partition frames, roof and wall battens to support tiles. Support for flashing, grounds for partitions and plaster, fencing posts, rails and fencing panels, formwork support, scaffolding support. Red softwood: laminated structural timbers, roof trim, roof gutters, window and door frames, frames for kitchen furniture, skirtings, architraves, dado and picture rails, doors, cills, boarding - roof decking internal floors and walls, some of which in tongue and grove, external boards, external paving and other garden uses. Hardwood: laminated structural timbers, civil engineering applications (notably when in contact with water) - jetties, piers, lock gates, breakwaters. Structural components, piling, cills and thresholds, lintels and arches, skirtings and architraves, window and doorframes, doors, internal floor and wall boards, external boards, block flooring.
Plywood	Formwork facings, flooring, soffit boards, hoarding, roof decking, doors, ceilings, wall lining, window boards.
Parquet, shuttering and shingles of wood	Parguet: floor covering. Shuttering: concrete formwork. Shingles: roofing
Particle board, oriented strand board, wood wool cement slabs	Chipboard: Six grades available according to application, Walls, ceiling liners, flooring, decking for flat roofs, joinery components, stair treads. Cement bonded: Flooring, sheathing, cable trunking, firestops, soffits, lining boards for fire resistance. Orientated strand board: Sarking pitched roofs, cladding agricultural buildings, flat roof decking, flooring, site hoardings. Wood wool cement slabs: Flat and pitched roofs, wall floors and ceilings and acoustic control applications.
Fibreboard	Medium Density Fibreboard (MDF): mouldings, furniture. MDF moisture resistant: skirting, window boards, architrave, comice mouldings, joinery components and stair treads. Soft board: notice boards, expansion joints, wall and ceiling liners, core for partitions. Hardboard: wall finishes, cabinet sides, floor coverings, underlay, structural wall panels.
Veneer sheets and densified wood	Veneer sheets: decorative finishes to doors, furniture, and ply layers.

3.6.2. Wood Waste and the Environment

Timber and wood products and their waste represent a substantial resource. The construction industries are identified among the responsible sectors in contributing to a large amount of wood waste (Wasteonline 2005). Table 3.17 shows the breakdown of construction wastes in the UK.

Table 3.17: UK construction wood waste breakdown by sector (Ed Suttie 2004)

Sector	**Weight (million tonnes)**
Construction	1.20
Demolition	2.10
Packaging from construction	1.30
Commercial	0.75
Industrial	0.84
Civic amenity sites	0.672
Municipal solid wastes	0.14
Furniture manufacturing	0.335
Fencing	0.06
Total	**7.397**

A study by Suttie (2004) revealed that building construction and demolition produced approximately 28 percent and 16 percent of wood waste respectively. Generally, wood wastes from this sector can be categorised into two (Wasteonline 2005);

- construction phase - *regularly comprises with off-cuts from structural or joinery timber, used shuttering and formwork, temporary site or supporting structures and wooden packing* cases

- demolition phase – *regularly comprises with doors, floorboards, cable reels, skirting boards, window frames and architrave*

Suttie (2004) reported that the UK generates 7.4 million tonnes of post consumer waste, where only 0.7 million tonnes are reclaimed and 0.9 million tonnes of it are recycled into panel products. Meanwhile the majority of the waste goes into landfill sites or incinerators. Figure 3.9 depict the fraction of construction wood waste.

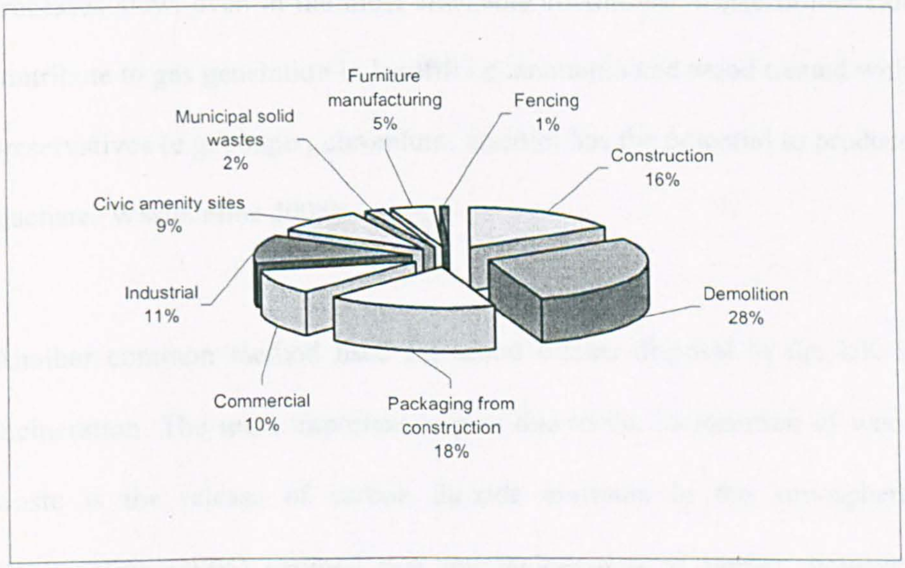

Figure 3.9: The fraction of UK wood waste flow
(Ed Suttie 2004)

3.6.3. Environmental Impact of Wood Waste

The impact of the wood waste is at least as important as or even more important than the impact of its production (Jungmeier, Merl et al. 2001). Reuse and recycling of wood waste will always be the best option, but generally in the UK at the end life most construction wood products will go either to landfill or incineration. Wasteonline (2005) claimed that the sizes of the construction wood waste at landfill sites which are always big and bulky make it difficult to compact. But once the material starts to decompose, large void spaces can result in landfill subsidence. The high carbon and nitrogen content of wood also make the decomposition processes slow, even in the most amenable conditions. Waste timber can contribute to gas generation in landfill i.e. ammonia and wood treated with preservatives (e.g. copper, chromium, arsenic) has the potential to produce leachate (Wasteonline 2005).

Another common method used for wood wastes disposal in the UK is incineration. The most important impact due to the incineration of wood waste is the release of carbon dioxide emission in the atmosphere. Wasteonline (2005) claimed that the incineration of timber, however, results in a concentrated release of carbon dioxide over a much shorter period and will cause overloaded carbon dioxide emissions in the environment.

Another impact caused by the disposal of wood wastes is toxicity due to the substances they contain. Wasteonline (2005) reported that fibreboard such as multi-density fibreboard (MDF) is in part made up of adhesives, which contain formaldehyde. Wasteonline (2005) also reported that formaldehyde is toxic, corrosive and is also carcinogenic and mutagenic to mammals, insects and micro-organisms. Besides, there is the potential to create acidification effects as it generates formic acid in air and water.

Wood impregnation is another source of impact of wood waste. Wood impregnation emits 22,000 tonnes of volatile organic compounds (VOCs) across the European Countries. Such emissions account for 1 percent of total industrial VOC releases (Wasteonline 2005). Wood impregnation contains substances that are carcinogenic to humans and animals. Boehncke and Mangelsdorf (2006) claimed that there is sufficient evidence that creosote or pentachlorophenol (PCP) used as preservative substances in wood impregnation, is carcinogenic to humans and animals due to the PAHs in the mixture (e.g. benzo(a)pyrene, dibenzo (a,h) anthracene).

Besides creosote, other substances used as chemicals for wood preservation contain potentially harmful substances. Among the substances used for their biocidal character are mercury, zinc and arsenic (Werner, Althaus et al. 2003). All these are classified as heavy metal substances that are very harmful to the health of human and animal if exposed in excessive amounts.

3.7. Summary

In summary, every single construction material and its waste could have an impact on the human and environment throughout its entire lifecycle from extraction and production to usage and disposal of material waste. The impact mainly comes from the use of energy like electricity and fuel and emissions. These could come from transportation vehicles and machinery that has been used at production stages and the process of disposal at the end of the material's life. Besides energy usage and emissions from transportation and machinery, during the disposal stage emissions could be released from the decomposition of the material, resulting in soil and water contamination. For some, material waste like concrete and plasterboard are considered as inert waste that could not harm the human or the environment, but the release of suspended particle matter (SPM) may be generated during the process of dismantling the material which can cause smog to form.

Chapter 4

METHODS FOR MODELLING THE ECO-COSTING OF CONSTRUCTION MATERIAL WASTE

4.1. Introduction

This chapter will discuss the overall processes which have been carried out to determine and to develop eco-costing models for construction material waste. Discussion starts with explanation of the life cycle assessment (LCA) methodology that has been used and the Impact Pathway Approach (IPA) that has been chosen to calculate emissions and monetary valuation of waste. As the research adapted the ISO 14040 LCA methodology, discussion continues with the general issues of LCA including the clarification of life cycle impact assessment (LCIA) processes based on the scope of research that has been established in the earliest chapter. In the next section, discussion continues with the explanation for the selection of environmental indicators, which is then followed by clarification of the method to evaluate the eco-costs from the LCIA results. Explanation on developing the model for the total eco-costs results is also discussed.

4.2. Life Cycle Assessment and Impact Pathway Approach

In Chapter 5, an explanation for the importance of evaluating the damage eco-costs will be established. For the purpose of the assessment of damage eco-costs, the impact pathway approach (IPA) has been chosen. An explanation of IPA will be made later in this section. Valuation of an impact was based on three from four main components recommended by The International Organisation for Standardisation (International Organization for Standardization (ISO) 1997-2000) of Life Cycle Assessment (LCA) framework namely, (1) goal and scope definition, (2) inventory analysis, (3) impact assessment, and (4) interpretation. The complete LCA framework recommended by ISO is shown in Figure 4.1.

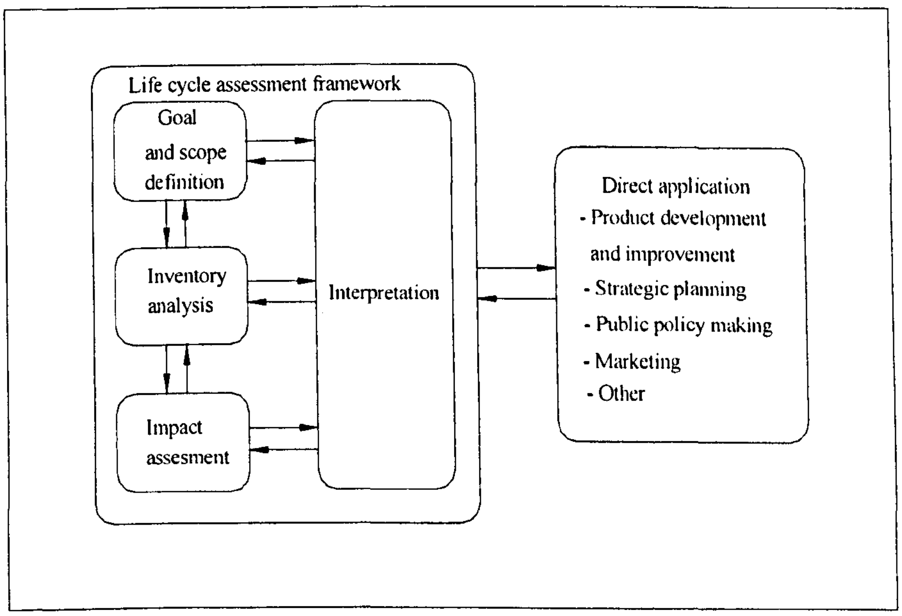

Figure 4.1: ISO 14040 LCA framework

Treloar, Love et al. (2000) argue that existing techniques such as LCA do not account adequately for upstream processes for the impact assessment of construction material because the LCA comprise mainly basic materials, whilst many other processes would still be neglected (Treloar 1997). For the purpose of this research, the goal and scope of definition and the inventory analysis for building material waste disposal are adapted from the comprehensive Swiss EcoInvent Life Cycle Inventory (LCI). This will be discussed in more detail in the following section. While for the impact assessment stage, Eco-indicator 95 Life Cycle Impact Assessment (LCIA) that uses the 'mid-point' assessment methodology has been chosen. This is because, the impact results from the characterisation process at mid-point level were found to be very appropriate in the calculation of the eco-cost. This will be elaborated in more detailed in Section 4.5

Due to the complexity of the assessment, SimaPro 7.0 LCA software was used as a tool to integrate between the EcoInvent LCI database and Eco-indicator 95 LCIA assessment methodology. Table 4.1 portrays the detailed processes of LCA methodology suggested by ISO 14040.

For the conversion from the impact scores into eco-cost, the 'mean' value of the external cost was obtained from the secondary data of the scientific and economic studies by the Department for Environment, Food and Rural Affairs (DEFRA), UK (Guy Turner, David Handley et al. 2004) and

ExternE (Externalities of Energy) by the European Commission were implemented.

Table 4.1: Detailed LCA methodology by ISO 14040

LCA stage	**Process**
Initial phase	Setting the system boundaries, defining the problem and establishing an inventory of important parameters
Inventory Phase	A detailed description of raw materials and energy inputs used at all points and the emissions, effluent and solid waste outputs. Examples of output are resource depletion (e.g. material and energy), pollutant emissions and discharges of chemical or physical load (e.g. substances, heat, and noise).
Impact Assessment Phase	Relating the identified inputs and outputs to the environmental impacts (often called Life Cycle Impact Assessment). It involves the following components (the first 3 are mandatory, the others optional): 1. Selection of impact categories, category indicators and characterization models. Impact categories are selected and defined with respect to the goal and scope of the LCA. 2. Assignment of LCI results (Classification). The environmental loads are classified according to the impact categories. (Some environmental loads belong to more than one impact category.) 3. Calculation of category indicator results (Characterization). The category indicator is modelled for the different environmental loads that cause environmental impacts e.g. the Global Warming Potential. 4. Normalization. Expressing category indicators relative to a standard e.g. tonne of CO2 equivalent. 5. Grouping. Sorting and possibly ranking of the impact categories. 6. Weighting. Expressing the (subjective) importance of an impact category: often the categories are sorted by theme or damage category. 7. Data Quality Analysis. Understanding the reliability of the indicator results.
Improvement phase	Using information obtained in analysis to improve overall environmental performance

However, the research only applied the first 3 important steps from the LCIA phase in Table 4.1, the reason being that results at this point were already appropriate in order to calculate the impact scores and finally to be used to estimate the eco-cost. Furthermore, ISO standards had also stated that the rest of the steps in the LCIA are optional.

A method of valuation of the impact and monetary assessment will follow the impact pathway approach (IPA). Illustration of this approach for this research is portrayed in Figure 4.2

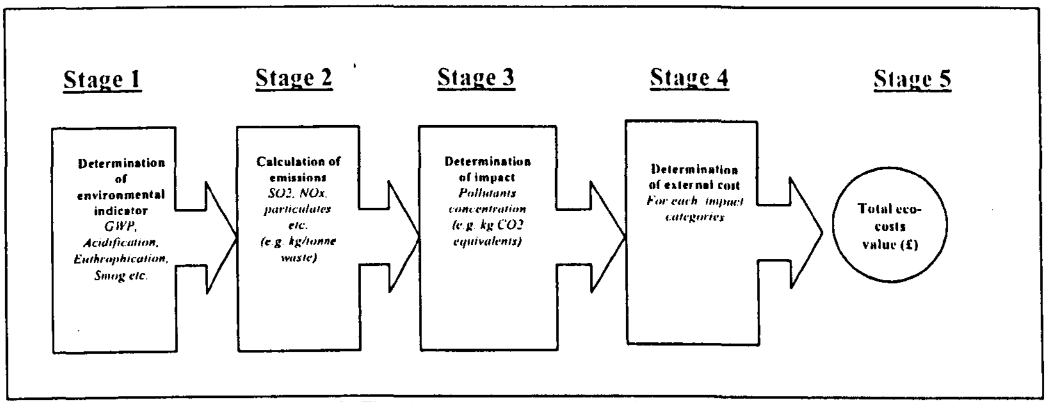

Figure 4.2: The 'impact pathway approach'.

IPA is a bottom-up approach whereby the investigation through the pathway is made from the beginning of the source of emissions, its consequences on the environment (i.e. changes to air, water and soil) and on the extent of the physical impact to the material and human before it can be translated into monetary valuations. This approach has been used in many studies for the assessment of environmental impact and evaluation of associated costs.

Essentially, the IPA of the research was carried out in six stages:

1. Determination of environment indicators
2. Calculation of emissions.

3. Determination of impact
4. External cost determination of environmental indicators
5. Translation of damage eco-cost results into monetary valuation.
6. Developing eco-costing modelling

4.3. Life Cycle Goal, Scope Definition and Inventory

The purpose of the LCA in this research is to discover the environmental, economic and social impacts of the three disposal options for construction and demolition waste namely recycling, sorting plant and landfill. The research focuses on selected construction material waste i.e. brick, concrete, metal, plasterboard and wood. The functional unit of the data during the assessment are one kilogram of these materials. As the whole research uses the Swiss EcoInvent inventory data, the assessment for the three different construction waste disposal options was made within the system boundaries as suggested by Swiss EcoInvent as shown in Figure 4.3.

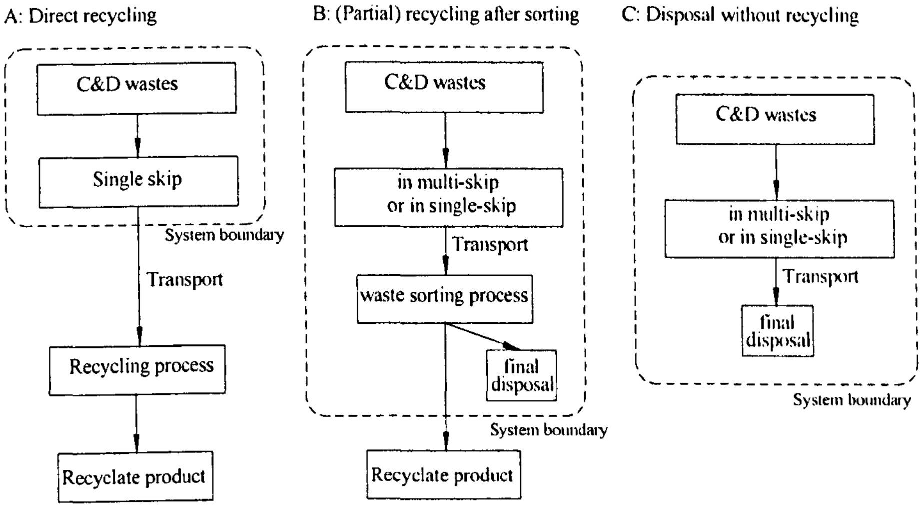

Figure 4.3: The system boundaries of LCA of
the disposal for construction material waste

To suit the objective of the research and based on the system boundaries above, the study will only focus on emissions from the three waste disposal options for selected material waste activities including all emissions from related upstream activities, which include fuel, power and electricity generation and associated transport. Other inputs and outputs such as labour cost and the construction and demolition of capital equipment are ignored because it is beyond the scope of the research.

4.4. Lifecycle inventory

Life cycle inventory is one of the important stages in the LCA. The database Swiss EcoInvent Inventory has been chosen for the research because the methodology used in developing the database had been included the input and output parameters that suit the current conditions of the Western European Countries including the United Kingdom which include geographical, current technology, products, services, market and consumptions (Althaus, Doka et al. 2004). The following discussion describes the background of important elements included in the inventory processes for the development of the database.

The inventory comprises a detailed compilation of inputs and outputs relating to the system boundary established earlier (Figure 4.3), in terms of energy and materials inputs, and emissions to air, water and solid waste. The model of the inventory assumes that building waste disposal followed the three options as shown in Table 4.2.

In the dismantling processes, dismantling burdens will include all energy consumption, dismantling infrastructure and dismantling emissions. EcoInvent uses the calculation of the inventoried energy demands as shown in Table 4.3

Table 4.2: Waste disposal options

Disposal option	**Type of waste disposal**	**Description**
1	Direct recycling	The material is separated from the original construction site, sorted into skips and transported off to recycling. Only dismantling burdens (energy and emissions) are inventoried.
2	Recycling after sorting (partial)	The material is separated from the original construction site, sorted into skips and transported off to sorting. The fractions separated in the sorting plant are either recycling, or dispose in landfill or incinerator. Dismantling burdens and transport to sorting plant are inventoried
3	Direct disposal without sorting or recycling (landfill or incineration)	The material is separated from the original construction site, sorted into skips and directly transported off to final disposal. Dismantling burdens, transport to disposal site and the final disposal in landfill or incinerator are inventoried

Table 4.3: Diesel consumption for different materials

	Unit	**Reinforced concrete**	**Reinforcement steel**	**plain concrete**	**Brick wall, gypsum board and cement fibre slab**
Tearing with hydraulic device	h/m3	0.173	-	0.118	0.0707
Diesel consumption	MJ/m3	140.85	-	96.22	57.50
Material density	kg/m3	2,300	-	2200	1600
Specific diesel consumption	**MJ/kg**	**0.0612**	**0.626**	**0.0437**	**0.0359**

Standard size skip bins of 7 m3 and weight 820 kilogram were used for the nominal volume of building waste. However, the load factor or lifetime period was not included as the information was not available at that particular time. Emissions associated with energy consumption were taken from the use of building machine (diesel) and direct emissions from the dismantling itself.

Sorting plants separated unwanted materials from other materials that can be recycled, where unwanted materials were then disposed into landfill or incinerator. The burden from the sorting plant includes emissions of unwanted disposal materials, energy demand, infrastructure for sorting plant and land use. Electricity demand for the sorting plant for the inventory is shown in Table 4.4

Table 4.4: Electricity demand for sorting plants

Facility	**$kWh_{elec.}$ Per tonne input**
Sorting plant incl. crusher	3.7
Sorting plant w/o crusher	2.2

The average value of 3.7 MJ/t of charging and discharging in sorting plants is taken for the fuel demand based on per m3 skid-steer loader 5.9 MJ. Heating for administrative building for landfill is taken as 3,220 MJ of fuel oil per year, with an estimated 161,000MJ to be used over a 50-year lifetime for one sorting plant.

The inventoried sorting plant for construction waste by EcoInvent was 200 kt/a. With the lifetime of infrastructure at 50 years, the plant will be able to process approximately 10 million tonnes of waste. The rock crusher used in the sorting plant could crush rocks to a size of <32mm with the capacity of 454 metric tonnes per hour with electricity consumption of 0.716 kWh/t. The infrastructure materials and replacement parts for a rock crusher in sorting plants is shown in Table 4.5 and 4.6 (Landfield and Karra 2000; Doka 2003)

Table 4.5: Infrastructure material for one rock crusher

Infrastructure materials	**kg perunit**
Steel	20,684.00
Iron	1,733.00
Bronze	338.00
Epoxy resin	80.00
Aluminium	17.00
Brass	0.64
Miscellaneous	957.40
Total	23,810.00

Table 4.6: Replacement parts of rock crusher for 25 years operation

Replacement component	**Life cycle masses with 200 kt/a (kg/unit)**
Liner	1,539.00
Mantle	16,791.00
Bowl liner	16,575.00
Torch ring	104.80
Total	35,009
Lubricating oil	2,502.00

All metal parts of the sorting plant were assumed to be recycled (not in the system boundary). The epoxy resin and lubricating oil was assumed to be incinerated in municipal incineration and hazardous waste incineration respectively.

In the transport inventory data, an average value of 17.7 km per lorry was adopted for transport construction material waste to sorting plants. Whereas epoxy resin and aluminium transport purposes for the infrastructure of sorting plant were estimated at 200 km by train and 50 km, the disposal of epoxy resin and oil were estimated at 10 km and 50 km by lorry respectively. All other materials transportation was estimated at 600 km by train and 50 km by lorry. However for transport of waste to final disposal the standard distances in Table 4.7 were applied

Table 4.7: Standards distance for transport to disposal facilities

Disposal facility	km lorry
Inert material landfill	15
Sanitary landfill	10
Municipal waste incineration	10
Hazardous waste incineration	50

4.5. Life Cycle Impact Assessment

Determination of the impact categories (environmental indicators) is crucial. Life Cycle Impact Assessment (LCIA) is used to assess a product based on its Life Cycle Inventory (LCI) system to better understand its environmental significance and to provide information for the interpretation phase (UNEP 2003). LCIA is a very important step because the impact results will be used to represent the global effect of the products or services at present and later stages (i.e. monetary valuation).

For the selection of the impact indicator, ISO standards allow the use of impact category indicators that are somewhere between the inventory result (i.e. emission) and the 'end-point'. Mid-point impact assessment models reflect the relative potency of the stressors at a common mid-point within the cause-effect chain. Analysis at a mid-point minimises the amount of forecasting and effect modelling incorporated into the LCIA, thereby reducing the complexity of the modelling and often simplifying communication. Mid-point modelling can also minimise assumptions and value choices, reflect a higher level of societal consensus, and be more comprehensive than model coverage for endpoint estimation (Bare J.C., Norris G.A. et al., 2003). Figure 4.4 depicts the above mid-point and end-point scenarios, while Figure 4.5 shows an example of the characterisation process for the mid-point modelling assessment

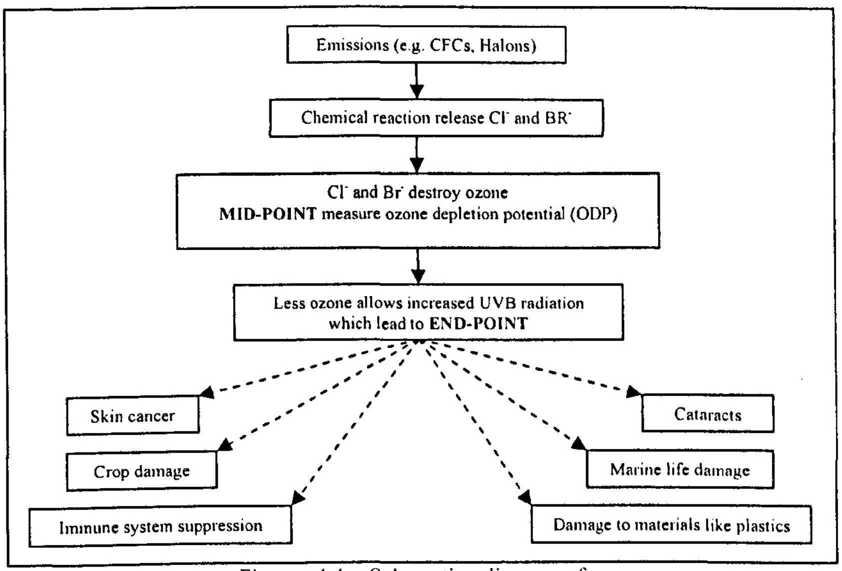

Figure 4.4: Schematic diagram for ozone depletion midpoint/endpoint modelling (Bare J.C., Norris G.A. et al. 2003; Scientific Applications International Corporation 2006)

Characterisation process

Global warming potential of CCL4

$$\begin{bmatrix} CO2 & 2100kg \\ CCL4 & 0.5kg \\ CBrH3 & 0.3kg \end{bmatrix} * \begin{bmatrix} & CO2 & CCL4 & CBrH3 \\ GW & 1 & 1400 & \\ OD & & 1.1 & 0.6 \\ HT & & 14000 & 12000 \end{bmatrix} = \begin{bmatrix} GW & 2800kg_{CO2-equ} \\ OD & 0.73kg_{CFC11-equ} \\ HT & 10600kg_{toluen-equ} \end{bmatrix}$$

Figure 4.2: Characterisation process during the mid-point modelling assessment (Goedkoop 2006)

In order to make sure that the selection of the impact categories will get a balanced view of the LCA assessment, the selection process will take into consideration the following scenarios (1) immediate or local impacts (e.g., human toxicity, smog formation) and (2) long-term or global concerns (e.g., global warming, depletion of non-renewable resources).

Although there is no absolute consensus on the categories of impacts to be included in a lifecycle impact assessment, it is generally accepted that they should reflect resources use and effects on ecological and human health (Udo de Haes H. A. and Wrisberg N. 1997; Craighill A. and Powell J. C. 1999). However, Bare J.C et al. (2003) recommended that in the absence of such a global consensus, the selection of the impact categories is left as one part of the goal and scope of each individual case study or is left to the discretion of the tool designer. Based on the above discussion and the capability of the mid-point methodology to evaluate the impact assessments, this research takes into consideration the impact categories (effect) as shown in Table 4.8. The assessment was based on (1) result in damage to ecosystem on a European scale, and (2) result in damage of human health on a European scale.

For the reasons already mentioned above, Eco-indicator 95 impact assessment methodology has been adapted for the LCIA in this research. In addition, the Eco-indicator 95 was not only found to be the model that used the 'mid-point' damage methodology assessment (where the effect indicators are chosen relatively close to the inventory result), but it also fulfilled the balanced view of the assessment requirement for the 'short-term and long-term' scenarios as discussed before. The structure of assessment of the Eco-indicator 95 is shown in Figure 4.6

Table 4.8: Effect scores and characterisation used in Eco-indicator 95

Impact Categories	**Characterisation**	**Description**
Greenhouse Effect	NOH LCA manual (IPCC)	The global warming potential (GWP) is the potential contribution of the substance to the green house effect. This value has been calculated for a number of substances over the periods of 20, 100, and 500 years because it is clear that certain substances gradually decompose and will become inactive in the long run GWP 100-year period will take into consideration because this is the most common choice.*
Acidification	NOH LCA manual	The acidification potential (AP) is expressed relative to the acidifying effect of SO2. Other known acidifying substances are nitrogen oxides and ammonia. SOx has been added with same value as SO2.*
Eutrophication	NOH LCA manual	The nutriphication potential (NP) is set at 1 for phosphate (PO4). Other emissions also influence euthrophication, notably nitrogen oxides and ammonium.*
Summer smog	NOH LCA manual	The photochemical ozone creation potential (POCP) indicates the potential capacity of a volatile organic substance to produce ozone. The value of ethane has been set at 1. The values for most other substances are less than this.*
Winter smog	Air Quality Guidelines (WHO)	Characterised by high levels of inorganic compounds, mainly particles, carbon monoxide and sulphur compounds. This latter type of smog causes bronchial irritation, coughing, etc. Winter smog, as far as considered as part of human toxicity. **
Airborne heavy metals	Air Quality Guidelines (WHO)	This effect score relates in particular to heavy metals because long-term exposure at low levels brings clear health risks. The risks relate particularly to the nervous system and the liver and can be assessed for toxicity to both human beings and ecosystems. It is assumed in general (Globe, Air Quality Guidelines) that human toxicity is the most important limiting factor*
Waterborne heavy metals	Quality Guidelines for Drinking Water (WHO)	The WHO 'Quality guidelines for drinking water' specify a number of values for persistent substances based on long-term, low-level exposure. These criteria have been drawn up to evaluate drinking water, based on established health effects. A selection is given below of substances that are persistent to a greater or lesser extent and that therefore accumulate in the environment*
Carcinogenic substances	Air Quality Guidelines (WHO)	The 'Air Quality Guidelines' do not specify acceptable levels, but calculate the probability of cancer at a level of 1 $\mu g/m^3$*
Ozone layer depletion	NOH LCA manual (IPCC)	Ozone Depletion Potential (ODP) values have been established mainly for hydrocarbons containing combined bromine, fluorine and chlorine, or CFCs. Here too, one of the substances (CFC-11) has been adopted as a reference. As for the greenhouse effect, we have added values for CFC (hard) and CFC (soft). The ODP equivalents for these groups are again those of CFC-12 and HCFC-22 respectively*
Energy resource	ExternE (Externalities of Energy)	ExternE (Externalities of Energy) Model by the European Commission

*(Mark Goedkoop, Michiel Oele et al. 2004)
**(Guinee J.B. 2002)

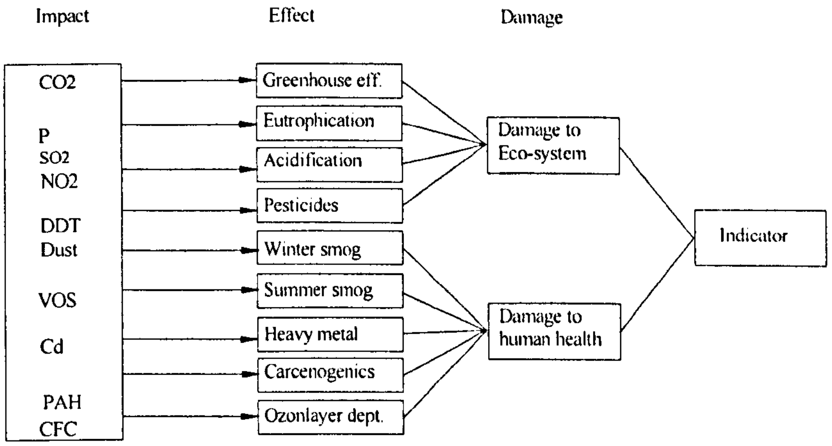

Figure 4.5: The structure of assessment of the Eco-indicator 95

Calculation for the impact assessment adopted in this research followed the Eco-indicator 95 methodology except for the energy resource which followed the European Commission ExternE Project methodology for the UK region. The summary of calculation for the impact used for the research is shown in Table 4.9. Eco-cost result is obtained from the impact results of the assessment by multiplying the characterised impact result with the external costs (damage cost) obtained from the DEFRA, UK and ExternE (Externalities of Energy). The characterisation process of the impact result was carried out by multiplying the impact results of assessment with the characterisation factor (see Appendix 1) of the required equivalent substance.

Table 4.9: Method of calculation for characterisation process in Eco-Indicator 95

Impact category	Description	Method of calculation
Global Warming Potential	The Global Warming Potential (GWP) is the potential contribution of a substance to the greenhouse effect.	The effect score for the greenhouse effect is calculated per substance as follows Greenhouse effect (kg) = (GWP 100 x airborne emission (kg))[1,2]
Acidification.	The Acidification Potential (AP) is expressed relative to the acidifying effect of SO2. Other known acidifying substances are nitrogen oxides and ammonia. SOx has been added, with the same value as SO2.	Acidification effect scores are calculated as follows: Acidification (kg) = (AP x airborne emission (kg))[1]
Eutrophication	The Nutriphication Potential (NP) is set at 1 for phosphate (PO4). Other emissions also influence eutrophication, notably nitrogen oxides and ammonium.	The eutrophication effect score is calculated as follows: Eutrophication (kg) = (NP x airborne emission (kg))[1]
Summer smog	The photochemical ozone creation potential (POCP) indicates the potential capacity of a volatile organic substance to produce ozone. Values have been published for a wide range of volatile organic substances. The value for ethene has been set at 1	The effect score for summer smog is calculated as follows: Smog (kg) = (POCP x airborne emission (kg))[1,4]
Winter smog	Only dust (SPM) and SO2 are factors in this problem. The weighting factors are thus both 1.	The effect score for winter smog is calculated as follows: Winter smog (SO2 or SPM eq.) = SO2 emission + SPM emission[1]
Heavy metal	SimaPro merges the scores for water and air. This is possible because they are both expressed as a lead equivalent and because the target reductions for air and water are the same.	Result will in the form of combination the two scores for heavy metals. This was possible since they are both expressed as a lead equivalent and since the weighting factors are identical. Heavy metal to air (kg lead eq.) = (AQG (lead)/AQG (substance) * emission)[1] Heavy metal to water (kg lead eq.) = (GDWQ (lead)/GDWQ (substance)* emission)[1]
Carcinogens	SimaPro uses PAH value equivalent to 1.	The effect score for winter smog is calculated as follows: Heavy metal to air (kg lead eq.) = (AQG (lead)/AQG (substance))[1]
Ozone layer depletion	Ozone Depletion Potential (ODP) values have been established mainly for hydrocarbons containing combined bromine, fluorine and chlorine, or CFCs. CFC-11 has been adopted as a reference.	The effect score for ozone layer depletion is calculated as follows: Ozone layer depletion (kg) = (ODP x airborne emission (kg))[1,3]
Energy resource	Based on European Commission ExternE Project Cost Modelling	The estimation energy resource value is £0.07 for every MJ/LHV of UK energy rate[5]

1 - (Goedkoop, Oele et al. 2004)
2 - (Houghton, Callender et al. 1992)
3 -(World Meteorological Organisation 1991)
4 - (United Nations 1991)
5 – ExternE, European Commission – excluded from the Eco-Indicator 95 characterisation calculation

4.6. Method of valuating of eco-cost

The world nowadays tends to be dominated by economic argument where quantification of the costs of action against the costs the consequences of inaction must at least be attempted (Houghton 1997). In that sense the valuation impact categories into monetary or eco-cost valuation has been made viable. On the basis of the characterisation result from the impact categories, the calculation of eco-cost can be made. External cost from secondary data of the scientific and economic studies by the Department for Environment, Food and Rural Affairs (DEFRA), UK and ExternE by the European Commission, as discussed in section 5.2, has been used as the damage eco-cost value for the research. The damage eco-cost value for the research is shown in Table 4.10 and Figure 4.7 shows how the general assessment and valuation procedure of eco-cost of the research has been done.

Table 4.10: Damage eco-cost value

Impact category	**Damage cost (£)**
Greenhouse (kg CO2 eq)	0.01
Acidification (kg SO2 eq.)	7.59
Euthrophication (kg NOx eq.)	7.55
Winter smog (kg SPM eq.)	35
Summer smog (kg VOC eq.)	1
Heavy metals (kg Pb eq.)	1220
Carcinogens (kg Ni eq.)	58
Ozone layer (kg CFC11 eq.)	7.5
Energy resource (MJ LHV)	0.07

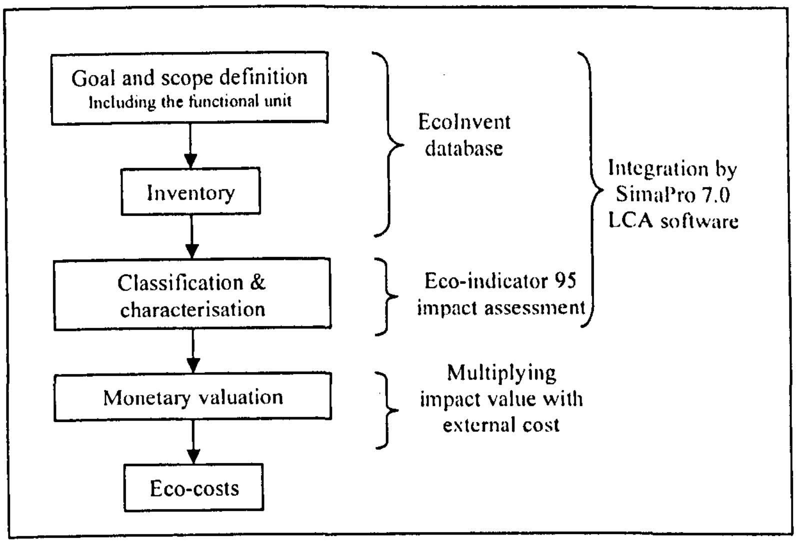

Figure 4.6: Stages of impact assessment and eco-cost valuation followed by this research

As shown in Figure 4.7, the eco-cost valuation for each impact category was made after impact assessment results had been obtained by Eco-indicator 95 methodology. Total eco-costs results were subsequently obtained from the summation of the eco-cost from the nine impact categories for the construction waste material. Detailed calculation of eco-cost for selected construction material wastes will be shown in Chapter 7

4.7. Developing the total eco-cost model

The main objective of the research is to develop a model to estimate eco-costing of construction material waste. Eco-cost results which have been described in the previous section were utilised. Based on linear relationship between weight and estimation of total eco-costs value for every type of construction material waste obtained from the previous process the results were then converted into a logarithmic graph in order to get a very clear relationship view between the three waste disposal options that are under consideration. Finally, the estimation of the total eco-cost can be estimated by using the developed graphs or equations model. The equation is then validated by checking the R square value in the regression result of the data. The whole eco-costing modelling process will be presented in Chapter 8.

4.8. Summary

In general, methods for eco-costing modelling can be classified into three phases. Phase 1 involves LCA processes, where LCIA results from LCA processes were taken as the main input for the next phases. Phase 2 is the stage where the results from the first phase were evaluated in term of an economic assessment. Environmental results are explained in terms of the economic view (money) equivalent to its quantity. Developing the model (graph and equation) is the final phase, where the results and their relationship with the amounts of generated waste are simplified into graphs and equations in order to be used as an eco-costing estimation tool for construction material waste.

Chapter 5

CONCEPT OF ECO-COST AND COST OF ENVIRONMENTAL INDICATORS

5.1. Introduction

In this chapter, discussion will mainly concentrate on the concept of eco-costing that has been chosen and the selected indicators to be used in this work. Discussion will start with an explanation of the definition of eco-cost adopted by this research. The discussion will then follow with the general concepts of eco-cost which include prevention and damage oriented costs. Detailed explanation of damage eco-cost which is one of the important elements of the research is also provided. The chapter will continue to explain damage eco-cost for every selected environmental indicator used in this research. The explanation will be reinforced with findings from several others past research results and with the help of some graphical figures and tables. A brief explanation of the previous studies regarding eco-costing are also presented.

5.2. Definition of eco-costs

Environmental burdens from pollutants that can cause damage to society and environment are called externalities. These can have a significant impact on human health, climate change, agriculture, ecosystem, and materials but not fully accounted to be born by the polluters. Many of the most important externalities are concerned with pollution and environment. Externalities can lead to inefficiency. Producers of the externalities do not have an incentive to take into account the effect of their action on others. Negative externalities are called external costs, whilst positive externalities are called external benefits. Externality which is also known as an external cost, arises when the social or economic activities of one group of persons have an impact on another group and when that impact is not fully accounted, or compensated for, by the first group (European Commission 1995). David Pearce (2001) defined an externality as when the following two conditions are met (1) some negative (or positive) impact is generated by an economic activity and imposed on third parties; (2) the impact must not be priced in the market place, i.e. if the effect is negative no compensation is paid by the generator of the externality to the sufferer. In addition, if the effect is positive, the generator of the externality must not appropriate the gains to the third party, e.g. via some price that is charged.

Environmental 'externalities' or 'external costs' can also be called 'damage eco-costs'. Godfrey (2002) defines eco-costs as the costs that are incurred in using products that have a negative impact on the environment which include the cost of pollution, toxic clean-ups, waste management and product disposal.

Eco-costs are one of the important indicators of sustainable development. Benefits from the results of any eco-costs estimation can be used as a guideline to define the right approach to minimize the environmental burden. Eco-costs can be either in the form of 'prevention oriented' cost or 'damage oriented' costs depend on how valuation of costs after the assessment of impact is made.

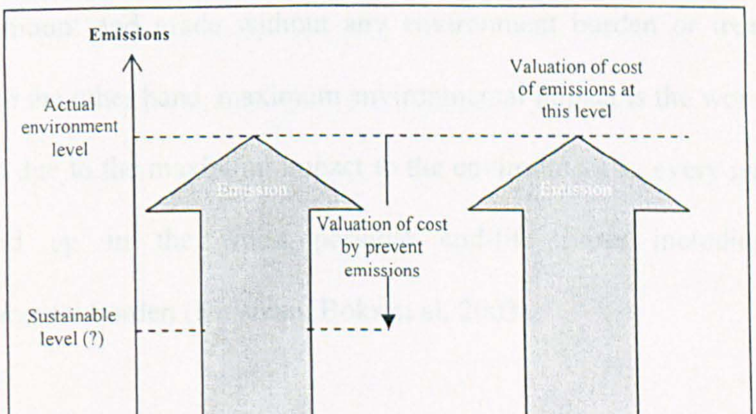

Figure 5.1: General concept of prevention and damage eco-cost

Figure 5.1 depicts the two concepts of the eco-cost scenario. The valuation of prevention oriented cost or prevention eco-costs of any product or/and its processes are made on the basis of preventing pollution and resource depletion to a sustainable level. However, our society is still far from sustainable (Vogtländer J. G. 2001) and it is not clear to what extent emissions must be prevented or which concentration or which absolute amount is still acceptable (Mark Goedkoop 1995). On the other hand, valuation of damage oriented costs or damage eco-costs calculations are based on the cost of impact cause by emissions in term of health, climate change, agriculture (i.e. forest), ecosystem and materials (i.e. buildings).

Minimum environmental impact is the best case scenario of the lower impact on the environment. More precisely, any material is recovered in its initial amount and grade without any environment burden or treatment steps. On the other hand, maximum environmental impact is the worst case scenario due to the maximum impact to the environment as every material will end up in the worst possible end-life route including the environmental burden (Huisman, Boks et al. 2003).

The following section will discuss in detail the damage eco-cost of the nine environmental impact categories chosen as shown in Table 2 in the previous chapter

5.3. Damage eco-costs

The phrase 'global warming' has become common nowadays when we discuss environmental issues. As the world is always being subjected to the economy, this scenario would be easy to explain if these scientific terms of the environment impact can be translated into monetary value. Houghton (2004) recommended that the quantification of the costs of action against the likely costs of the consequences of inaction must at least be attempted.

The cost impacts are often overlooked. The true costs are uncertain because of the lack of data for many countries, but these cost estimates amount to a fairly consistent 0.2-0.5 percent of GNP (Gross National Product) (Pearce and Turner 1994; Pearce and Brisson 1995)

5.3.1. Damage cost of global warming

According to Houghton, J. T (2004), the first warming effect of the greenhouse gases in the atmosphere was recognized in 1827 by the French scientist Jean-Baptiste Fourier, best known for his contributions to mathematics by pointing out the similarity between what happens in the atmosphere and in the glass of a greenhouse, which led to the name 'greenhouse effect'. The most important greenhouse gas is CO2 and it is continuously increasing in atmospheric concentration because of human activities. The increase in carbon dioxide (CO2) has contributed about 70 percent of the enhanced greenhouse effect to date, methane (CH4) about 24 percent, and nitrous oxide (N2O) about 6 percent (Houghton 2004). These direct greenhouse effects are also known as the Global Warming Potential (GWP), due to their potential on contribution of a substance to the greenhouse effect. CO2 has been chosen globally as the main reference of global warming effect with characteristic factor equivalent to 1. That means, for the purpose of quantification of all other greenhouse gases, these gases will be referred to and expressed in the CO2 equivalent. The calculation of CO2 is based on the amount of carbon that will normally be taken into account in the marginal damage cost (that is the cost of the damage due to one extra tonne of carbon emitted now) and estimated by different economists in the range of 5–125 US dollar. It is estimated that a potential damage cost is about one percent of the global world product for a warming of 2.5°C (Nodhaus W.D. and Boyer J. 2000; Houghton 2004).

The damage cost and the prevention may also be applicable for the costs-benefits assessment in order to find the 'optimal' reduction of CO2 level as illustrated in Figure 5.2.

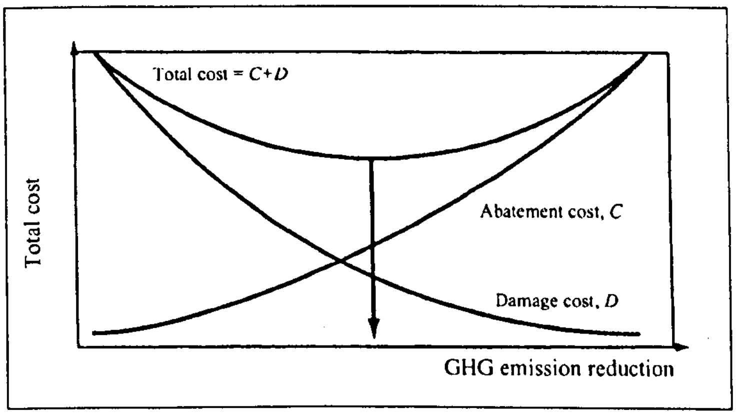

Figure 5.2: Illustration for the 'Optimal' reduction of CO2 level (Houghton 2004)

Houghton (2004) described that from the damage cost together with the abatement cost of greenhouse gases (GHG), estimation for the optimal level of GHG can be made. This can be done by calculating and plotting the different values of both damage and abatement cost of GHG. The optimal value of GHG is located at the lowest point of the plotted curve graph.

5.3.2. Damage eco-costs of acidification

Acidification occurs when acid deposition from emissions such as sulphur dioxide, nitrogen oxides and ammonia give damages indication to soils, vegetation, fresh waters and buildings. The principal effects of the deposition of acid atmospheric pollutants are the acidification of soils and water which result in a decline of fish and other aquatic life, damaging forests levels, damage to ecosystems, damage to crops and buildings and to human health (Ekins 1999) as shown in Table 5.1.

Table 5.1 also shows the damage cost of acidification result with the upper limit and the lower limit of acidification results giving wide range uncertainty to the data. Derivation made by Pearce (1992) revealed that 74 per cent of the UK acidification costs are obtained from the damage cost to buildings, while some other studies like ECOTEC (1994) and Hohmeyer (1988) concluded that the damage contributed to the health effects as well. Similar to ECOTEC (1994) and Hohmeyer (1988), research conducted by ExternE (1998) covering all categories like health, crops, building materials, forests and ecosystems were mainly subjected to the health costs.

5.3.3. Damage cost of eutrophication

Eutrophication is the enrichment process of an ecosystem typically caused by nitrogen or phosphorus. Traditionally eutrophication promotes enrichment of aquatic systems by 'over-fertilization' into lakes, bays, or other semi-enclosed waters (even slow-moving rivers), terrestrial ecosystems. It is considered a form of pollution because adding fertilizers will encourage plants to become overgrown resulting in disruption to the functioning of the ecosystem. It will cause an impact to human health by decreasing the resource value of rivers, lakes, and estuaries. As a result, activities such as recreation, fishing, hunting, and aesthetic enjoyment are hindered. In addition, health-related problems can occur where eutrophic conditions can interfere with drinking water treatment (Ingrid Chorus and Jamie Bartram 1999).

Table 5.1:Estimated damage cost from sulphur emission

Study	Country	Damage cost US$(1990)/ tonne S emitted	Comment
Pearce(1992)	UK	4,611	74% building costs
ECOTEC(1992)	UK	861-5,191	21-87% health costs
	Germany	3,959-4,368	77-85% health costs
ECOTEC(1994)	UK1	L: 107-272	78% buildings, 21% health costs
		C:796-2,011	15% buildings, 81% health costs
		H:989-2,499	16% buildings, 65% health costs
	UK2	L:98-267	62% buildings, 38% health costs
		C:1,221-3,080	7% buildings, 90% health costs
		H:1,351-3,402	8% buildings, 81% health costs
Alfsen et al.(1992)	Norway	500-8,960	80-90% health costs
Hohmeyer(1988)	Germany (West)	1,589-8,533	L:61% plant life, 16% health cost
ExternE(1998)	Austria	18,000	Mainly health costs throughout
	Belgium	22,776-24,282	
	Denmark	5,980-8,432	
	Finland	2,054-2,972	
	France	15,000-30,600	
	Germany	3,600-27,376	
	Greece	3,956-15,664	
	Ireland	5,600-10,600	
	Italy	11,400-24,000	
	The Netherlands	12,410-15,162	
	Portugal	9,920-10,848	
	Spain	8,438-19,166	
	Sweeden	4,714-5,620	
	United Kingdom	12,054-20,050	

A study by Pretty et al. (2000) on the external costs of UK agriculture proved that the damage cost by eutrophication is very substantial. For example the damage cost of drinking water was estimated at £231 million per year due to the existence of pesticide, nitrate, phosphate and soil in source of drinking water. Meanwhile the estimated annual damage costs of fresh water eutrophication in the UK range between 105-160 million

million dollars which is approximately 55-85 million pounds a year (Pretty, Mason et al. 2003)

In another study, H. Scott Matthews and Lester B. Lave (2000) reported that damage cost of nitrogen oxide (NOx) from nine studies estimated the mean value of external costs for air emission at approximately 1500 pound per tonne air emission.

5.3.4. Damage cost of smog

Typically, smog formation is caused by emissions of nitrogen oxides (NOx) and volatile organic compounds (VOCs) into the atmosphere. Amongst the sources of NOx substance are coal or fuel combustion for power production, vehicles and waste incineration, while the VOC sources come mostly from combustion processes. Substances that are included in the formation of VOC are benzene ethanol and trichloroethane and industrial processes respectively. When these two emissions (NOx and VOCs) reacts with UV from the sunlight (especially during a very hot day), the UV will tend to break their molecules and then will combine with existing free oxygen in the air to form ozone (O_3). Subsequently, the combination of this ozone and dust will then mix together to create smog.

Generally, the above scenario can be shown in the following simple equations,

$$NOx + VOCs + UV = O_3$$

$$O_3 + dust = SMOG$$

Photochemical smog is harmful to human health, leads to the degradation of many materials and reduces yield of crops in agriculture. The possible effects of photochemical smog include damage to plants, human health and materials. According to the latest assessment, smog damage to crops to Europe's farmers is estimated at more than six billion Euros a year (Pearce 2002).

5.3.5. Damage cost of heavy metal and carcinogens

A carcinogen is any substance or chemical or agent that can have short and long term effects on humans. Short-term effects caused by benzo[a]pyrene or polycyclic aromatic hydrocarbons (PAH) include red blood cell damage, leading to anaemia, suppressed immune system. Long-term effects are on the developmental and reproductive systems and cancer. It was reported by the International Agency for Research on Cancer that approximately 400 chemical agents have been identified as carcinogenic or potentially carcinogenic to humans, which include PAH that can be found as an additive or preservative substance in construction materials (International Agency for Research on Cancer 2006). Among construction materials that contained carcinogenic substance are PAH in asphalt mixture (Ono, Uemura et al. 2000), aluminium and wood preservatives (European Commission DG Environment 2001) adhesives, epoxy, (Spee, Van Duivenbooden et al. 2006) asbestos, silica, solvents (Jarvholm 2006) etc.

One example of a source of PAH in building waste is from demolition waste which mainly originates from roofing material and soot from chimneys and amounts vary from 10 to 200 mg/kg (Mulder, Brouwer et al. 2001). Most of the PAH emissions in construction reportedly come from material like roofing material, combustion of wood and other fuels and from the use of transportation fuel (European Commission DG Environment 2001). Common building construction materials that potentially have carcinogenic effects are presented in Table 5.2.

Table 5.2: Construction materials with potentially carcinogenic substances

Building element	**Products/materials**	**Toxic substances used to make product**	**Health effects**
Foundations	chemical dpc bituminous dpc/dpm	organic compound	nausea nervous system headaches
Structure	timber preservatives	phenols copper-chrome-arsenic (CCA)	nausea nervous system headaches
Secondary element	timber preservative for windows and doors	organic solvents	nausea nervous system headaches
	medium density fibreboard, skirtings, linings	formaldehyde	irritant to skin, eyes, respiratory system
	urea-formaldehyde insulation	formaldehyde	possible carcinogen
Fittings	chipboard kitchen units	formaldehyde	irritant to skin, eyes, respiratory system
	melamine worktop	resins (manufacturer stage only)	possible carcinogen
Services	pvc wiring	plasticizers	carcinogen
	pvc rainwater goods		
	lead piping	lead	nervous system
	pvc underground drainage	vinyl chloride (manufacturer stage only)	carcinogen
Finishes	gloss paint varnishes emulsion paint solvents wood sealant adhesives	xylene toluene white spirit benzene	nausea headaches nervous system reproductive effects
	pvc flooring	plasticizers vinyl chloride (manufacturer stage only)	carcinogen
	fungicides	formaldehyde	allergenic irritant to skin, eyes, respiratory system possible carcinogen

Source: (Stevenson and Williams 2000)

5.3.6. Damage cost of ozone layer depletion

Molecules of ozone (O3) are located at the bottom layer of atmosphere, called the troposphere and the next layer is called stratosphere. Natural ozone at trophospheric layer is produced by natural processes from soil and plants at ground-level. Another source of natural ozone at this trophospheric layer is from the small amounts of ozone that migrate from the stratospheric layer. Due to the very small amounts of ozone from these two sources, it is considered not to pose any threat to the health of humans or the environment. However, the ozone that is produced from any human activities from a by-product (for example from the automobiles and industry) are called 'bad' ozone because it is one of the smog formation sources and also classified as one of the green house gasses.

Stratospheric ozone which is located approximately 10 to 50-km above the earth's surface (Morris, Gage et al. 2003) is considered as 'good' ozone as it helps to protect ultraviolet (UV) radiation from the sunlight from travelling excessively to the ground. UV from sunlight is considered harmful to human heath and the environment. For example, if a human is exposed to UV due to the depletion of the ozone layer, it will significantly increase the risk of skin cancers, eye cataracts, and immune system suppression. Substances that are considered to be the cause of ozone depletion potential (ODP) values mainly come from the hydrocarbons which containing combined bromine, fluorine and chlorine, or CFCs.

External cost generated due to the depletion of ozone at the stratosphere layer is considered significant. It was estimated that the total damage eco-cost due to SO_2 and ozone in Madrid amounted to 9675 million Euro in 1992 and 7664 million Euro in 1995 representing 7 percent of the GDP of the area in 1995 (Lechon Y., Cabal H. et al. 2002). At present, ozone is considered as the most serious air pollutant problem for the agriculture sector in Europe. It was reported that the farmers' losses for 1990 are estimated at £4.3 billion across Europe. Even though the losses across Europe due to the ozone smog to the Europe's farmers is estimated will decline approximately 28 percent in 2010 by assuming the implementation of the Gothenburg protocol across Europe, Even with this reduction, the farmers still have to absorb losses valued at £3.1 billion (Holland, Mills et al. 2002).

5.3.7. Damage cost of energy

Energy and its production could also damage the natural and built environment by it side effects like air pollution. In terms of cost, the damage costs or 'hidden cost' of emission from the production of energy like electricity by the producers and consumers of energy is always imposed on the society and the environment without taking into account the 'true' market price. Study by an EU-funded project called 'External costs of Energy' (ExternE) to evaluate and estimate the external costs of a wide range of different fuel cycle found that the cost of producing the energy from electricity and transportation could produce external or damage cost to society and the environment. The damage assessment approach used by the project to determine the damage costs of energy and transport was the impact pathways method which includes health, environmental effects like global warming, ecosystem, plants and building material. As for the UK, the damage costs study that has been carried out as part of the project was considered to be the major fuel cycles assessment for the UK including coal and gas together with some which may become significant in the future such as biomass and orimulsion (Berry, Holland et al. 1998). The UK results of the damage costs assessment is presented in Table 5.3

Table 5.3: Damage cost for electricity production in the UK

Method of production	**Damage costs (EUR-cent per kWh)**
Coal and lignite	4-7
Oil	3-5
Gas	1-2
Nuclear	0.25
Biomass	1
Wind	0.15

Source: (European Commission 2001)

5.4. Eco-costing in Construction

The principle of eco-cost has been used by several researchers like Vogtlander (2001) and Huisman (2003) for their study. Vogtlander (2001) used eco-cost to calculate Eco-costs/Value Ratio (EVR) of products or services in order to indicates a future sustainability of society. Eco-cost of EVR was calculated based on the pollution prevention cost where the lower EVR value indicates that the products and services are more sustainable. However, Huisman (2003) has used the concept of eco-cost to quantify the environmental and eco-efficiency of end-of-life treatment consumer electronics products.

In construction, Yahya and Boussabaine (2006) have proposed a framework of eco-cost to be used in measuring sustainability in construction site processes. The framework suggests using five important elements as shown in Figure 5.3

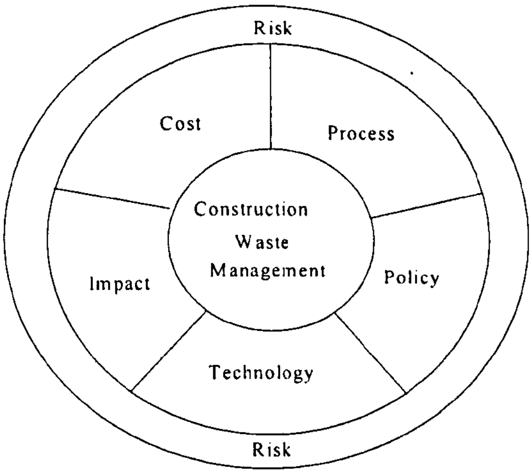

Figure 5.3: Framework of eco-cost to be used in measuring sustainability in construction site processes

Eco-cost is measured during all stages of the construction processes which include in five main categories namely process, policy, technology, impact and other related cost and presented in the following mathematical equation,

Total of Eco-costs = $C_{wc} + C_{wd} + C_{ep} + C_e + C_{rr} + C_i + C_{em} + C_{de} + C_{lab}$

Where,

$C_{wc} = \Sigma$ Cost of waste control

$C_{rr} = \Sigma$ Cost saving of recycling and reuse,

$C_{wd} = \Sigma$ Cost of waste disposal,

$C_i = \Sigma$ Cost of impact

$C_{ep} = \Sigma$ Cost of eco policy

$C_e = \Sigma$ Cost of energy, $\Sigma C_{ei,}$, $i = 1$ to n (energy consumption)

$C_{em} = \Sigma$ Cost of emission of equipments

$C_{de} = \Sigma$ Cost of depreciation of equipments

$C_{lab} = \Sigma$ Cost related to labour

5.5. Summary

The use of impact result from environmental data to measure eco-cost results could assist in determining the sustainability of products or services. It is important to determine the damage eco-costs for the nine identified environmental indicators. These costs should be incorporated with the environmental impact result to produce a total eco-cost result for the three waste disposal options of construction and demolition waste. By using the eco-cost results, strategy and planning can be justified from the very early stage to minimise site wastes from the construction stages and to select a suitable waste disposal option. The implementation of this concept in other industries presented by several studies had proved the importance of eco-cost in measuring sustainability of products and services. Ultimately, it aims to reduce the total cost with the help of green or eco-friendly alternatives in all the stages of the life cycle of any product (Durairaj, Ong et al. 2002).

Chapter 6

ENVIRONMENTAL IMPACT RESULTS

6.1. Introduction

This chapter presents the results of ecological impact of five common construction materials waste namely brick, concrete, metal, plasterboard and wood and their impact based on selected waste disposal options is made. The results will cover six from nine potential environmental indicators based on three waste disposal options i.e. final disposal, recycling and sorting plant that has been assessed. The six potential indicators are the indicators that produced a significant impact cost (eco-cost) results. They are global warming potential (GWP), acidification (AP), eutrophication (EP), winter smog (WS), heavy metal (HM) and energy resource potential (ER). The other three potential indicators that give less significant impacts are summer smog (SS), carcinogenic (CP) and ozone layer depletion (ODP).

The discussions on the six indicators will also focussing on the quantity and percentage of potential environmental impacts based on their related main waste disposal activities and its up-stream activities. However all the nine indicators results will be taken into account for the calculation of total impact results in order to define the total impact eco-cost of every type of construction material waste selected. This will be discussed further in the following chapters.

Data for all relevant impacts was extracted from EcoInvent construction waste database and the indicator results were obtained with the use of SimaPro 7 model from Pre Consultant. Results presentation will be shown only for the top ten contributors as in most cases the remaining activities produced a lower contribution percentage (less than 2 percent) which was considered less significant.

6.2. Impact Assessment of End-Of-Life Brick Waste

Impact assessment of end-of-life brick waste has been carried out in the system boundaries already set in Chapter 4 for the three different waste disposal options i.e. recycling, sorting plant and final disposal. Assessment is made on the specific emissions from the disposal activities that are related to the nine selected environmental indicators as explained in the previous section i.e. GWP, AP, EP, SS, WS, HM, CP, ODP and ER. Results are discussed with the help of figures of contribution percentage for every single indicator.

6.2.1. Global Warming Potential of Brick Waste

Life cycle impact assessment result shows that the total of GWP due to the final disposal of a kilogram of bricks was 0.0137 kg CO2 equivalent. The consumption of diesel by machinery in the building during the dismantling of bricks and the operation lorry for transportation of brick waste contributed 70.20 percent to the total GWP. These two activities generated 36.57 percent and 33.72 percent of GWP, equivalent to 5.01E-03 and 4.62E-03 kg CO2 respectively.

However the total of GWP results for the recycling option is 0.00322 kg CO2 equivalent for every kilogram of brick waste. The result is very much lower if compared to the final disposal option and was significantly dominated by the consumption of diesel by building machinery during the dismantling work. The estimated GWP value was around 3.92E-3 kg CO_2 equivalent which is 82.61 percent of the total GWP for this option.

In the sorting plant option, as in the final disposal option above, the result on GWP was again mainly contributed by transportation of bricks and the consumption of diesel by machinery during the dismantling of bricks. However the contribution rank of GWP for this option was vice versa. From the total GWP of 1.39E-02 kg CO2 equivalent, the operation of lorry for transportation of brick waste generated 4.82E-03 kg CO2 equivalent and the burning of diesel by building machinery generated 4.36E-03 kg CO2 equivalent. The percentage value from these two processes is estimated at 66.04 percent from the total amount of sorting plant GWP. Other contributors to the GWP are mainly from the upstream processes like fuel production and energy activities as shown.

It is clearly shown that the recycling option produced the lowest GWP value compared to the other two waste disposal options. While the final disposal and the sorting plant generated the same amount of GWP (see Appendix 2). The highest contribution by transportation in sorting plant is due to the distance of sorting plant location which is normally located in the outskirt area with the average taken by the inventory being 17.7 kilometres. Lorries have to make a long distance round trip from the collecting point (most of the waste is generated in the urban areas) to the sorting plant.

Contribution percentages of GWP for brick waste disposal options are shown in Figure 6.1, 6.2 and 6.3 and GWP results are presented in Table 1 in Appendix 2.

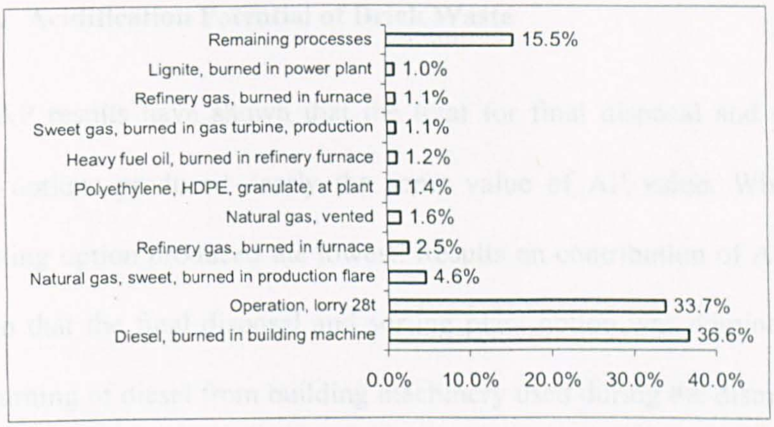

Figure 6.1: Contribution percentage of GWP for the brick final disposal

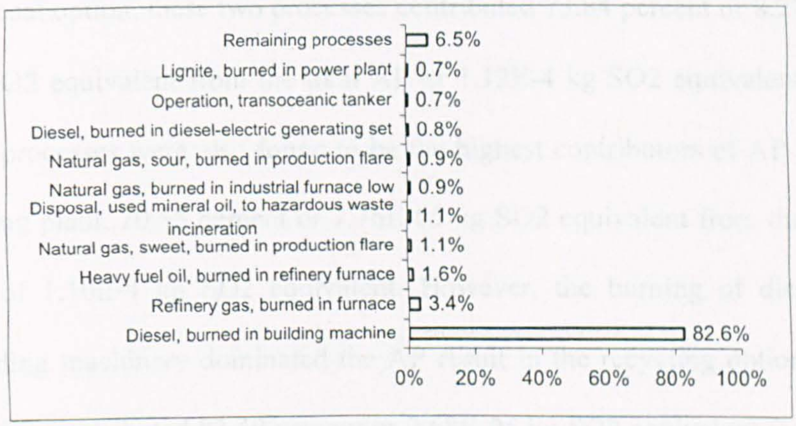

Figure 6.2: Contribution percentage of GWP for the brick recycling

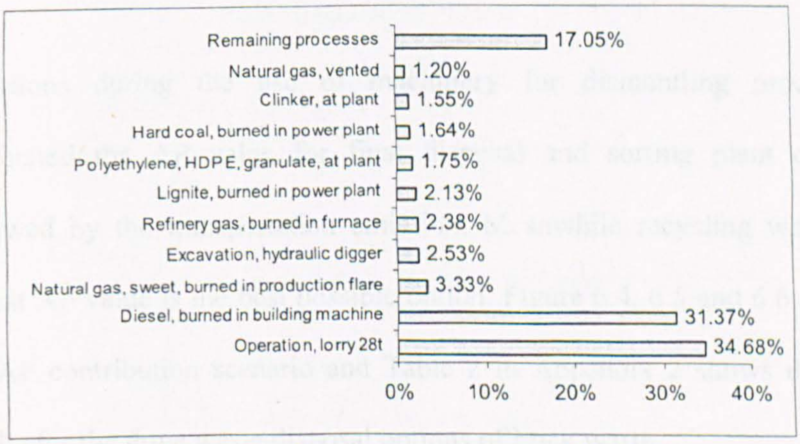

Figure 6.3: Contribution percentage of GWP for the brick sorting plant

6.2.2. Acidification Potential of Brick Waste

The AP results have shown that the total for final disposal and sorting plant options produced nearly the same value of AP value. While the recycling option produced the lowest. Results on contribution of AP have shown that the final disposal and sorting plant option was dominated by the burning of diesel from building machinery used during the dismantling process and the operation of lorry for waste transportation. In the final disposal option, these two processes contributed 73.84 percent or 8.27E-05 kg SO2 equivalent from the total AP of 1.12E-4 kg SO2 equivalent. The two processes were also found to be the highest contributors of AP in the sorting plant, 70.55 percent or 7.76E-05 kg SO2 equivalent from the total AP of 1.10E-4 kg SO2 equivalent. However, the burning of diesel in building machinery dominated the AP result in the recycling option. The process contributed 83.49 percent or 2.68E-05 kg SO2 equivalent from the total AP value of 3.21E-05 kg SO2 equivalent.

Emissions during the use of machinery for dismantling processes dominated the AP value for final disposal and sorting plant option followed by the transportation emission. Meanwhile recycling with the lowest AP value is the best possible option. Figure 6.4, 6.5 and 6.6 depict the AP contribution scenario and Table 2 in Appendix 2 shows the AP results for the three waste disposal options of brick waste.

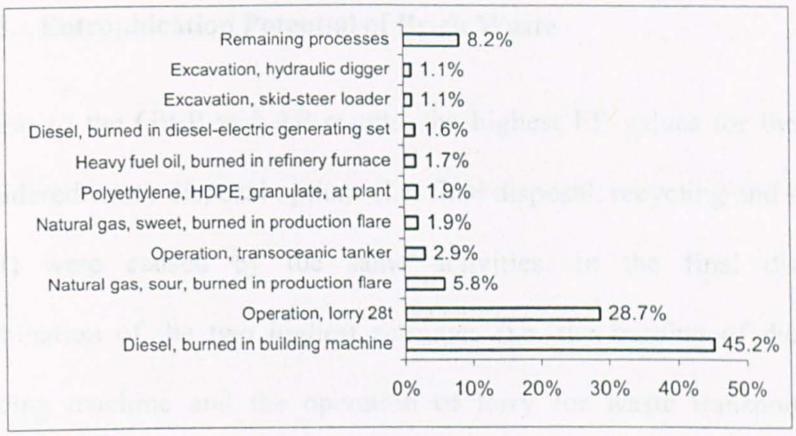

Figure 6.4: Contribution percentage of AP for the brick final disposal

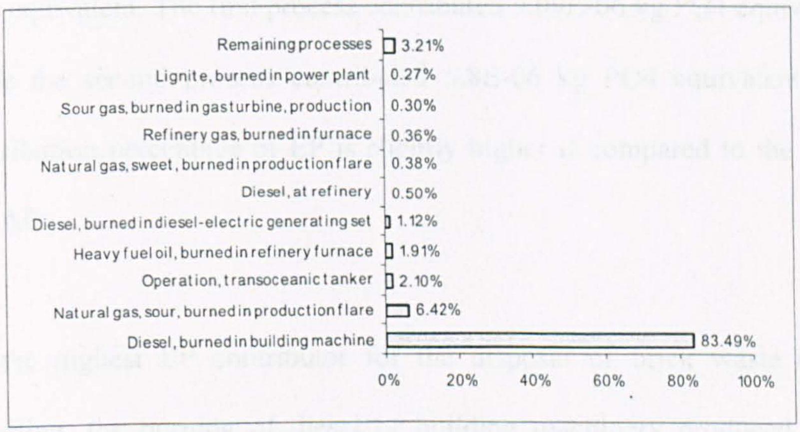

Figure 6.5: Contribution percentage of AP for the brick recycling

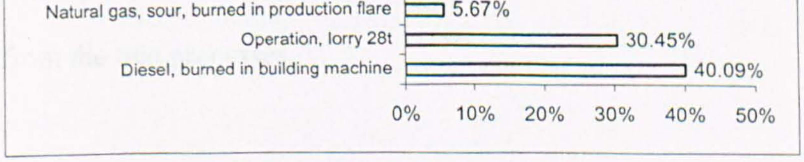

Figure 6.6: Contribution percentage of AP for the brick sorting plant

6.2.3. Eutrophication Potential of Brick Waste

Similar to the GWP and AP results, the highest EP values for the three considered waste disposal options (i.e. final disposal, recycling and sorting plant) were caused by the same activities. In the final disposal, combination of the two highest activities (i.e. the burning of diesel of building machine and the operation of lorry for waste transportation) contributed approximately 80.05 percent of the total EP of 1.86E-05 kg PO4 equivalent. The first process contributed 9.09E-06 kg PO4 equivalent, while the second process contributed 5.8E-06 kg PO4 equivalent. The contribution percentage of EP is slightly higher if compared to the GWP and AP.

As the highest EP contributor for the disposal of brick waste to the recycling, the burning of diesel of building machinery produced 88.95 percent or 4.83E-06 kg PO4 equivalent from the total EP of 5.43E-06 kg PO4 equivalent. This activity was again found to be the highest contributor of EP for the sorting plant option followed by the operation of lorry for brick waste transportation. The total of EP for the disposal of brick waste to sorting plant is 1.44E-06 kg PO4 equivalent, of which 70.30 percent was from the two processes.

Results show that the diesel used for the machinery during the dismantling phase and transportation of waste activities was found to be the highest contributor to EP for all disposal options. Sorting plant produced a slightly higher EP value compared to the final disposal option. The remaining processes that contributed other EP can be seen in Figure 6.7, 6.8, 6.9 and detailed EP contribution value is shown in Table 3 in Appendix 2.

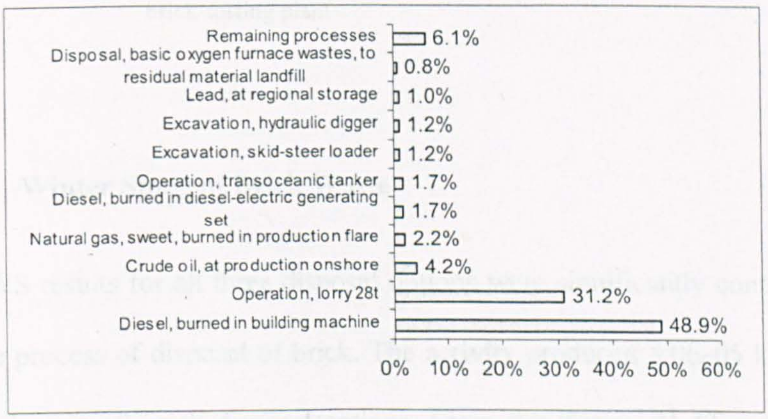

Figure 6.7: Contribution percentage of EP for the brick final disposal

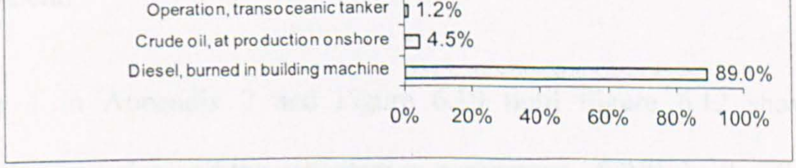

Figure 6.8: Contribution percentage of EP for the brick recycling

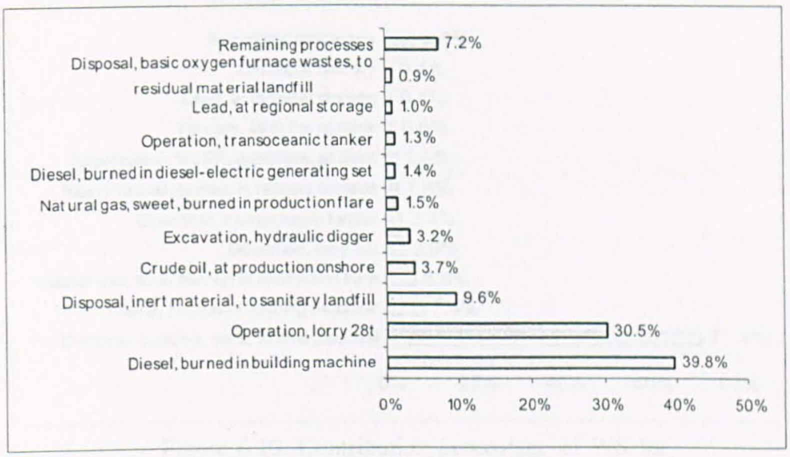

Figure 6.9: Contribution percentage of EP for the brick sorting plant

6.2.4. Winter Smog of Brick Waste

The WS results for all three disposal options were significantly contributed by the process of disposal of brick. The activity produced 8.0E-05 kg SPM equivalent in all brick disposal options. From this figure, 71.43 percent of WS contribution was from the final disposal option, 89.99 percent in the recycling option and 70.80 percent in the sorting plant option. Total WS values for the fate of a kilogram of brick to the final disposal, recycling and sorting plant are estimated at 1.12E-04, 8.89E-5 and 1.13E-4 kg SPM equivalent.

Table 4 in Appendix 2 and Figure 6.10 until Figure 6.12 show the contribution value and the contribution percentage of WS for the disposal option of brick waste

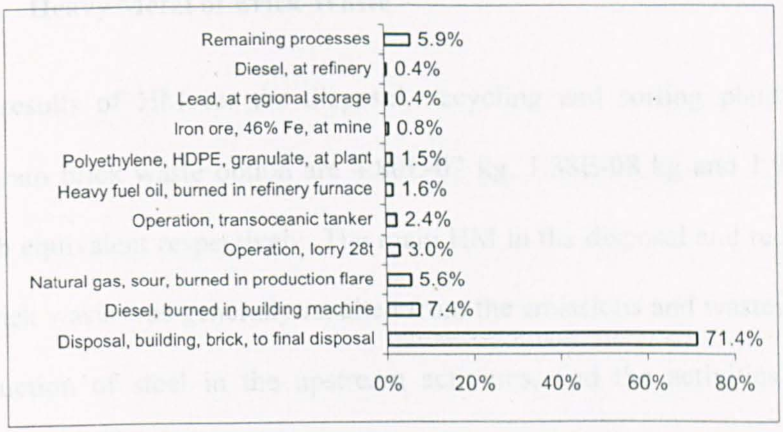

Figure 6.10: Contribution percentage of WS for the brick final disposal

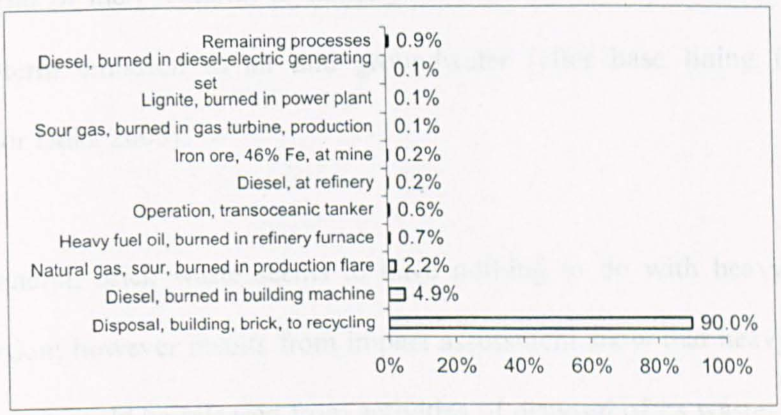

Figure 6.11: Contribution percentage of WS for the brick recycling

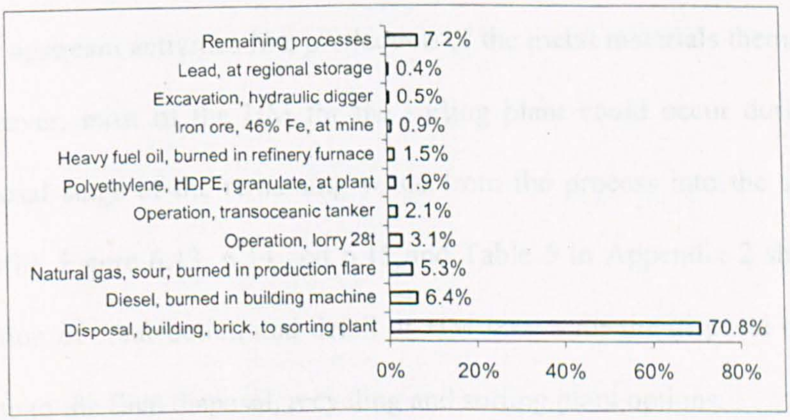

Figure 6.12: Contribution percentage of WS for the brick sorting plant

6.2.5. Heavy Metal of Brick Waste

The results of HM for the disposal, recycling and sorting plant for a kilogram brick waste option are 4.80E-07 kg, 1.38E-08 kg and 1.93E-05 kg Pb equivalent respectively. The main HM in the disposal and recycling of brick waste was generally resulted from the emissions and wastes of the production of steel in the upstream activities, and the activities of oil production. The highest contributor for the HM in sorting plant was the disposal of inert material to sanitary landfill. This was due to short and long-term emission to air and groundwater (after base lining failure) (Gabor Doka 2003).

In general, brick waste seems to have nothing to do with heavy metal emission; however results from impact assessment show that heavy metal emission could be released from activities of disposal of its waste. For the final disposal and recycling options, most HM emission comes from the very upstream activities like production of the metal materials themselves. However, most of the HM for the sorting plant could occur during the disposal stage of the remaining waste from the process into the sanitary landfill. Figure 6.13, 6.14 and 6.15 and Table 5 in Appendix 2 show the fraction of contribution and detail of HM scores for the disposal of brick waste to the final disposal, recycling and sorting plant options.

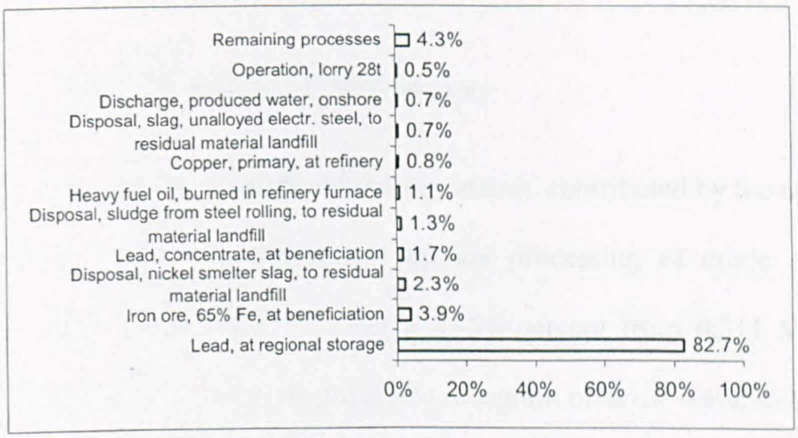

Figure 6.13: Contribution percentage of HM for the brick final disposal

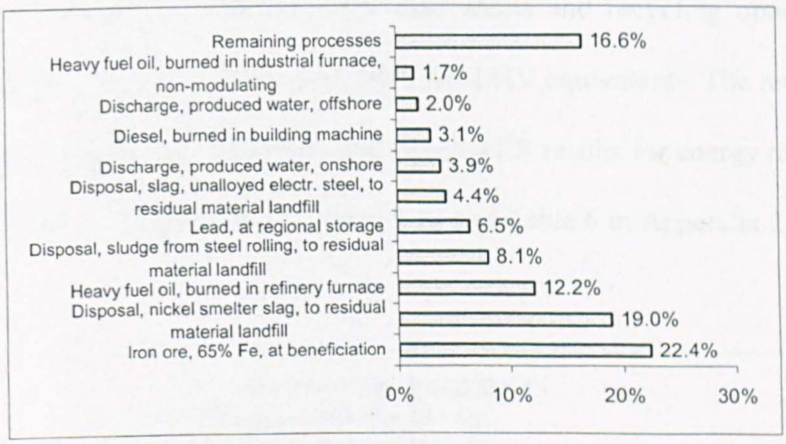

Figure 6.14: Contribution percentage of HM for the brick recycling

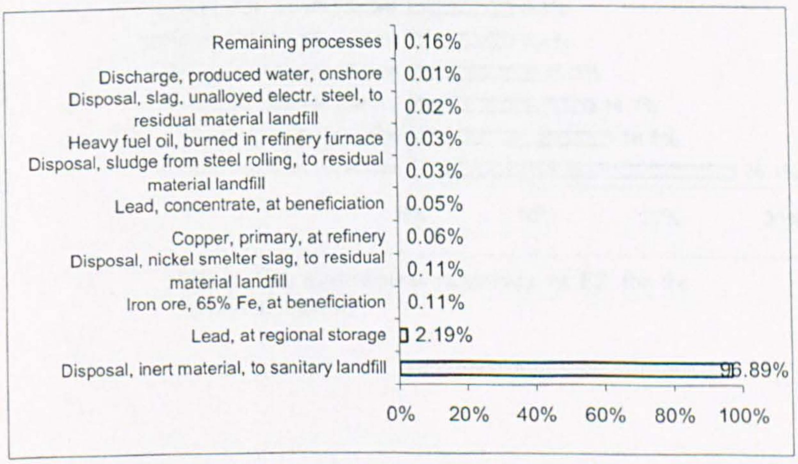

Figure 6.15: Contribution percentage of HM for the brick sorting plant

6.2.6. Energy Resource of Brick Waste

ER of the disposal of brick waste were mainly contributed by the upstream activities and mostly dominated by the processing of crude oil. The processing of crude oil contributed 83.76 percent from 0.311 MJ LHV equivalent of ER for the disposal of a kilogram of brick waste to the final disposal. The processing of crude oil in the sorting plant option generated 89.60 percent of 0.309 MJ LHV equivalents and recycling option with 70.26 percent the ER value of 0.0495 MJ LHV equivalents. The remaining and percentage of contributors and detailed ER results for energy resources are shown in Figure 6.16, 6.17 and 6.18 and Table 6 in Appendix 2.

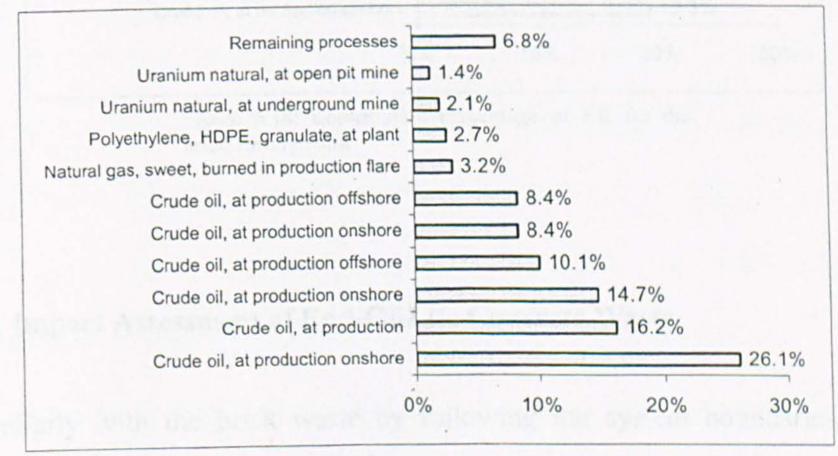

Figure 6.16: Contribution percentage of ER for the brick final disposal

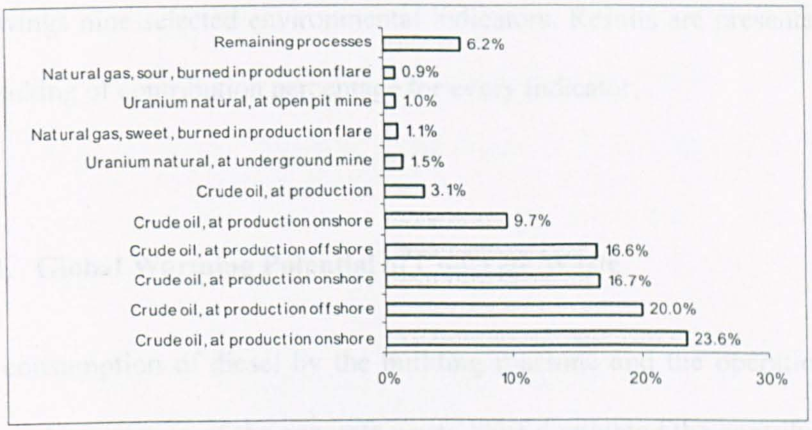

Figure 6.17: Contribution percentage of ER for the brick recycling

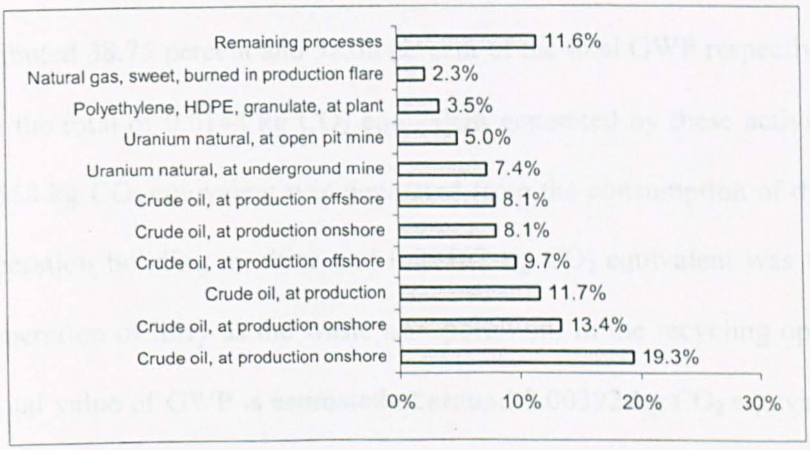

Figure 6.18: Contribution percentage of ER for the brick sorting plant

6.3. Impact Assessment of End-Of-Life Concrete Waste

Similarly with the brick waste by following the system boundaries that already been set earlier, the impact assessment of end-of-life concrete waste has been carried out for the three different waste disposal options on the specific emissions from the disposal activities that are related to the followings nine selected environmental indicators. Results are presented in the ranking of contribution percentage for every indicator.

6.3.1. Global Warming Potential of Concrete Waste

The consumption of diesel by the building machine and the operation of lorry in transporting of the concrete waste have dominated the contribution result of GWP for the final disposal of concrete. The two activities contributed 38.75 percent and 32.08 percent of the total GWP respectively. From the total of 0.0144 kg CO_2 equivalent generated by these activities, 0.00558 kg CO_2 equivalent was generated from the consumption of diesel of operation building machine and 0.00462 kg CO_2 equivalent was from the operation of lorry as the waste transportation. In the recycling option, the total value of GWP is estimated at around 0.00392 kg CO_2 equivalent. The consumption of diesel by the building machine again dominated the contribution towards generating GWP with the value of 0.00323 kg CO_2 equivalent which was 82.40 percent of total GWP. The second highest GWP contributor with the value of 0.000133 kg CO_2 equivalent was generated from direct emissions due to the combustion of refinery gas in refinery furnaces and generators. While in the sorting plant option, the consumption of diesel by the building machine and the operation of lorry in transporting of the concrete waste were again found to be the major contributors for the GWP. The GWP value from the assessment was

0.0145 kg CO_2 equivalent and it is estimated that the two activities produced approximately 34.07 percent and 33.24 percent of the total GWP respectively. Table 7 in Appendix 2 and Figure 6.19, 6.20 and 6.21 depict the percentage contribution of the GWP for the concrete waste disposal.

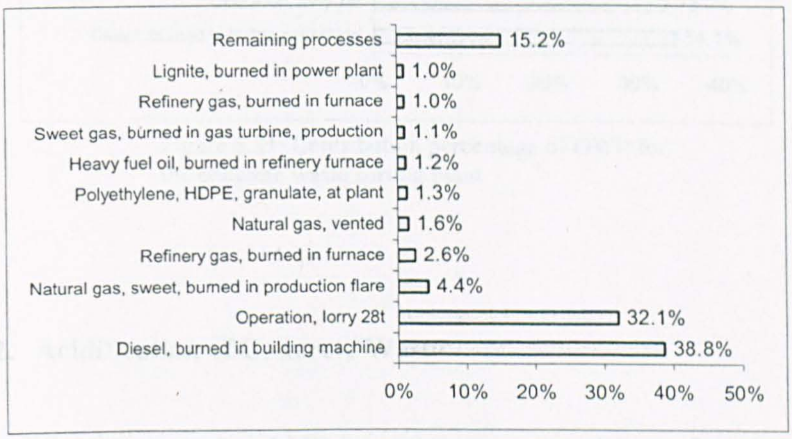

Figure 6.19: Contribution percentage of GWP for the concrete waste final disposal

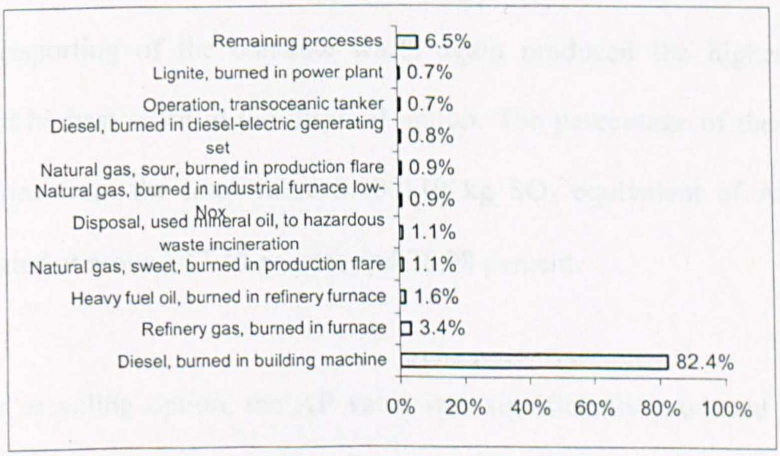

Figure 6.20: Contribution percentage of GWP for the concrete waste recycling

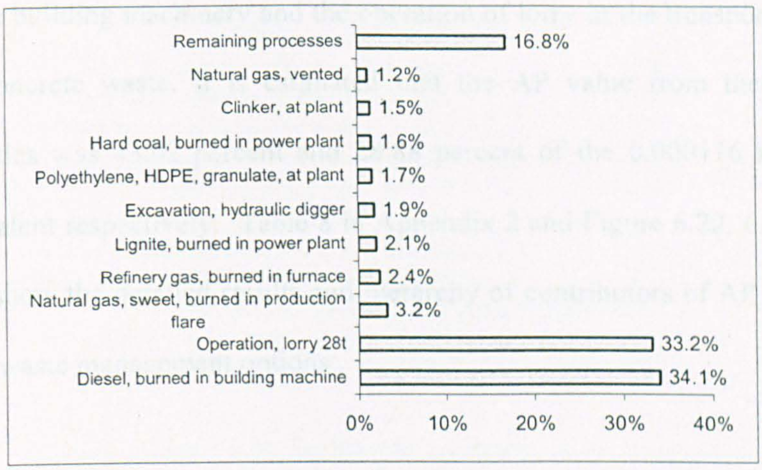

Figure 6.21: Contribution percentage of GWP for the concrete waste sorting plant

6.3.2. Acidification of Concrete Waste

In acidification potential (AP) impact assessment, it was found that the consumption of diesel by the building machine and the operation of lorry in transporting of the concrete waste again produced the highest and second highest score in the disposal option. The percentage of these two activities from the total value 0.000119 kg SO_2 equivalent of AP was estimated at around 47.40 percent and 26.98 percent.

In the recycling option, the AP value was significantly produced by the consumption of diesel of the building machinery. The estimated percentage was 83.63 percent of the total AP value 0.0000391 kg SO_2 equivalent. Similarly with the disposal option, total AP value of sorting plant option has significantly been generated by the consumption of diesel by the building machinery and the operation of lorry in the transporting of the concrete waste. It is estimated that the AP value from these two activities was 43.02 percent and 28.88 percent of the 0.000116 kg SO_2 equivalent respectively. Table 8 in Appendix 2 and Figure 6.22, 6.23 and 6.24 show the detailed results and hierarchy of contributors of AP for the three waste management options.

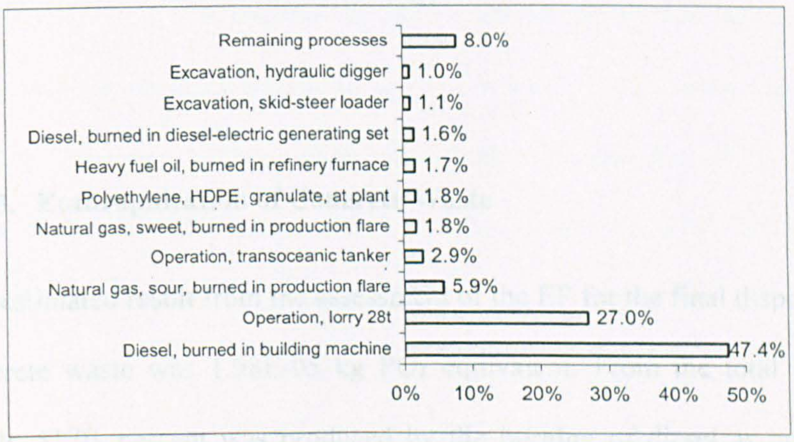

Figure 6.22: Contribution percentage of AP for the concrete waste final disposal

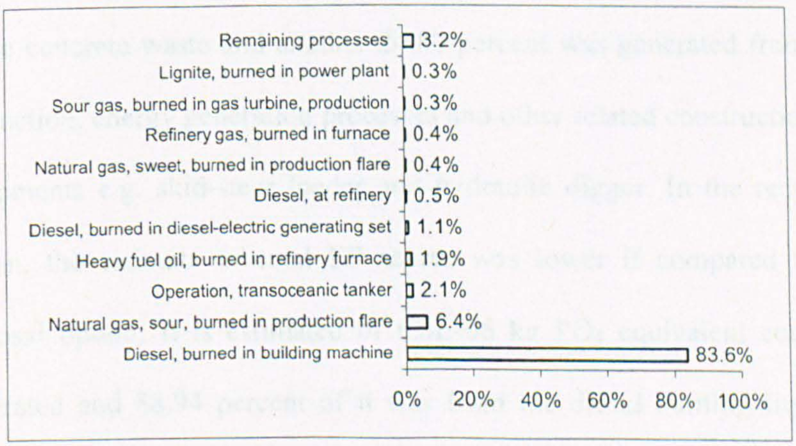

Figure 6.23: Contribution percentage of AP for the concrete waste recycling

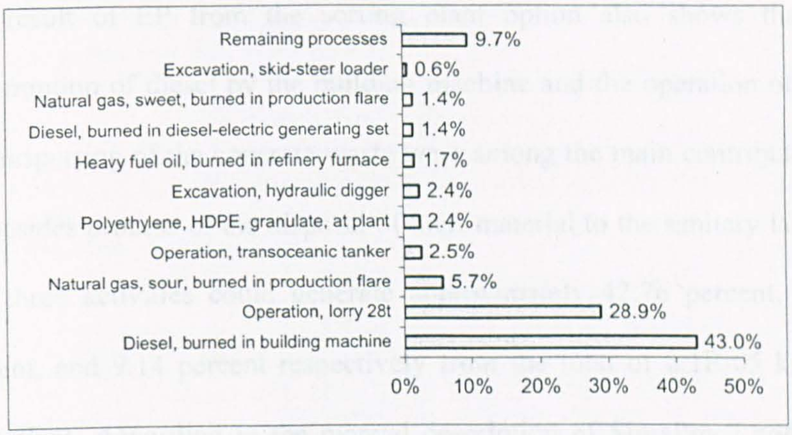

Figure 6.24: Contribution percentage of AP for the concrete waste sorting plant

6.3.3. Euthrophication of Concrete Waste

The estimated result from the assessment of the EP for the final disposal of concrete waste was 1.98E-05 kg PO_4 equivalent. From the total of the result, 51.01 percent was produced by the burning of diesel as building machine fuel, 29.29 percent was from the operation of lorry in transporting of the concrete waste and another 24.80 percent was generated from fuel production, energy generation processes and other related construction site equipments e.g. skid-steer loader and hydraulic digger. In the recycling option, the estimate of total EP scores was lower if compared to the disposal option. It is estimated of 6.6E-06 kg PO_4 equivalent could be generated and 88.94 percent of it was from the diesel burning from the operating of building machinery.

The result of EP from the sorting plant option also shows that the consumption of diesel by the building machine and the operation of lorry in transporting of the concrete waste were among the main contributors of EP besides process of the disposal of inert material to the sanitary landfill. The three activities could generate approximately 42.76 percent, 28.86 percent, and 9.14 percent respectively from the total of 2.1E-05 kg PO_4 equivalent. According to the manual description of SimaPro 7 software, the impacts from the disposal of inert material to the sanitary landfill include the short-term emissions to air via landfill gas incineration and landfill leachate, burdens from treatment of short-term leachate in wastewater treatment plant and long-term emissions from landfill to groundwater after the base failure lining.

Figure 6.25, 6.26 and 6.27 show the list of top ten contributors and hierarchy of contribution percentage of EP by the three waste disposal options of concrete wastes. Details of the EP results are shown in Table 9 in Appendix 2

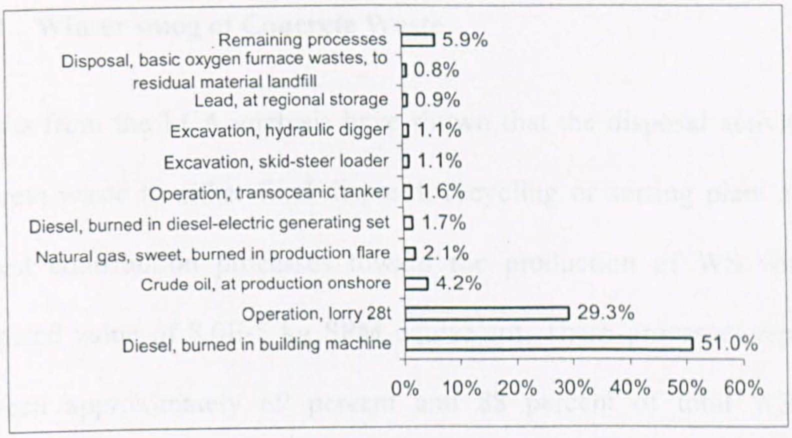

Figure 6.25: Contribution percentage of EP for the concrete waste final disposal

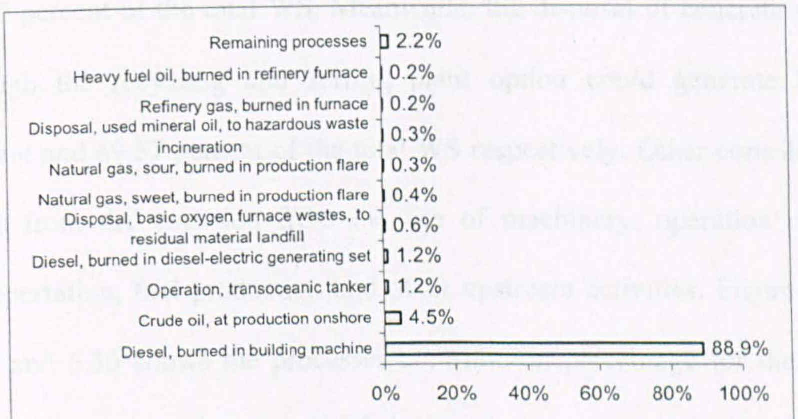

Figure 6.26: Contribution percentage of EP for the concrete waste recycling

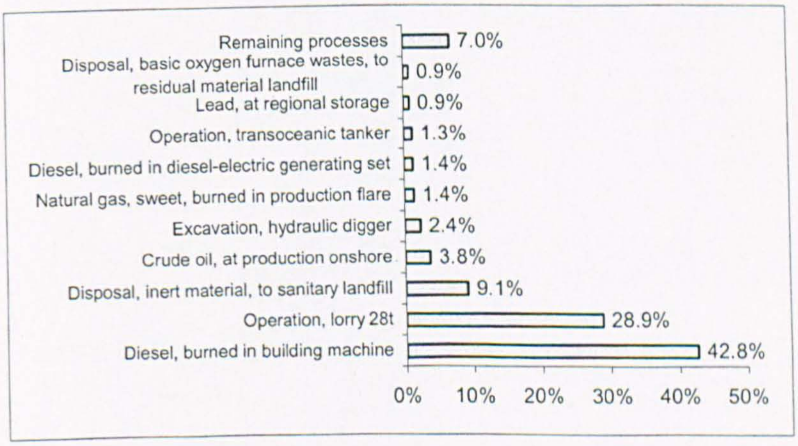

Figure 6.27: Contribution percentage of EP for the concrete waste sorting plant

6.3.4. Winter smog of Concrete Waste

Results from the LCA analysis have shown that the disposal activities of concrete waste to either final disposal, recycling or sorting plant are the highest contribution processes toward the production of WS with the estimated value of 8.0E-5 kg SPM equivalent. These processes represent between approximately 69 percent and 88 percent of total WS. The disposal of concrete to the final disposal could generate approximately 70.17 percent of the total WS. Meanwhile, the disposal of concrete waste through the recycling and sorting plant option could generate 88.11 percent and 69.57 percent of the total WS respectively. Other contribution came from the emission from the use of machinery, operation of the transportation, fuel production and other upstream activities. Figure 6.28, 6.29 and 6.30 shows the processes contribution percentage for the three disposal options, while detail of the result is portrayed in Table10 in Appendix 2

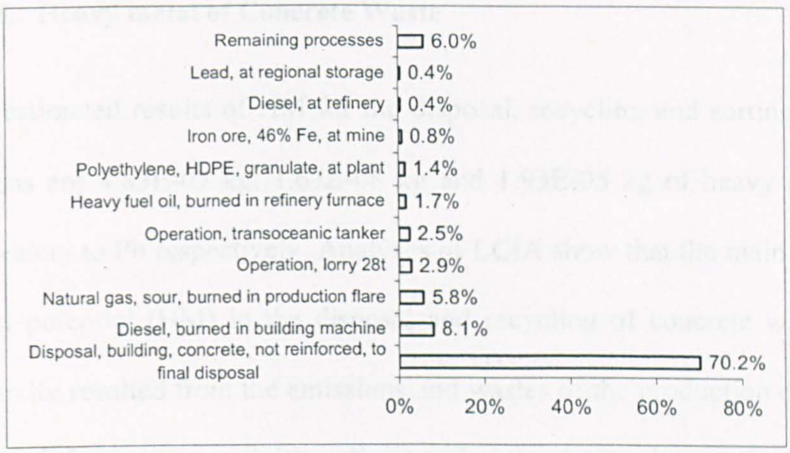

Figure 6.28: Contribution percentage of WS for the concrete waste final disposal

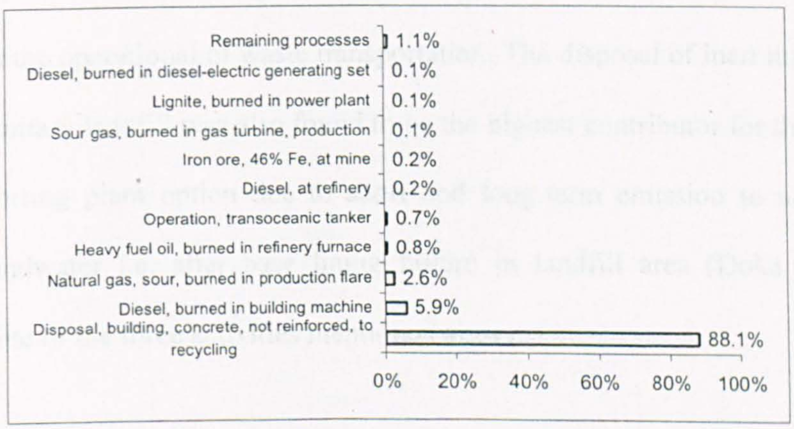

Figure 6.29: Contribution percentage of WS for the concrete waste recycling

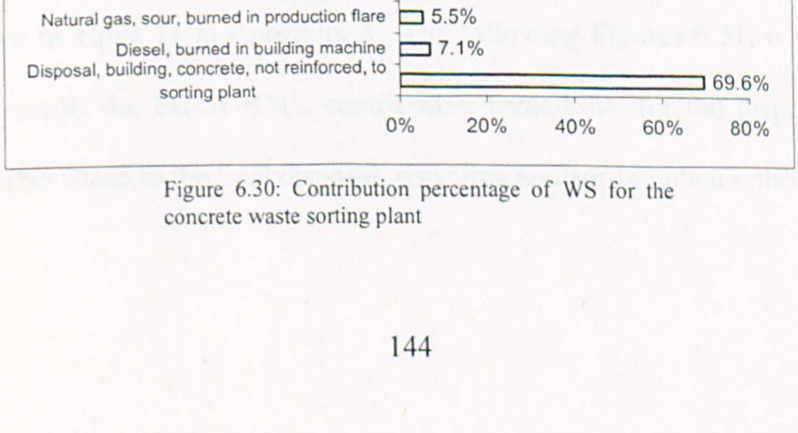

Figure 6.30: Contribution percentage of WS for the concrete waste sorting plant

6.3.5. Heavy metal of Concrete Waste

The estimated results of HM for the disposal, recycling and sorting plant options are 4.83E-07 kg, 1.67E-08 kg and 1.93E-05 kg of heavy metals equivalent to Pb respectively. Analyses of LCIA show that the main heavy metal potential (HM) in the disposal and recycling of concrete waste is generally resulted from the emissions and wastes of the production of steel for the infrastructure activities, direct emissions due to the combustion of heavy fuel oil in refinery furnaces and generators and direct emissions from the operational of waste transportation. The disposal of inert material to sanitary landfill was also found to be the highest contributor for the HM in sorting plant option due to short and long-term emission to air and groundwater i.e. after base lining failure in landfill area (Doka 2003) despite of the three activities mentioned above.

Similarly to the other HM result, the HM for the final disposal and recycling of concrete mostly originated from the production of metal material at upstream stages, while HM for the sorting plant was generated by the activities of disposing the remaining waste from sorting plant to the sanitary landfill. Results of HM for concrete waste disposal options are shown in Table 11 in Appendix 2. The following Figures 6.31, 6.32 and 6.33 depict the list of HM's contribution breakdown for the disposal of concrete waste to the final disposal, recycling and sorting plant options.

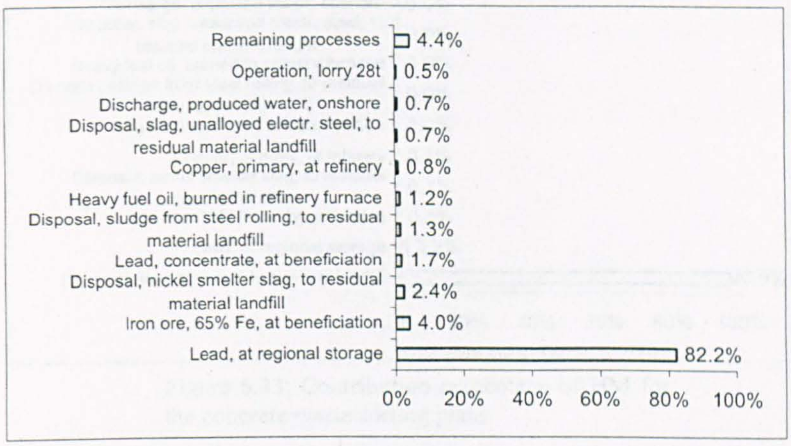

Figure 6.31: Contribution percentage of HM for the concrete waste final

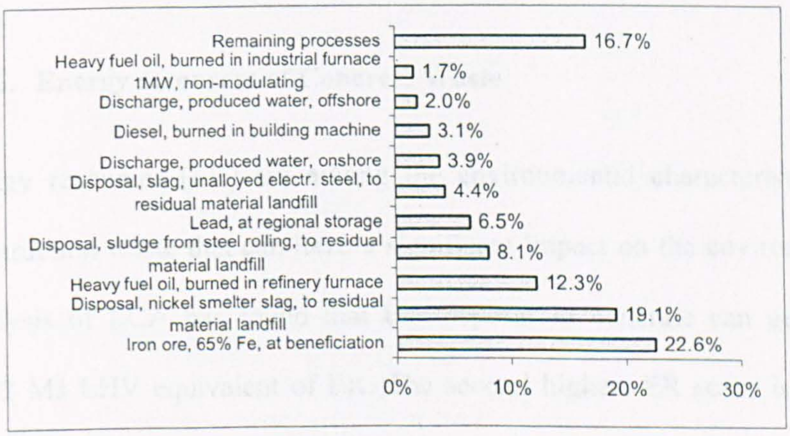

Figure 6.32: Contribution percentage of HM for the concrete waste recycling

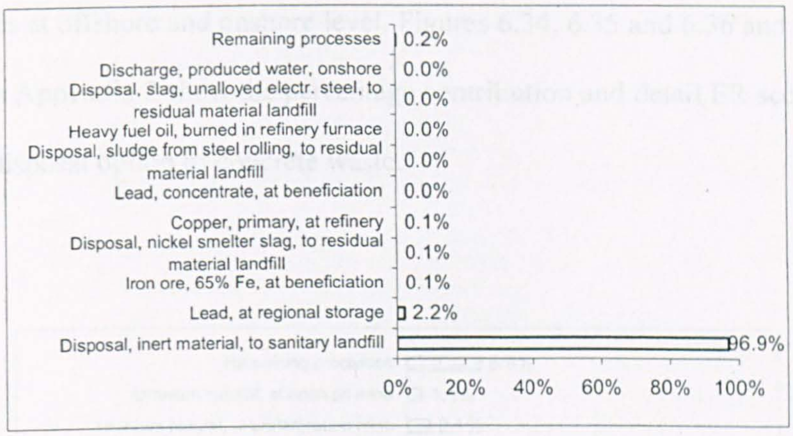

Figure 6.33: Contribution percentage of HM for the concrete waste sorting plant

6.3.6. Energy resources of Concrete Waste

Energy resources (ER) are among the environmental characteristics of construction waste that can have a significant impact on the environment. Analysis of LCA has found that the disposal of concrete can generate 0.322 MJ LHV equivalent of ER. The second highest ER score is 0.318 MJ LHV equivalents and these values were generated from the sorting plant activities. However, the recycling of concrete emerged with the lowest score with ER value of 0.0603 MJ LHV equivalents. Most of the contribution of the three options of managing the concrete waste was from the activities of on-shore and off-shore for the production of crude oil. This is because crude oil is the source of fuel to all machinery operation in managing the concrete waste along its life cycle pathway. It is very clear that the ER results were mostly dominated by the crude oil production stages at offshore and onshore level. Figures 6.34, 6.35 and 6.36 and Table 12 in Appendix 2 show the percentage contribution and detail ER score for the disposal option of concrete waste.

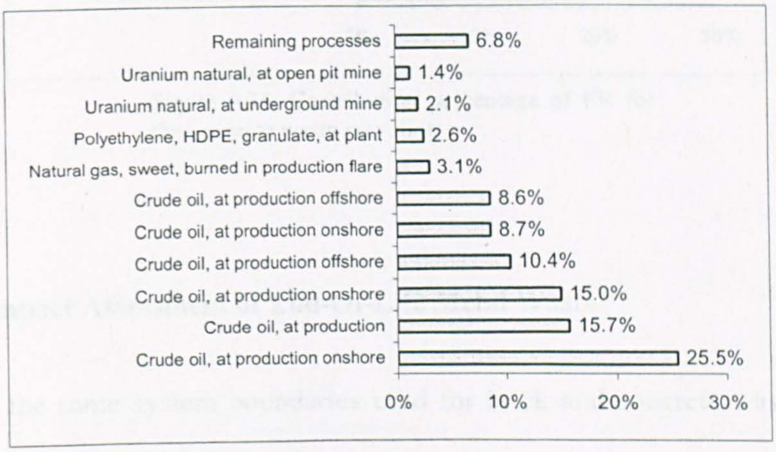

Figure 6.34: Contribution percentage of ER for the concrete waste final

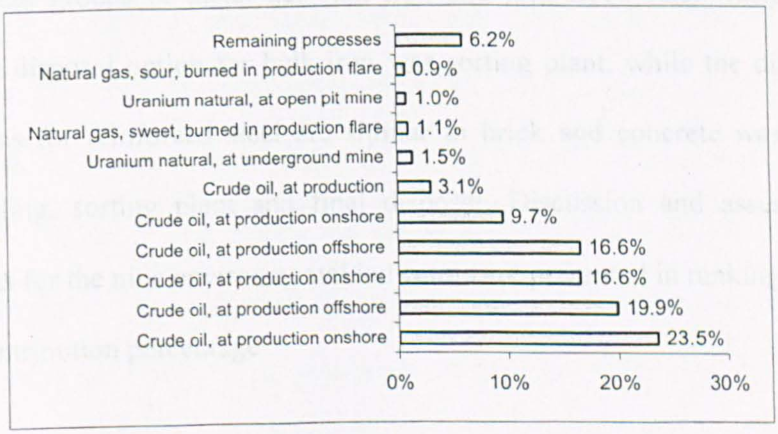

Figure 6.35: Contribution percentage of ER for the concrete waste recycling

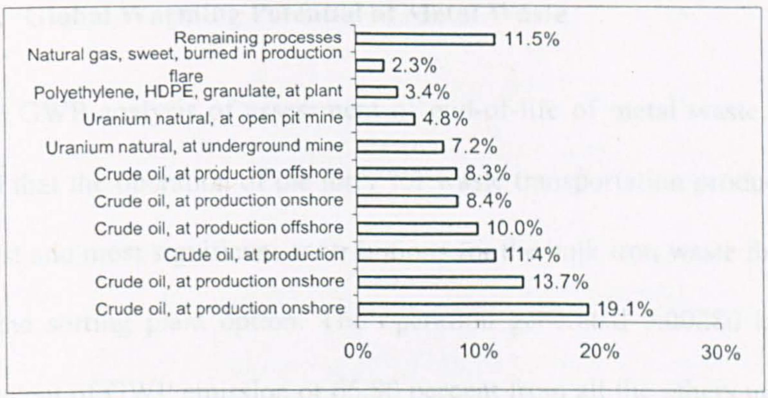

Figure 6.36: Contribution percentage of ER for the concrete waste recycling

6.4. Impact Assessment of End-Of-Life Metal Waste

With the same system boundaries used for brick and concrete waste, the impact assessment of end-of life metal waste has been carried out for two different groups of metal i.e. bulk iron and reinforced steel waste. The waste disposal option for bulk iron was sorting plant, while the disposal options for reinforced steel are similar to brick and concrete waste i.e. recycling, sorting plant and final disposal. Discussion and assessment results for the nine environmental indicators are presented in ranking graph of contribution percentage

6.4.1. Global Warming Potential of Metal Waste

In the GWP analysis of assessment of end-of-life of metal waste, it was found that the operation of the lorry for waste transportation produced the highest and most significant contributions for the bulk iron waste that goes into the sorting plant option. The operation generated 0.00286 kg CO2 equivalent of GWP emission or 66.80 percent from all the others upstream activities like fuel production. Meanwhile, both the use of diesel from the building machinery and the operation of the lorry had dominated the emission contribution towards the generation of GWP in the disposal of reinforcement steel waste. The value of GWP is estimated at 0.00688 and 0.00462 kg CO2 equivalent respectively or with the total percentage of 71.90 percent from all life-cycle activities. However the use of diesel by building machinery was found to be the main cause of GWP with percentage of CO2 equivalent emission. This was as high as 82.5 percent or with the equivalent value of 0.00453 kg from the total of 0.00549 kg CO2 equivalent. But again, the burning of diesel from the building machinery and the operation of lorry was found to be the main cause in generating the GWP for the reinforced steel waste that goes to the sorting plant option. The value of GWP the two activities generated was 0.00619 kg and 0.00477 kg CO2 equivalents. These two results are equal to 69.4 percent from the total GWP results of 0.0158 kg CO2 equivalent.

As a comparison of the total GWP results from three waste disposal options of metal waste, the reinforced steel waste that goes to the final disposal option and sorting plant option is found to be the waste disposal option with the highest CO2 equivalent emission. The two activities produced 0.016 and 0.0158 kg CO2 equivalent respectively. This is followed by the recycling option of reinforced steel waste with the GWP value of 0.00549 kg CO2 equivalent. While the sorting plant option of bulk iron processes give the very low GWP result of 0.00428 kg CO2 equivalent. Figures 6.37 to 6.40 present the percentage breakdown of GWP for the four metal waste disposal options. Details of the results can be seen in Table 13 in Appendix 2.

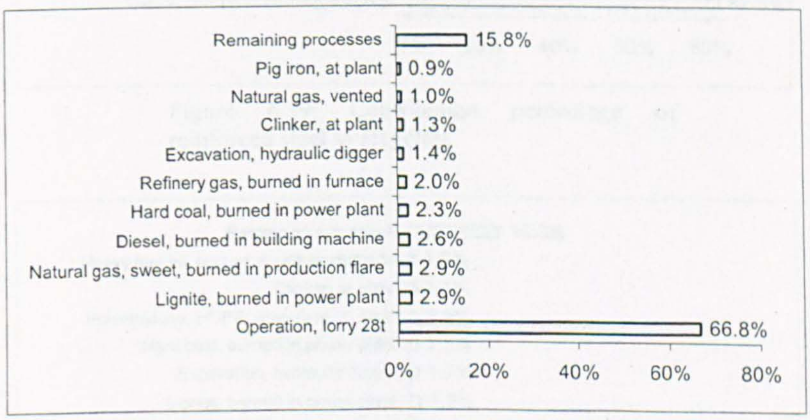

Figure 6.37: Contribution percentage of GWP for bulk iron waste to sorting plant

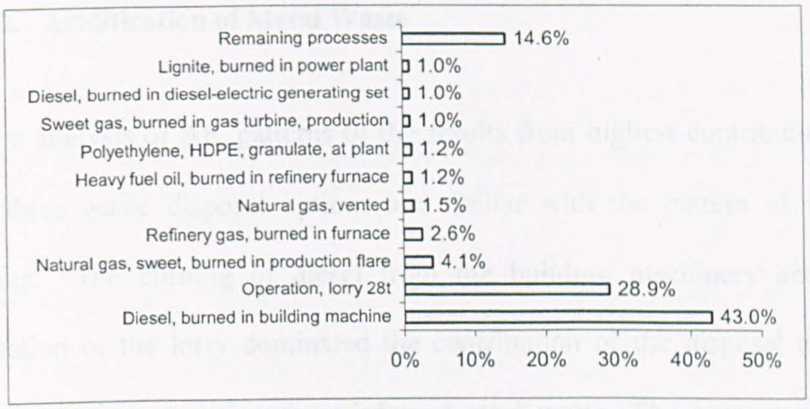

Figure 6.38: Contribution percentage of GWP for reinforced steel waste to final disposal

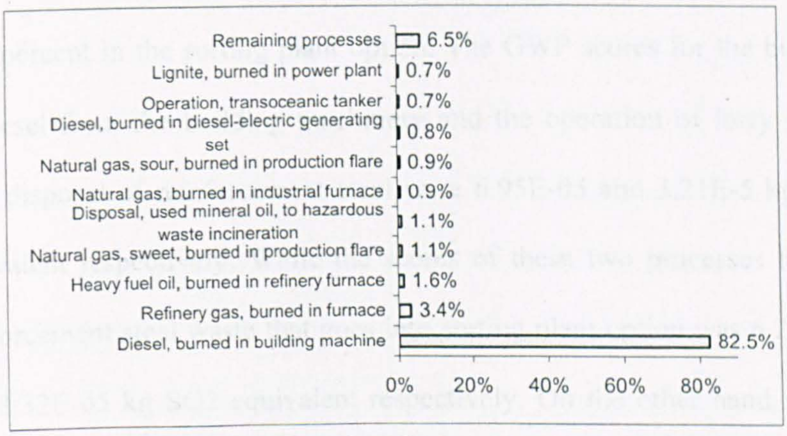

Figure 6.39: Contribution percentage of reinforced steel to recycling

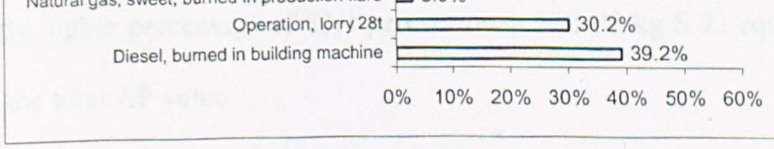

Figure 6.40: Contribution percentage of GWP for reinforced steel to sorting plant

6.4.2. Acidification of Metal Waste

In the analysis of AP, patterns of the results from highest contribution of the three waste disposal options are similar with the pattern of GWP results. The burning of diesel from the building machinery and the operation of the lorry dominated the contribution of the disposal option and sorting plant option for reinforced steel waste. The percentages of contribution from these options are 75.3 percent in disposal option and 73.6 percent in the sorting plant option. The GWP scores for the burning of diesel from the building machinery and the operation of lorry in the final disposal of reinforcement steel were 6.95E-05 and 3.21E-5 kg SO2 equivalent respectively. While the scores of these two processes for the reinforcement steel waste that goes into sorting plant option was 6.25E-05 and 3.32E-05 kg SO2 equivalent respectively. On the other hand, as the main contributor of AP in the sorting of bulk iron processes option, the operation of the lorry contributed 67.9 percent of the total AP value or 1.99E-05 kg SO2 equivalent. Similarly with the GWP for the reinforcement steel waste that goes into recycling option, diesel in building machine has also been found to be the main contributor of AP but with the slightly higher percentage of 83.4 percent or 4..57E-05 kg SO2 equivalent from the total AP value.

From the AP results of the four disposal option processes above, the final disposal sorting plant options for reinforced steel have been found as the highest source, the total AP score with approximate value of 1.35E-04 kg SO2 equivalent. This is because these two options required the extraction of the steel from the block of concrete processes by using a machine like a rock crusher which resulted in the release of related AP emissions. These scenarios can be shown in the following Figures 6.41 to 6.44. Detailed AP analysis results are shown in Table 14 in Appendix 2.

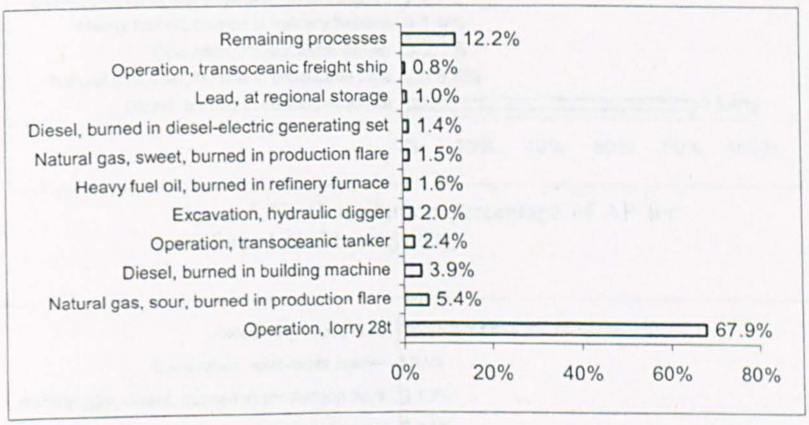

Figure 6.41: Contribution percentage of AP for bulk iron to sorting plant

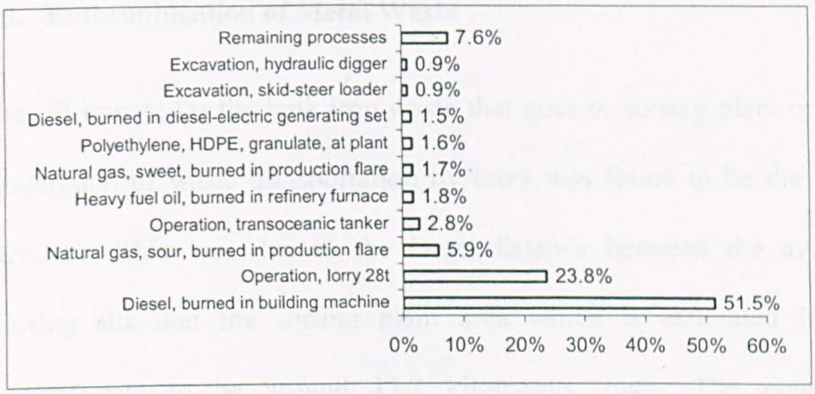

Figure 6.42: Contribution percentage of AP for reinforced steel to final disposal

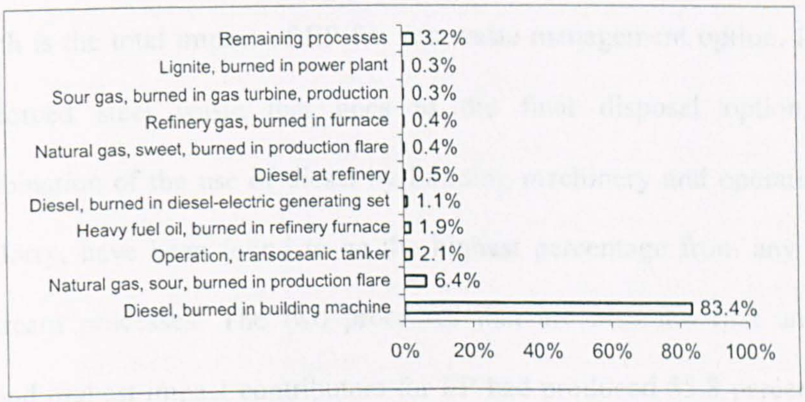

Figure 6.43: Contribution percentage of AP for reinforced steel to recycling

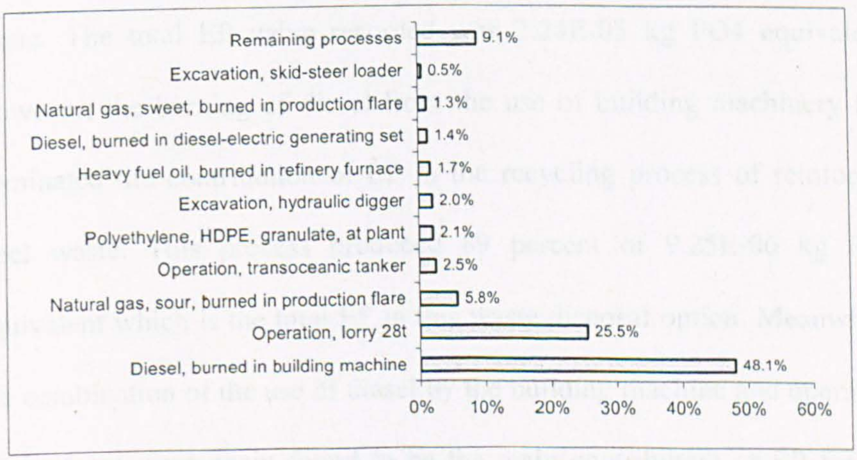

Figure 6.44: Contribution percentage of AP for reinforced steel to sorting plant

6.4.3. Euthrophication of Metal Waste

In the EP impact for the bulk iron waste that goes to sorting plant option, the operation of waste transportation by lorry was found to be the main contributor. This was due to the large distance between the average collecting site and the sorting plant area which is estimated in the inventory data to be around 17.7 kilometres away. The operation contributed approximately 74 percent of the 4.88E-06 kg PO4 equivalent which is the total impact of EP for this waste management option. In the reinforced steel waste that goes to the final disposal option, the combination of the use of diesel by building machinery and operation of the lorry, have been found to be the highest percentage from any other upstream processes. The two processes that are also the first and the second highest impact contributors for EP had produced 55.8 percent and 25.9 percent from the total EP in final disposal option for reinforced steel waste. The total EP value recorded was 2.24E-05 kg PO4 equivalent. However, the burning of diesel from the use of building machinery had dominated the contribution of EP in the recycling process of reinforced steel waste. This process produced 89 percent of 9.25E-06 kg PO4 equivalent which is the total EP in this waste disposal option. Meanwhile, the combination of the use of diesel by the building machine and operation of the lorry were again found to be the main contributors of EP for the reinforcement steel waste that goes to the sorting plant option. The burning of diesel from building machinery contributed 48.1 percent and the operation of the lorry for transporting the reinforced steel waste contributed 25.7 percent for the total EP. The total of EP for this option was 2.33E-05 kg PO4 equivalent.

From the above results, the disposal option of reinforced steel through the sorting plant was found to be the highest EP contributors with EP value of 2.33E-05 kg PO4 equivalent. This was due to the process of extraction of steel from the concrete that needs to be done prior to disposal and this process has been found to be the main contributor in all disposal options for reinforced steel. However, for the bulk iron waste to sorting plant results show the operation of the lorry to be the main EP contributor. The reason is similar to the case given earlier in this section where the distance from collecting point to the plant was quite far away. Contribution percentage values of the four waste management options are shown in Figure 6.45, 6.46, 6.47 and 6.48 and detail of result analysis is shown in Table 15 in Appendix 2.

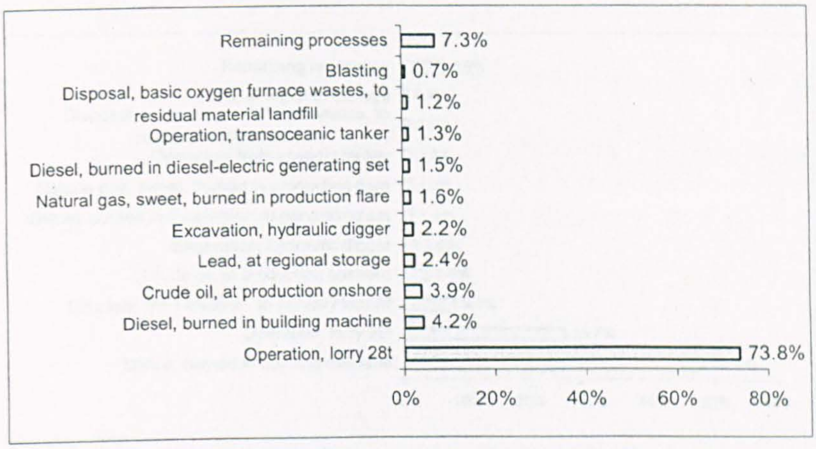

Figure 6.45: Contribution percentage of EP for bulk iron to sorting plant

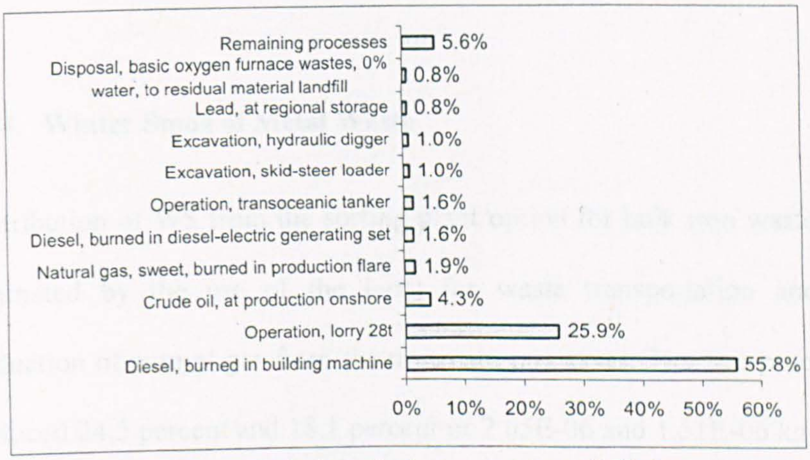

Figure 6.46: Contribution percentage of EP for reinforced steel to final disposal

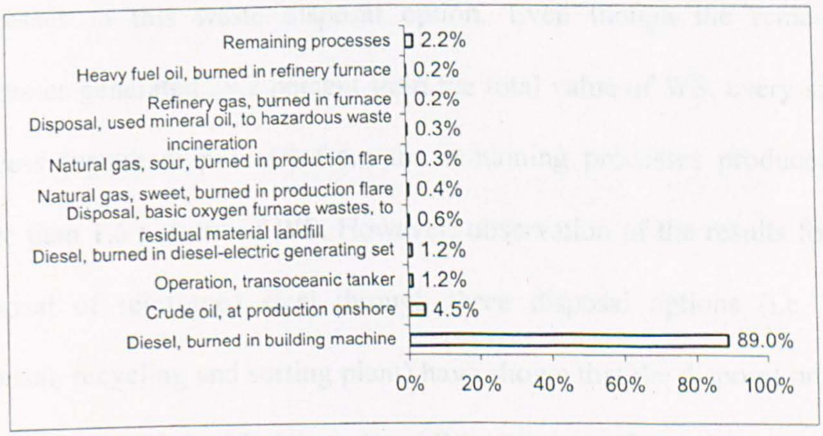

Figure 6.47: Contribution percentage of EP for reinforced steel to recycling

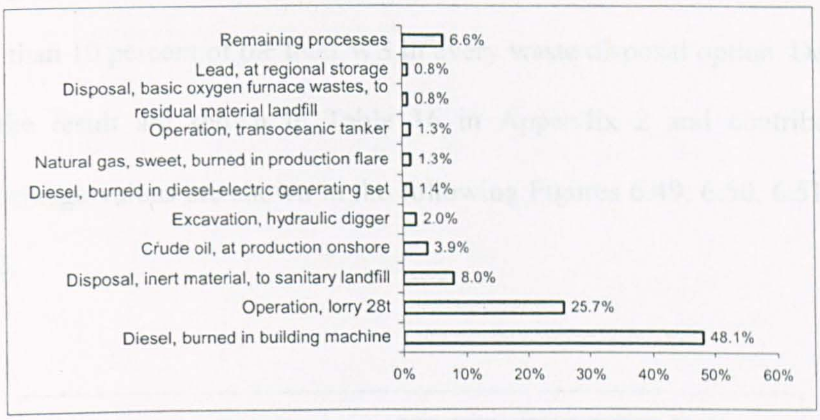

Figure 6.48: Contribution percentage of EP for reinforced steel to sorting plant

6.4.4. Winter Smog of Metal Waste

Contribution of WS from the sorting plant option for bulk iron waste was dominated by the use of the lorry for waste transportation and the production of natural gas from the upstream processes. The two processes produced 24.5 percent and 18.1 percent or 2.05E-06 and 1.51E-06 kg SPM equivalent from the total WS of 8.36E-06 kg SPM equivalent from all processes in this waste disposal option. Even though the remaining processes generated 29.2 percent from the total value of WS, every single process (upstream process) from the remaining processes produced no more than 1.6 percent of WS. However, observation of the results for the disposal of reinforced steel through three disposal options (i.e. final disposal, recycling and sorting plant) have shown that the disposal process itself contributed significant results of WS. All the options generated 8.0E-

05 kg SPM equivalent WS. Other related processes had only produced WS less than 10 percent of the total WS in every waste disposal option. Details of the result are shown in Table 16 in Appendix 2 and contribution percentage values are shown in the following Figures 6.49, 6.50, 6.51 and 6.52.

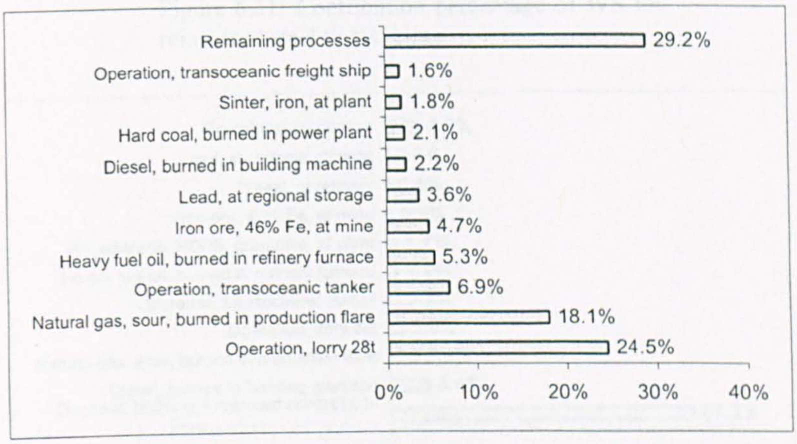

Figure 6.49: Contribution percentage of WS for bulk iron to sorting plant

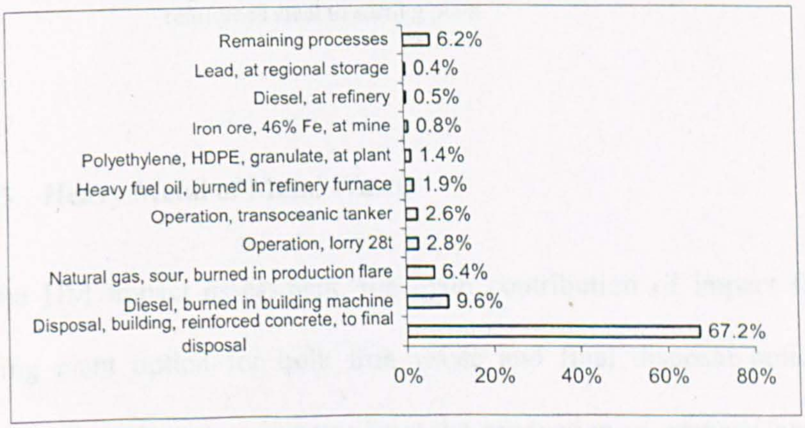

Figure 6.50: Contribution percentage of WS for reinforced steel to final disposal

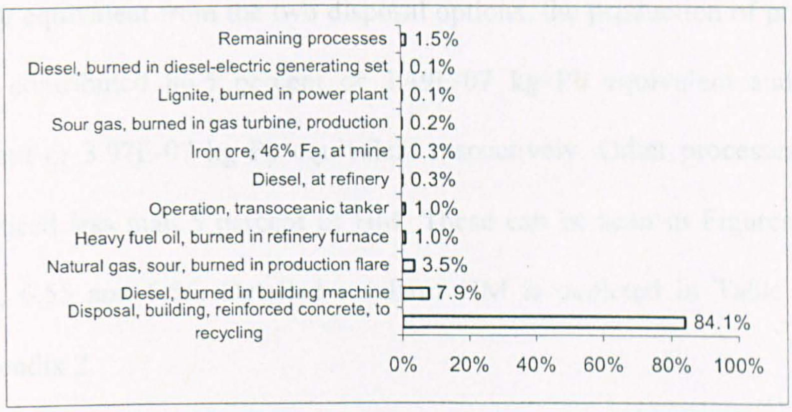

Figure 6.51: Contribution percentage of WS for reinforced steel to recycling

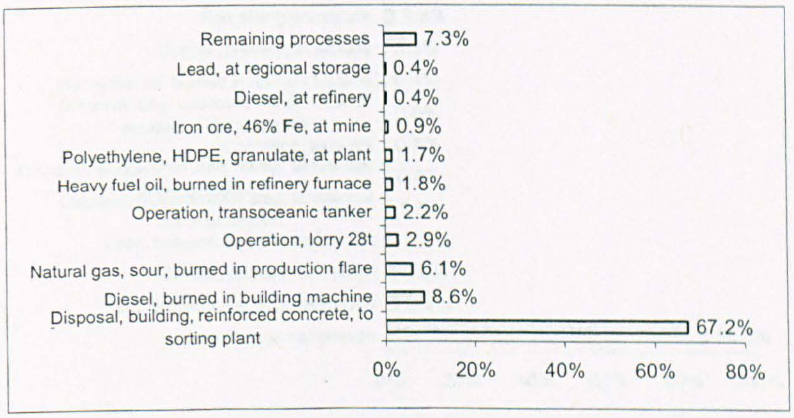

Figure 6.52: Contribution percentage of WS for reinforced steel to sorting plant

6.4.5. Heavy Metal of Metal Waste

In the HM impact assessment, the main contribution of impact for the sorting plant option for bulk iron waste and final disposal option for reinforced steel waste originates from the production of primary lead with the use of a sinter/blast furnace for the other upstream activities. From the total impact potential of HM of 2.88E-07 kg Pb equivalent and 4.89E-07 kg Pb equivalent from the two disposal options, the production of primary lead contributed 86.5 percent or 2.49E-07 kg Pb equivalent and 81.2 percent or 3.97E-07 kg Pb equivalent respectively. Other processes only produced less than 5 percent of HM. These can be seen in Figures 6.53, 6.54, 6.55 and 6.56. Detailed result of HM is depicted in Table 17 in Appendix 2

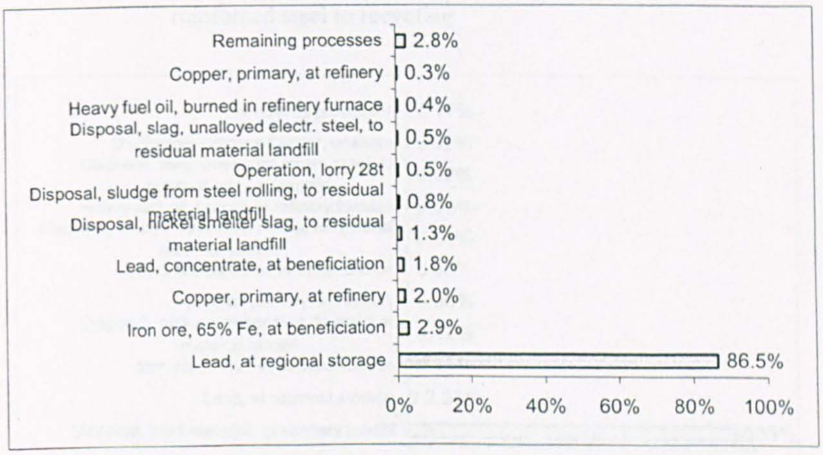

Figure 6.53: Contribution percentage of HM for bulk iron to sorting plant

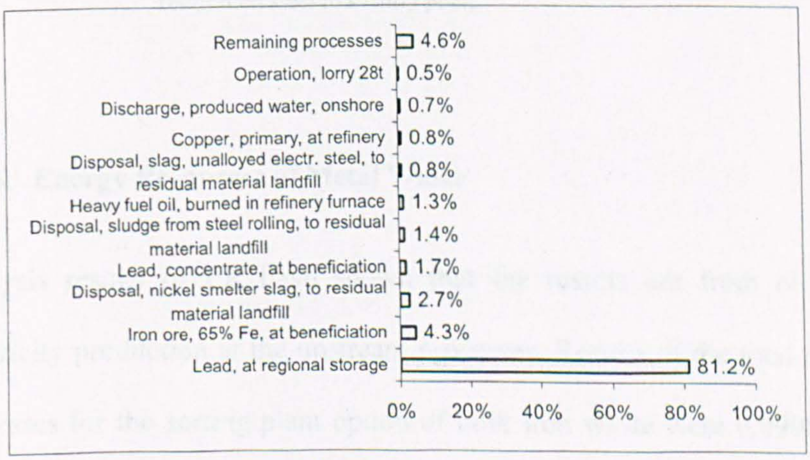

Figure 6.54: Contribution percentage of HM for reinforced steel to final disposal

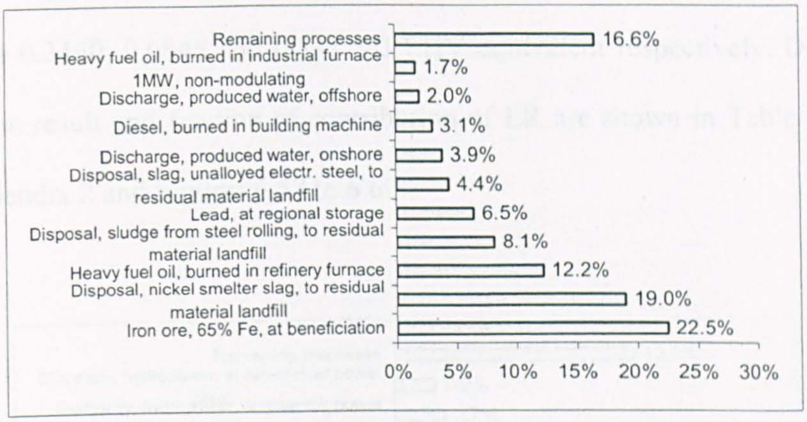

Figure 6.55: Contribution percentage of HM for reinforced steel to recycling

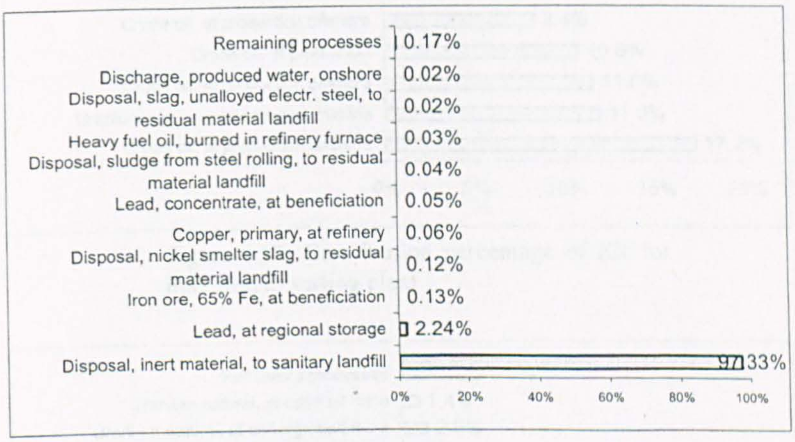

Figure 6.56: Contribution percentage of HM for reinforced steel to sorting plant

6.4.6. Energy Resources of Metal Waste

Analysis results of ER have shown that the results are from oil and electricity production at the upstream processes. Results of the total of all processes for the sorting plant option of bulk iron waste were 0.0908 MJ LHV equivalents. Meanwhile, results of the total of all processes for the final disposal, recycling and sorting plant option for reinforced steel waste were 0.3460, 0.0845 and 0.338 MJ LHV equivalent respectively. Details of the result and fraction of contribution of ER are shown in Table 18 in Appendix 2 and Figures 6.57 to 6.60.

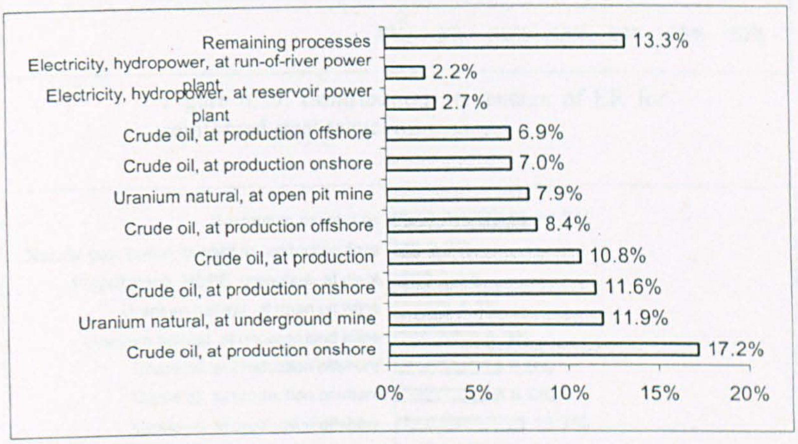

Figure 6.57: Contribution percentage of ER for bulk iron to sorting plant

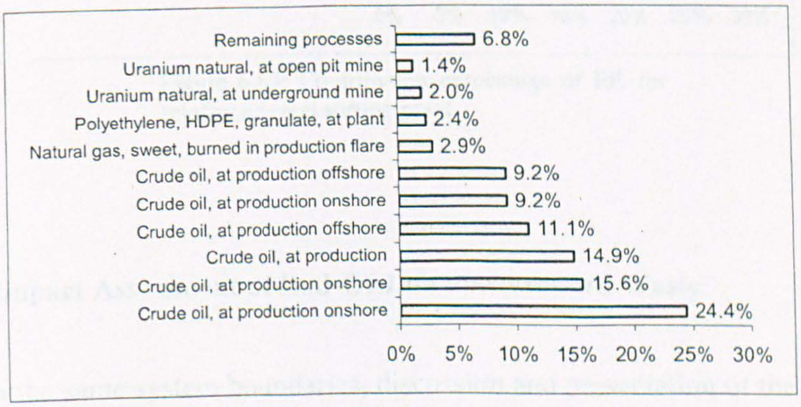

Figure 6.58: Contribution percentage of for reinforced steel to final disposal

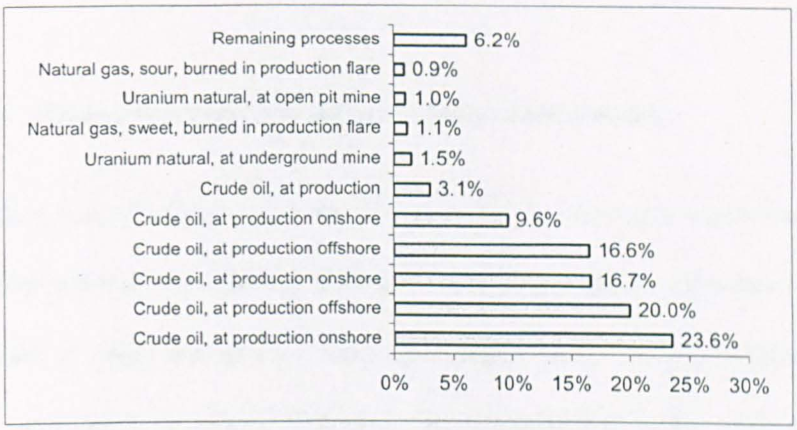

Figure 6.59: Contribution percentage of ER for reinforced steel recycling

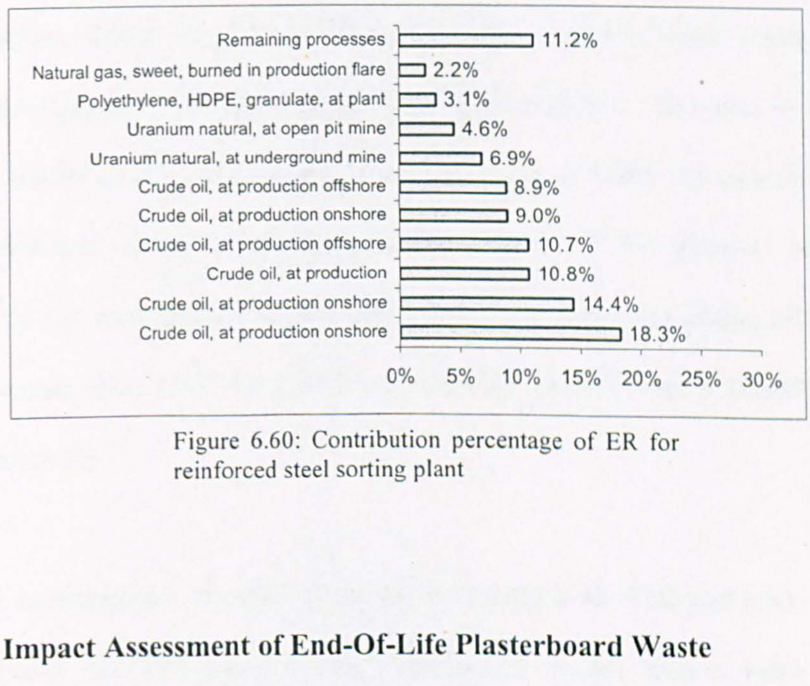

Figure 6.60: Contribution percentage of ER for reinforced steel sorting plant

6.5. Impact Assessment of End-Of-Life Plasterboard Waste

With the same system boundaries, discussion and presentation of the result of the impact assessment analysis have been done in a similar way to brick and concrete waste.

6.5.1. Global Warming Potential of Plasterboard Waste

In GWP, transportation of waste was found to be the main contributor for the disposal and sorting plant activities. The transportation of waste for the disposal of 1kg plasterboard waste generated approximately 0.00462 kg CO^2 equivalent of GWP. While if 1kg plasterboard waste goes to the sorting plant, it will generate 0.00706 kg CO^2 equivalent of GWP. However, GWP for the recycling of 1kg of plasterboard waste was dominated by the activities at the plant of oil refinery. The value of GWP was 0.00011 CO^2 equivalents. The total value of GWP for construction plasterboard waste is estimated at around 0.0137 for disposal option, 0.0216 for sorting plant option and 0.00322 for recycling option with the eco-costs value of £0.14, £0.22 and £0.03 for every tonne of plasterboard respectively.

The contribution of impact is shown in Figures 6.61, 6.62 and 6.63, while details of the GWP result for the plasterboard can bee seen in Table 19 in Appendix 2.

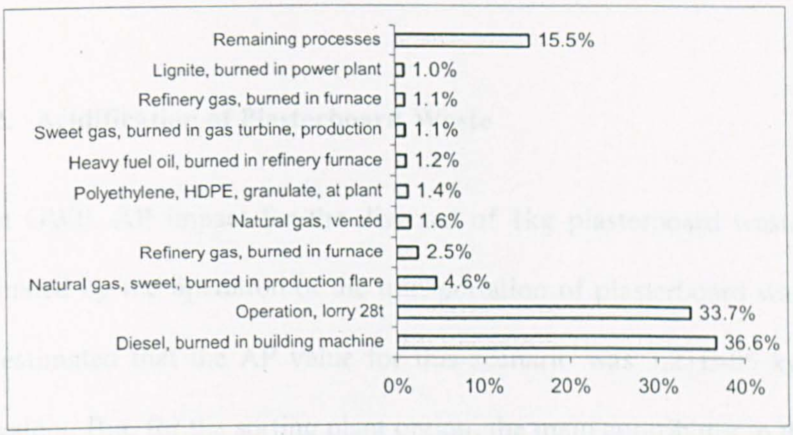

Figure 6.61: Contribution percentage of GWP for plasterboard waste to final disposal

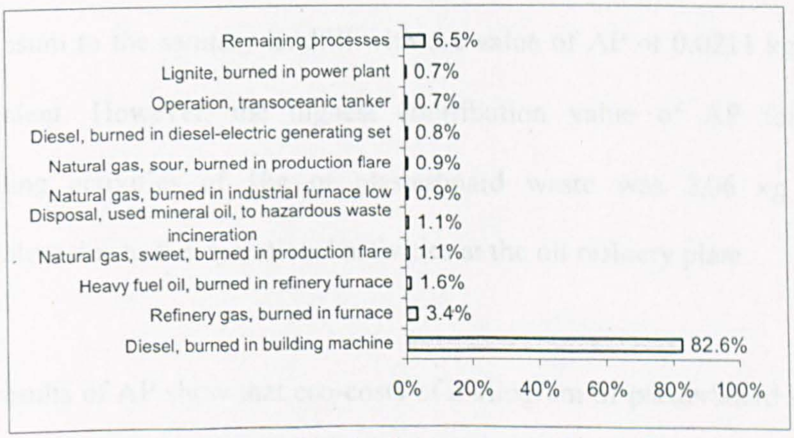

Figure 6.62: Contribution percentage of GWP for plasterboard waste to recycling

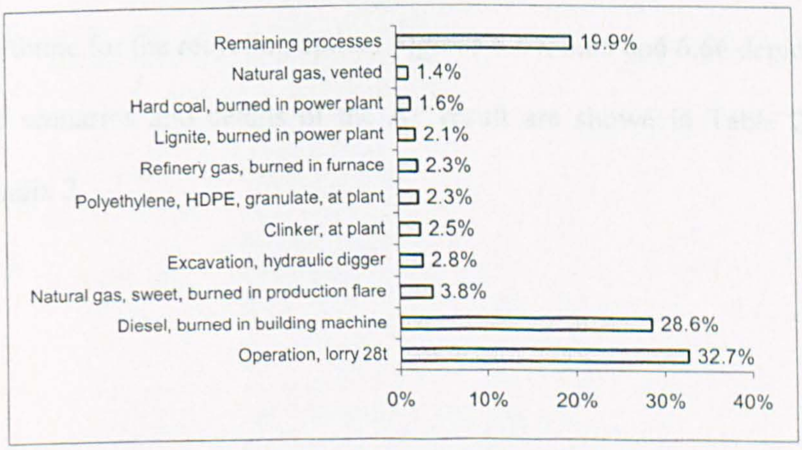

Figure 6.63: Contribution percentage of GWP for plasterboard waste to sorting plant

6.5.2. Acidification of Plasterboard Waste

As in GWP, AP impact for the disposal of 1kg plasterboard waste was dominated by the operation of the transportation of plasterboard waste. It was estimated that the AP value for this scenario was 3.21E-05 kg SO^2 equivalent. But, for the sorting plant option, the main contributor to the AP impact for the 1kg plasterboard waste to the sorting plant was the disposal of gypsum to the sanitary landfill with the value of AP of 0.0211 kg SO^2 equivalent. However, the highest contribution value of AP for the recycling activities of 1kg of plasterboard waste was 2.06 kg SO^2 equivalent due to the operational activities at the oil refinery plant.

The results of AP show that eco-costs of a kilogram of plasterboard waste to sorting plant is the highest with the value of £161.67/tonne of plasterboard waste, followed by £0.85/tonne for the disposal option and £0.25/tonne for the recycling option. Figures 6.64, 6.65 and 6.66 depict the above scenarios and details of the AP result are shown in Table 20 in Appendix 2

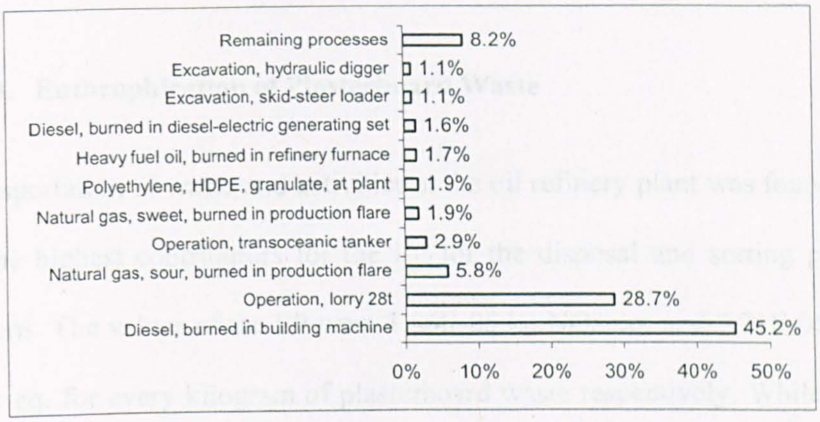

Figure 6.64: Contribution percentage of AP for plasterboard waste to final disposal

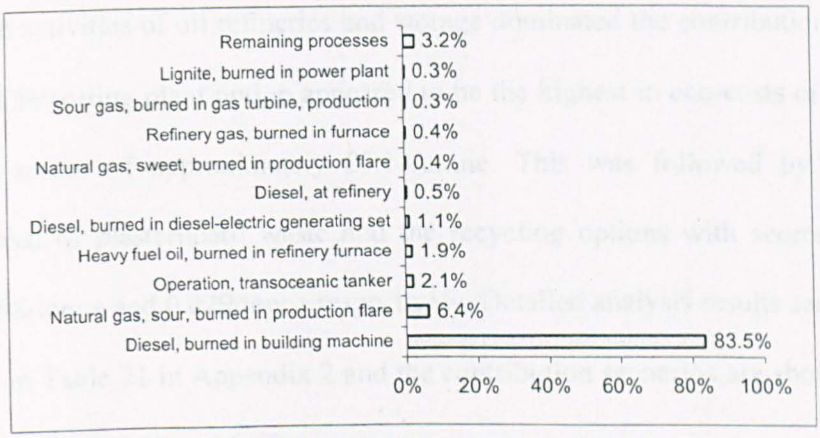

Figure 6.65: Contribution percentage of AP for plasterboard waste to recycling

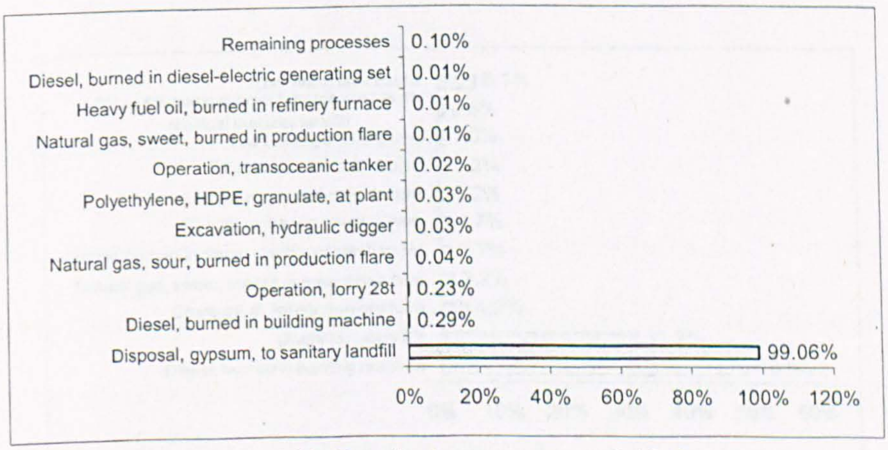

Figure 6.66: Contribution percentage of AP for plasterboard waste to sorting plant

6.5.3. Euthrophication of Plasterboard Waste

Transportation of waste and activities at the oil refinery plant was found to be the highest contributors for the EP for the disposal and sorting plant options. The values of the EP were 1.86E-05 kg NOx eq. and 2.71E-05 kg NOx eq. for every kilogram of plasterboard waste respectively. While the recycling option shows the lowest value of EP with 5.43E-06 kg NOx eq as the activities of oil refineries and storage dominated the contribution of EP. The sorting plant option appeared to be the highest in eco-costs of EP with scores of approximately £0.14/tonne. This was followed by the disposal of plasterboard waste and the recycling options with scores of £0.098/tonne and 0.029/tonne respectively. Detailed analysis results can be seen in Table 21 in Appendix 2 and the contribution scenarios are show in Figures 6.67, 6.68 and 6.69.

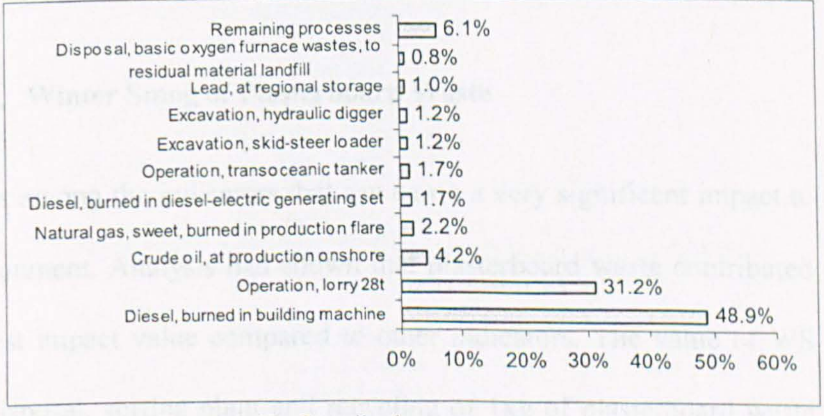

Figure 6.67: Contribution percentage of EP for plasterboard waste to final disposal

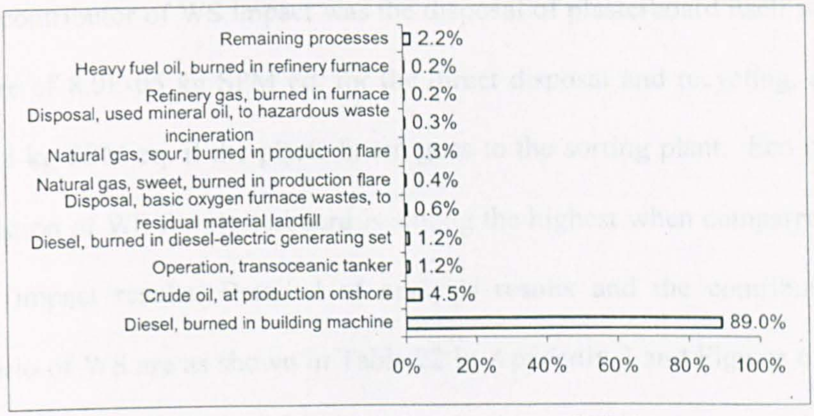

Figure 6.68: Contribution percentage of EP for plasterboard wastes to recycling

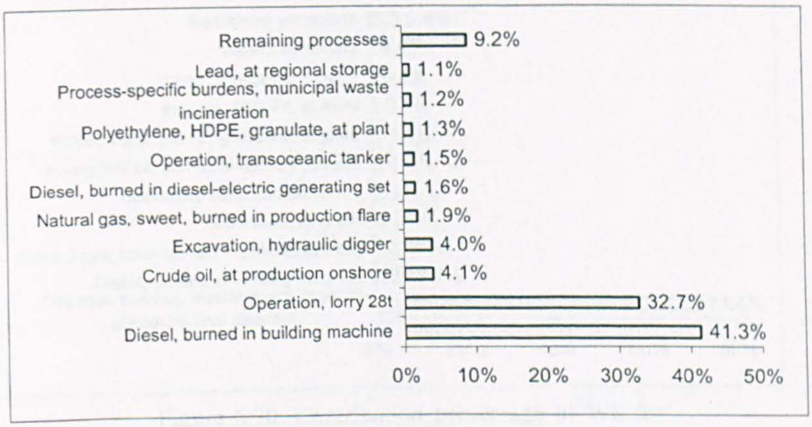

Figure 6.69: Contribution percentage of EP for plasterboard waste to sorting plant

6.5.4. Winter Smog of Plasterboard Waste

WS is among the indicators that can cause a very significant impact to the environment. Analysis had shown that plasterboard waste contributed the highest impact value compared to other indicators. The value of WS for the disposal, sorting plant and recycling of 1kg of plasterboard waste are 1.12E-04 kg SPM eq., 0.021 kg SPM eq., and 8.89E-05 kg SPM eq. The main contributor of WS impact was the disposal of plasterboard itself with a score of 8.0E-05 kg SPM eq. for the direct disposal and recycling, and 0.0208 kg SPM eq. if the plasterboard goes to the sorting plant. Eco-cost estimation of WS for plasterboard is among the highest when compared to other impact results. Detailed of analysis results and the contribution scenario of WS are as shown in Table 22 in Appendix 2 and Figures 6.70, 6.71 and 6.72.

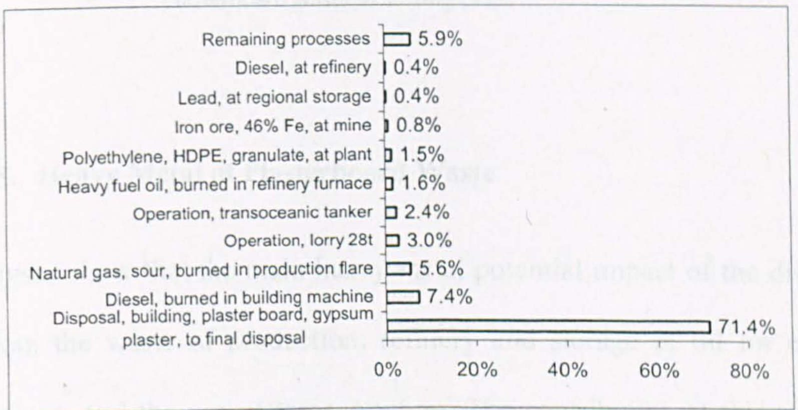

Figure 6.70: Contribution percentage of WS for plasterboard waste to final disposal

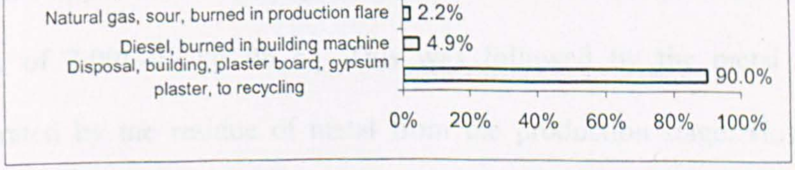

Figure 6.71: Contribution percentage of WS for plasterboard waste to recycling

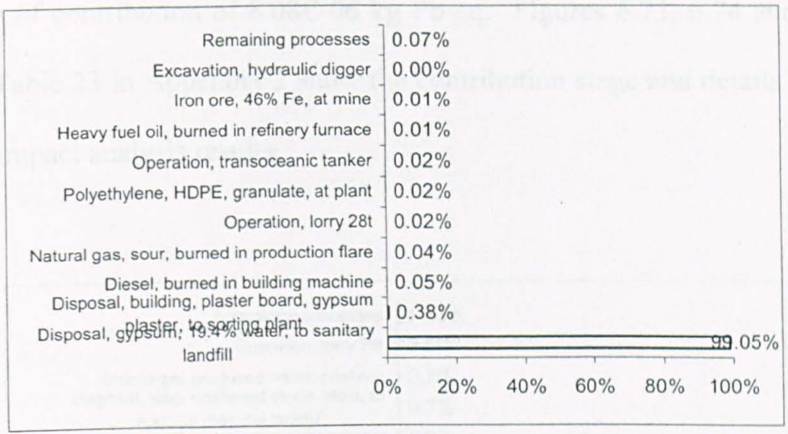

Figure 6.72: Contribution percentage of WS for plasterboard waste to sorting plant

6.5.5. Heavy Metal of Plasterboard Waste

Analyses show that the main heavy metal potential impact of the disposal is from the waste of production, refinery and storage of oil for energy resources, and the use of transportation. The contribution at this stage is 3.97E-07 kg Pb eq. The impact from the recycling option is from the use of metal type materials at the stage of production and delivery of construction facilities like building machinery and the use of oil as a source of energy. The milling and sorting of crude ore for the production of metal appears to be the highest contributor to the heavy metal with the value of 3.09E-09 kg Pb eq. This was followed by the metal waste generated by the residue of metal from the production stage. However, results show that the disposal of gypsum to the sanitary landfill appears to be the highest contributor to the HM for the sorting plant option with the value of contribution of 8.08E-06 kg Pb eq. Figures 6.73, 6.74 and 6.75 and Table 23 in Appendix 2 show the contribution stage and details of the HM impact analysis results.

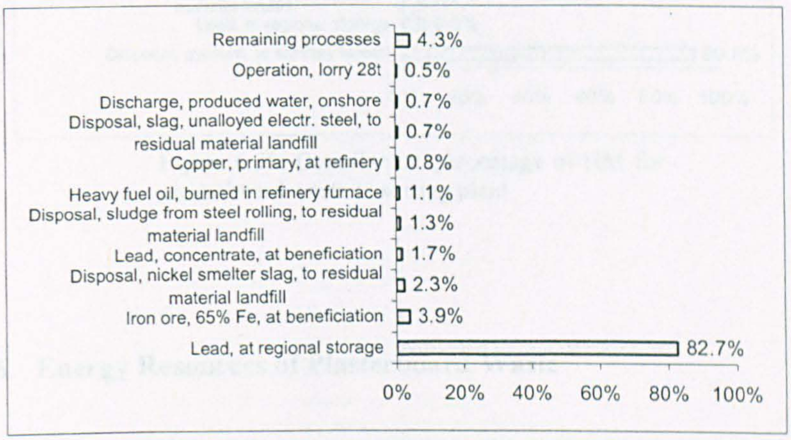

Figure 6.73: Contribution percentage of HM for plasterboard waste to final disposal

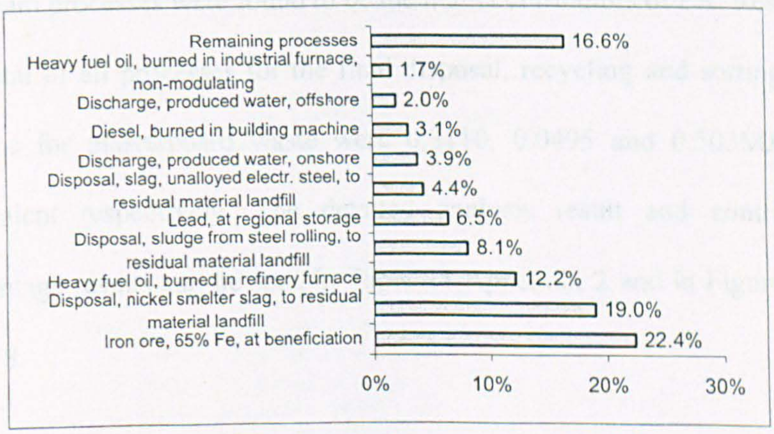

Figure 6.74: Contribution percentage of HM for plasterboard waste to recycling

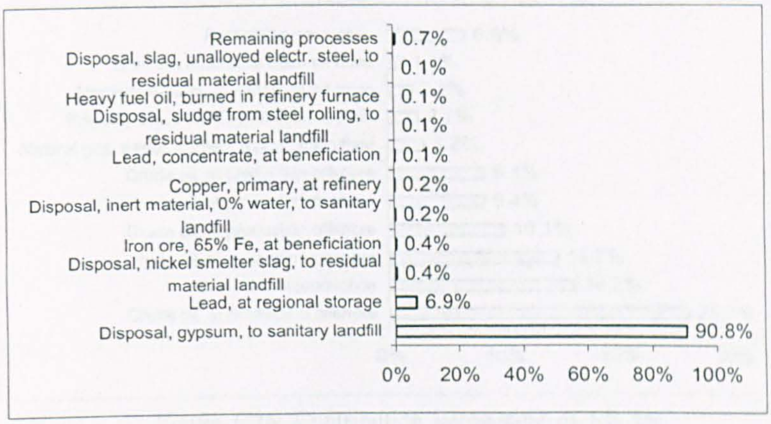

Figure 6.75: Contribution percentage of HM for plasterboard waste to sorting plant

6.5.6. Energy Resources of Plasterboard Waste

Results have shown that oil production and electricity production at the upstream processes were found to be the main contributors of ER. Results of the total of all processes for the final disposal, recycling and sorting plant options for plasterboard waste were 0.3110, 0.0495 and 0.503MJ LHV equivalent respectively. The detailed analysis result and contribution percentage results can be seen in Table 24 Appendix 2 and in Figures 6.76 to 6.78.

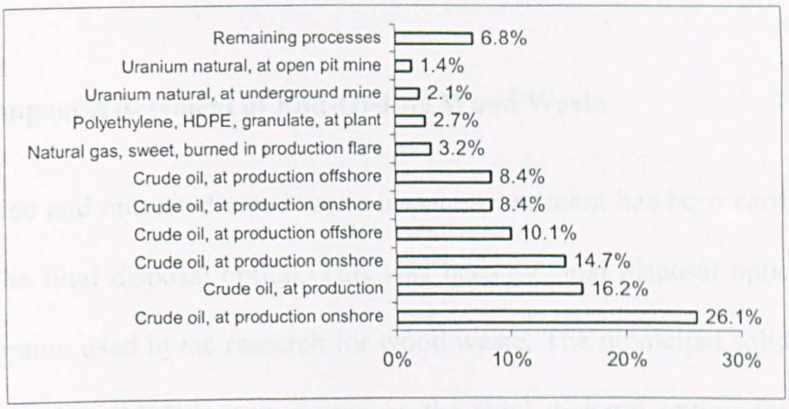

Figure 6.76: Contribution percentage of ER for plasterboard waste to final disposal

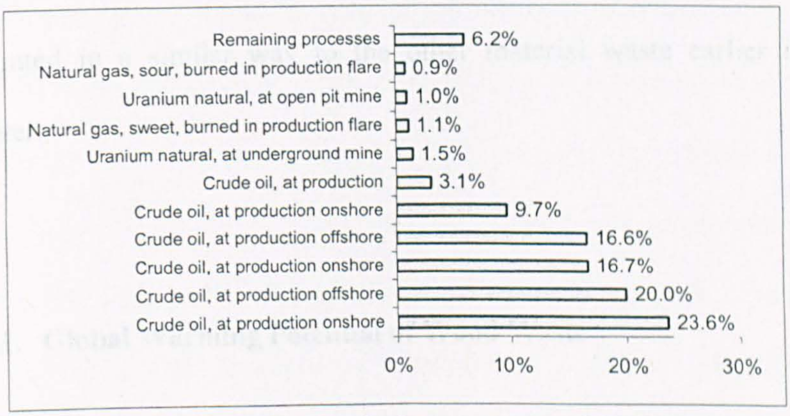

Figure 6.77: Contribution percentage of ER for plasterboard waste to recycling

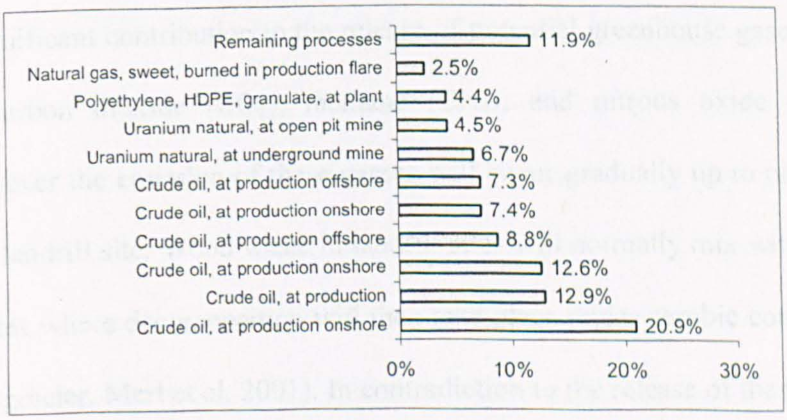

Figure 6.78: Contribution percentage of ER for plasterboard waste to sorting plant

6.6. Impact Assessment of End-Of-Life Wood Waste

Treated and untreated wood waste impact assessment has been carried out for the final disposal option. This was because final disposal option was the option used in the research for wood waste. The municipal solid waste incineration (MSWI) was chosen as the final disposal option for wood waste in this research. Discussion and results for every indicator are presented in a similar way to the other material waste earlier in this chapter.

6.6.1. Global Warming Potential of Wood Waste

As discussed in the previous section, high carbon and nitrogen content of wood during its decomposition in landfill and the incineration process give a significant contribution to the release of potential greenhouse gases such as carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O). However the emission of these gasses will occur gradually up to one year in a landfill site. Wood waste in landfill sites will normally mix with other wastes where decomposition will then take place under aerobic conditions (Jungmeier, Merl et al. 2001). In contradiction to the release of these gases in the landfill scenario, incineration of wood waste releases greenhouse gases over a much shorter period and this will potentially make the amount of these gases overloaded before they can be finally dispersed into the environment e.g. through the plants and trees the CO_2-uptake during photosynthesis and the embodiment of solar energy (de Feyter 1995, Althaus et al. 2003).

LCIA of the study has found that MSWI for both treated and untreated wood waste was the main contributor to the release of global warming potential gases (GWP). Approximately 14.6 kg CO_2 equivalent of GWP per kilogram material waste. The other process found to produce burdens in the form of GWP was from the operation of the municipal waste incineration process itself. Although this operation did not attribute to specific waste, GWP was emitted through fuel input from high pressure network, infrastructure (boiler), and electricity needed for operation of the incinerator. This process produced approximately 0.00304 kg CO_2 equivalent of GWP per kilogram material waste. Two other processes found to generate GWP were from the manufacturing of infrastructure of the MSWI plant and transportation of waste, approximately 0.003257 CO_2 equivalents of GWP and 0.000803 CO_2 equivalents of GWP per kilogram material waste respectively. Detailed analysis results and GWP scenarios of treated and untreated wood wastes to final disposal are shown in Table 25 in Appendix 2 and Figures 6.79 and 6.80.

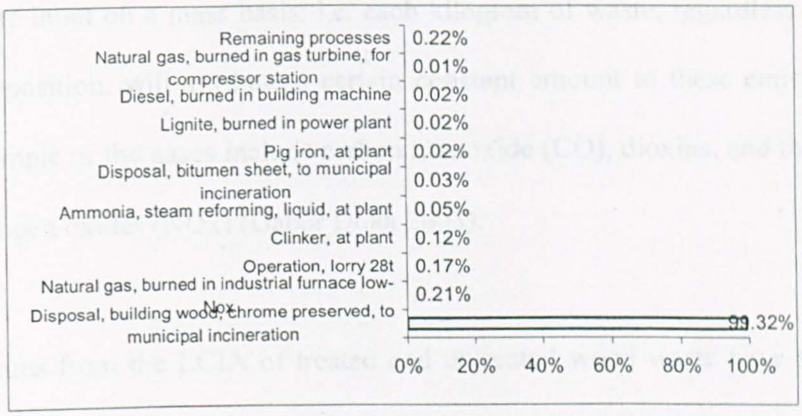

Figure 6.79: Contribution percentage of GWP for treated wood waste to final disposal

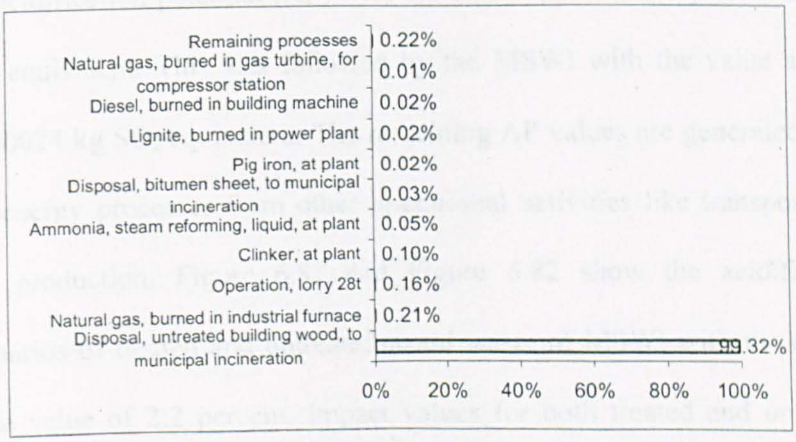

Figure 6.80: Contribution percentage of GWP for untreated wood waste to final disposal

6.6.2. Acidification of Wood Waste

The process of the specific burdens from MSWI has been found to be the main cause of the acidification impact. Also known as 'process-specific emissions', they are generated from the operating conditions rather than being dependent on waste input that include temperature, flow velocities and oxygen concentrations. These emissions are evenly attributed to the waste input on a mass basis; i.e. each kilogram of waste, regardless of its composition, will attribute a certain constant amount to these emissions. Example of the gases include carbon monoxide (CO), dioxins, and thermal nitrogen oxides (NOx) (Gabor Doka 2003).

Results from the LCIA of treated and untreated wood waste have shown that the process-specific burden of MSWI was the highest contributor of the acidification potential (AP) with the value approximately 0.000237 kg SO_2 equivalent. This was followed by the MSWI with the value around 0.000024 kg SO_2 equivalent. The remaining AP values are generated from the energy processes from other operational activities like transportation and production. Figure 6.81 and Figure 6.82 show the acidification scenarios of treated and untreated wood waste of MSWI with the cut-off node value of 2.2 percent. Impact values for both treated and untreated wood waste for AP are estimated at around 0.000307 kg SO_2. Details of the AP result for wood waste can be seen in Table 26 in Appendix 2

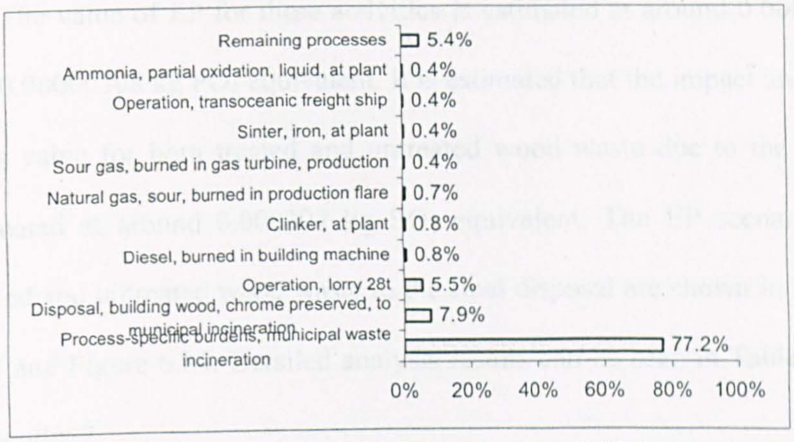

Figure 6.81: Contribution percentage of AP for treated wood waste to final disposal

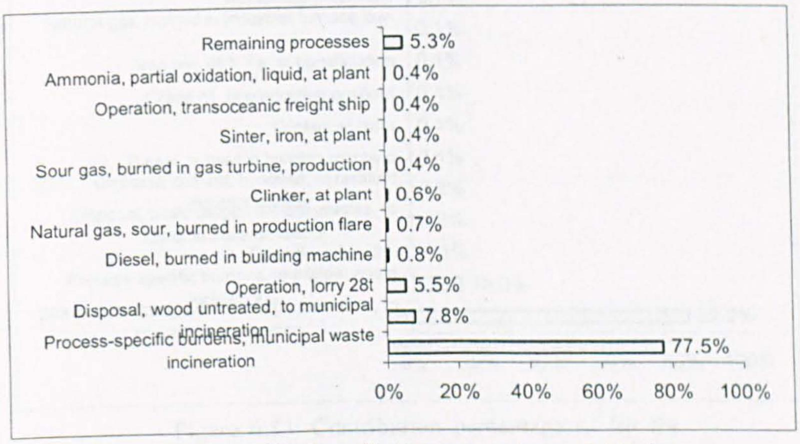

Figure 6.82: Contribution percentage of AP for untreated wood waste to final disposal

6.6.3. Euthrophication of Wood Waste

Unlike the acidification impact, MSWI for both treated and untreated wood waste was found to be the main contributor to the euthophication potential (EP) effect. It was estimated around 0.00024 kg PO_4 equivalent emitted from MSWI, while the process-specific emissions and transportation have been determined as other activities that produce the

EP. The value of EP for these activities is estimated at around 0.0000439 and 0.00000308 kg PO_4 equivalent. It is estimated that the impact and eco-costs value for both treated and untreated wood waste due to the EP is estimated at around 0.000307 kg SO_2 equivalent. The EP scenarios of treated and untreated wood waste to the final disposal are shown in Figure 6.83 and Figure 6.84. Detailed analysis results can be seen in Table 27 in Appendix 2.

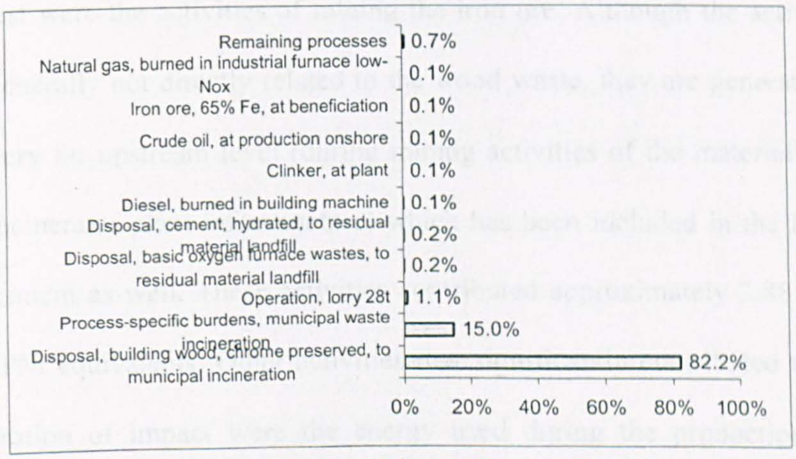

Figure 6.83: Contribution percentage of EP for treated wood waste to final disposal

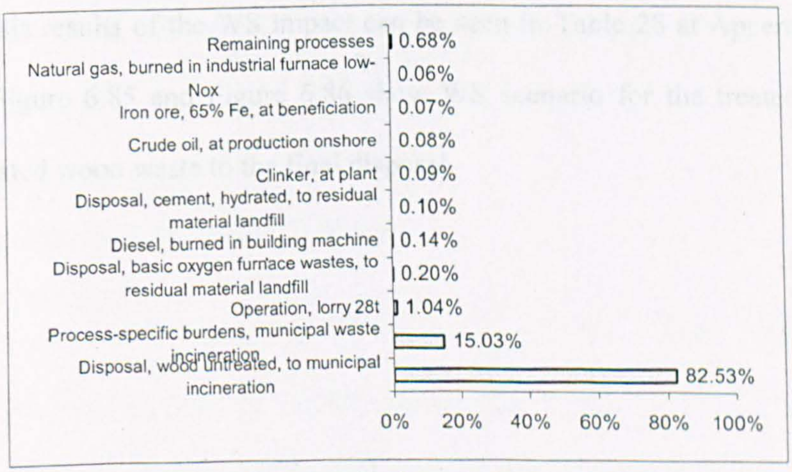

Figure 6.84: Contribution percentage of AP for untreated wood waste to final disposal

6.6.4. Winter Smog of Wood Waste

Winter smog contributed considerably to eco-costs. LCIA results show that process-specific burdens were found to be the main contributor of winter smog potential (WS). It is estimated that the process-specific burdens contribute approximately 6.0×10^{-6} kg SPM equivalent. Second highest were the activities of mining the iron ore. Although the activities are generally not directly related to the wood waste, they are generated at the very far upstream level (during mining activities of the material used for incinerator plant infrastructure) which has been included in the LCIA assessment as well. These activities contributed approximately 2.88×10^{-6} kg SPM equivalents. Other activities that significantly contributed to the generation of impact were the energy used during the production and transportation of waste and fuel at the incineration plant. Details for the analysis results of the WS impact can be seen in Table 28 at Appendix 2 and Figure 6.85 and Figure 6.86 show WS scenario for the treated and untreated wood waste to the final disposal

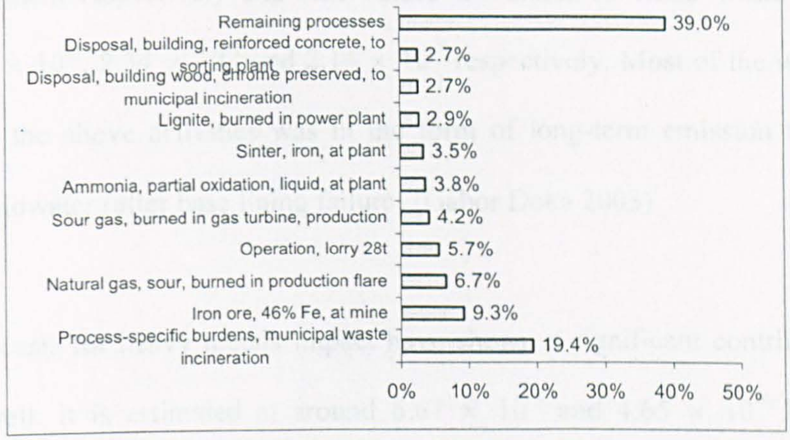

Figure 6.85: Contribution percentage of WS for treated wood waste to final disposal

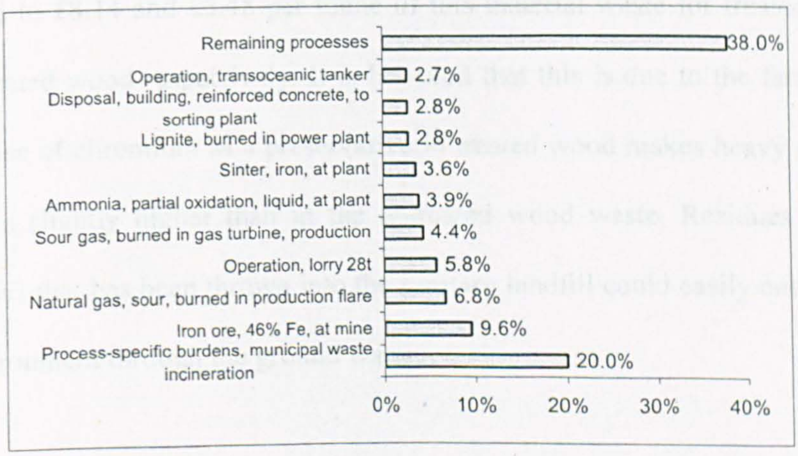

Figure 6.86: Contribution percentage of WS for untreated wood waste to final disposal

6.6.5. Heavy Metal of Wood Waste

Analyses of LCIA show that the main heavy metal potential (HM) is generally resulted from the MSWI, residue from MSWI to sanitary landfill and fuel for transportation. The HM values for treated wood waste at these stages were at around 5.99×10^{-6}, 2.34×10^{-7} and 2.17×10^{-7} kg Pb equivalent respectively and HM values for untreated wood waste were 3.98×10^{-6}, 2.34×10^{-7} and 2.14×10^{-7} respectively. Most of the impact from the above activities was in the form of long-term emission to the groundwater (after base lining failure) (Gabor Doka 2003).

Eco-costs for heavy metals impact have shown a significant contribution as well. It is estimated at around 6.67×10^{-6} and 4.65×10^{-6} kg Pb equivalent of HM values for treated and untreated wood waste. This is equal to £8.14 and £5.48 per tonne of this material waste for treated and untreated wood respectively. It is believed that this is due to the fact that the use of chromium as a preservative in treated wood makes heavy metal traces slightly higher than in the untreated wood waste. Residues from MSWI that has been thrown into the sanitary landfill could easily enter the environment through the ground water.

Figure 6.87 and Figure 6.88 and Table 29 in Appendix 2 show the HM scenario and details of the analysis results of treated and untreated wood waste to the final disposal.

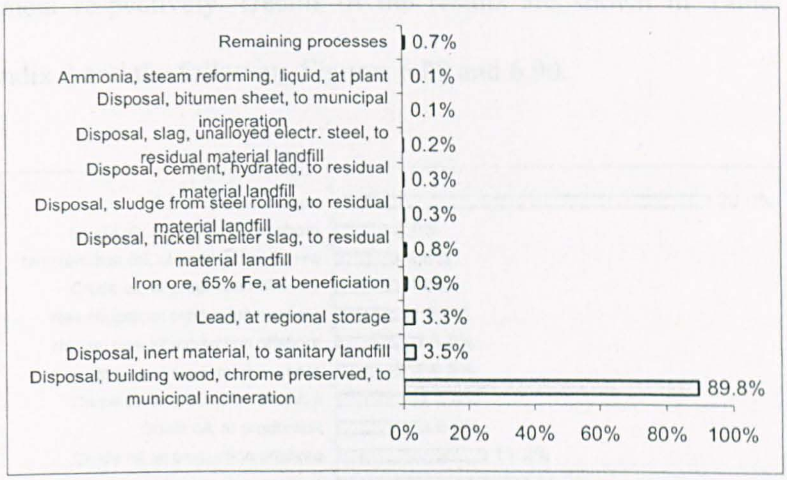

Figure 6.87: Contribution percentage of HM for treated wood waste to final disposal

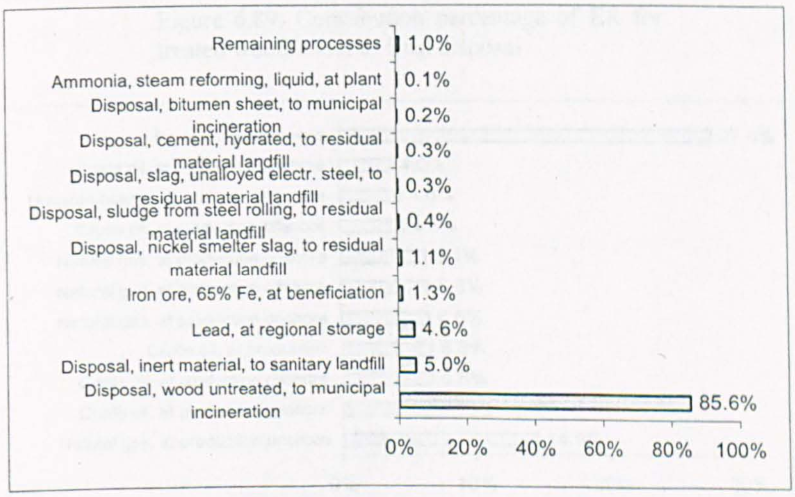

Figure 6.88: Contribution percentage of HM for untreated wood waste to final disposal

6.6.6. Energy Resource of Wood Waste

Analysis results of ER have shown that the results came from natural gas, oil and electricity production at the upstream processes. Results of final disposal for treated and untreated wood waste was 0.208 and 0.204 MJ LHV equivalent respectively. Details of the results are shown in Table 30 in Appendix 2 and the following Figures 6.89 and 6.90.

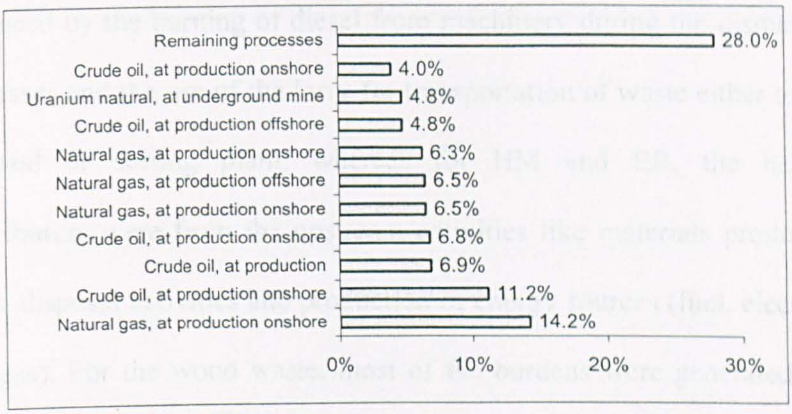

Figure 6.89: Contribution percentage of ER for treated wood waste to final disposal

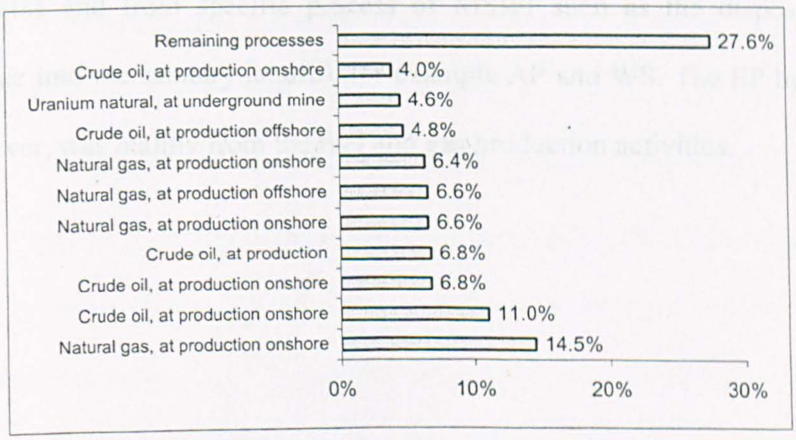

Figure 6.90: Contribution percentage of ER for untreated wood waste to final disposal

6.7. Summary

Generally, the heaviest contributors for GWP, AP, EP and WS were produced by the burning of diesel from machinery during the dismantling processes and the use of the lorry for transportation of waste either to final disposal or sorting plant, whereas for HM and ER, the heaviest contributors were from the upstream activities like materials production, waste disposal activities and production of energy sources (fuel, electricity and gas). For the wood waste, most of the burdens were generated from activities of disposal of the wood waste itself, for example the GWP, EP and HM and from specific process of MSWI such as the disposal of residue into the sanitary landfill, for example AP and WS. The EP burden however, was mainly from the fuel and gas production activities.

Chapter 7

ECO-COST OF CONSTRUCTION MATERIAL WASTE

7.1. Introduction

This chapter will discuss the result of eco-cost modelling of five common construction materials i.e. brick, concrete, metal, plasterboard and wood. In this chapter, only six out of nine environmental indicators will be discussed in detail because of their significant eco-cost results. However, for the purpose of the calculation of eco-cost for the materials, all results from nine indicators will be taken into account. The eco-cost calculation for the five common construction materials was based on the nine potential environmental indicators, characteristic factors and estimated damage cost result. Comparison in terms of the eco-cost results will also be made between the waste disposal options for every type of material waste in order to define the best waste management option. Comparison and discussion between the same types of indicator will also be made. The basic eco-cost calculation will be made based on a kilogram of related waste as shown in Appendix 3 and the unit of tonnage will be used throughout the discussion in this chapter.

7.2. Calculating the Eco-Cost of Construction Materials Waste

From Heijungs, Koning et. al., general calculations for the eco-cost of the selected material wastes are based on the following Equation 7-1 to Equation 7-3:

$$IR_C = \sum_s CF_{Cs} \times m_s \qquad \text{(Equation 7-1)}$$

Where IR_c is the indicator result for impact category c, CF_{Cs} the characterisation factor that connects intervention s with impact category c, and m_s the size of interventions (i.e. the mass of substance s emitted). This approach has been used to calculate every impact category, example for the global warming potential of waste by using the following Equation 7-2,

$$IR_{GWP} = \sum_s CF_{GWPs} \times m_s \qquad \text{(Equation 7-2)}$$

Where, IR_{GWP} is the indicator result for climate change, and CF_{GWPs} is the characterisation factor for global warming potential for substance s and m_s the size of interventions (i.e. the mass of substances emitted)

Calculation for the total nine indicators eco-cost of the material wastes impact that were considered in this study are based on the following general Equation 7.3,

$$\sum EC_{wi} = \sum_{c} (IR_C \times IC_C) \qquad \text{(Equation 7-3)}$$

Where, EC_{wi} is the total eco-cost of wastes impact, IR_C the impact results for impact category c and IC_C the impact costs for impact category c extracted from Table 4.1 in Chapter 4.

As described above, the calculation of eco-cost of brick waste was based on a kilogram of material waste for the three different waste disposal options i.e. final disposal, recycling and sorting plant and then converted into the unit of tonne. But for the purpose of obtaining a clear perspective of the real construction scenario, the eco-cost for a kilogram of the selected building material wastes will be converted into the unit of tonne in the discussion in the following sections.

7.2.1. Eco-Cost of Brick Waste

The total eco-cost for every tonne of brick waste that went to the final disposal option was £27.37 where ER produced 80 percent of the total eco-cost for the final disposal of brick which was the highest eco-cost value of £21.77. This was followed by WS, AP, HM, GWP and EP, each of them producing £3.92, £0.85, £0.59, £0.14, and £0.10 respectively.

In the recycling option, total eco-cost for every tonne of brick waste that went into it was slightly lower if compared with the total eco-cost of the material that goes into final disposal option. Total eco-cost of brick waste for this waste disposal option was £6.90. Results have shown that the ER score was 50 percent, which is 5 percent higher than WS contribution percentage value. The eco-cost result for ER at this point was £3.47. With 45 percent contribution, WS became the second highest with the eco-costs value of £3.11. Other eco-cost contribution results generated by AP, GWP, EP, and HM were £0.24, £0.03, £0.03 and £0.02 respectively.

In comparison, for every tonne that went through the sorting plant option quite a high eco-cost result was produced. The total eco-cost value of brick waste for this option was £50.22. The HM indicator produced the highest percentage contribution value of eco-cost in the sorting plant option with the eco-cost value of £23.55 and followed by ER, WS, AP, GWP and EP with the eco-cost value of £21.63, £3.96, £0.83, £0.14, and £0.11 respectively. Carcinogens and ODP results however show their insignificant contribution for all three waste disposal options.

For Eco-cost results of brick all waste disposal options clearly show that it was dominated by the use of energy. For final disposal options, the ER result was mainly contributed by ER. For the recycling, the ER and WS result represents 95 percent the total eco-cost of the option with ER contributing half of the total eco-cost for this option. Results for sorting plant revealed that the ER and HM represent 90 percent of the total eco-cost for sorting plant option with ER as the second highest after HM. Recycling was found to be the best possible option of brick waste disposal, followed by the final disposal and sorting plant options. Table 7.1 and eco-cost contribution percentage for the three different waste management options for a tonne of brick waste is shown in Figures 7.1 to 7.3.

Table 7.1: Eco-cost of a tonne of brick waste for three different waste disposal options

Impact category	Final disposal eco-cost (£)	Recycling eco-cost (£)	Sorting plant eco-cost (£)
greenhouse	0.14	0.03	0.14
acidification	0.85	0.24	0.83
eutrophication	0.10	0.03	0.11
winter smog	3.92	3.11	3.96
summer smog	0.01	0.001	.0.01
heavy metals	0.59	0.02	23.55
carcinogens	8.0E-05	4.0E-05	8.0E-05
ozone layer	3.0E-05	4.0E-06	3.0E-05
energy resources	21.77	3.47	21.63
total	27.37	6.90	50.22

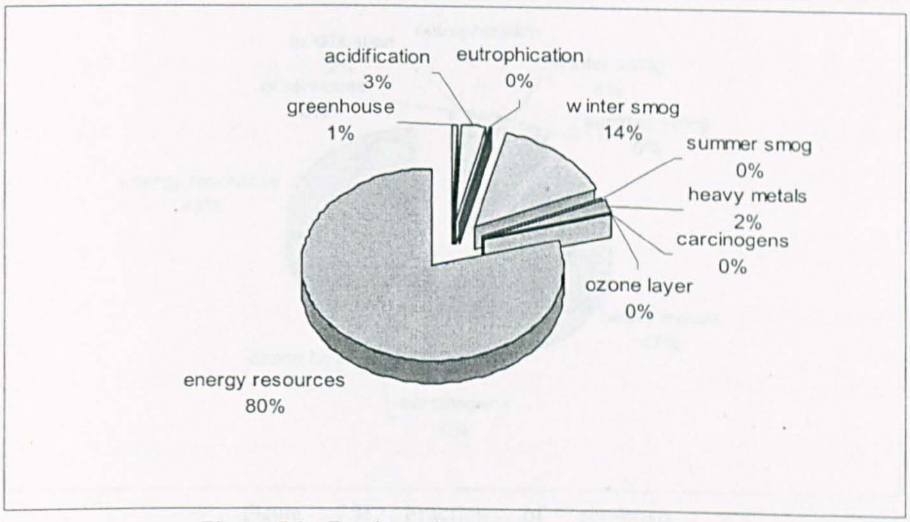

Figure 7.1: Fraction of eco-costs contribution by indicators for the final disposal of brick waste

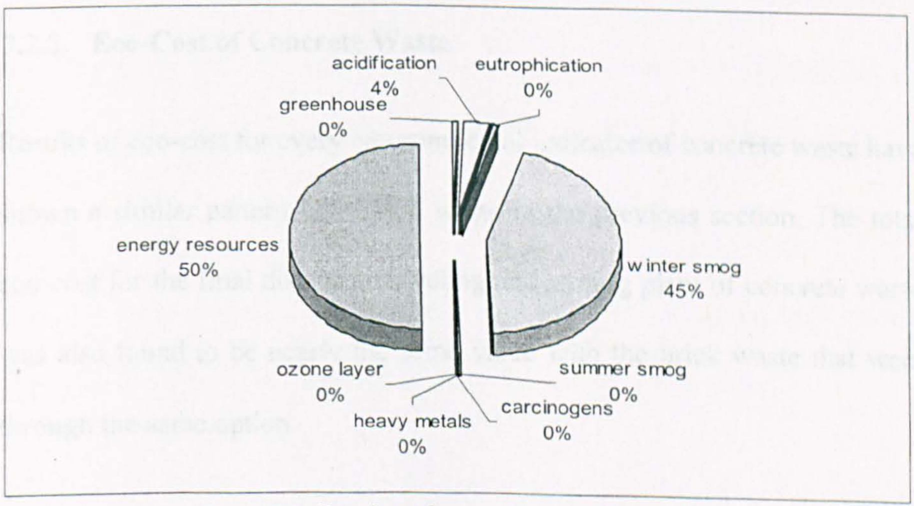

Figure 7.2: Fraction of eco-costs contribution by indicators for the recycling of brick waste

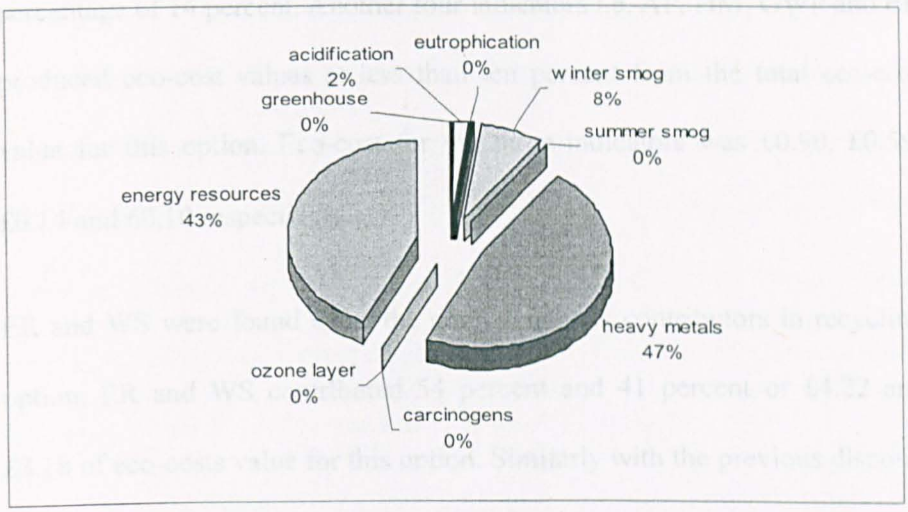

Figure 7.3: Fraction of eco-costs contribution by indicators for the sorting plant of brick waste

7.2.2. Eco-Cost of Concrete Waste

Results of eco-cost for every environmental indicator of concrete waste have shown a similar pattern with brick waste in the previous section. The total eco-cost for the final disposal, recycling and sorting plant of concrete waste was also found to be nearly the same value with the brick waste that went through the same option.

It is estimated that for every tonne of concrete waste that passes through into this option a total eco-cost of £28.28 could be produced. ER was found to be the highest indicator that can generate £22.54 of eco-cost which is equivalent to 80 percent of the total eco-costs for the final disposal option. The second highest was WS with the eco-cost value of £3.99 or contribution percentage of 14 percent. Another four indicators i.e. AP, HM, GWP and EP produced eco-cost values at less than ten percent from the total eco-cost value for this option. Eco-cost for the three indicators was £0.90, £0.59, £0.14 and £0.10 respectively.

ER and WS were found to be the main eco-costs contributors in recycling option. ER and WS contributed 54 percent and 41 percent or £4.22 and £3.18 of eco-costs value for this option. Similarly with the previous disposal option, the remaining indicators results show that the contribution percentages were below 10 percent of the total eco-cost in this disposal option. But in the sorting plant, HM and ER were found to be the main contributors of eco-costs. HM and ER results show the two indicators contributed 46 and 44 percent, equivalent to £23.55 and £22.26 respectively. The other indicators, however, contributed less than 10 percent of overall eco-cost in the sorting plant option.

Another two indicators i.e. carcinogens and ODP had given insignificant eco-cost contribution value for all three waste disposal options.

Results of eco-cost for disposal option for concrete waste have a similar pattern to brick waste. In the final disposal option, ER was found to be the main eco-cost contributor. With nearly the same proportion as brick waste to recycling option, ER and WS emerged as the first and the second highest contributors for eco-cost of concrete waste. In sorting plant, HM and ER was the highest contributor with nearly the same percentage contribution value. Eco-cost value of a tonne of kilogram concrete waste for three different waste disposal options is shown in Table 7.2. Estimated eco-cost percentage for the three different waste management options for a tonne of concrete waste is shown in Figures 7.4 to 7.6. Besides brick waste, recycling is still the best possible option for disposal concrete waste followed by the final disposal and sorting plant option.

Table 7.2: Eco-cost of a tonne of concrete waste for three different waste disposal options

Impact Category	Final disposal eco-cost (£)	Recycling eco-cost (£)	Sorting plant eco-cost (£)
greenhouse	0.14	0.04	0.15
acidification	0.90	0.30	0.88
eutrophication	0.10	0.03	0.11
winter smog	3.99	3.18	4.03
summer smog	0.01	0.00	0.01
heavy metals	0.59	0.02	23.55
carcinogens	8.0E-05	5.0E-05	8.0E-05
ozone layer	3.0E-05	6.0E-06	2.0E-05
energy resources	22.54	4.22	22.26
total	28.28	7.79	50.98

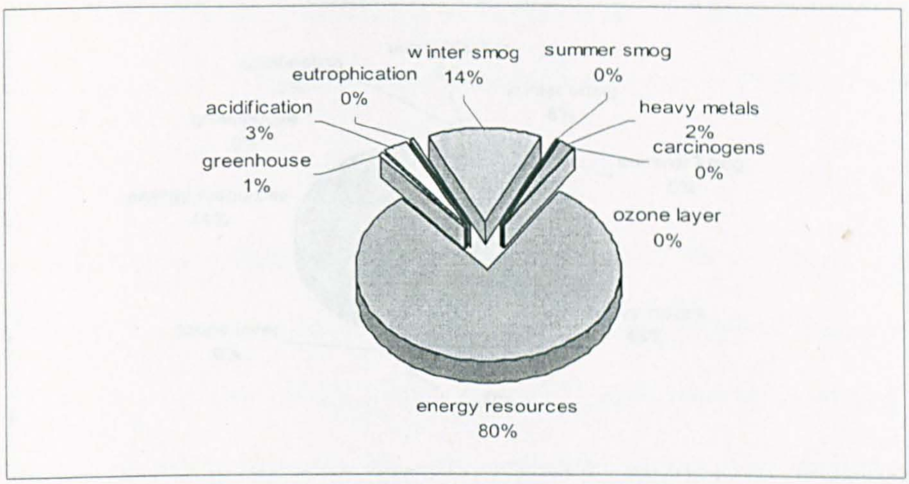

Figure 7.4: Fraction of eco-costs contribution by indicators for the final disposal of concrete waste

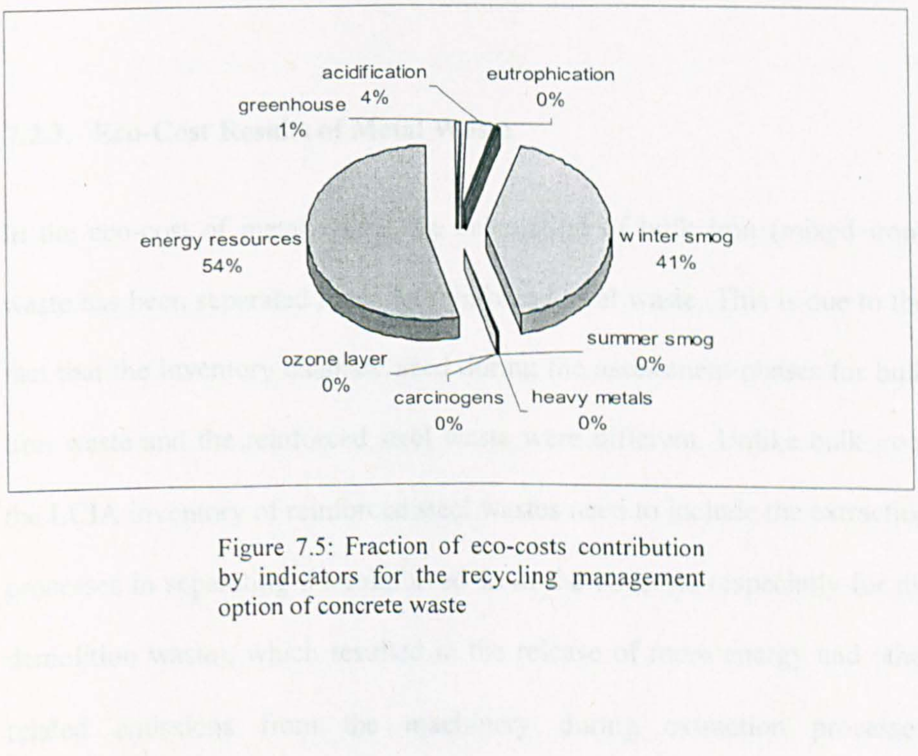

Figure 7.5: Fraction of eco-costs contribution by indicators for the recycling management option of concrete waste

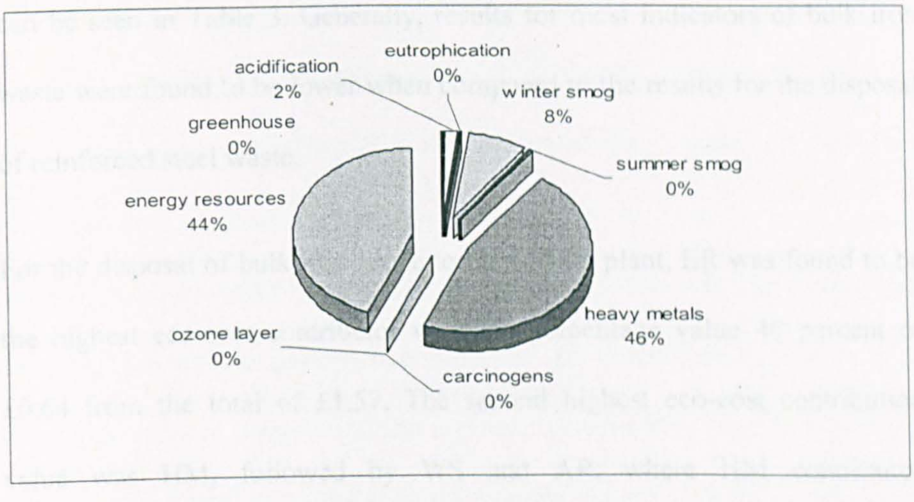

Figure 7.6: Fraction of eco-costs contribution by indicators for the sorting plant management option of concrete waste

7.2.3. Eco-Cost Results of Metal Waste

In the eco-cost of metal waste, the calculation of bulk iron (mixed iron) waste has been separated from the reinforced steel waste. This is due to the fact that the inventory database used during the assessment phases for bulk iron waste and the reinforced steel waste were different. Unlike bulk iron, the LCIA inventory of reinforced steel wastes need to include the extraction processes in separating the reinforced from the concrete (especially for the demolition waste), which resulted in the release of more energy and other related emissions from the machinery during extraction processes. Meanwhile, bulk iron waste (excluding the reinforced steel) was normally sent to the mixed bin waste without prior extraction processes. Comparison of the eco-cost result between the bulk iron waste and reinforcement waste can be seen in Table 3. Generally, results for most indicators of bulk iron waste were found to be lower when compared to the results for the disposal of reinforced steel waste.

For the disposal of bulk iron waste to the sorting plant, ER was found to be the highest eco-cost contributor with the percentage value 40 percent or £0.64 from the total of £1.57. The second highest eco-cost contribution value was HM, followed by WS and AP, where HM contributed approximately 22 percent or £0.35, while WS and AP contributed 19 and 14 percent or £0.29 and £0.22 respectively. However, GWP and EP only contributed £0.04 and £0.03 which was less than 10 percent of the total eco-cost value.

The total eco-cost for the three waste disposal options of reinforced steel waste was found to be very much higher than bulk iron waste disposal options. The total eco-cost for the final disposal option of reinforced steel was £92.35, of which ER was the highest eco-cost contributor with the percentage contribution value of 86 percent or eco-cost value of £79.10. The WS and AP ranked second and third with the contribution percentage values of 7 and 5 percent or eco-cost values £6.23 and £4.87. HM, GWP and EP contributed less than 5 percent with their eco-cost values of £0.86, £0.67 and £0.57 respectively. The second highest score for the total eco-cost between the three different waste disposal options of reinforced steel waste was the sorting plant.

The sorting plant option produced the highest total eco-cost contributed to the total eco-cost at approximately £79.92, while the recycling option produced the lowest eco-cost (£71.56). Pattern of the indicators contribution for these two disposal options was similar with the final disposal option, where ER became the highest contributor among the nine other indicators with the percentage contribution value of 86 percent or £60.48 for the recycling and 85 percent £67.90 for the sorting plant. The WS and AP became the second and third with percentage values of 8 and 6 percent or eco-cost values of £5.43 and £4.26 in the recycling and 7 and 6 percent or eco-cost values of £5.71 and £4.49 in the sorting plant. While HM, GWP and EP were again found to contribute less than 5 percent with their eco-cost values of £0.29, £0.56 and £0.50 in the recycling and £0.65, £0.61 and £0.53 in the sorting plant respectively. The other two indicators i.e. carcinogens and ODP produced insignificant eco-costs results.

Similar to the above results, recycling is found to be the best possible option to treat metal waste. However for this research, only sorting plant option was available for bulk iron waste as the waste was assumed to have been mixed with other types of metals in one skip and needed to be separated before recycling. However, the result for this option was not significant. In general total eco-cost value for bulk iron waste to sorting plant was found to have the lowest total eco-cost value in contrast with the other three total eco-costs of disposal option for reinforced steel waste. ER was found to be the major contributor for the total eco-cost of bulk iron and reinforced steel waste disposal option. These scenarios can clearly be seen in Table 7.3 and Figures 7.7 to 7.10.

Table 7.3: Eco-cost of a tonne of metal waste for three different waste disposal options

Impact category	Bulk iron waste to sorting plant eco-cost (£)	R/steel waste to final disposal eco-cost (£)	R/steel waste to recycling eco-cost (£)	R/steel waste to sorting plant eco-cost (£)
greenhouse	0.04	0.67	0.56	0.61
acidification	0.22	4.87	4.26	4.49
eutrophication	0.03	0.57	0.50	0.53
winter smog	0.29	6.23	5.43	5.71
summer smog	0.00	0.05	0.04	0.05
heavy metals	0.35	0.86	0.29	0.65
carcinogens	7.0E-06	6.8E-04	6.3E-04	6.4E-04
ozone layer	6.7E-06	9.8E-05	7.1E-05	7.7E-05
energy resources	0.64	79.10	60.48	67.90
total	1.57	92.35	71.56	79.92

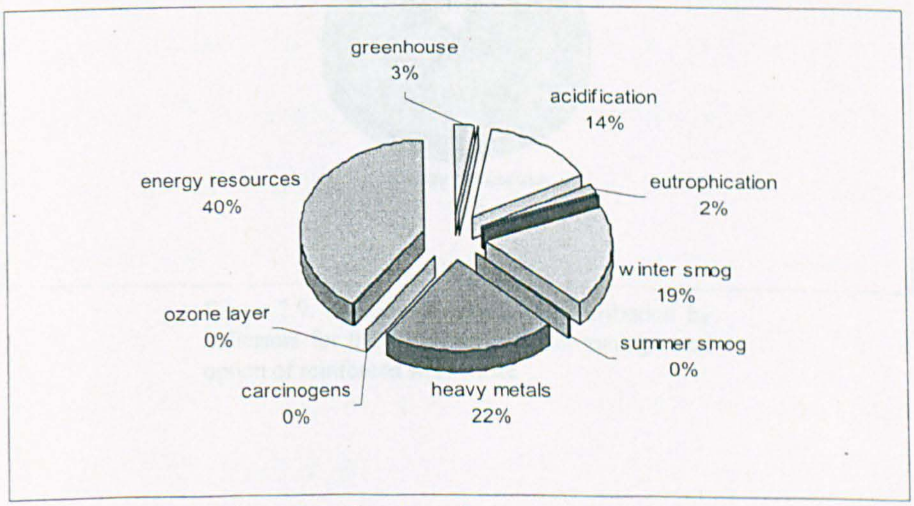

Figure 7.7: Fraction of eco-costs contribution by indicators for the sorting plant management option of bulk iron waste

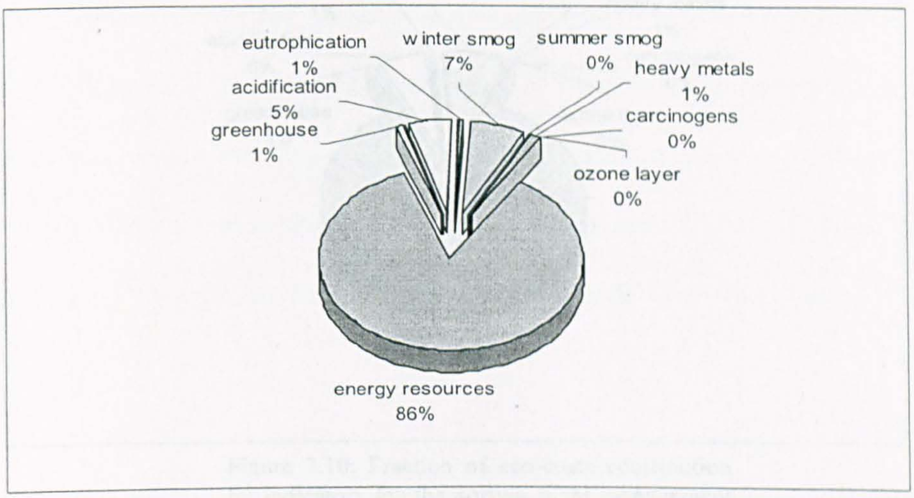

Figure 7.8: Fraction of eco-costs contribution by indicators for the final disposal management option of reinforced steel waste

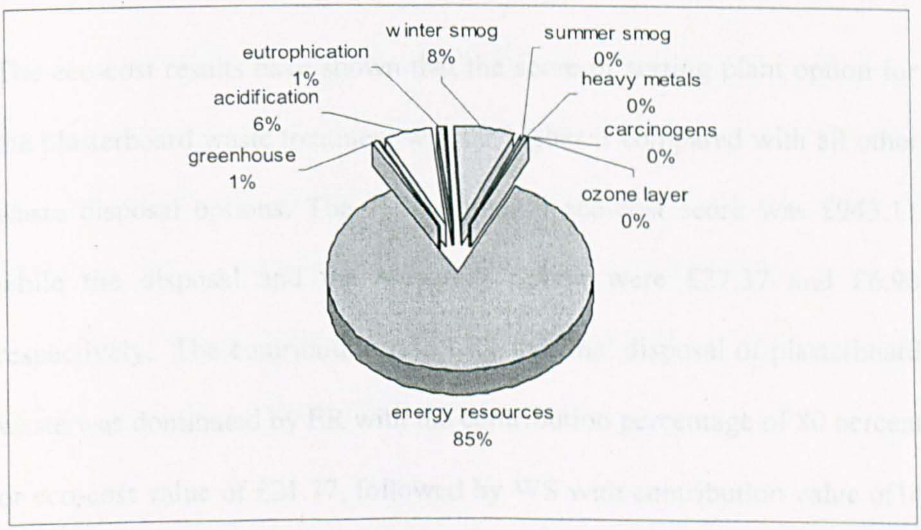

Figure 7.9: Fraction of eco-costs contribution by indicators for the recycling disposal management option of reinforced steel waste

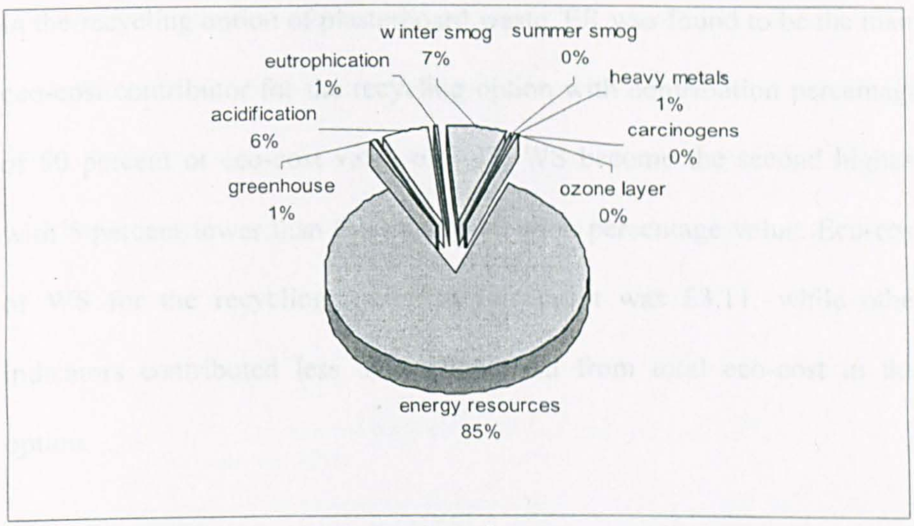

Figure 7.10: Fraction of eco-costs contribution by indicators for the sorting plant management option of reinforced steel waste

7.2.4. Eco-Cost Result of Plasterboard Waste

The eco-cost results have shown that the score of sorting plant option for the plasterboard waste treatment was far higher if compared with all other waste disposal options. The sorting plant's eco-cost score was £943.11 while the disposal and the recycling option were £27.37 and £6.90 respectively. The contributing result for the final disposal of plasterboard waste was dominated by ER with the contribution percentage of 80 percent or eco-cost value of £21.77, followed by WS with contribution value of14 percent, equivalent to eco-cost value of £3.92. However AP, GWP, EP and HM had contributed less than 10 percent with the total eco-cost value of £0.85, £0.14, £0.10 and £0.59.

In the recycling option of plasterboard waste, ER was found to be the main eco-cost contributor for the recycling option with contribution percentage of 50 percent or eco-cost value of 3.47. WS become the second highest with 5 percent lower than the ER contribution percentage value. Eco-cost of WS for the recycling option at this point was £3.11, while other indicators contributed less than 10 percent from total eco-cost in this option.

In the sorting plant option, WS was found to be the major eco-cost contributor in the sorting plant with the contribution percentage of 78 percent, equivalent to the eco-cost value of £735.00. This was followed by AP with contribution percentage of 18 percent or eco-cost value of £161.67. However, other indicators contributed less than 10 percent from total eco-cost in this option, of which the total eco-cost of the remaining indicators was not more than £36. Carcinogens and ODP were again found to be the indicators that give less significant contribution to the total eco-costs for the three different waste disposal options

As final disposal option for other materials before, ER again emerged as the major contributor for the total eco-cost of plasterboard waste. It then constituted approximately half of the total eco-cost of recycling at several percentages higher than the WS result. However, in sorting plant option, WS was found to be the major contributor of the total eco-cost value for plasterboard waste. Details of the eco-cost result for a tonne of plasterboard waste for three different waste disposal options is shown in Table 7.4, while the eco-cost contribution percentage for three different waste management options of plasterboard waste are shown in Figures 7.11 to 7.13.

Table 7.4: Eco-cost of a tonne of plasterboard waste for three different waste disposal options

Impact category	**Final disposal eco-cost (£)**	**Recycling eco-cost (£)**	**Sorting plant eco-cost (£)**
greenhouse	0.14	0.03	0.22
acidification	0.85	0.24	161.67
eutrophication	0.10	0.03	0.14
winter smog	3.92	3.11	735
summer smog	0.01	2.3E-03	0.02
heavy metals	0.59	0.02	10.86
carcinogens	7.9E-05	3.6E-05	1.2E-04
ozone layer	3.1E-05	4.0E-06	4.2E-05
energy resources	21.77	3.47	35.21
total	27.37	6.90	943.11

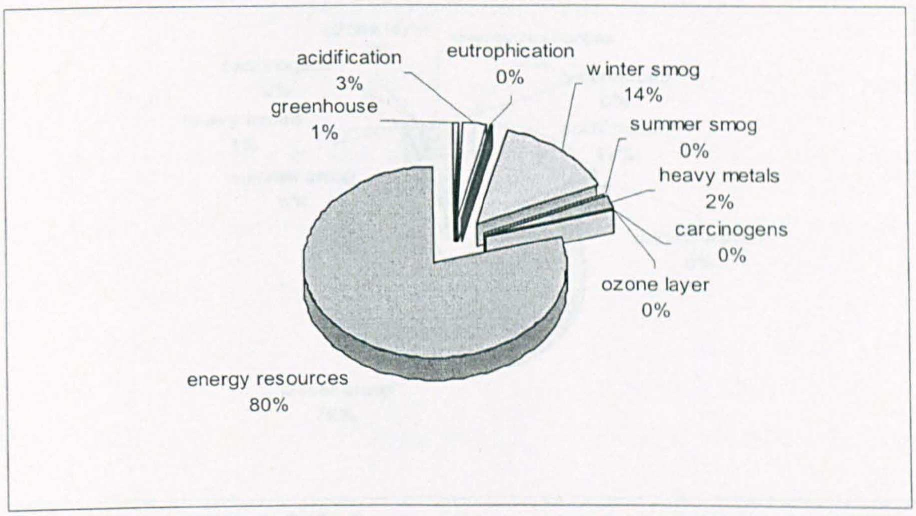

Figure 7.11: Fraction of eco-costs contribution by indicators for the final disposal management option of plasterboard waste

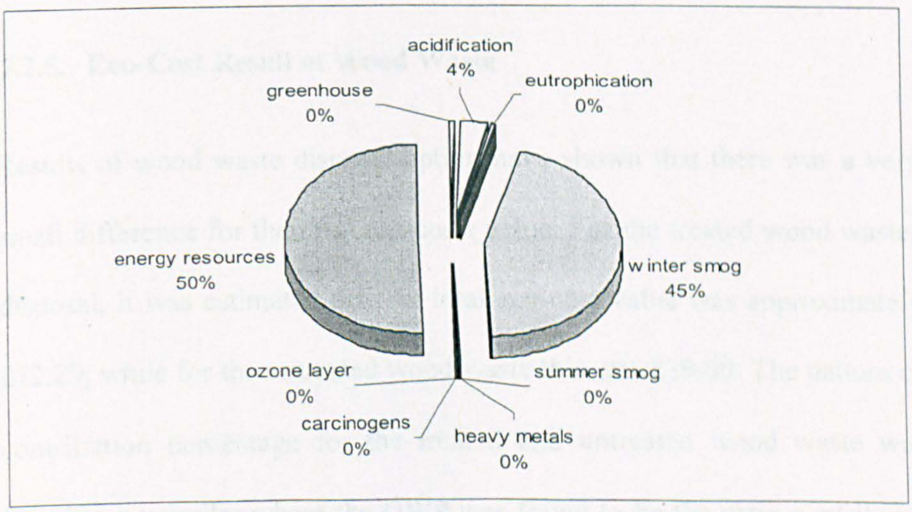

Figure 7.12: Fraction of eco-costs contribution by indicators for the recycling management option of plasterboard waste

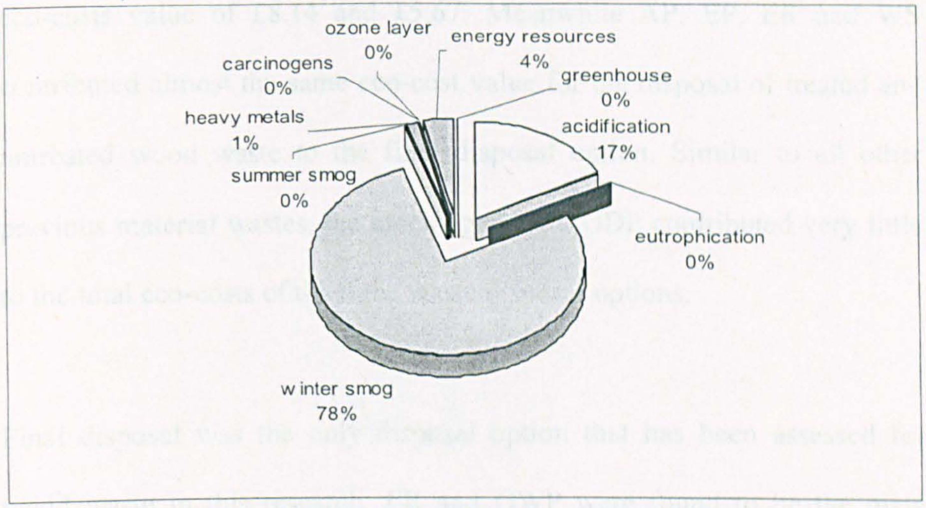

Figure 7.13: Fraction of eco-costs contribution by indicators for the sorting plant management option of plasterboard waste

7.2.5. Eco-Cost Result of Wood Waste

Results of wood waste disposal option have shown that there was a very small difference for the total eco-costs value. For the treated wood wastes disposal, it was estimated that the total eco-cost value was approximately £42.29, while for the untreated wood waste this was £39.60. The pattern of contribution percentage for the treated and untreated wood waste was found to be similar where the GWP was found to be the main contributor with the contribution percentage value of 37 and 35 percent or eco-cost value £14.60 and £14.70 respectively. ER came second with the percentage value for the treated and untreated wood waste of 34 and 36 percent or £14.56 and £14.28. The third highest contributor was HM with the contribution percentage value of 19 and 14 percent, equivalent to the eco-costs value of £8.14 and £5.67. Meanwhile AP, EP, ER and WS contributed almost the same eco-cost value for the disposal of treated and untreated wood waste to the final disposal option. Similar to all other previous material wastes, the carcinogens and ODP contributed very little to the total eco-costs of the three waste disposal options.

Final disposal was the only disposal option that has been assessed for wood waste in this research. ER and GWP were found to be the main contributors of total eco-cost for the treated and untreated wood waste. A combination of these two indicator results represents 70 percent of the total eco-cost. These can be seen in Table 7.5 and Figure 7.14 and Figure 7.15.

Table 7.5: Eco-cost of a tonne of wood waste for three different waste disposal options

Impact category	Treated wood waste Final disposal eco-cost (£)	Untreated wood waste Final disposal eco-cost (£)
greenhouse	14.60	14.70
acidification	2.33	2.32
eutrophication	1.54	1.54
winter smog	1.09	1.05
summer smog	0.03	0.03
heavy metals	8.14	5.67
carcinogens	3.1E-05	3.1E-05
ozone layer	1.4E-05	1.3E-05
energy resources	14.56	14.28
total	42.29	39.60

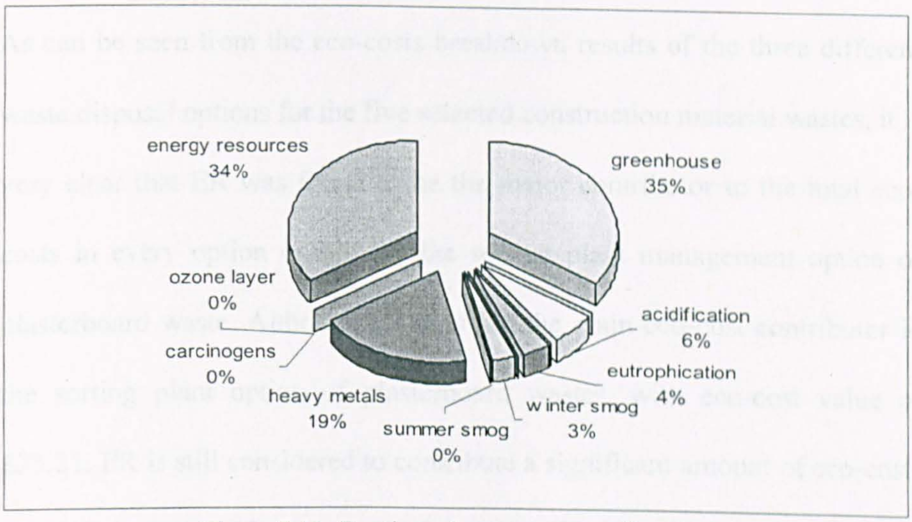

Figure 7.14: Fraction of eco-costs contribution by indicators for the final disposal management option of treated wood waste

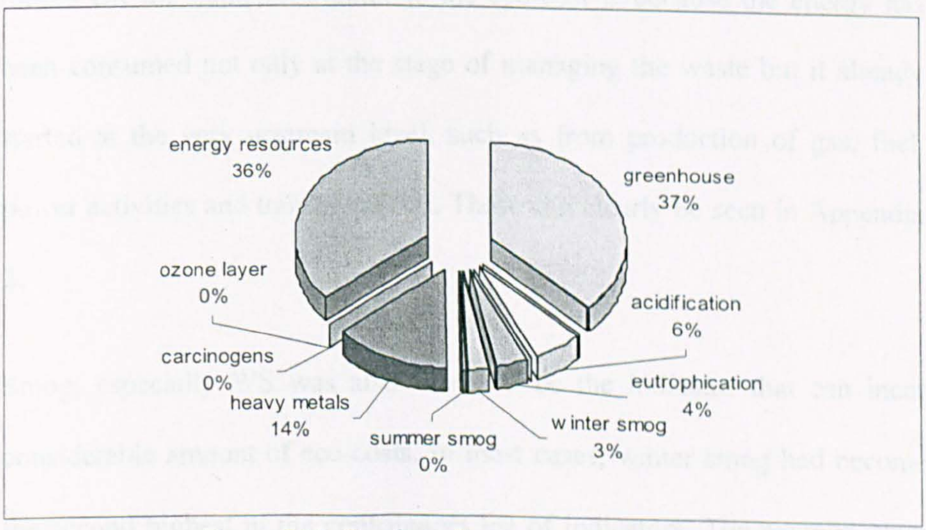

Figure 7.15: Fraction of eco-costs contribution by indicators for the final disposal management option of untreated wood waste

7.3. Summary

As can be seen from the eco-costs breakdown results of the three different waste disposal options for the five selected construction material wastes, it is very clear that ER was found to be the major contributor to the total eco-costs in every option except for the sorting plant management option of plasterboard waste. Although ER was not the main eco-cost contributor in the sorting plant option of plasterboard wastes, with eco-cost value of £35.21, ER is still considered to contribute a significant amount of eco-costs which is in fact within the range of eco-cost of its classification in the waste disposal options for other ER material waste results. The main factor that makes ER the main contributor to the eco-cost is because the energy has been consumed not only at the stage of managing the waste but it already started at the very upstream level, such as from production of gas, fuel, power activities and transportations. These can clearly be seen in Appendix 2.

Smog, especially WS was also found to be the indicator that can incur considerable amount of eco-costs. In most cases, winter smog had become the second highest in the contributors list of indicators. The average score for winter smog eco-costs value is £3.50. This value is estimated with the exception of the winter smog result for the sorting plant management option of plasterboard waste which is found to be higher if compared to the other winter smog results. In many cases GWP, AP and HM were also found to contribute a considerable amount to eco-cost, although not as much as ER and WS.

Chapter 8

TOTAL ECO-COST MODEL OF CONSTRUCTION MATERIAL WASTE

8.1. Introduction

This chapter describes the most important findings of the research. Based on the results in the previous chapters, comparison and discussion of each waste disposal options is made. Mathematical relationships are developed to show the eco-costs of the waste disposal options. The discussion will also concentrate on the development of mathematical models for the estimation of eco-costs of the three waste disposal options for the five selected construction material wastes. The model is applied to the real world examples.

8.2. Developing Eco-Costs Model Equation

In this chapter, the results from Chapter 7 are utilised to obtain the eco-cost estimation of the three waste disposal options for the five selected construction material wastes. In order to make the estimation of eco-costs, the expression of the relationship between the eco-cost result and the weight of waste material should be developed. The best way is to express this relationship through mathematical models. Although it was expected that there would be a linear relationship between the weights of waste and the eco-costs result it is very difficult to present this in graphical format. This is because the range of some of the eco-cost result value was too large i.e. plasterboard waste to sorting plant result. Therefore, to have a clear representation, the relationship for the weight of the waste material is made with a log value of the eco-cost result. The expression of the mathematical model is then developed based on this relationship.

Even though it was expected that the weight of waste and the eco-cost would have a linear relationship, statistical measurements have been made to validate the developed equation of the mathematical models. For this purpose, SPSS Version 13 has been used and the statistical measurement results are shown in Appendix 4, where three model equations have been made to choose the best fit curves for the estimation of construction material waste eco-cost base on the value of R square namely linear, logarithmic and cubic equations. The logarithmic equation was found to be the best fit curve with the value of R square is equivalent to 1 compared to the other two equations. This proved that any assumed given for x value in an equation will produce an accurate predictions for the y value.

8.3. Estimation Model for Eco-Cost by Indicators

In this section, discussion regarding the relationship curves of log eco-costs for all nine environmental indicators versus weight of construction material waste is made. Based on significant results, two selected construction materials (i.e. brick and plasterboard) will be discussed to show a comparison of impacts based on the nine environmental values. Simplified mathematical models of eco-costs for the three waste disposal options are also presented.

8.3.1. Estimation Model for Eco-Cost of Brick Waste by Indicators

Eco-cost results by indicators for brick waste have shown that the use of ER was the highest eco-cost contributor compared to the other eight indicators. WS was the second highest contributor but shows nearly the same value as EP in recycling option. From all nine indicator results SS, CP and ODP have shown less significant eco-cost contribution results. Figures 8.1 to 8.3 show the graph of log eco-costs versus weight by indicators and Equations 8-1 to 8-27 represent the equation model of brick waste for three waste disposal options.

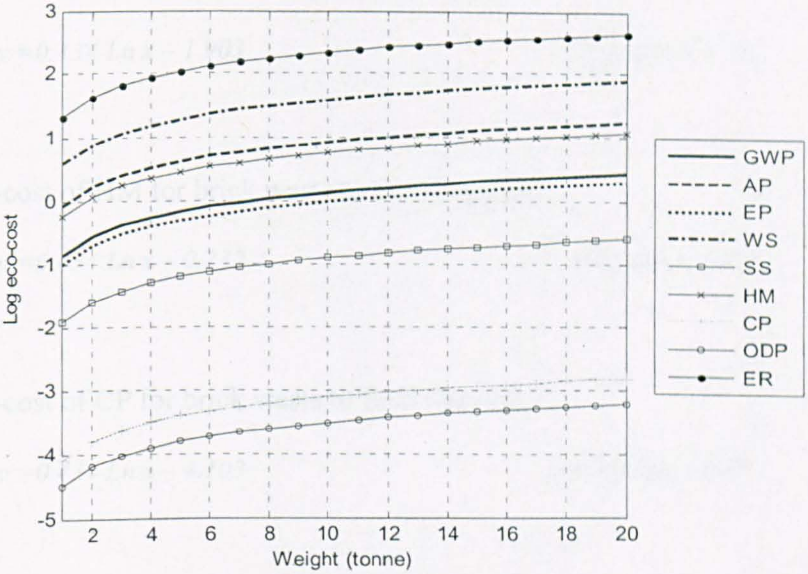

Figure 8.1: Graph of log eco-costs versus weight by indicators of brick waste to final disposal

Eco-cost of GWP for brick waste to final disposal,

$Log\ y = 0.434\ Ln\ x - 0.863$ (Equation 8-1)

Eco-cost of AP for brick waste to final disposal,

$Log\ y = 0.434\ Ln\ x - 0.071$ (Equation 8-2)

Eco-cost of EP for brick waste to final disposal,

$Log\ y = 0.434\ Ln\ x - 1.007$ (Equation 8-3)

Eco-cost of WS for brick waste to final disposal,

$Log\ y = 0.434\ Ln\ x + 0.593$ (Equation 8-4)

Eco-cost of SS for brick waste to final disposal,

$Log\, y = 0.434\, Ln\, x - 1.903$ (Equation 8-5)

Eco-cost of HM for brick waste to final disposal,

$Log\, y = 0.434\, Ln\, x - 0.232$ (Equation 8-6)

Eco-cost of CP for brick waste to final disposal,

$Log\, y = 0.434\, Ln\, x - 4.103$ (Equation 8-7)

Eco-cost of ODP for brick waste to final disposal,

$Log\, y = 0.434\, Ln\, x - 4.505$ (Equation 8-8)

Eco-cost of ER for brick waste to final disposal,

$Log\, y = 0.434\, Ln\, x + 1.338$ (Equation 8-9)

Where, y is eco-costs and x is material waste in tonne.

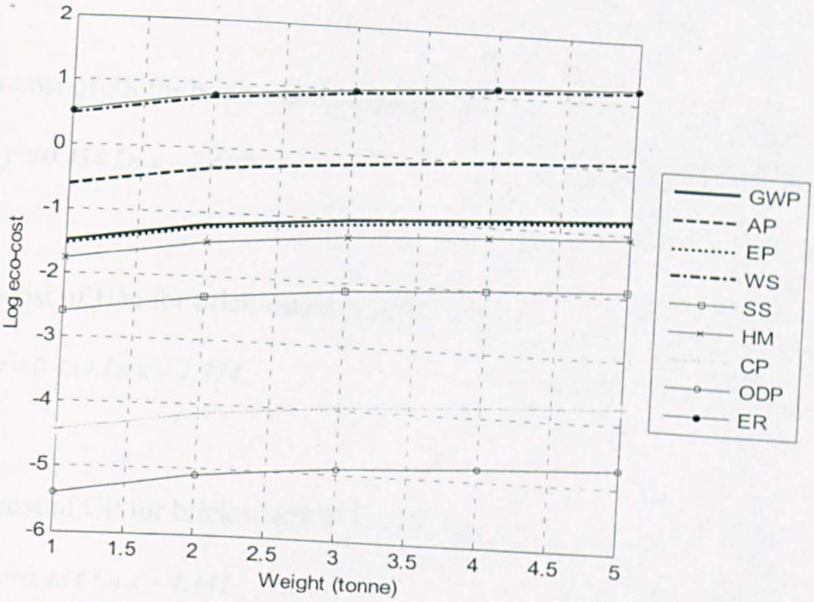

Figure 8.2: Graph of log eco-costs versus weight by indicators of brick waste to recycling

Eco-cost of GWP for brick waste to recycling,

$$Log\ y = 0.434\ Ln\ x - 1.492 \qquad \text{(Equation 8-10)}$$

Eco-cost of AP for brick waste to recycling,

$$Log\ y = 0.434\ Ln\ x - 0.613 \qquad \text{(Equation 8-11)}$$

Eco-cost of EP for brick waste to recycling,

$$Log\ y = 0.434\ Ln\ x - 1.542 \qquad \text{(Equation 8-12)}$$

Eco-cost of WS for brick waste to recycling,

$$Log\ y = 0.434\ Ln\ x + 0.493 \qquad \text{(Equation 8-13)}$$

Eco-cost of SS for brick waste to recycling,

$Log\, y = 0.434\, Ln\, x - 2.607$ (Equation 8-14)

Eco-cost of HM for brick waste to recycling,

$Log\, y = 0.434\, Ln\, x - 1.774$ (Equation 8-15)

Eco-cost of CP for brick waste to recycling,

$Log\, y = 0.434\, Ln\, x - 4.441$ (Equation 8-16)

Eco-cost of ODP for brick waste to recycling,

$Log\, y = 0.434\, Ln\, x - 5.393$ (Equation 8-17)

Eco-cost of ER for brick waste to recycling,

$Log\, y = 0.434\, Ln\, x + 0.540$ (Equation 8-18)

Where, y is eco-costs and x is material waste in tonne.

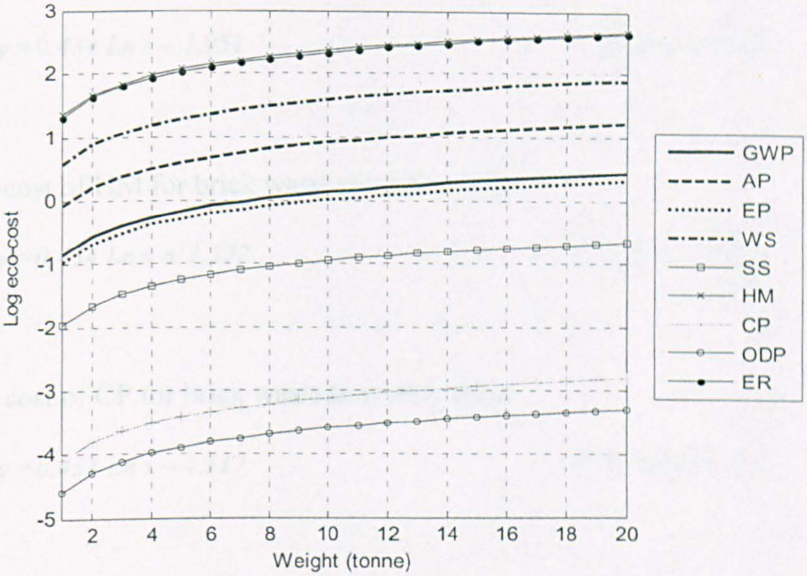

Figure 8.3: Graph of log eco-costs versus weight by indicators of brick waste to sorting plant

Eco-cost of GWP for brick waste to sorting plant,

$Log\ y = 0.434\ Ln\ x - 0.857$ (Equation 8-19)

Eco-cost of AP for brick waste to sorting plant,

$Log\ y = 0.434\ Ln\ x - 0.078$ (Equation 8-20)

Eco-cost of EP for brick waste to sorting plant,

$Log\ y = 0.434\ Ln\ x - 0.978$ (Equation 8-21)

Eco-cost of WS for brick waste to sorting plant,

$Log\ y = 0.434\ Ln\ x + 0.597$ (Equation 8-22)

Eco-cost of SS for brick waste to sorting plant,

$Log\, y = 0.434\, Ln\, x - 1.951$ (Equation 8-23)

Eco-cost of HM for brick waste to sorting plant,

$Log\, y = 0.434\, Ln\, x + 1.372$ (Equation 8-24)

Eco-cost of CP for brick waste to sorting plant,

$Log\, y = 0.434\, Ln\, x - 4.117$ (Equation 8-25)

Eco-cost of ODP for brick waste to sorting plant,

$Log\, y = 0.434\, Ln\, x - 4.599$ (Equation 8-26)

Eco-cost of ER for brick waste to sorting plant,

$Log\, y = 0.434\, Ln\, x + 1.335$ (Equation 8-27)

Where, y is eco-costs and x is material waste in tonne.

8.3.2. Estimation Model for Eco-Cost of Plasterboard Waste by Indicators

The curves of eco-costs results versus weight of waste material by indicators for all nine indicators of plasterboard waste is found to have a similar pattern to the brick waste in the final disposal and recycling option. In fact the equation model for the final disposal was also found to be similar to the same waste disposal option for brick waste. Similar characteristics were found in the recycling option where the eco-cost equations for all indicators were the same as the equations in brick for the same option except for GWP. Plasterboard produced slightly higher GWP eco-cost value compared with brick disposal.

However in sorting plant, plasterboard shows a very significant contribution compared with the brick waste contribution. WS was again found to be the second highest contributor but shows nearly the same value as ER in recycling option. SS, CP and ODP have shown less significant eco-cost contribution results compared to other environmental indicators. Figures 8.4 to 8.6 shows the graph of log eco-costs versus weight by indicators and Equations 8-28 to 8-54 represent the equation model of plasterboard waste for three waste disposal options.

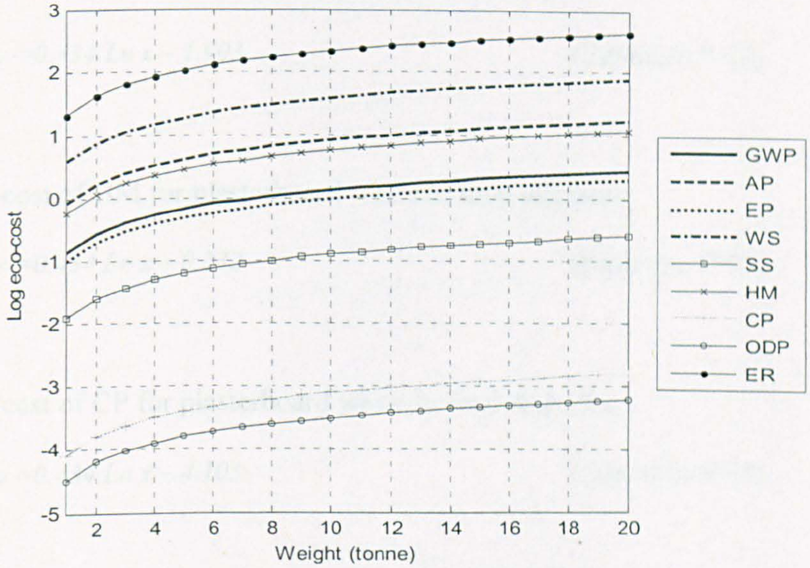

Figure 8.4: Graph of log eco-costs versus weight by indicators of plasterboard waste to final disposal

Eco-cost of GWP for plasterboard waste to final disposal,

$\log y = 0.434 \ln x - 0.863$ (Equation 8-28)

Eco-cost of AP for plasterboard waste to final disposal,

$\log y = 0.434 \ln x - 0.071$ (Equation 8-29)

Eco-cost of EP for plasterboard waste to final disposal,

$\log y = 0.434 \ln x - 1.007$ (Equation 8-30)

Eco-cost of WS for plasterboard waste to final disposal,

$\log y = 0.434 \ln x + 0.593$ (Equation 8-31)

Eco-cost of SS for plasterboard waste to final disposal,

$$Log\,y = 0.434\,Ln\,x - 1.903 \qquad \text{(Equation 8-32)}$$

Eco-cost of HM for plasterboard waste to final disposal,

$$Log\,y = 0.434\,Ln\,x - 0.232 \qquad \text{(Equation 8-33)}$$

Eco-cost of CP for plasterboard waste to final disposal,

$$Log\,y = 0.434\,Ln\,x - 4.103 \qquad \text{(Equation 8-34)}$$

Eco-cost of ODP for plasterboard waste to final disposal,

$$Log\,y = 0.434\,Ln\,x - 4.505 \qquad \text{(Equation 8-35)}$$

Eco-cost of ER for plasterboard waste to final disposal,

$$Log\,y = 0.434\,Ln\,x + 1.338 \qquad \text{(Equation 8-36)}$$

Where, y is eco-costs and x is material waste in tonne

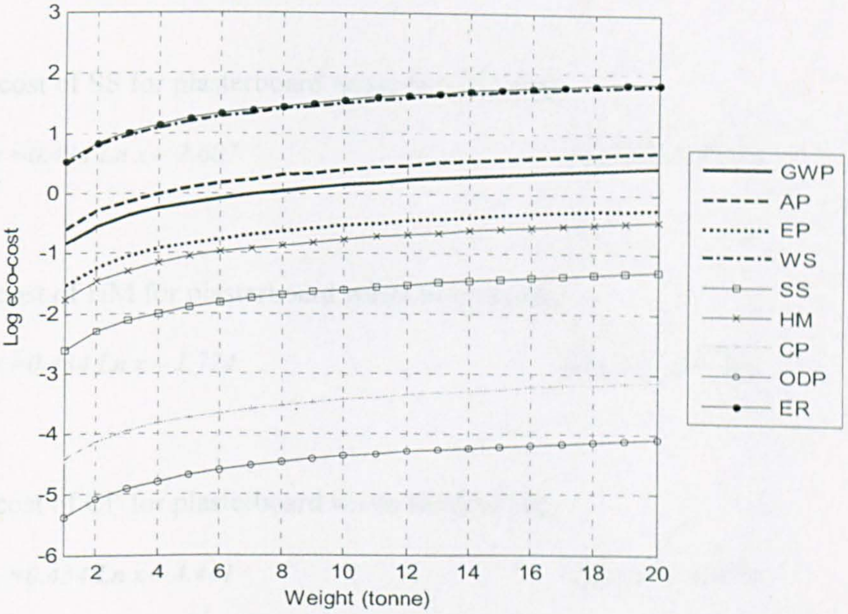

Figure 8.5: Graph of log eco-costs versus weight by indicators of plasterboard waste to recycling

Eco-cost of GWP for plasterboard waste to recycling,

$$\log y = 0.434 \ln x - 0.863 \quad \text{(Equation 8-37)}$$

Eco-cost of AP for plasterboard waste to recycling,

$$\log y = 0.434 \ln x - 0.613 \quad \text{(Equation 8-38)}$$

Eco-cost of EP for plasterboard waste to recycling,

$$\log y = 0.434 \ln x - 1.542 \quad \text{(Equation 8-39)}$$

Eco-cost of WS for plasterboard waste to recycling,

$$\log y = 0.434 \ln x + 0.493 \quad \text{(Equation 8-40)}$$

Eco-cost of SS for plasterboard waste to recycling,

$$Log\,y = 0.434\,Ln\,x - 2.607 \qquad \text{(Equation 8-41)}$$

Eco-cost of HM for plasterboard waste to recycling,

$$Log\,y = 0.434\,Ln\,x - 1.774 \qquad \text{(Equation 8-42)}$$

Eco-cost of CP for plasterboard waste to recycling,

$$Log\,y = 0.434\,Ln\,x - 4.441 \qquad \text{(Equation 8-43)}$$

Eco-cost of ODP for plasterboard waste to recycling,

$$Log\,y = 0.434\,Ln\,x - 5.393 \qquad \text{(Equation 8-44)}$$

Eco-cost of ER for plasterboard waste to recycling,

$$Log\,y = 0.434\,Ln\,x + 0.540 \qquad \text{(Equation 8-45)}$$

Where, y is eco-costs and x is material waste in tonne.

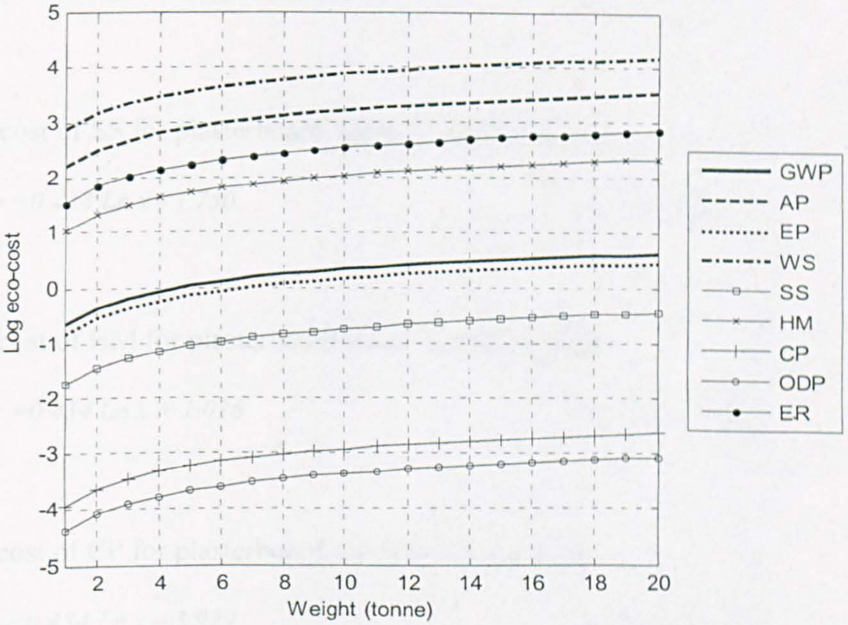

Figure 8.6: Graph of log eco-costs versus weight by indicators of plasterboard waste to sorting plant

Eco-cost of GWP for plasterboard waste to sorting plant,

$Log\ y = 0.434\ Ln\ x - 0.666$ (Equation 8-46)

Eco-cost of AP for plasterboard waste to sorting plant,

$Log\ y = 0.434\ Ln\ x + 2.209$ (Equation 8-47)

Eco-cost of EP for plasterboard waste to sorting plant,

$Log\ y = 0.434\ Ln\ x - 0.844$ (Equation 8-48)

Eco-cost of WS for plasterboard waste to sorting plant,

$Log\,y = 0.434\,Ln\,x + 2.866$ (Equation 8-49)

Eco-cost of SS for plasterboard waste to sorting plant,

$Log\,y = 0.434\,Ln\,x - 1.750$ (Equation 8-50)

Eco-cost of HM for plasterboard waste to sorting plant,

$Log\,y = 0.434\,Ln\,x + 1.036$ (Equation 8-51)

Eco-cost of CP for plasterboard waste to sorting plant,

$Log\,y = 0.434\,Ln\,x - 3.929$ (Equation 8-52)

Eco-cost of ODP for plasterboard waste to sorting plant,

$Log\,y = 0.434\,Ln\,x - 4.375$ (Equation 8-53)

Eco-cost of ER for plasterboard waste to sorting plant,

$Log\,y = 0.434\,Ln\,x + 1.547$ (Equation 8-54)

Where, y is eco-costs and x is material waste in tonne.

8.4. Estimation Model for Total Eco-Cost

Total eco-cost is the sum of all eco-costs by indicator for the three material waste disposal options. In this section, discussion about the relationship curves of log total eco-costs versus weight of construction material waste is presented. Basically, total eco-costs are the eco-cost summations for all nine eco-costs indicator results for three waste disposal options in Section 8.2. But in order to keep the model as simple as possible the estimation total eco-costs will also be expressed in mathematical models. The curve of relationship between eco-cost and weight of construction material waste models for the three waste disposal options are also presented.

8.4.1. Estimation Model for Total Eco-Cost of Brick Waste

Total eco-cost results have shown that the sorting plant option was the highest total eco-cost contributor in the disposal of brick waste compared with the two other options. The disposal option was the second highest with total eco-cost values of 45.5 percent lower from total eco-costs of sorting plant. Meanwhile, recycling is the lowest with total eco-cost values approximately 86 percent lower from total eco-costs of sorting plant.

Figure 8.7 shows the graph of log total eco-costs versus weight of brick waste for three waste disposal options.

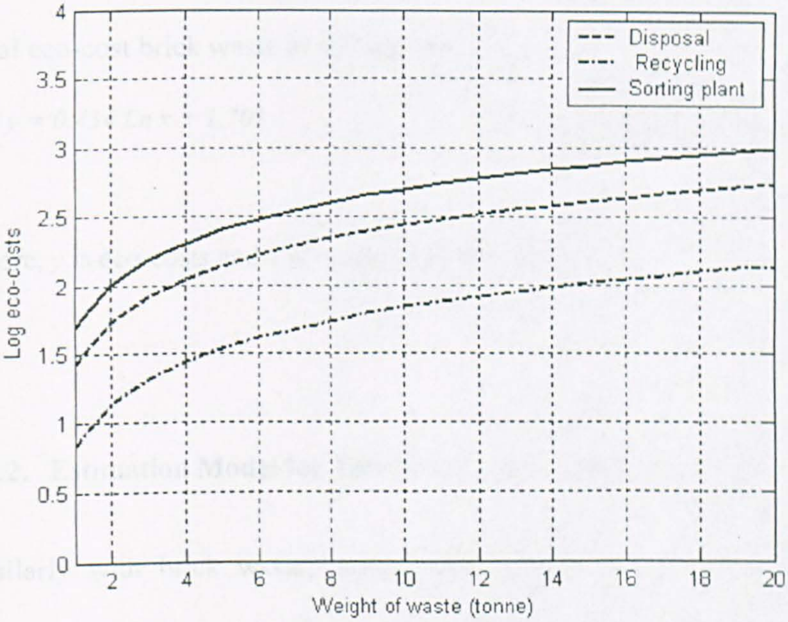

Figure 8.7: Graph of log eco-costs versus weight of brick waste for three waste disposal options

Based on the graph in Figure 8.7, the following estimation of total eco-costs mathematical models is developed as shown as Equation 8-55, 8-56 and 8-57.

Total eco-cost of brick waste to final disposal:

$Log\ y = 0.434\ Ln\ x + 1.437$ (Equation 8-55)

Total eco-cost brick waste to recycling:

$Log\ y = 0.434\ Ln\ x + 0.839$ (Equation 8-56)

Total eco-cost brick waste to sorting plant:

$$\log y = 0.434 \ln x + 1.701 \qquad \text{(Equation 8-57)}$$

Where, y is eco-costs and x is material waste in tonne.

8.4.2. Estimation Model for Total Eco-Cost of Concrete Waste

Similarly with brick waste, sorting plant option was found to be the highest total eco-cost contributor in the disposal of brick waste with the disposal and recycling option coming second and third. The value of total eco-cost for the disposal and recycling option are approximately 44.5 and 85 percent lower than the sorting plant total eco-costs value.

Figure 8.8 shows the graph of log total eco-costs versus weight of concrete waste for the three waste disposal options.

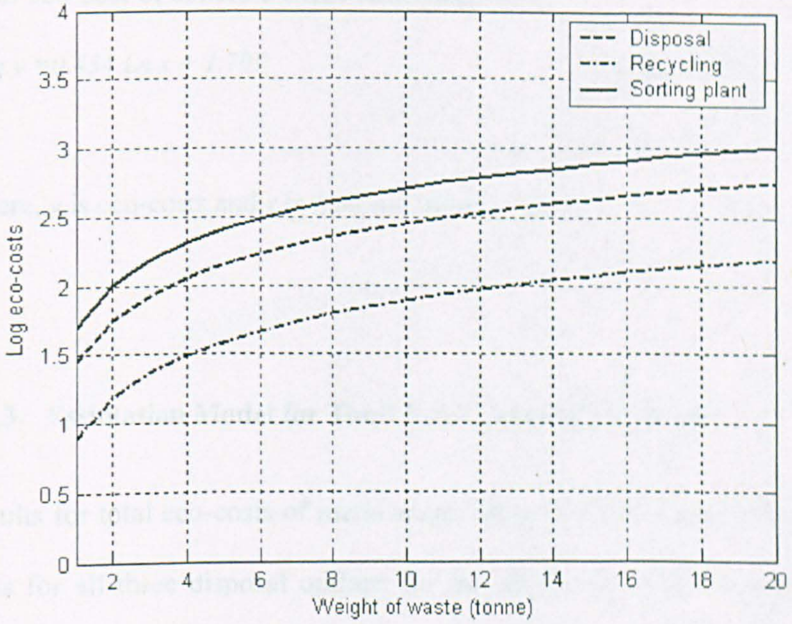

Figure 8.8: Graph of log eco-costs versus weight of concrete waste for three waste disposal options

Based on the graph in Figure 8.8, developed mathematical models as shown as Equation 8.58, 8.59 and 8.60 can be used to estimate the total eco-costs concrete waste.

Total eco-cost of concrete waste to final disposal,

$Log\ y = 0.434\ Ln\ x + 1.451$ (Equation 8-58)

Total eco-cost of concrete waste to recycling,

$Log\ y = 0.434\ Ln\ x + 0.892$ (Equation 8-59)

Total eco-cost of concrete waste to sorting plant,

$$Log\, y = 0.434\, Ln\, x + 1.707 \qquad \text{(Equation 8-60)}$$

Where, y is eco-costs and x is material waste in tonne.

8.4.3. Estimation Model for Total Eco-Cost of Metal Waste

Results for total eco-costs of metal waste show that the range of total eco-costs for all three disposal options for the reinforced steel is very small. The graph lines for the three options shown in Figure 8.3 are so close to each other, especially for the recycling and the sorting plant. Unlike the two material waste total eco-cost results before, the final disposal option happens to be the highest total eco-cost score for reinforced steel waste. Sorting plant and recycling options come second and third with 13.5 and 22.5 percent lower than the total eco-costs of final disposal option.

Compared with the three waste disposal options for reinforced steel, bulk iron waste that goes through sorting plant produced the lowest total eco-costs value. The total eco cost of bulk iron waste for this option is 98 percent lower than the eco-costs of reinforced steel waste to the final disposal. Figure 8.9 shows the graph of log total eco-costs versus weight of metal waste for the three waste disposal options.

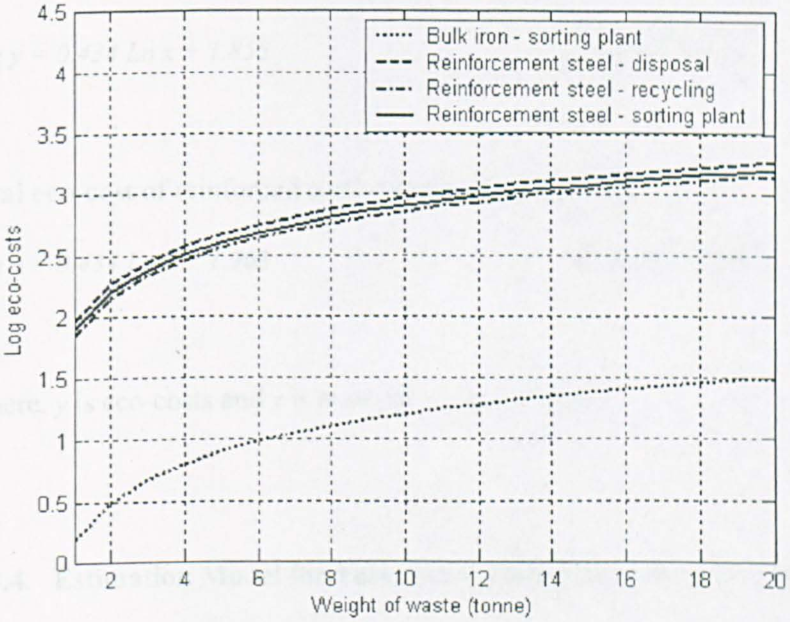

Figure 8.9: Graph of log eco-costs versus weight of metal waste for three waste disposal options

Based on Figure 8.9, estimation mathematical models of total eco-cost for all four metal waste disposal options is developed as shown as Equation 8-61, 8-62, 8-63 and 8-64.

Total eco-cost of bulk iron waste to sorting plant,

$Log\ y = 0.434\ Ln\ x + 0.196$ (Equation 8-61)

Total eco-cost of reinforcement steel waste to final disposal,

$Log\ y = 0.434\ Ln\ x + 1.965$ (Equation 8-62)

Total eco-cost of reinforced steel waste to recycling,

$$Log\, y = 0.434\, Ln\, x + 1.855 \qquad \text{(Equation 8-63)}$$

Total eco-cost of reinforced steel waste to sorting plant,

$$Log\, y = 0.434\, Ln\, x + 1.903 \qquad \text{(Equation 8-64)}$$

Where, y is eco-costs and x is material waste in tonne.

8.4.4. Estimation Model for Total Eco-Cost of Plasterboard Waste

The ranking of total eco-cost results for plasterboard waste is found to be similar to the brick and concrete waste disposal option, where the highest total eco-costs were from the sorting plant and followed by the disposal as the second highest and recycling as the lowest total eco-costs score. However, the sorting plant total eco-costs result for plasterboard waste is found to be far higher than the other two waste disposal options. Total eco-costs for the final disposal and recycling options are found to be approximately 97 percent and 99 percent lower that the sorting plant option.

Figure 8.10 shows the graph of log total eco-costs versus weight of plasterboard waste for the three waste disposal options.

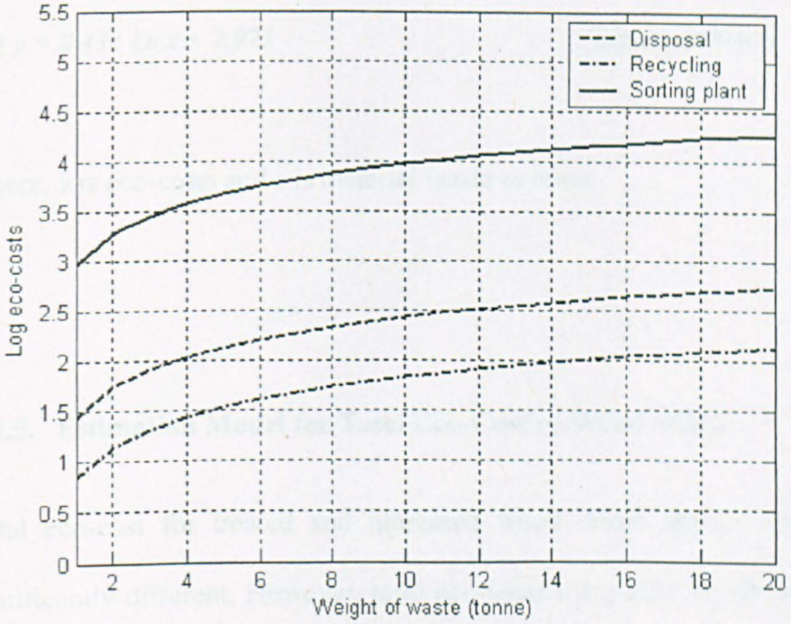

Figure 8.10: Graph of log eco-costs versus weight of plasterboard waste for three waste disposal options

Based on the graph in Figure 8.10, Equation 8-65, 8-66 and 8-67 are used as mathematical models to estimate total eco-cost of the plasterboard waste disposal option.

Total eco-cost of plasterboard waste to final disposal

$Log\ y = 0.434\ Ln\ x + 1.437$ (Equation 8-65)

Total eco-cost of plasterboard waste to recycling

$Log\ y = 0.434\ Ln\ x + 0.839$ (Equation 8-66)

Total eco-cost of plasterboard waste to sorting plant

$Log\, y = 0.434\, Ln\, x + 2.975$ (Equation 8-67)

Where, y is eco-costs and x is material waste in tonne.

8.4.5. Estimation Model for Total Eco-Cost of Wood Waste

Total eco-cost for treated and untreated wood waste appear not to be significantly different. However, total eco-costs for treated wood waste are highest if compared with untreated wood waste. The total eco-costs for untreated wood waste are found to be only 6.4 percent lower than the treated wood waste.

Figure 8.11 shows the graph of log total eco-costs versus weight of wood wastes for the three waste disposal options.

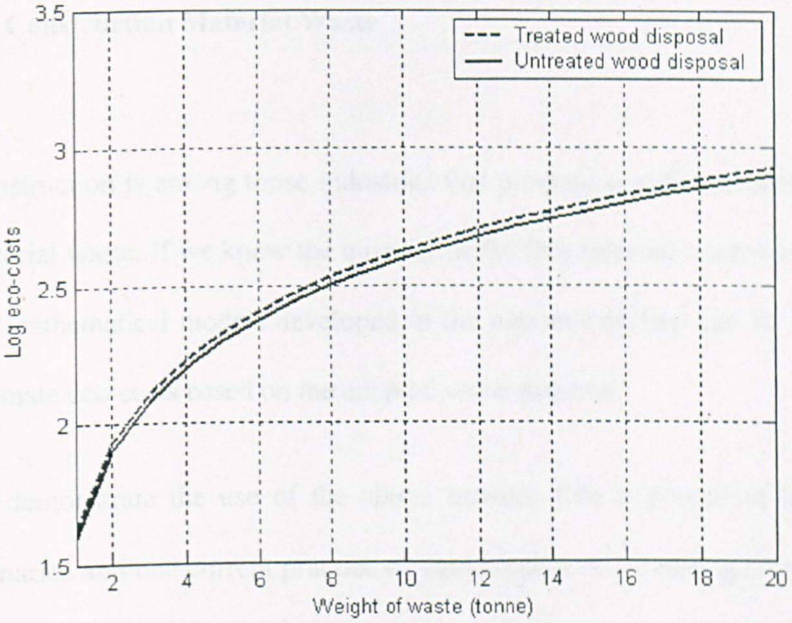

Figure 8.11: Graph of log eco-costs versus weight of wood plasterboard waste for three waste disposal options

Equation 8-68 and 8-69 which is based on Figure 8.11 is used as amathematical model to estimate the total eco-costs of wood waste disposal options.

Eco-cost of treated wood waste to final disposal:

$Log\ y = 0.434\ Ln\ x + 1.626$ (Equation 8-68)

Eco-cost of untreated wood waste to final disposal

$Log\ y = 0.434\ Ln\ x + 1.598$ (Equation 8-69)

Where, y is eco-costs and x is material waste in tonne.

8.5. The Use of Mathematical Models to Estimate Total Eco-Costs of Construction Material Waste

Construction is among those industries that produce significant amounts of material waste. If we know the quantity of the five selected material wastes, the mathematical models developed in the previous section can be used to estimate eco-costs based on the adopted waste disposal.

To demonstrate the use of the above models, five hypothetical baseline scenarios and one current practice of construction waste management have been chosen for the management of waste disposal option for the selected waste, including disposal, recycling, sorting plant, and a combination of these methods as shown in Table 8.1.

Table 8.1: Scenario of waste disposal option

Scenario	**Total waste (%)**	**Recycling (%)**	**Sorting plant (%)**	**Disposal (%)**
Disposal	100			100
Recycling	100	100		
Recycling/disposal	100	50		50
Recycling/sorting plant	100	50	50	
All	100	33.33	33.33	33.33
Current practice in the UK*	100	80	13	7

* Source: BRE (2006)

Real data from three case studies on waste construction which have been studied in the UK and the United States will be used. The first data which was from the research carried out by British Research Establishment -

BRE (2006) construction waste in the UK housing sector for every cubic metre per 100 square metre of floor area as shown in Table 8.2. This was based on the BRE benchmarking data for environmental performance indicator (EPI) for 23 housing projects. In the financial year 2004/05 it is estimated that around 190,000 houses were built in the UK.

Table 8.2: Construction waste from the residential construction in the UK

Waste type	**Weight of waste (tonne)**	**Yearly estimated waste (million tonne)**
Bricks*	2.00	0.38
Concrete	2.80	0.53
Metals	1.40	0.27
Plasterboards**	1.00	0.19
Woods	0.39	0.07

Note:
* Total amount of brick waste was estimated from ceramic and inert waste of the study
** Total amount of plasterboard was estimated from plaster and cement waste of the study

Second data was adopted from one case study conducted by Laquatra and

Research by Pierce (2004) on Managing Waste at the Residential Construction Site in the United States was based on the weight in cubic metres for construction material waste for one residential unit per 176 metre square floor area as shown in Table 8.3. It is estimated that 1,636,000 houses were built in the US in 2005 (U.S. Census Bureau 2006).

Table 8.3: Construction waste from the residential construction in the United States

Waste type		Weight of waste (tonne)	Yearly estimated waste (million tonne)
Bricks		0.07	0.12
Concrete		NA	NA
Metals		0.04	0.07
Plasterboards		0.80	1.31
Woods	treated	0.03	0.05
	untreated	0.61	1.0

The third data was obtained from the British Research Establishment - BRE (2006) yearly estimation for demolition waste on all sectors in the UK as shown in Table 8.4.

Table 8.4: Yearly estimation for demolition waste on all sectors in the UK

Waste type	Weight of waste (million tonne)
Bricks*	3.0
Concrete	14.0
Metals	0.78
Plasterboards	NA
Woods	1.04

Note:

* Total amount of brick waste was estimated from masonry waste of the study

By using the developed mathematical model equations (Equation 8-1 to Equation 8-15), waste disposal option scenario in (Table 8.1) and yearly data available (Table 8.2, 8.3 and 8.4), the results of eco-costs are shown in Table 8.5.

In general the results have shown that the yearly eco-cost results for brick waste from residential construction site were approximately 87 percent lower than the demolition site. The difference is very much lower for eco-costs results for concrete waste and wood waste with an approximate average difference of 96 and 93 percent respectively. Results for metal waste have shown that the residential construction site generated 70 percent lower than the demolition site. However results for plasterboard waste could not be compared as the data for the demolition site was not available.

Results on residential construction waste between the UK and the US scenario revealed that the differences in yearly eco-cost result depended on types of materials waste. For example, eco-cost results for brick and metal waste have shown that the UK produced approximately three times more if compared with the US. However eco-cost results for plasterboard and wood have shown that the UK had produced approximately 84 and 93 percent lower than the US respectively. However comparison results for concrete waste could not be made as the data for the US region was not available.

Recycling is the best disposal option for all material waste. Table 8.6 shows total eco-cost value of recycling for all material waste that have found to be the lowest compared to other possible options. However to recycle all the material is very difficult to implement and can be seen as an 'unrealistic' expectation because 100 recycling or zero waste in construction is believe to be an unachievable plan.

Table 8.6 also shows that the UK's current practice of waste disposal option is found to be the best possible option next to recycling. Total eco-cost for this option is the lowest except for plasterboard waste as disposal option for plasterboard is found to be second best after recycling. Eco-cost result for sorting plant option in plasterboard waste is believed to be the reason why the waste disposal option use by the UK is found to be higher than the other disposal options. Since 100 percent disposal is always to be avoided, recycling/disposal is found as the best possible option to dispose of plasterboard for construction without going through the sorting plant. However comparison for disposal option of metal and wood waste cannot be made because the eco-cost data available for those material wastes were only for sorting plant and disposal options respectively.

Table 8.5: Yearly estimation of eco-costs of waste disposal option for brick, concrete, metal, plasterboard and wood wastes

Waste type	**Case**		**Recycling** (million £)	**Sorting plant** (million £)	**Disposal** (million £)	**Recycling/ disposal** (million £)		**Recycling/sorting plant** (million £)		**All** (million £)			**Current practice in the UK** (million £)		
						Recycle	**Disposal**	**Recycle**	**Sorting plant**	**Recycle**	**Sorting plant**	**Disposal**	**Recycle**	**Sorting plant**	**Disposal**
			100%	100%	100%	50%	50%	50%	50%	33.3%	33.3%	33.3%	80%	13%	7%
Brick	1		2.60	18.90	10.30	1.30	5.15	1.30	9.47	0.87	6.31	3.44	2.08	2.46	0.72
	2		0.82	5.98	3.26	0.41	1.63	0.411	2.99	0.27	1.99	1.09	0.66	0.78	0.23
	3		20.50	149.00	81.20	10.30	40.60	10.30	74.608	6.84	49.80	27.10	16.40	19.40	5.70
Concrete	1		4.10	26.80	14.80	2.05	7.42	2.05	13.40	1.37	8.92	4.95	3.28	3.48	1.04
	2														
	3		108.00	705.00	391.00	54.00	196.00	54.00	353.00	36.00	235.00	130.00	86.40	91.80	27.40
Metal	1			0.42											
	2			0.11											
	3			1.21											
Plasterboard	1		1.30	178.00	5.15	0.65	2.58	0.65	89.00	0.43	59.30	1.72	1.04	23.20	0.36
	2		8.96	1220.00	35.50	4.48	17.80	4.48	613.00	2.99	409.00	11.80	7.17	159.00	2.49
	3														
Wood*	1	treated			0.15										
		untreated			2.62										
	2	treated			2.10										
		untreated			39.30										
	3	treated			2.18										
		untreated			38.80										

Key: 1 - Construction waste from the residential construction in the UK 2 - Construction waste from the residential construction in the U S 3. - Demolition waste on all sectors in the UK

Note: *Assumed 5% of total wood wastes are treated wood

Table 8.6: Summary of yearly estimation of eco-costs of waste disposal option for brick, concrete, metal, plasterboard and wood wastes

Waste type	**Case**	**Recycling million £**	**Sorting plant million £**	**Disposal million £**	**Recycling /disposal million £**	**Recycling /sorting plant million £**	**All million £**	**Current practice in the UK million £**
Brick	1	2.60	18.90	10.30	6.45	10.77	10.62	5.26
	2	0.82	5.98	3.26	2.04	3.40	3.35	1.67
	3	20.50	149.00	81.20	50.90	84.91	83.74	41.50
Concrete	1	4.10	26.80	14.80	9.47	15.45	15.24	7.80
	2							
	3	108.00	705.00	391.00	250.00	407.00	401.00	205.60
Plasterboard	1	1.30	178.00	5.15	3.23	89.65	61.45	24.60
	2	8.96	1220.00	35.50	22.28	617.48	423.79	168.66
	3							

Key: 1 - Construction waste from the residential construction in the UK
2 - Construction waste from the residential construction in the U.S.
3. - Demolition waste on all sectors in the UK

8.6. Summary

Based on the developed eco-costs mathematical modelling, three real construction waste data from residential buildings in the UK and the US including demolition waste data in the UK has been used to calculate the total eco-cost. In every case, the best disposal scenario was the 100 percent recycle option which in an unrealistic option. Therefore, the current practice in the UK was found to be the best realistic waste disposal option in contrast with other disposal scenarios. Although the plasterboard disposal results for 50-50 percent of recycling and disposal is shown to be the best option, for the 50 percent disposal of plasterboard this imposes a greater burden on the landfill area besides generating sulphate contamination in the soil and water course. Generally, the results have shown that the UK generates higher eco-costs in comparison with the US for brick and metal waste, but produced lower in plasterboard and wood waste. The results also revealed that the total eco-cost of demolition waste in the UK is very substantial.

The estimation model of eco-cost of waste disposal option could also be used during the pre-construction stages to establish a framework in minimising the environmental impact of construction project waste. Furthermore, by incorporating the element of minimising the environmental impact of construction project waste in the bidding process as suggested by Fishbein (1998), this will encourage contractors to implement waste prevention strategies by developing their waste prevention goal for their project sites.

Chapter 9

CONCLUSION AND RECOMMENDATION

9.1. Introduction

The focus of this research is to extract the eco-cost of construction waste of a selected sample of materials. The estimation is based on the environmental impact, caused by the wastes which were described in monetary terms. In this chapter the overall work is reviewed and findings are summarised. Knowledge contribution and recommendations for future research are made.

9.2. Discussion

Generally, methods for eco-costing modelling can be classified into three main phases which are,

1. LCA processes
2. Monetary valuation of the impact of waste and it disposal option, and
3. Developing the model to estimate eco-cost for the construction material wastes.

The LCA approach was used for the life cycle impact assessment of construction waste disposal option for nine environmental indicators namely GWP, AP, EP, WS, SS, HM, CP, ODP and ER. Subsequently, the external cost from DEFRA (Table 4.49 in Chapter 4) was used as an eco-cost equivalent value for the indicators

The use of impact result from environmental data to measure eco-cost results could assist us to determine the sustainability of products or services. Strategy and planning can be justified by using the eco-cost results, at the early stage of construction or demolition to minimise wastes and impact as well as to select a suitable waste disposal option for the project. The implementation of this concept in other industries presented by several studies such as Vogtlander (2001) and Huisman (2003) has proved the importance of eco-cost in measuring sustainability of products and services. Ultimately, it aims to reduce the total cost with the help of green or eco-friendly alternatives in all the stages of the life cycle of any product (Durairaj, Ong et al. 2002).

Waste generation by construction activities has a significant impact on the environment. The need to establish indicators to measure the sustainability of construction and demolition site activities is crucial. Eco-cost is one of the indicators that can help to monitor sustainable construction.

Developing a sustainable waste quantification eco-costs model based on LCA methodology is essential

Every type of construction material and especially its waste could have an impact on the human and environment throughout its entire lifecycle which includes extraction, production, usage and disposal of material waste. For the waste case scenario, the impact mainly comes from the use of energy like electricity and fuel and emission from vehicles as transportation and also machinery that has been used at production stages. The process of the waste disposal at the end of the materials' life could have a significant impact. Emissions could also be released from the decomposition of the material in the landfill which may result in the soil and water contamination. As for material wastes like concrete and plasterboard the impact from the release of suspended particle matter (SPM) may be generated during the process of dismantling the material which can cause the forming of smog.

9.3. Research findings

The use of diesel from machinery during the dismantling processes and the use of the lorry for transportation of waste either to final disposal or sorting plant were the greatest contributors for GWP, AP, EP and WS.

While the upstream activities like materials production of infrastructure for the use of waste disposal activities and production of energy sources (fuel, electricity and gas) are heavy contributors for HM and ER, meanwhile, most of the burdens for wood waste were generated from activities of disposal of the wood waste itself, for example the GWP, EP and HM and from specific process of MSWI such as the disposal of residue into the sanitary landfill, for example AP and WS. The EP burden however, was still contributed to by the fuel and gas production activities.

As can be seen in Chapter 7, the eco-costs results of all three different waste disposal options for the construction material wastes, ER was found to be the major contributor to the total eco-costs in every option except for the sorting plant management option of plasterboard waste and ER is still considered to be a significant contributor of eco-costs for sorting plant as well. The reason why ER is considered to be the main contributor of the eco-cost is because of the energy consumption at all stages during the LCA.

Besides ER, smog especially WS was also found as an indicator that can incur considerable eco-costs. In most cases, winter smog has become the second highest in the contributors list of indicators. It was found in many cases that GWP, AP and HM also contributed considerably to eco-cost although not as much as ER and WS.

By using the developed eco-costs mathematical modelling to estimate the eco-costs real construction waste cases, it was revealed that current practice of waste disposal option in the UK was found to be the best and a realistic waste disposal strategy. The eco-cost results also shown that the UK generates more eco-cost in comparison with the US for brick and metal waste in residential construction, but produced less in plasterboard and wood waste. The results also revealed that the total eco-cost from the demolition waste in the UK is very substantial.

9.4. Knowledge Contribution

The aim of this research is to develop an estimation model of eco-cost for construction waste disposal options. This research has contributed the followings to existing knowledge

1. Determination of the LCA for the method on assessing the impact of construction waste disposal options
2. Determination of the environmental indicator for the LCIA analysis of construction waste disposal options
3. The extraction of the impact value for the environmental indicators of construction waste disposal options (Chapter 6)
4. Determination of eco-cost value for the nine environmental indicators i.e. GWP, AP, EP, WS, SS, HM, CP, ODP, and ER.

(Table 4.50 in Chapter 4) to be used as a reference to convert environmental impact value to eco-costs results of construction and demolition waste disposal options.

5. The development of mathematical and graphical modelling to calculate and estimate the eco-costing value for the environmental indicators of the above material waste disposal option (Section 8.2 in Chapter 8).
6. The development of mathematical modelling as well as graphical modelling to calculate and estimate eco-costing value for the total eco-cost for the brick, concrete, metal, plasterboard and wood waste from construction and demolition site waste disposal option (Section 8.3 in Chapter 8)..

9.5. Recommendation

Although the main objective of the research was achieved there is still space of improvement that needs to be conducted as future research on this topic. The following recommendations are proposed as a continuation of the research;

1. Development of eco-cost modelling at end-point stage. Comparing the mid-point impact assessment with the end-point impact assessment could be made.

2. Development of prevention eco-cost models for the construction material waste disposal options

3. To compare damage eco-cost models with prevention eco-cost models to get the current optimum weight of waste that need to be achieved in practice

4. Development of eco-cost models for building material use throughout the whole life cycle of the buildings.

5. Developing the total eco-cost modelling which include waste control, recycling and reuse, waste disposal, repair, impact, eco-policy (i.e. taxes and levies), labour, equipment, emissions and energy as suggested by Yahya and Boussabaine (2004)

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APPENDIX 1

Table 1: Characteristic factors, mass based [Goedkoop (1995), Vogtlander (2001)]

Substance		Weighing factor	Substance		Weighing factor
Global warming			**Carcinogenics**		
CO2	Air	1	PAH	Air	in summer smog
N2O	Air	270	Benzo[a]pyrene	Air	1
Dichloromethane	Air	15	As	Air	0.044
HFD-125	Air	3400	CxHy aromatic	Air	0.000011
HFC-134a	Air	1200	Benzene	Air	in summer smog
HFC-143a	Air	3800	Fluoranthene	Air	1
HFC-152a	Air	150	Ni	Air	0.44
Methane	Air	in summer smog	Cr (6+)	Air	0.44
Trichloromethane	Air	25	Tar	Air	0.000011
Acidification			Ethylbenzene	Air	0.000011
Nox	Air	0.7	**Summer Smog**		
SO2	Air	1	CxHy	Air	0.398
HCL	Air	0.88	Phthalic acid anhyride	Air	0.761
HF	Air	1.6	Terpentine	Air	0.377
Ammonia	Air	1.88	Aldehydes	Air	0.443
NO	Air	1.07	PAH	Air	0.761
SOx	Air	1	Methyl mercaptane	Air	0.377
NO2	Air	0.7	Ethanol	Air	0.268
Euthrophication			Vinylacetate	Air	0.223
Nox	Air	in acidification	Crude oil	Air	0.398
Ammonia	Air	in acidification	Ethylene glycol	Air	0.196
NO	Air	in acidification	Ethylene oxide	Air	0.377
NO2	Air	in acidification	Caprolactam	Air	0.761
Nitrates	Air	0.42	Viny;chloride	Air	0.021
Phosphate	Air	1	Hydroxy compounds	Air	0.377
COD	Water	0.022	Ketones	Air	0.326
NH3	Water	0.33	Diethyl ether	Air	0.398
Phosphate	Water	1	Tetrachlorometane	Air	0.021
NH4+	Water	0.33	1,1,1-trichloroethane	Air	0.021
Ptot	Water	3.06	Dichlorometane	Air	0.01
Ntot	Water	0.42	Methane	Air	0.007
Heavy Metals			Hexachlorobiphenyl	Air	0.761
Hg	Air	1	Petrol	Air	0.398
Pb	Air	1	Alcohols	Air	0.196
Cd	Air	50	CxHy aliphatic	Air	0.398
Cadnium oxyde	Air	50	CxHy chloro	Air	0.021
Heavy Metals	Air	1	CxHy aromatic	Air	0.761
Mn	Air	1	Diphenyl	Air	0.761
Pb	Water	1	Isopropanol	Air	0.196
Hg	Water	10	Benzene	Air	0.189
Cd	Water	3	Ethene	Air	1
Sb	Water	2	Propane	Air	0.42
Cr	Water	0.2	Propene	Air	1.03
Cu	Water	0.005	Styrene	Air	0.761
Mo	Water	0.14	Toluene	Air	0.563
As	Water	1	Xylene	Air	0.85
Ba	Water	0.14	Phenl	Air	0.761
Ni	Water	0.5	VOC	Air	0.398
Mn	Water	0.02	Methyl ethyl ketone	Air	0.473
B	Water	0.03	Formaldehyde	Air	0.421
Winter Smog			Pentane	Air	0.408
Dust (SPM)	Air	1	Non methane VOC	Air	0.416
SO2	Air	in acidification	Acetone	Air	0.178
Carbon black	Air	1	Trichloroethene	Air	0.066
Soot	Air	1	Chlorophenols	Air	0.761
Iron dust	Air	1	Acetylene	Air	0.168
			Propionaldehyde, propanal	Air	0.603
			Naphtalene	Air	0.761
			1,2-dichloroethene	Air	0.021

APPENDIX 2

Table 1: GWP contribution value for brick waste

A: Brick waste to final disposal

No	Process	Unit equivalent	Contribution value of GWP
1	Diesel, burned in building machine	kg CO2	0.00501
2	Operation, lorry 28t	kg CO2	0.00462
3	Natural gas, sweet, burned in production flare	kg CO2	0.000628
4	Refinery gas, burned in furnace	kg CO2	0.000346
5	Natural gas, vented	kg CO2	0.000224
6	Polyethylene, HDPE, granulate, at plant	kg CO2	0.00019
7	Heavy fuel oil, burned in refinery furnace	kg CO2	0.00016
8	Sweet gas, burned in gas turbine, production	kg CO2	0.00015
9	Refinery gas, burned in furnace	kg CO2	0.000147
10	Lignite, burned in power plant	kg CO2	0.000137
	Remaining processes	kg CO2	0.00212
	Total of all processes	**kg CO2**	**0.0137**

B: Brick waste to recycling

No	Process	Unit equivalent	Contribution value of GWP
1	Diesel, burned in building machine	kg CO2	0.00266
2	Refinery gas, burned in furnace	kg CO2	0.00011
3	Heavy fuel oil, burned in refinery furnace	kg CO2	5.07E-05
4	Natural gas, sweet, burned in production flare	kg CO2	3.53E-05
5	Disposal, used mineral oil, to hazardous waste incineration	kg CO2	0.000034
6	Natural gas, burned in industrial furnace low-NOx	kg CO2	2.76E-05
7	Natural gas, sour, burned in production flare	kg CO2	2.76E-05
8	Diesel, burned in diesel-electric generating set	kg CO2	0.000026
9	Operation, transoceanic tanker	kg CO2	2.35E-05
10	Lignite, burned in power plant	kg CO2	2.15E-05
	Remaining processes	kg CO2	0.000209
	Total of all processes	**kg CO2**	**0.00322**

C: Brick waste to sorting plant

No	Process	Unit equivalent	Contribution value of GWP
1	Operation, lorry 28t	kg CO2	0.00482
2	Diesel, burned in building machine	kg CO2	0.00436
3	Natural gas, sweet, burned in production flare	kg CO2	0.000463
4	Excavation, hydraulic digger	kg CO2	0.000351
5	Refinery gas, burned in furnace	kg CO2	0.000331
6	Lignite, burned in power plant	kg CO2	0.000296
7	Polyethylene, HDPE, granulate, at plant	kg CO2	0.000243
8	Hard coal, burned in power plant	kg CO2	0.000228
9	Clinker, at plant	kg CO2	0.000216
10	Natural gas, vented	kg CO2	0.000167
	Remaining processes	kg CO2	0.00237
	Total of all processes	**kg CO2**	**0.0139**

Table 2: AP contribution value for brick waste

A: Brick waste to final disposal

No	Process	Unit equivalent	Contribution value of AP
1	Diesel, burned in building machine	kg SO2	5.06E-05
2	Operation, lorry 28t	kg SO2	3.21E-05
3	Natural gas, sour, burned in production flare	kg SO2	6.53E-06
4	Operation, transoceanic tanker	kg SO2	3.3E-06
5	Natural gas, sweet, burned in production flare	kg SO2	2.17E-06
6	Polyethylene, HDPE, granulate, at plant	kg SO2	2.17E-06
7	Heavy fuel oil, burned in refinery furnace	kg SO2	1.94E-06
8	Diesel, burned in diesel-electric generating set	kg SO2	1.84E-06
9	Excavation, skid-steer loader	kg SO2	1.26E-06
10	Excavation, hydraulic digger	kg SO2	1.2E-06
	Remaining processes	kg SO2	9.21E-06
	Total of all processes	**kg SO2**	**0.000112**

B: Brick waste to recycling

No	Process	Unit equivalent	Contribution value of AP
1	Diesel, burned in building machine	kg SO2	2.68E-05
2	Natural gas, sour, burned in production flare	kg SO2	2.06E-06
3	Operation, transoceanic tanker	kg SO2	6.73E-07
4	Heavy fuel oil, burned in refinery furnace	kg SO2	6.14E-07
5	Diesel, burned in diesel-electric generating set	kg SO2	3.58E-07
6	Diesel, at refinery	kg SO2	1.62E-07
7	Natural gas, sweet, burned in production flare	kg SO2	1.22E-07
8	Refinery gas, burned in furnace	kg SO2	1.16E-07
9	Sour gas, burned in gas turbine, production	kg SO2	9.73E-08
10	Lignite, burned in power plant	kg SO2	8.69E-08
	Remaining processes	kg SO2	1.03E-06
	Total of all processes	**kg SO2**	**3.21E-05**

C: Brick waste to sorting plant

No	Process	Unit equivalent	Contribution value of AP
1	Diesel, burned in building machine	kg SO2	4.41E-05
2	Operation, lorry 28t	kg SO2	3.35E-05
3	Natural gas, sour, burned in production flare	kg SO2	6.24E-06
4	Excavation, hydraulic digger	kg SO2	3.55E-06
5	Operation, transoceanic tanker	kg SO2	2.82E-06
6	Polyethylene, HDPE, granulate, at plant	kg SO2	2.77E-06
7	Heavy fuel oil, burned in refinery furnace	kg SO2	1.85E-06
8	Natural gas, sweet, burned in production flare	kg SO2	1.6E-06
9	Diesel, burned in diesel-electric generating set	kg SO2	1.59E-06
10	Excavation, skid-steer loader	kg SO2	7.13E-07
	Remaining processes	kg SO2	1.09E-05
	Total of all processes	**kg SO2**	**0.00011**

Table 3: EP contribution value for brick waste

A: Brick waste to final disposal

No	Process	Unit equivalent	Contribution value of EP
1	Diesel, burned in building machine	kg PO4	9.09E-06
2	Operation, lorry 28t	kg PO4	5.8E-06
3	Crude oil, at production onshore	kg PO4	7.79E-07
4	Natural gas, sweet, burned in production flare	kg PO4	4.04E-07
5	Diesel, burned in diesel-electric generating set	kg PO4	3.21E-07
6	Operation, transoceanic tanker	kg PO4	3.08E-07
7	Excavation, skid-steer loader	kg PO4	2.27E-07
8	Excavation, hydraulic digger	kg PO4	2.17E-07
9	Lead, at regional storage	kg PO4	1.84E-07
10	Disposal, basic oxygen furnace wastes, to residual material landfill	kg PO4	1.51E-07
	Remaining processes	kg PO4	1.13E-06
	Total of all processes	**kg PO4**	**1.86E-05**

B: Brick waste to recycling

No	Process	Unit equivalent	Contribution value of EP
1	Diesel, burned in building machine	kg PO4	4.83E-06
2	Crude oil, at production onshore	kg PO4	2.46E-07
3	Operation, transoceanic tanker	kg PO4	6.28E-08
4	Diesel, burned in diesel-electric generating set	kg PO4	6.26E-08
5	Disposal, basic oxygen furnace wastes, to residual material landfill	kg PO4	3.01E-08
6	Natural gas, sweet, burned in production flare	kg PO4	2.27E-08
7	Natural gas, sour, burned in production flare	kg PO4	1.77E-08
8	Disposal, used mineral oil, to hazardous waste incineration	kg PO4	1.55E-08
9	Refinery gas, burned in furnace	kg PO4	1.14E-08
10	Heavy fuel oil, burned in refinery furnace	kg PO4	1.14E-08
	Remaining processes	kg PO4	1.21E-07
	Total of all processes	**kg PO4**	**5.43E-06**

C: Brick waste to sorting plant

No	Process	Unit equivalent	Contribution value of EP
1	Diesel, burned in building machine	kg PO4	7.93E-06
2	Operation, lorry 28t	kg PO4	6.06E-06
3	Disposal, inert material, to sanitary landfill	kg PO4	1.92E-06
4	Crude oil, at production onshore	kg PO4	7.45E-07
5	Excavation, hydraulic digger	kg PO4	6.39E-07
6	Natural gas, sweet, burned in production flare	kg PO4	2.98E-07
7	Diesel, burned in diesel-electric generating set	kg PO4	2.79E-07
8	Operation, transoceanic tanker	kg PO4	2.63E-07
9	Lead, at regional storage	kg PO4	1.96E-07
10	Disposal, basic oxygen furnace wastes, to residual material landfill	kg PO4	1.78E-07
	Remaining processes	kg PO4	1.44E-06
	Total of all processes	**kg PO4**	**1.99E-05**

Table 4: WS contribution value for brick waste

A: Brick waste to final disposal

No	Process	Unit equivalent	Contribution value of WS
1	Disposal, building, brick, to final disposal	kg SPM	0.00008
2	Diesel, burned in building machine	kg SPM	8.28E-06
3	Natural gas, sour, burned in production flare/MJ	kg SPM	6.23E-06
4	Operation, lorry 28t	kg SPM	3.31E-06
5	Operation, transoceanic tanker	kg SPM	2.72E-06
6	Heavy fuel oil, burned in refinery furnace	kg SPM	1.82E-06
7	Polyethylene, HDPE, granulate, at plant	kg SPM	1.64E-06
8	Iron ore, at mine	kg SPM	8.87E-07
9	Lead, at regional storage	kg SPM	4.76E-07
10	Diesel, at refinery	kg SPM	4.55E-07
	Remaining processes	kg SPM	6.61E-06
	Total of all processes	**kg SPM**	**0.000112**

B: Brick waste to recycling

No	Process	Unit equivalent	Contribution value of WS
1	Disposal, building, brick, to recycling	kg SPM	0.00008
2	Diesel, burned in building machine	kg SPM	4.39E-06
3	Natural gas, sour, burned in production flare/MJ	kg SPM	1.97E-06
4	Heavy fuel oil, burned in refinery furnace	kg SPM	5.78E-07
5	Operation, transoceanic tanker	kg SPM	5.55E-07
6	Diesel, at refinery	kg SPM	1.48E-07
7	Iron ore, at mine	kg SPM	1.46E-07
8	Sour gas, burned in gas turbine, production/MJ	kg SPM	9.46E-08
9	Lignite, burned in power plant	kg SPM	8.14E-08
10	Diesel, burned in diesel-electric generating set	kg SPM	8.03E-08
	Remaining processes	kg SPM	8.16E-07
	Total of all processes	**kg SPM**	**8.89E-05**

C: Brick waste to sorting plant

No	Process	Unit equivalent	Contribution value of WS
1	Disposal, building, brick, to sorting plant	kg SPM	0.00008
2	Diesel, burned in building machine	kg SPM	7.22E-06
3	Natural gas, sour, burned in production flare	kg SPM	5.96E-06
4	Operation, lorry 28t	kg SPM	3.46E-06
5	Operation, transoceanic tanker	kg SPM	2.33E-06
6	Polyethylene, HDPE, granulate, at plant	kg SPM	2.1E-06
7	Heavy fuel oil, burned in refinery furnace	kg SPM	1.74E-06
8	Iron ore, at mine	kg SPM	1.03E-06
9	Excavation, hydraulic digger	kg SPM	5.82E-07
10	Lead, at regional storage	kg SPM	5.08E-07
	Remaining processes	kg SPM	8.13E-06
	Total of all processes	**kg SPM**	**0.000113**

Table 5: HM contribution value for brick waste

A: Brick waste to final disposal

No	Process	Unit equivalent	Contribution value of HM
1	Lead, at regional storage	kg Pb	3.97E-07
2	Iron ore, at beneficiation	kg Pb	1.88E-08
3	Disposal, nickel smelter slag, to residual material landfill	kg Pb	1.12E-08
4	Lead, concentrate, at beneficiation	kg Pb	8.35E-09
5	Disposal, sludge from steel rolling, to residual material landfill	kg Pb	6.27E-09
6	Heavy fuel oil, burned in refinery furnace	kg Pb	5.31E-09
7	Copper, primary, at refinery	kg Pb	3.69E-09
8	Disposal, slag, unalloyed electr. steel, to residual material landfill	kg Pb	3.47E-09
9	Discharge, produced water, onshore	kg Pb	3.18E-09
10	Operation, lorry 28t	kg Pb	2.33E-09
	Remaining processes	kg Pb	2.06E-08
	Total of all processes	**kg Pb**	**4.8E-07**

B: Brick waste to recycling

No	Process	Unit equivalent	Contribution value of HM
1	Iron ore, at beneficiation	kg Pb	3.09E-09
2	Disposal, nickel smelter slag, to residual material landfill	kg Pb	2.62E-09
3	Heavy fuel oil, burned in refinery furnace	kg Pb	1.68E-09
4	Disposal, sludge from steel rolling, to residual material landfill	kg Pb	1.12E-09
5	Lead, at regional storage	kg Pb	8.92E-10
6	Disposal, slag, unalloyed electr. steel, to residual material landfill	kg Pb	6.04E-10
7	Discharge, produced water, onshore	kg Pb	5.38E-10
8	Diesel, burned in building machine	kg Pb	4.21E-10
9	Discharge, produced water, offshore	kg Pb	2.73E-10
10	Heavy fuel oil, burned in industrial furnace 1MW, non-modulating	kg Pb	2.28E-10
	Remaining processes	kg Pb	2.29E-09
	Total of all processes	kg Pb	1.38E-08

B: Brick waste to sorting plant

No	Process	Unit equivalent	Contribution value of HM
1	Disposal, inert material, 0% water, to sanitary landfill	kg Pb	1.87E-05
2	Lead, at regional storage	kg Pb	4.22E-07
3	Iron ore, at beneficiation	kg Pb	2.18E-08
4	Disposal, nickel smelter slag, to residual material landfill	kg Pb	2.18E-08
5	Copper, primary, at refinery	kg Pb	1.12E-08
6	Lead, concentrate, at beneficiation	kg Pb	8.9E-09
7	Disposal, sludge from steel rolling, to residual material landfill	kg Pb	6.7E-09
8	Heavy fuel oil, burned in refinery furnace	kg Pb	5.07E-09
9	Disposal, slag, unalloyed electr. steel, to residual material landfill	kg Pb	3.91E-09
10	Discharge, produced water, onshore	kg Pb	2.64E-09
	Remaining processes	kg Pb	3.06E-08
	Total of all processes	**kg Pb**	**1.93E-05**

Table 6: ER contribution value for brick waste

A: Brick waste to final disposal

No	Process	Unit equivalent	Contribution value of ER
1	Crude oil, at production onshore	MJ LHV	0.0811
2	Crude oil, at production	MJ LHV	0.0503
3	Crude oil, at production onshore	MJ LHV	0.0457
4	Crude oil, at production offshore	MJ LHV	0.0313
5	Crude oil, at production onshore/	MJ LHV	0.0261
6	Crude oil, at production offshore	MJ LHV	0.026
7	Natural gas, sweet, burned in production flare	MJ LHV	0.00981
8	Polyethylene, HDPE, granulate, at plant	MJ LHV	0.00836
9	Uranium natural, at underground mine	MJ LHV	0.00659
10	Uranium natural, at open pit mine	MJ LHV	0.00439
	Remaining processes	MJ LHV	0.0212
	Total of all processes	**MJ LHV**	**0.311**

B: Brick waste to recycling

No	Process	Unit equivalent	Contribution value of ER
1	Crude oil, at production onshore	MJ LHV	0.0117
2	Crude oil, at production offshore	MJ LHV	0.00989
3	Crude oil, at production onshore	MJ LHV	0.00825
4	Crude oil, at production offshore	MJ LHV	0.00821
5	Crude oil, at production onshore	MJ LHV	0.00478
6	Crude oil, at production	MJ LHV	0.00152
7	Uranium natural, at underground mine	MJ LHV	0.000719
8	Natural gas, sweet, burned in production flare	MJ LHV	0.000551
9	Uranium natural, at open pit mine	MJ LHV	0.00048
10	Natural gas, sour, burned in production flare	MJ LHV	0.00043
	Remaining processes	MJ LHV	0.00305
	Total of all processes	**MJ LHV**	**0.0495**

B: Brick waste to sorting plant

No	Process	Unit equivalent	Contribution value of ER
1	Crude oil, at production onshore	MJ LHV	0.0597
2	Crude oil, at production onshore	MJ LHV	0.0414
3	Crude oil, at production	MJ LHV	0.0361
4	Crude oil, at production offshore	MJ LHV	0.03
5	Crude oil, at production onshore	MJ LHV	0.025
6	Crude oil, at production offshore	MJ LHV	0.0249
7	Uranium natural, at underground mine	MJ LHV	0.0229
8	Uranium natural, at open pit mine	MJ LHV	0.0153
9	Polyethylene, HDPE, granulate, at plant	MJ LHV	0.0107
10	Natural gas, sweet, burned in production flare/MJ	MJ LHV	0.00723
	Remaining processes	MJ LHV	0.0358
	Total of all processes	**MJ LHV**	**0.309**

Table 7: GWP contribution value for concrete waste

A: Concrete waste to final disposal

No	Process	Unit equivalent	Contribution value of GWP
1	Diesel, burned in building machine	kg CO2	0.00558
2	Operation, lorry 28t	kg CO2	0.00462
3	Natural gas, sweet, burned in production flare	kg CO2	0.000636
4	Refinery gas, burned in furnace	kg CO2	0.00037
5	Natural gas, vented	kg CO2	0.000228
6	Polyethylene, HDPE, granulate, at plant	kg CO2	0.00019
7	Heavy fuel oil, burned in refinery furnace	kg CO2	0.000171
8	Sweet gas, burned in gas turbine, production	kg CO2	0.000153
9	Refinery gas, burned in furnace	kg CO2	0.000147
10	Lignite, burned in power plant	kg CO2	0.000141
	Remaining processes	kg CO2	0.00219
	Total of all processes	**kg CO2**	**0.0144**

B: Concrete waste to sorting plant

No	Process	Unit equivalent	Contribution value of GWP
1	Diesel, burned in building machine	kg CO2	0.00494
2	Operation, lorry 28t	kg CO2	0.00482
3	Natural gas, sweet, burned in production flare	kg CO2	0.00047
4	Refinery gas, burned in furnace	kg CO2	0.000351
5	Lignite, burned in power plant	kg CO2	0.0003
6	Excavation, hydraulic digger	kg CO2	0.000274
7	Polyethylene, HDPE, granulate, at plant	kg CO2	0.000243
8	Hard coal, burned in power plant	kg CO2	0.000231
9	Clinker, at plant	kg CO2	0.000217
10	Natural gas, vented	kg CO2	0.00017
	Remaining processes	kg CO2	0.00244
	Total of all processes	**kg CO2**	**0.0145**

B Concrete waste to recycling

No	Process	Unit equivalent	Contribution value of GWP
1	Diesel, burned in building machine	kg CO2	0.00323
2	Refinery gas, burned in furnace	kg CO2	0.000133
3	Heavy fuel oil, burned in refinery furnace	kg CO2	6.17E-05
4	Natural gas, sweet, burned in production flare	kg CO2	0.000043
5	Disposal, used mineral oil, to hazardous waste incineration	kg CO2	4.14E-05
6	Natural gas, burned in industrial furnace low-NOx	kg CO2	3.36E-05
7	Natural gas, sour, burned in production flare	kg CO2	3.36E-05
8	Diesel, burned in diesel-electric generating set	kg CO2	3.17E-05
9	Operation, transoceanic tanker	kg CO2	2.86E-05
10	Lignite, burned in power plant	kg CO2	2.61E-05
	Remaining processes	kg CO2	0.000255
	Total of all processes	**kg CO2**	**0.00392**

Table 8: AP contribution value for concrete waste

A: Concrete waste to final disposal

No	Process	Unit equivalent	Contribution value of AP
1	Diesel, burned in building machine	kg SO2	5.64E-05
2	Operation, lorry 28t	kg SO2	3.21E-05
3	Natural gas, sour, burned in production flare	kg SO2	6.97E-06
4	Operation, transoceanic tanker	kg SO2	3.45E-06
5	Natural gas, sweet, burned in production flare	kg SO2	2.2E-06
6	Polyethylene, HDPE, granulate, at plant	kg SO2	2.17E-06
7	Heavy fuel oil, burned in refinery furnace	kg SO2	2.07E-06
8	Diesel, burned in diesel-electric generating set	kg SO2	1.91E-06
9	Excavation, skid-steer loader	kg SO2	1.27E-06
10	Excavation, hydraulic digger	kg SO2	1.2E-06
	Remaining processes	kg SO2	9.53E-06
	Total of all processes	**kg SO2**	**0.000119**

B: Concrete waste to sorting plant

No	Process	Unit equivalent	Contribution value of AP
1	Diesel, burned in building machine	kg SO2	4.99E-05
2	Operation, lorry 28t	kg SO2	3.35E-05
3	Natural gas, sour, burned in production flare	kg SO2	6.63E-06
4	Operation, transoceanic tanker	kg SO2	2.95E-06
5	Polyethylene, HDPE, granulate, at plant	kg SO2	2.77E-06
6	Excavation, hydraulic digger	kg SO2	2.76E-06
7	Heavy fuel oil, burned in refinery furnace	kg SO2	1.97E-06
8	Diesel, burned in diesel-electric generating set	kg SO2	1.66E-06
9	Natural gas, sweet, burned in production flare	kg SO2	1.63E-06
10	Excavation, skid-steer loader	kg SO2	7.13E-07
	Remaining processes	kg SO2	1.12E-05
	Total of all processes	**kg SO2**	**0.000116**

B: Concrete waste to recycling

No	Process	Unit equivalent	Contribution value of AP
1	Diesel, burned in building machine	kg SO2	3.27E-05
2	Natural gas, sour, burned in production flare	kg SO2	2.51E-06
3	Operation, transoceanic tanker	kg SO2	8.19E-07
4	Heavy fuel oil, burned in refinery furnace	kg SO2	7.48E-07
5	Diesel, burned in diesel-electric generating set	kg SO2	4.36E-07
6	Diesel, at refinery	kg SO2	1.97E-07
7	Natural gas, sweet, burned in production flare	kg SO2	1.49E-07
8	Refinery gas, burned in furnace	kg SO2	1.41E-07
9	Sour gas, burned in gas turbine, production	kg SO2	1.18E-07
10	Lignite, burned in power plant	kg SO2	1.06E-07
	Remaining processes	kg SO2	1.25E-06
	Total of all processes	**kg SO2**	**3.91E-05**

Table 9: EP contribution value for concrete waste

A: Concrete waste to final disposal

No	Process	Unit equivalent	Contribution value of EP
1	Diesel, burned in building machine	kg PO4	1.01E-05
2	Operation, lorry 28t	kg PO4	5.8E-06
3	Crude oil, at production onshore	kg PO4	8.33E-07
4	Natural gas, sweet, burned in production flare	kg PO4	4.09E-07
5	Diesel, burned in diesel-electric generating set	kg PO4	3.35E-07
6	Operation, transoceanic tanker	kg PO4	3.22E-07
7	Excavation, skid-steer loader	kg PO4	2.27E-07
8	Excavation, hydraulic digger	kg PO4	2.17E-07
9	Lead, at regional storage	kg PO4	1.84E-07
10	Disposal, basic oxygen furnace wastes, to residual material landfill	kg PO4	1.58E-07
	Remaining processes	kg PO4	1.17E-06
	Total of all processes	**kg PO4**	**1.98E-05**

B: Concrete waste to recycling

No	Process	Unit equivalent	Contribution value of EP
1	Diesel, burned in building machine	kg PO4	5.87E-06
2	Crude oil, at production onshore	kg PO4	2.99E-07
3	Operation, transoceanic tanker	kg PO4	7.65E-08
4	Diesel, burned in diesel-electric generating set	kg PO4	7.62E-08
5	Disposal, basic oxygen furnace wastes, to residual material landfill	kg PO4	3.67E-08
6	Natural gas, sweet, burned in production flare	kg PO4	2.76E-08
7	Natural gas, sour, burned in production flare	kg PO4	2.16E-08
8	Disposal, used mineral oil, to hazardous waste incineration	kg PO4	1.89E-08
9	Refinery gas, burned in furnace	kg PO4	1.39E-08
10	Heavy fuel oil, burned in refinery furnace	kg PO4	1.39E-08
	Remaining processes	kg PO4	1.46E-07
	Total of all processes	**kg PO4**	**6.6E-06**

B: Concrete waste to sorting plant

No	Process	Unit equivalent	Contribution value of EP
1	Diesel, burned in building machine	kg PO4	8.98E-06
2	Operation, lorry 28t	kg PO4	6.06E-06
3	Disposal, inert material, to sanitary landfill	kg PO4	1.92E-06
4	Crude oil, at production onshore	kg PO4	7.91E-07
5	Excavation, hydraulic digger	kg PO4	4.97E-07
6	Natural gas, sweet, burned in production flare	kg PO4	3.02E-07
7	Diesel, burned in diesel-electric generating set	kg PO4	2.9E-07
8	Operation, transoceanic tanker	kg PO4	2.75E-07
9	Lead, at regional storage	kg PO4	1.96E-07
10	Disposal, basic oxygen furnace wastes, to residual material landfill	kg PO4	1.83E-07
	Remaining processes	kg PO4	1.47E-06
	Total of all processes	**kg PO4**	**0.000021**

Table 10: WS contribution value for concrete waste

A: Concrete waste to final disposal

No	Process	Unit equivalent	Contribution value of WS
1	Disposal, building, concrete, not reinforced, to final disposal	kg SPM	0.00008
2	Diesel, burned in building machine	kg SPM	9.24E-06
3	Natural gas, sour, burned in production flare	kg SPM	6.66E-06
4	Operation, lorry 28t	kg SPM	3.31E-06
5	Operation, transoceanic tanker	kg SPM	2.84E-06
6	Heavy fuel oil, burned in refinery furnace	kg SPM	1.95E-06
7	Polyethylene, HDPE, granulate, at plant	kg SPM	1.64E-06
8	Iron ore, at mine	kg SPM	9.19E-07
9	Diesel, at refinery	kg SPM	4.87E-07
10	Lead, at regional storage	kg SPM	4.77E-07
	Remaining processes	kg SPM	6.84E-06
	Total of all processes	**kg SPM**	**0.000114**

B: Concrete waste to recycling

No	Process	Unit equivalent	Contribution value of WS
1	Disposal, building, concrete, not reinforced, to recycling	kg SPM	0.00008
2	Diesel, burned in building machine	kg SPM	5.35E-06
3	Natural gas, sour, burned in production flare	kg SPM	2.39E-06
4	Heavy fuel oil, burned in refinery furnace	kg SPM	7.04E-07
5	Operation, transoceanic tanker	kg SPM	6.75E-07
6	Diesel, at refinery	kg SPM	1.8E-07
7	Iron ore, at mine	kg SPM	1.77E-07
8	Sour gas, burned in gas turbine, production	kg SPM	1.15E-07
9	Lignite, burned in power plant	kg SPM	9.91E-08
10	Diesel, burned in diesel-electric generating set	kg SPM	9.77E-08
	Remaining processes	kg SPM	9.94E-07
	Total of all processes	**kg SPM**	**9.08E-05**

B: Concrete waste to sorting plant

No	Process	Unit equivalent	Contribution value of WS
1	Disposal, building, concrete, not reinforced, to sorting plant	kg SPM	0.00008
2	Diesel, burned in building machine	kg SPM	8.17E-06
3	Natural gas, sour, burned in production flare	kg SPM	6.33E-06
4	Operation, lorry 28t	kg SPM	3.46E-06
5	Operation, transoceanic tanker	kg SPM	2.43E-06
6	Polyethylene, HDPE, granulate, at plant	kg SPM	2.1E-06
7	Heavy fuel oil, burned in refinery furnace	kg SPM	1.85E-06
8	Iron ore, at mine	kg SPM	1.05E-06
9	Lead, at regional storage	kg SPM	5.08E-07
10	Diesel, at refinery	kg SPM	4.63E-07
	Remaining processes	kg SPM	8.34E-06
	Total of all processes	**kg SPM**	**0.000115**

Table 11: HM contribution value for concrete waste

A: Concrete waste to final disposal

No	Process	Unit equivalent	Contribution value of HM
1	Lead, at regional storage	kg Pb	3.97E-07
2	Iron ore, at beneficiation	kg Pb	1.95E-08
3	Disposal, nickel smelter slag, to residual material landfill	kg Pb	1.17E-08
4	Lead, concentrate, at beneficiation	kg Pb	8.36E-09
5	Disposal, sludge from steel rolling, to residual material landfill	kg Pb	6.51E-09
6	Heavy fuel oil, burned in refinery furnace	kg Pb	5.67E-09
7	Copper, primary, at refinery	kg Pb	3.72E-09
8	Disposal, slag, unalloyed electr. steel, to residual material landfill	kg Pb	3.6E-09
9	Discharge, produced water, onshore	kg Pb	3.29E-09
10	Operation, lorry 28t	kg Pb	2.33E-09
	Remaining processes	kg Pb	2.12E-08
	Total of all processes	**kg Pb**	**4.83E-07**

B: Concrete waste to sorting plant

No	Process	Unit equivalent	Contribution value of HM
1	Disposal, inert material, to sanitary landfill	kg Pb	1.87E-05
2	Lead, at regional storage	kg Pb	4.23E-07
3	Iron ore, at beneficiation	kg Pb	2.23E-08
4	Disposal, nickel smelter slag, to residual material landfill	kg Pb	2.22E-08
5	Copper, primary, at refinery	kg Pb	1.12E-08
6	Lead, concentrate, at beneficiation	kg Pb	8.9E-09
7	Disposal, sludge from steel rolling, to residual material landfill	kg Pb	6.89E-09
8	Heavy fuel oil, burned in refinery furnace	kg Pb	5.39E-09
9	Disposal, slag, unalloyed electr. steel, to residual material landfill	kg Pb	4.01E-09
10	Discharge, produced water, onshore	kg Pb	2.74E-09
	Remaining processes	kg Pb	3.11E-08
	Total of all processes	**kg Pb**	**1.93E-05**

B: Concrete waste to recycling

No	Process	Unit equivalent	Contribution value of HM
1	Iron ore, at beneficiation	kg Pb	3.77E-09
2	Disposal, nickel smelter slag, to residual material landfill	kg Pb	3.19E-09
3	Heavy fuel oil, burned in refinery furnace	kg Pb	2.05E-09
4	Disposal, sludge from steel rolling, to residual material landfill	kg Pb	1.36E-09
5	Lead, at regional storage	kg Pb	1.09E-09
6	Disposal, slag, unalloyed electr. steel, to residual material landfill	kg Pb	7.36E-10
7	Discharge, produced water, onshore	kg Pb	6.55E-10
8	Diesel, burned in building machine	kg Pb	5.13E-10
9	Discharge, produced water, offshore	kg Pb	3.32E-10
10	Heavy fuel oil, burned in industrial furnace 1MW, non-modulating	kg Pb	2.78E-10
	Total of all processes	kg Pb	1.67E-08
	Remaining processes	**kg Pb**	**2.79E-09**

Table 12: ER contribution value for concrete waste

A: Concrete waste to final disposal

No	Process	Unit equivalent	Contribution value of ER
1	Crude oil, at production onshore	MJ LHV	0.0822
2	Crude oil, at production	MJ LHV	0.0506
3	Crude oil, at production onshore	MJ LHV	0.0483
4	Crude oil, at production offshore	MJ LHV	0.0335
5	Crude oil, at production onshore	MJ LHV	0.0279
6	Crude oil, at production offshore	MJ LHV	0.0278
7	Natural gas, sweet, burned in production flare	MJ LHV	0.00993
8	Polyethylene, HDPE, granulate, at plant	MJ LHV	0.00837
9	Uranium natural, at underground mine	MJ LHV	0.00674
10	Uranium natural, at open pit mine	MJ LHV	0.00449
	Remaining processes	MJ LHV	0.0219
	Total of all processes	**MJ LHV**	**0.322**

B: Concrete waste to sorting plant

No	Process	Unit equivalent	Contribution value of ER
1	Crude oil, at production onshore	MJ LHV	0.0606
2	Crude oil, at production onshore	MJ LHV	0.0436
3	Crude oil, at production	MJ LHV	0.0364
4	Crude oil, at production offshore	MJ LHV	0.0318
5	Crude oil, at production onshore	MJ LHV	0.0266
6	Crude oil, at production offshore	MJ LHV	0.0264
7	Uranium natural, at underground mine	MJ LHV	0.023
8	Uranium natural, at open pit mine	MJ LHV	0.0154
9	Polyethylene, HDPE, granulate, at plant	MJ LHV	0.0107
10	Natural gas, sweet, burned in production flare	MJ LHV	0.00734
	Remaining processes	MJ LHV	0.0365
	Total of all processes	**MJ LHV**	**0.318**

B: Concrete waste to recycling

No	Process	Unit equivalent	Contribution value of ER
1	Crude oil, at production onshore	MJ LHV	0.0142
2	Crude oil, at production offshore	MJ LHV	0.012
3	Crude oil, at production onshore	MJ LHV	0.01
4	Crude oil, at production offshore	MJ LHV	0.01
5	Crude oil, at production onshore	MJ LHV	0.00582
6	Crude oil, at production	MJ LHV	0.00185
7	Uranium natural, at underground mine	MJ LHV	0.000876
8	Natural gas, sweet, burned in production flare	MJ LHV	0.000671
9	Uranium natural, at open pit mine	MJ LHV	0.000584
10	Natural gas, sour, burned in production flare	MJ LHV	0.000524
	Remaining processes	MJ LHV	0.00371
	Total of all processes	**MJ LHV**	**0.0603**

Table 13: GWP contribution value for iron/steel waste

A Bulk iron waste to sorting plant

No	Process	Unit equivalent	Contribution value of GWP
1	Operation, lorry 28t	kg CO2	0.00286
2	Lignite, burned in power plant	kg CO2	0.000126
3	Natural gas, sweet, burned in production flare	kg CO2	0.000123
4	Diesel, burned in building machine	kg CO2	0.000112
5	Hard coal, burned in power plant	kg CO2	9.78E-05
6	Refinery gas, burned in furnace	kg CO2	8.36E-05
7	Excavation, hydraulic digger	kg CO2	5.82E-05
8	Clinker, at plant	kg CO2	5.73E-05
9	Natural gas, vented	kg CO2	4.46E-05
10	Pig iron, at plant	kg CO2	4.01E-05
	Remaining processes	kg CO2	0.000675
	Total of all processes	**kg CO2**	**0.00428**

B: Reinforcement steel waste to final disposal

No	Process	Unit equivalent	Contribution value of GWP
1	Diesel, burned in building machine	kg CO2	0.00688
2	Operation, lorry 28t	kg CO2	0.00462
3	Natural gas, sweet, burned in production flare	kg CO2	0.000653
4	Refinery gas, burned in furnace	kg CO2	0.000423
5	Natural gas, vented	kg CO2	0.000235
6	Heavy fuel oil, burned in refinery furnace	kg CO2	0.000196
7	Polyethylene, HDPE, granulate, at plant	kg CO2	0.00019
8	Sweet gas, burned in gas turbine, production	kg CO2	0.000159
9	Diesel, burned in diesel-electric generating set	kg CO2	0.000152
10	Lignite, burned in power plant	kg CO2	0.000152
	Remaining processes	kg CO2	0.00234
	Total of all processes	**kg CO2**	**0.016**

C: Reinforcement steel waste to recycling

No	Process	Unit equivalent	Contribution value of GWP
1	Diesel, burned in building machine	kg CO2	0.00453
2	Refinery gas, burned in furnace	kg CO2	0.000187
3	Heavy fuel oil, burned in refinery furnace	kg CO2	8.64E-05
4	Natural gas, sweet, burned in production flare	kg CO2	6.02E-05
5	Disposal, used mineral oil, to hazardous waste incineration	kg CO2	5.79E-05
6	Natural gas, burned in industrial furnace low-NOx	kg CO2	4.71E-05
7	Natural gas, sour, burned in production flare	kg CO2	0.000047
8	Diesel, burned in diesel-electric generating set	kg CO2	4.44E-05
9	Operation, transoceanic tanker	kg CO2	4.01E-05
10	Lignite, burned in power plant	kg CO2	3.66E-05
	Remaining processes	kg CO2	0.000357
	Total of all processes	**kg CO2**	**0.00549**

D. Reinforcement steel to sorting plant

No	Process	Unit equivalent	Contribution value of GWP
1	Diesel, burned in building machine	kg CO2	0.00619
2	Operation, lorry 28t	kg CO2	0.00477
3	Natural gas, sweet, burned in production flare	kg CO2	0.000478
4	Refinery gas, burned in furnace	kg CO2	0.000401
5	Lignite, burned in power plant	kg CO2	0.000307
6	Excavation, hydraulic digger	kg CO2	0.000263
7	Hard coal, burned in power plant	kg CO2	0.000237
8	Polyethylene, HDPE, granulate, at plant	kg CO2	0.000236
9	Clinker, at plant	kg CO2	0.000214
10	Heavy fuel oil, burned in refinery furnace	kg CO2	0.000185
	Remaining processes	kg CO2	0.00257
	Total of all processes	**kg CO2**	**0.0158**

Table 14: AP contribution value for iron/steel waste

A Bulk iron waste to sorting plant

No	Process	Unit equivalent	Contribution value of AP
1	Operation, lorry 28t	kg SO2	1.99E-05
2	Natural gas, sour, burned in production flare	kg SO2	1.58E-06
3	Diesel, burned in building machine	kg SO2	1.13E-06
4	Operation, transoceanic tanker	kg SO2	7.02E-07
5	Excavation, hydraulic digger	kg SO2	5.89E-07
6	Heavy fuel oil, burned in refinery furnace	kg SO2	4.69E-07
7	Natural gas, sweet, burned in production flare	kg SO2	4.26E-07
8	Diesel, burned in diesel-electric generating set	kg SO2	4.16E-07
9	Lead, at regional storage	kg SO2	2.97E-07
10	Operation, transoceanic freight ship	kg SO2	2.28E-07
	Remaining processes	kg SO2	3.57E-06
	Total of all processes	**kg SO2**	**2.93E-05**

B: Reinforcement steel waste to final disposal

No	Process	Unit equivalent	Contribution value of AP
1	Diesel, burned in building machine	kg SO2	6.95E-05
2	Operation, lorry 28t	kg SO2	3.21E-05
3	Natural gas, sour, burned in production flare	kg SO2	7.98E-06
4	Operation, transoceanic tanker	kg SO2	3.77E-06
5	Heavy fuel oil, burned in refinery furnace	kg SO2	2.37E-06
6	Natural gas, sweet, burned in production flare	kg SO2	2.26E-06
7	Polyethylene, HDPE, granulate, at plant	kg SO2	2.17E-06
8	Diesel, burned in diesel-electric generating set	kg SO2	2.09E-06
9	Excavation, skid-steer loader	kg SO2	1.27E-06
10	Excavation, hydraulic digger	kg SO2	1.2E-06
	Remaining processes	kg SO2	1.03E-05
	Total of all processes	**kg SO2**	**0.000135**

C: Reinforcement steel waste to recycling

No	Process	Unit equivalent	Contribution value of AP
1	Diesel, burned in building machine	kg SO2	4.57E-05
2	Natural gas, sour, burned in production flare	kg SO2	3.51E-06
3	Operation, transoceanic tanker	kg SO2	1.15E-06
4	Heavy fuel oil, burned in refinery furnace	kg SO2	1.05E-06
5	Diesel, burned in diesel-electric generating set	kg SO2	6.1E-07
6	Diesel, at refinery	kg SO2	2.75E-07
7	Natural gas, sweet, burned in production flare	kg SO2	2.08E-07
8	Refinery gas, burned in furnace	kg SO2	1.98E-07
9	Sour gas, burned in gas turbine, production	kg SO2	1.66E-07
10	Lignite, burned in power plant	kg SO2	1.48E-07
	Remaining processes	kg SO2	1.75E-06
	Total of all processes	**kg SO2**	**5.48E-05**

D Reinforcement steel to sorting plant

No	Process	Unit equivalent	Contribution value of AP
1	Diesel, burned in building machine	kg SO2	6.25E-05
2	Operation, lorry 28t	kg SO2	3.32E-05
3	Natural gas, sour, burned in production flare	kg SO2	7.56E-06
4	Operation, transoceanic tanker	kg SO2	3.23E-06
5	Polyethylene, HDPE, granulate, at plant	kg SO2	2.69E-06
6	Excavation, hydraulic digger	kg SO2	2.65E-06
7	Heavy fuel oil, burned in refinery furnace	kg SO2	2.25E-06
8	Diesel, burned in diesel-electric generating set	kg SO2	1.81E-06
9	Natural gas, sweet, burned in production flare	kg SO2	1.65E-06
10	Excavation, skid-steer loader	kg SO2	6.93E-07
	Remaining processes	kg SO2	1.18E-05
	Total of all processes	**kg SO2**	**0.00013**

Table 15: EP contribution value for iron/steel waste

A Bulk iron waste to sorting plant

No	Process	Unit equivalent	Contribution value of EP
1	Operation, lorry 28t	kg PO4	3.6E-06
2	Diesel, burned in building machine	kg PO4	2.03E-07
3	Crude oil, at production onshore	kg PO4	1.89E-07
4	Lead, at regional storage	kg PO4	1.15E-07
5	Excavation, hydraulic digger	kg PO4	1.06E-07
6	Natural gas, sweet, burned in production flare	kg PO4	7.92E-08
7	Diesel, burned in diesel-electric generating set	kg PO4	7.28E-08
8	Operation, transoceanic tanker	kg PO4	6.56E-08
9	Disposal, basic oxygen furnace wastes, to residual material landfill	kg PO4	6.06E-08
10	Blasting	kg PO4	3.61E-08
	Remaining processes	kg PO4	3.58E-07
	Total of all processes	**kg PO4**	**4.88E-06**

B Reinforcement steel waste to final disposal

No	Process	Unit equivalent	Contribution value of EP
1	Diesel, burned in building machine	kg PO4	1.25E-05
2	Operation, lorry 28t	kg PO4	5.8E-06
3	Crude oil, at production onshore	kg PO4	9.52E-07
4	Natural gas, sweet, burned in production flare	kg PO4	4.2E-07
5	Diesel, burned in diesel-electric generating set	kg PO4	3.65E-07
6	Operation, transoceanic tanker	kg PO4	3.52E-07
7	Excavation, skid-steer loader	kg PO4	2.28E-07
8	Excavation, hydraulic digger	kg PO4	2.17E-07
9	Lead, at regional storage	kg PO4	1.84E-07
10	Disposal, basic oxygen furnace wastes, to residual material landfill	kg PO4	1.73E-07
	Remaining processes	kg PO4	1.26E-06
	Total of all processes	**kg PO4**	**2.24E-05**

C: Reinforcement steel waste to recycling

No	Process	Unit equivalent	Contribution value of EP
1	Diesel, burned in building machine	kg PO4	8.23E-06
2	Crude oil, at production onshore	kg PO4	4.19E-07
3	Operation, transoceanic tanker	kg PO4	1.07E-07
4	Diesel, burned in diesel-electric generating set	kg PO4	1.07E-07
5	Disposal, basic oxygen furnace wastes, to residual material landfill	kg PO4	5.13E-08
6	Natural gas, sweet, burned in production flare	kg PO4	3.87E-08
7	Natural gas, sour, burned in production flare	kg PO4	3.02E-08
8	Disposal, used mineral oil, to hazardous waste incineration	kg PO4	2.64E-08
9	Refinery gas, burned in furnace	kg PO4	1.95E-08
10	Heavy fuel oil, burned in refinery furnace	kg PO4	1.94E-08
	Remaining processes	kg PO4	2.04E-07
	Total of all processes	**kg PO4**	**9.25E-06**

D Reinforcement steel to sorting plant

No	Process	Unit equivalent	Contribution value of EP
1	Diesel, burned in building machine	kg PO4	1.12E-05
2	Operation, lorry 28t	kg PO4	5.99E-06
3	Disposal, inert material, to sanitary landfill	kg PO4	1.87E-06
4	Crude oil, at production onshore	kg PO4	9.02E-07
5	Excavation, hydraulic digger	kg PO4	4.77E-07
6	Diesel, burned in diesel-electric generating set	kg PO4	3.17E-07
7	Natural gas, sweet, burned in production flare	kg PO4	3.07E-07
8	Operation, transoceanic tanker	kg PO4	3.02E-07
9	Disposal, basic oxygen furnace wastes, to residual material landfill	kg PO4	1.95E-07
10	Lead, at regional storage	kg PO4	1.94E-07
	Remaining processes	kg PO4	1.53E-06
	Total of all processes	**kg PO4**	**2.33E-05**

Table 16: WS contribution value for iron/steel waste

A Bulk iron waste to sorting plant

No	Process	Unit equivalent	Contribution value of WS
1	Operation, lorry 28t	kg SPM	2.05E-06
2	Natural gas, sour, burned in production flare	kg SPM	1.51E-06
3	Operation, transoceanic tanker	kg SPM	5.79E-07
4	Heavy fuel oil, burned in refinery furnace	kg SPM	4.41E-07
5	Iron ore, at mine	kg SPM	3.93E-07
6	Lead, at regional storage	kg SPM	2.99E-07
7	Diesel, burned in building machine	kg SPM	1.85E-07
8	Hard coal, burned in power plant	kg SPM	1.77E-07
9	Sinter, iron, at plant	kg SPM	1.49E-07
10	Operation, transoceanic freight ship	kg SPM	1.34E-07
	Remaining processes	kg SPM	2.44E-06
	Total of all processes	**kg SPM**	**8.36E-06**

B: Reinforcement steel waste to final disposal

No	Process	Unit equivalent	Contribution value of WS
1	Disposal, building, reinforced concrete, to final disposal	kg SPM	0.00008
2	Diesel, burned in building machine	kg SPM	1.14E-05
3	Natural gas, sour, burned in production flare	kg SPM	7.62E-06
4	Operation, lorry 28t	kg SPM	3.31E-06
5	Operation, transoceanic tanker	kg SPM	3.11E-06
6	Heavy fuel oil, burned in refinery furnace	kg SPM	2.23E-06
7	Polyethylene, HDPE, granulate, at plant	kg SPM	1.64E-06
8	Iron ore, at mine	kg SPM	9.9E-07
9	Diesel, at refinery	kg SPM	5.59E-07
10	Lead, at regional storage	kg SPM	4.77E-07
	Remaining processes	kg SPM	7.36E-06
	Total of all processes	**kg SPM**	**0.000119**

C: Reinforcement steel waste to recycling

No	Process	Unit equivalent	Contribution value of WS
1	Disposal, building, reinforced concrete, to recycling	kg SPM	0.00008
2	Diesel, burned in building machine	kg SPM	7.49E-06
3	Natural gas, sour, burned in production flare	kg SPM	3.35E-06
4	Heavy fuel oil, burned in refinery furnace	kg SPM	9.85E-07
5	Operation, transoceanic tanker	kg SPM	9.46E-07
6	Diesel, at refinery	kg SPM	2.52E-07
7	Iron ore, at mine	kg SPM	2.49E-07
8	Sour gas, burned in gas turbine, production	kg SPM	1.61E-07
9	Lignite, burned in power plant	kg SPM	1.39E-07
10	Diesel, burned in diesel-electric generating set	kg SPM	1.37E-07
	Remaining processes	kg SPM	1.39E-06
	Total of all processes	**kg SPM**	**9.51E-05**

D. Reinforcement steel to sorting plant

No	Process	Unit equivalent	Contribution value of WS
1	Disposal, building, reinforced concrete, to sorting plant	kg SPM	0.00008
2	Diesel, burned in building machine	kg SPM	1.02E-05
3	Natural gas, sour, burned in production flare	kg SPM	7.22E-06
4	Operation, lorry 28t	kg SPM	3.42E-06
5	Operation, transoceanic tanker	kg SPM	2.67E-06
6	Heavy fuel oil, burned in refinery furnace	kg SPM	2.11E-06
7	Polyethylene, HDPE, granulate, at plant	kg SPM	2.04E-06
8	Iron ore, at mine	kg SPM	1.11E-06
9	Diesel, at refinery	kg SPM	5.3E-07
10	Lead, at regional storage	kg SPM	5.03E-07
	Remaining processes	kg SPM	8.7E-06
	Total of all processes	**kg SPM**	**0.000119**

Table 17: HM contribution value for iron/steel waste

A Bulk iron waste to sorting plant

No	Process	Unit equivalent	Contribution value of HM
1	Lead, at regional storage	kg Pb	2.49E-07
2	Iron ore, at beneficiation	kg Pb	8.33E-09
3	Copper, primary, at refinery	kg Pb	5.9E-09
4	Lead, concentrate, at beneficiation	kg Pb	5.25E-09
5	Disposal, nickel smelter slag, to residual material landfill	kg Pb	3.81E-09
6	Disposal, sludge from steel rolling, to residual material landfill	kg Pb	2.17E-09
7	Operation, lorry 28t	kg Pb	1.44E-09
8	Disposal, slag, unalloyed electr. steel, to residual material landfill	kg Pb	1.32E-09
9	Heavy fuel oil, burned in refinery furnace	kg Pb	1.28E-09
10	Copper, primary, at refinery	kg Pb	8.51E-10
	Remaining processes	kg Pb	8.02E-09
	Total of all processes	kg Pb	2.88E-07

B: Reinforcement steel waste to final disposal

No	Process	Unit equivalent	Contribution value of HM
1	Lead, at regional storage	kg Pb	3.97E-07
2	Iron ore, at beneficiation	kg Pb	2.1E-08
3	Disposal, nickel smelter slag, to residual material landfill	kg Pb	1.3E-08
4	Lead, concentrate, at beneficiation	kg Pb	8.37E-09
5	Disposal, sludge from steel rolling, water, to residual material landfill	kg Pb	7.06E-09
6	Heavy fuel oil, burned in refinery furnace	kg Pb	6.49E-09
7	Disposal, slag, unalloyed electr. steel, to residual material landfill	kg Pb	3.89E-09
8	Copper, primary, at refinery	kg Pb	3.78E-09
9	Discharge, produced water, onshore	kg Pb	3.56E-09
10	Operation, lorry 28t	kg Pb	2.33E-09
	Remaining processes	kg Pb	2.27E-08
	Total of all processes	kg Pb	4.89E-07

C: Reinforcement steel waste to recycling

No	Process	Unit equivalent	Contribution value of HM
1	Iron ore, at beneficiation	kg Pb	5.28E-09
2	Disposal, nickel smelter slag, to residual material landfill	kg Pb	4.46E-09
3	Heavy fuel oil, burned in refinery furnace	kg Pb	2.87E-09
4	Disposal, sludge from steel rolling, to residual material landfill	kg Pb	1.91E-09
5	Lead, at regional storage	kg Pb	1.52E-09
6	Disposal, slag, unalloyed electr. steel, to residual material landfill	kg Pb	1.03E-09
7	Discharge, produced water, onshore	kg Pb	9.18E-10
8	Diesel, burned in building machine	kg Pb	7.18E-10
9	Discharge, produced water, offshore	kg Pb	4.65E-10
10	Heavy fuel oil, burned in industrial furnace 1MW, non-modulating	kg Pb	3.89E-10
	Remaining processes	kg Pb	3.9E-09
	Total of all processes	kg Pb	2.35E-08

D. Reinforcement steel to sorting plant

No	Process	Unit equivalent	Contribution value of HM
1	Disposal, inert material, to sanitary landfill	kg Pb	1.82E-05
2	Lead, at regional storage	kg Pb	4.18E-07
3	Iron ore, at beneficiation	kg Pb	2.35E-08
4	Disposal, nickel smelter slag, to residual material landfill	kg Pb	2.31E-08
5	Copper, primary, at refinery	kg Pb	1.12E-08
6	Lead, concentrate, at beneficiation	kg Pb	8.81E-09
7	Disposal, sludge from steel rolling, to residual material landfill	kg Pb	7.33E-09
8	Heavy fuel oil, burned in refinery furnace	kg Pb	6.15E-09
9	Disposal, slag, unalloyed electr. steel, to residual material landfill	kg Pb	4.24E-09
10	Discharge, produced water, onshore	kg Pb	2.96E-09
	Remaining processes	kg Pb	3.21E-08
	Total of all processes	kg Pb	1.87E-05

Table 18: ER contribution value for iron/steel waste

A Bulk iron waste to sorting plant

No	Process	Unit equivalent	Contribution value of ER
1	Crude oil, at production onshore	MJ LHV	0.0156
2	Uranium natural, at underground mine	MJ LHV	0.0108
3	Crude oil, at production onshore	MJ LHV	0.0105
4	Crude oil, at production	MJ LHV	0.00977
5	Crude oil, at production offshore	MJ LHV	0.00759
6	Uranium natural, at open pit mine	MJ LHV	0.0072
7	Crude oil, at production onshore	MJ LHV	0.00633
8	Crude oil, at production offshore	MJ LHV	0.0063
9	Electricity, hydropower, at reservoir power plant	MJ LHV	0.00249
10	Electricity, hydropower, at run-of-river power plant	MJ LHV	0.00202
	Remaining processes	MJ LHV	0.0121
	Total of all processes	MJ LHV	0.0908

B: Reinforcement steel waste to final disposal

No	Process	Unit equivalent	Contribution value of ER
1	Crude oil, at production onshore	MJ LHV	0.0845
2	Crude oil, at production onshore	MJ LHV	0.054
3	Crude oil, at production	MJ LHV	0.0514
4	Crude oil, at production offshore	MJ LHV	0.0383
5	Crude oil, at production onshore	MJ LHV	0.032
6	Crude oil, at production offshore	MJ LHV	0.0318
7	Natural gas, sweet, burned in production flare/MJ	MJ LHV	0.0102
8	Polyethylene, HDPE, granulate, at plant	MJ LHV	0.00837
9	Uranium natural, at underground mine	MJ LHV	0.00709
10	Uranium natural, at open pit mine	MJ LHV	0.00473
	Remaining processes	MJ LHV	0.0236
	Total of all processes	MJ LHV	0.346

C: Reinforcement steel waste to recycling

No	Process	Unit equivalent	Contribution value of ER
1	Crude oil, at production onshore	MJ LHV	0.0199
2	Crude oil, at production offshore	MJ LHV	0.0169
3	Crude oil, at production onshore	MJ LHV	0.0141
4	Crude oil, at production offshore	MJ LHV	0.014
5	Crude oil, at production onshore	MJ LHV	0.00815
6	Crude oil, at production	MJ LHV	0.00259
7	Uranium natural, at underground mine	MJ LHV	0.00123
8	Natural gas, sweet, burned in production flare/MJ	MJ LHV	0.00094
9	Uranium natural, at open pit mine	MJ LHV	0.000817
10	Natural gas, sour, burned in production flare/MJ	MJ LHV	0.000734
	Remaining processes	MJ LHV	0.0052
	Total of all processes	MJ LHV	0.0845

D. Reinforcement steel to sorting plant

No	Process	Unit equivalent	Contribution value of ER
1	Crude oil, at production onshore	MJ LHV	0.0618
2	Crude oil, at production onshore	MJ LHV	0.0487
3	Crude oil, at production	MJ LHV	0.0364
4	Crude oil, at production offshore	MJ LHV	0.0363
5	Crude oil, at production onshore	MJ LHV	0.0303
6	Crude oil, at production offshore	MJ LHV	0.0301
7	Uranium natural, at underground mine	MJ LHV	0.0232
8	Uranium natural, at open pit mine	MJ LHV	0.0155
9	Polyethylene, HDPE, granulate, at plant	MJ LHV	0.0104
10	Natural gas, sweet, burned in production flare/MJ	MJ LHV	0.00747
	Remaining processes	MJ LHV	0.0378
	Total of all processes	MJ LHV	0.338

Table 19: GWP contribution value for plasterboard waste

A: Plasterboard waste to final disposal

No	Process	Unit equivalent	Contribution value of GWP
1	Diesel, burned in building machine	kg CO2	0.00501
2	Operation, lorry 28t	kg CO2	0.00462
3	Natural gas, sweet, burned in production flare	kg CO2	0.000628
4	Refinery gas, burned in furnace	kg CO2	0.000346
5	Natural gas, vented	kg CO2	0.000224
6	Polyethylene, HDPE, granulate, at plant	kg CO2	0.00019
7	Heavy fuel oil, burned in refinery furnace	kg CO2	0.00016
8	Sweet gas, burned in gas turbine, production	kg CO2	0.00015
9	Refinery gas, burned in furnace	kg CO2	0.000147
10	Lignite, burned in power plant	kg CO2	0.000137
	Remaining processes	kg CO2	0.00212
	Total of all processes	**kg CO2**	**0.0137**

B: Plasterboard waste to recycling

No	Process	Unit equivalent	Contribution value of GWP
1	Diesel, burned in building machine	kg CO2	0.00266
2	Refinery gas, burned in furnace	kg CO2	0.00011
3	Heavy fuel oil, burned in refinery furnace	kg CO2	5.07E-05
4	Natural gas, sweet, burned in production flare	kg CO2	3.53E-05
5	Disposal, used mineral oil, to hazardous waste incineration	kg CO2	0.000034
6	Natural gas, burned in industrial furnace low-NOx	kg CO2	2.76E-05
7	Natural gas, sour, burned in production flare	kg CO2	2.76E-05
8	Diesel, burned in diesel-electric generating set	kg CO2	0.000026
9	Operation, transoceanic tanker	kg CO2	2.35E-05
10	Lignite, burned in power plant	kg CO2	2.15E-05
	Remaining processes	kg CO2	0.000209
	Total of all processes	**kg CO2**	**0.00122**

C: Plasterboard to sorting plant

No	Process	Unit equivalent	Contribution value of GWP
1	Operation, lorry 28t	kg CO2	0.00706
2	Diesel, burned in building machine	kg CO2	0.00617
3	Natural gas, sweet, burned in production flare	kg CO2	0.000816
4	Excavation, hydraulic digger	kg CO2	0.000597
5	Clinker, at plant	kg CO2	0.000541
6	Polyethylene, HDPE, granulate, at plant	kg CO2	0.000505
7	Refinery gas, burned in furnace	kg CO2	0.000489
8	Lignite, burned in power plant	kg CO2	0.000446
9	Hard coal, burned in power plant	kg CO2	0.000344
10	Natural gas, vented	kg CO2	0.000292
	Remaining processes	kg CO2	0.0043
	Total of all processes	**kg CO2**	**0.0216**

Table 20: AP contribution value for plasterboard waste

A: Plasterboard waste to final disposal

No	Process	Unit equivalent	Contribution value of AP
1	Diesel, burned in building machine	kg SO2	5.06E-05
2	Operation, lorry 28t	kg SO2	3.21E-05
3	Natural gas, sour, burned in production flare	kg SO2	6.53E-06
4	Operation, transoceanic tanker	kg SO2	3.3E-06
5	Natural gas, sweet, burned in production flare	kg SO2	2.17E-06
6	Polyethylene, HDPE, granulate, at plant	kg SO2	2.17E-06
7	Heavy fuel oil, burned in refinery furnace	kg SO2	1.94E-06
8	Diesel, burned in diesel-electric generating set	kg SO2	1.84E-06
9	Excavation, skid-steer loader	kg SO2	1.26E-06
10	Excavation, hydraulic digger	kg SO2	1.2E-06
	Remaining processes	kg SO2	9.21E-06
	Total of all processes	**kg SO2**	**0.000112**

B: Plasterboard waste to recycling

No	Process	Unit equivalent	Contribution value of AP
1	Diesel, burned in building machine	kg SO2	2.68E-05
2	Natural gas, sour, burned in production flare	kg SO2	2.06E-06
3	Operation, transoceanic tanker	kg SO2	6.73E-07
4	Heavy fuel oil, burned in refinery furnace	kg SO2	6.14E-07
5	Diesel, burned in diesel-electric generating set	kg SO2	3.58E-07
6	Diesel, at refinery	kg SO2	1.62E-07
7	Natural gas, sweet, burned in production flare	kg SO2	1.22E-07
8	Refinery gas, burned in furnace	kg SO2	1.16E-07
9	Sour gas, burned in gas turbine, production	kg SO2	9.73E-08
10	Lignite, burned in power plant	kg SO2	8.69E-08
	Remaining processes	kg SO2	1.03E-06
	Total of all processes	**kg SO2**	**3.21E-05**

C: Plasterboard to sorting plant

No	Process	Unit equivalent	Contribution value of AP
1	Disposal, gypsum, to sanitary landfill	kg SO2	0.0211
2	Diesel, burned in building machine	kg SO2	6.24E-05
3	Operation, lorry 28t	kg SO2	4.91E-05
4	Natural gas, sour, burned in production flare	kg SO2	9.24E-06
5	Excavation, hydraulic digger	kg SO2	6.03E-06
6	Polyethylene, HDPE, granulate, at plant	kg SO2	5.76E-06
7	Operation, transoceanic tanker	kg SO2	4.48E-06
8	Natural gas, sweet, burned in production flare	kg SO2	2.82E-06
9	Heavy fuel oil, burned in refinery furnace	kg SO2	2.74E-06
10	Diesel, burned in diesel-electric generating set	kg SO2	2.54E-06
	Remaining processes	kg SO2	0.000021
	Total of all processes	**kg SO2**	**0.0213**

Table 21: EP contribution value for plasterboard waste

A: Plasterboard waste to final disposal

No	Process	Unit equivalent	Contribution value of EP
1	Diesel, burned in building machine	kg PO4	9.09E-06
2	Operation, lorry 28t	kg PO4	5.8E-06
3	Crude oil, at production onshore	kg PO4	7.79E-07
4	Natural gas, sweet, burned in production flare	kg PO4	4.04E-07
5	Diesel, burned in diesel-electric generating set	kg PO4	3.21E-07
6	Operation, transoceanic tanker	kg PO4	3.08E-07
7	Excavation, skid-steer loader	kg PO4	2.27E-07
8	Excavation, hydraulic digger	kg PO4	2.17E-07
9	Lead, at regional storage	kg PO4	1.84E-07
10	Disposal, basic oxygen furnace wastes, to residual material landfill	kg PO4	1.51E-07
	Remaining processes	kg PO4	1.13E-06
	Total of all processes	**kg PO4**	**1.86E-05**

B: Plasterboard waste to recycling

No	Process	Unit equivalent	Contribution value of EP
1	Diesel, burned in building machine	kg PO4	4.83E-06
2	Crude oil, at production onshore	kg PO4	2.46E-07
3	Operation, transoceanic tanker	kg PO4	6.28E-08
4	Diesel, burned in diesel-electric generating set	kg PO4	6.26E-08
5	Disposal, basic oxygen furnace wastes, to residual material landfill	kg PO4	3.01E-08
6	Natural gas, sweet, burned in production flare	kg PO4	2.27E-08
7	Natural gas, sour, burned in production flare	kg PO4	1.77E-08
8	Disposal, used mineral oil, to hazardous waste incineration	kg PO4	1.55E-08
9	Refinery gas, burned in furnace	kg PO4	1.14E-08
10	Heavy fuel oil, burned in refinery furnace	kg PO4	1.14E-08
	Remaining processes	kg PO4	1.2E-07
	Total of all processes	**kg PO4**	**5.43E-06**

C: Plasterboard to sorting plant

No	Process	Unit equivalent	Contribution value of EP
1	Diesel, burned in building machine	kg PO4	1.12E-05
2	Operation, lorry 28t	kg PO4	8.87E-06
3	Crude oil, at production onshore	kg PO4	1.1E-06
4	Excavation, hydraulic digger	kg PO4	1.08E-06
5	Natural gas, sweet, burned in production flare	kg PO4	5.24E-07
6	Diesel, burned in diesel-electric generating set	kg PO4	4.44E-07
7	Operation, transoceanic tanker	kg PO4	4.19E-07
8	Polyethylene, HDPE, granulate, at plant	kg PO4	3.62E-07
9	Process-specific burdens, municipal waste incineration	kg PO4	3.33E-07
10	Lead, at regional storage	kg PO4	2.86E-07
	Remaining processes	kg PO4	2.48E-06
	Total of all processes	**kg PO4**	**2.71E-05**

Table 22: WS contribution value for plasterboard waste

A: Plasterboard waste to final disposal

No	Process	Unit equivalent	Contribution value of WS
1	Disposal, building, plaster board, gypsum plaster, to final disposal	kg SPM	0.00008
2	Diesel, burned in building machine	kg SPM	8.28E-06
3	Natural gas, sour, burned in production flare	kg SPM	6.23E-06
4	Operation, lorry 28t	kg SPM	3.31E-06
5	Operation, transoceanic tanker	kg SPM	2.72E-06
6	Heavy fuel oil, burned in refinery furnace	kg SPM	1.82E-06
7	Polyethylene, HDPE, granulate, at plant	kg SPM	1.64E-06
8	Iron ore, at mine	kg SPM	8.87E-07
9	Lead, at regional storage	kg SPM	4.76E-07
10	Diesel, at refinery	kg SPM	4.55E-07
	Remaining processes	kg SPM	6.61E-06
	Total of all processes	**kg SPM**	**0.000112**

B: Plasterboard waste to recycling

No	Process	Unit equivalent	Contribution value of WS
1	Disposal, building, plaster board, gypsum plaster, to recycling	kg SPM	0.00008
2	Diesel, burned in building machine	kg SPM	4.39E-06
3	Natural gas, sour, burned in production flare	kg SPM	1.97E-06
4	Heavy fuel oil, burned in refinery furnace	kg SPM	5.78E-07
5	Operation, transoceanic tanker	kg SPM	5.55E-07
6	Diesel, at refinery	kg SPM	1.48E-07
7	Iron ore, at mine	kg SPM	1.46E-07
8	Sour gas, burned in gas turbine, production	kg SPM	9.46E-08
9	Lignite, burned in power plant	kg SPM	8.14E-08
10	Diesel, burned in diesel-electric generating set	kg SPM	8.03E-08
	Remaining processes	kg SPM	8.16E-07
	Total of all processes	**kg SPM**	**8.89E-05**

C: Plasterboard to sorting plant

No	Process	Unit equivalent	Contribution value of WS
1	Disposal, gypsum, to sanitary landfill	kg SPM	0.0208
2	Disposal, building, plaster board, gypsum plaster, to sorting plant	kg SPM	0.00008
3	Diesel, burned in building machine	kg SPM	1.02E-05
4	Natural gas, sour, burned in production flare	kg SPM	8.83E-06
5	Operation, lorry 28t	kg SPM	5.06E-06
6	Polyethylene, HDPE, granulate, at plant	kg SPM	4.36E-06
7	Operation, transoceanic tanker	kg SPM	3.7E-06
8	Heavy fuel oil, burned in refinery furnace	kg SPM	2.58E-06
9	Iron ore, at mine	kg SPM	1.6E-06
10	Excavation, hydraulic digger	kg SPM	9.87E-07
	Remaining processes	kg SPM	1.39E-05
	Total of all processes	**kg SPM**	**0.021**

Table 23: HM contribution value for plasterboard waste

A: Plasterboard waste to final disposal

No	Process	Unit equivalent	Contribution value of HM
1	Lead, at regional storage	kg Pb	3.97E-07
2	Iron ore, at beneficiation	kg Pb	1.88E-08
3	Disposal, nickel smelter slag, to residual material landfill	kg Pb	1.12E-08
4	Lead, concentrate, at beneficiation	kg Pb	8.35E-09
5	Disposal, sludge from steel rolling, to residual material landfill	kg Pb	6.27E-09
6	Heavy fuel oil, burned in refinery furnace	kg Pb	5.31E-09
7	Copper, primary, at refinery	kg Pb	3.69E-09
8	Disposal, slag, unalloyed electr. steel, to residual material landfill	kg Pb	3.47E-09
9	Discharge, produced water, onshore	kg Pb	3.18E-09
10	Operation, lorry 28t	kg Pb	2.33E-09
	Remaining processes	kg Pb	2.06E-08
	Total of all processes	**kg Pb**	**4.8E-07**

B: Plasterboard waste to recycling

No	Process	Unit equivalent	Contribution value of HM
1	Iron ore, at beneficiation	kg Pb	3.09E-09
2	Disposal, nickel smelter slag, to residual material landfill	kg Pb	2.62E-09
3	Heavy fuel oil, burned in refinery furnace	kg Pb	1.68E-09
4	Disposal, sludge from steel rolling, to residual material landfill	kg Pb	1.12E-09
5	Lead, at regional storage	kg Pb	8.92E-10
6	Disposal, slag, unalloyed electr. steel, to residual material landfill	kg Pb	6.04E-10
7	Discharge, produced water, onshore	kg Pb	5.38E-10
8	Diesel, burned in building machine	kg Pb	4.21E-10
9	Discharge, produced water, offshore	kg Pb	2.73E-10
10	Heavy fuel oil, burned in industrial furnace 1MW, non-modulating	kg Pb	2.28E-10
	Remaining processes	kg Pb	2.29E-09
	Total of all processes	**kg Pb**	**1.38E-08**

C: Plasterboard to sorting plant

No	Process	Unit equivalent	Contribution value of HM
1	Disposal, gypsum, 19.4% water, to sanitary landfill	kg Pb	8.08E-06
2	Lead, at regional storage	kg Pb	6.18E-07
3	Disposal, nickel smelter slag, 0% water, to residual material landfill	kg Pb	3.94E-08
4	Iron ore, 65% Fe, at beneficiation	kg Pb	3.39E-08
5	Disposal, inert material, 0% water, to sanitary landfill	kg Pb	2.14E-08
6	Copper, primary, at refinery	kg Pb	1.62E-08
7	Lead, concentrate, at beneficiation	kg Pb	1.3E-08
8	Disposal, sludge from steel rolling, 20% water, to residual material landfill	kg Pb	1.07E-08
9	Heavy fuel oil, burned in refinery furnace/MJ	kg Pb	7.5E-09
10	Disposal, slag, unalloyed electr. steel, 0% water, to residual material landfill	kg Pb	6.21E-09
	Remaining processes	kg Pb	5.85E-08
	Total of all processes	**kg Pb**	**8.9E-06**

Table 24: ER contribution value for plasterboard waste

A: Plasterboard waste to final disposal

No	Process	Unit equivalent	Contribution value of HM
1	Crude oil, at production onshore	MJ LHV	0.0811
2	Crude oil, at production	MJ LHV	0.0503
3	Crude oil, at production onshore	MJ LHV	0.0457
4	Crude oil, at production offshore	MJ LHV	0.0313
5	Crude oil, at production onshore	MJ LHV	0.0261
6	Crude oil, at production offshore	MJ LHV	0.026
7	Natural gas, sweet, burned in production flare	MJ LHV	0.00981
8	Polyethylene, HDPE, granulate, at plant	MJ LHV	0.00836
9	Uranium natural, at underground mine	MJ LHV	0.00659
10	Uranium natural, at open pit mine	MJ LHV	0.00439
	Remaining processes	MJ LHV	0.0212
	Total of all processes	**MJ LHV**	**0.311**

B: Plasterboard waste to recycling

No	Process	Unit equivalent	Contribution value of HM
1	Crude oil, at production onshore	MJ LHV	0.0117
2	Crude oil, at production offshore	MJ LHV	0.00989
3	Crude oil, at production onshore	MJ LHV	0.00825
4	Crude oil, at production offshore	MJ LHV	0.00821
5	Crude oil, at production onshore	MJ LHV	0.00478
6	Crude oil, at production	MJ LHV	0.00152
7	Uranium natural, at underground mine	MJ LHV	0.000719
8	Natural gas, sweet, burned in production flare	MJ LHV	0.000551
9	Uranium natural, at open pit mine	MJ LHV	0.00048
10	Natural gas, sour, burned in production flare	MJ LHV	0.00043
	Remaining processes	MJ LHV	0.00305
	Total of all processes	**MJ LHV**	**0.0495**

C: Plasterboard to sorting plant

No	Process	Unit equivalent	Contribution value of HM
1	Crude oil, at production onshore	MJ LHV	0.105
2	Crude oil, at production	MJ LHV	0.0648
3	Crude oil, at production onshore	MJ LHV	0.0634
4	Crude oil, at production offshore	MJ LHV	0.0443
5	Crude oil, at production onshore	MJ LHV	0.037
6	Crude oil, at production offshore	MJ LHV	0.0368
7	Uranium natural, at underground mine	MJ LHV	0.0339
8	Uranium natural, at open pit mine	MJ LHV	0.0226
9	Polyethylene, HDPE, granulate, at plant	MJ LHV	0.0222
10	Natural gas, sweet, burned in production flare	MJ LHV	0.0127
	Remaining processes	MJ LHV	0.0598
	Total of all processes	**MJ LHV**	**0.503**

Table 25: GWP contribution scenario of wood wastes

A: Treated wood wastes in MSWI

No	Process	Unit equivalent	Contribution value of GWP
1	Disposal, preserved building wood, to municipal incineration	kg CO2	1.45
2	Natural gas, burned in industrial furnace	kg CO2	0.00304
3	Operation, lorry 28t	kg CO2	0.00245
4	Clinker, at plant	kg CO2	0.00175
5	Ammonia, steam reforming, liquid, at plant	kg CO2	0.000694
6	Disposal, bitumen sheet, to municipal incineration	kg CO2	0.000461
7	Pig iron, at plant	kg CO2	0.000294
8	Lignite, burned in power plant	kg CO2	0.000255
9	Diesel, burned in building machine	kg CO2	0.000241
10	Natural gas, burned in gas turbine, for compressor station	kg CO2	0.000208
	Remaining processes	kg CO2	0.00328
	Total of all processes	**kg CO2**	**1.46**

B: : Untreated wood wastes for MSWI

No	Process	Unit equivalent	Contribution value of GWP
1	Disposal, wood untreated, to municipal incineration	kg CO2	1.46
2	Natural gas, burned in industrial furnace low-NOx	kg CO2	0.00304
3	Operation, lorry 28t	kg CO2	0.00242
4	Clinker, at plant	kg CO2	0.00145
5	Ammonia, steam reforming, liquid, at plant	kg CO2	0.000694
6	Disposal, bitumen sheet, to municipal incineration	kg CO2	0.000461
7	Pig iron, at plant	kg CO2	0.000293
8	Lignite, burned in power plant	kg CO2	0.000243
9	Diesel, burned in building machine	kg CO2	0.00023
10	Natural gas, burned in gas turbine, for compressor station	kg CO2	0.000207
	Remaining processes	kg CO2	0.00318
	Total of all processes	**kg CO2**	**1.47**

Table 26: AP contribution scenario of wood wastes

A: Ttreated wood wastes in MSWI

No	Process	Unit equivalent	Contribution value of AP
1	Process-specific burdens, municipal waste incineration	kg SO2	0.000237
2	Disposal, building wood, chrome preserved, to municipal incineration	kg SO2	2.43E-05
3	Operation, lorry 28t	kg SO2	0.000017
4	Diesel, burned in building machine	kg SO2	2.43E-06
5	Clinker, at plant	kg SO2	2.38E-06
6	Natural gas, sour, burned in production flare	kg SO2	2.17E-06
7	Sour gas, burned in gas turbine, production	kg SO2	1.35E-06
8	Sinter, iron, at plant	kg SO2	1.24E-06
9	Operation, transoceanic freight ship	kg SO2	1.18E-06
10	Ammonia, partial oxidation, liquid, at plant	kg SO2	1.13E-06
	Remaining processes	kg SO2	1.67E-05
	Total of all processes	**kg SO2**	**0.000307**

B:Untreated wood wastes for MSWI

No	Process	Unit equivalent	Contribution value of AP
1	Process-specific burdens, municipal waste incineration	kg SO2	0.000237
2	Disposal, wood untreated, to municipal incineration	kg SO2	0.000024
3	Operation, lorry 28t	kg SO2	1.68E-05
4	Diesel, burned in building machine	kg SO2	2.32E-06
5	Natural gas, sour, burned in production flare	kg SO2	2.13E-06
6	Clinker, at plant	kg SO2	1.97E-06
7	Sour gas, burned in gas turbine, production	kg SO2	1.35E-06
8	Sinter, iron, at plant	kg SO2	1.24E-06
9	Operation, transoceanic freight ship	kg SO2	1.17E-06
10	Ammonia, partial oxidation, liquid, at plant	kg SO2	1.13E-06
	Remaining processes	kg SO2	1.62E-05
	Total of all processes	**kg SO2**	**0.000306**

Table 27: EP contribution scenario of wood wastes

A: Ttreated wood wastes in MSWI

No	Process	Unit equivalent	Contribution value of EP
1	Disposal, building wood, chrome preserved, to municipal incineration	kg PO4	0.00024
2	Process-specific burdens, municipal waste incineration	kg PO4	4.39E-05
3	Operation, lorry 28t	kg PO4	3.08E-06
4	Disposal, basic oxygen furnace wastes, to residual material landfill	kg PO4	5.77E-07
5	Disposal, cement, hydrated, to residual material landfill	kg PO4	4.47E-07
6	Diesel, burned in building machine	kg PO4	4.37E-07
7	Clinker, at plant	kg PO4	3.04E-07
8	Crude oil, at production onshore	kg PO4	2.49E-07
9	Iron ore, at beneficiation	kg PO4	2.12E-07
10	Natural gas, burned in industrial furnace low-NOx	kg PO4	1.62E-07
	Remaining processes	kg PO4	2.04E-06
	Total of all processes	**kg PO4**	**0.000292**

B:Untreated wood wastes for MSWI

No	Process	Unit equivalent	Contribution value of EP
1	Disposal, wood untreated, to municipal incineration	kg PO4	0.000241
2	Process-specific burdens, municipal waste incineration	kg PO4	4.39E-05
3	Operation, lorry 28t	kg PO4	3.04E-06
4	Disposal, basic oxygen furnace wastes, to residual material landfill	kg PO4	5.76E-07
5	Diesel, burned in building machine	kg PO4	4.18E-07
6	Disposal, cement, hydrated, to residual material landfill	kg PO4	2.8E-07
7	Clinker, at plant	kg PO4	2.51E-07
8	Crude oil, at production onshore	kg PO4	2.44E-07
9	Iron ore, at beneficiation	kg PO4	2.12E-07
10	Natural gas, burned in industrial furnace low-NOx	kg PO4	1.62E-07
	Remaining processes	kg PO4	1.99E-06
	Total of all processes	**kg PO4**	**0.000292**

Table 28: WS contribution scenario of wood wastes

A: Ttreated wood wastes in MSWI

No	Process	Unit equivalent	Contribution value of WS
1	Process-specific burdens, municipal waste incineration	kg SPM	0.000006
2	Iron ore, at mine	kg SPM	2.88E-06
3	Natural gas, sour, burned in production flare	kg SPM	2.07E-06
4	Operation, lorry 28t	kg SPM	1.76E-06
5	Sour gas, burned in gas turbine, production	kg SPM	1.31E-06
6	Ammonia, partial oxidation, liquid, at plant	kg SPM	1.17E-06
7	Sinter, iron, at plant	kg SPM	1.09E-06
8	Lignite, burned in power plant	kg SPM	8.87E-07
9	Disposal, building wood, chrome preserved, to municipal incineration	kg SPM	8.44E-07
10	Disposal, building, reinforced concrete, to sorting plant	kg SPM	8.26E-07
	Remaining processes	kg SPM	1.21E-05
	Total of all processes	**kg SPM**	**0.000031**

B:Untreated wood wastes for MSWI

No	Process	Unit equivalent	Contribution value of WS
1	Process-specific burdens, municipal waste incineration	kg SPM	0.000006
2	Iron ore, at mine	kg SPM	2.88E-06
3	Natural gas, sour, burned in production flare	kg SPM	2.03E-06
4	Operation, lorry 28t	kg SPM	1.74E-06
5	Sour gas, burned in gas turbine, production	kg SPM	1.31E-06
6	Ammonia, partial oxidation, liquid, at plant	kg SPM	1.17E-06
7	Sinter, iron, at plant	kg SPM	1.09E-06
8	Lignite, burned in power plant	kg SPM	8.48E-07
9	Disposal, building, reinforced concrete, to sorting plant	kg SPM	8.26E-07
10	Operation, transoceanic tanker	kg SPM	7.99E-07
	Remaining processes	kg SPM	1.14E-05
	Total of all processes	**kg SPM**	**0.00003**

Table 29: HM contribution scenario of wood wastes

A: Ttreated wood wastes in MSWI

No	Process	Unit equivalent	Contribution value of HM
1	Disposal, building wood, chrome preserved, to municipal incineration	kg Pb	5.99E-06
2	Disposal, inert material, to sanitary landfill	kg Pb	2.34E-07
3	Lead, at regional storage	kg Pb	2.17E-07
4	Iron ore, at beneficiation	kg Pb	6.12E-08
5	Disposal, nickel smelter slag, to residual material landfill	kg Pb	5.37E-08
6	Disposal, sludge from steel rolling, to residual material landfill	kg Pb	1.93E-08
7	Disposal, cement, hydrated, to residual material landfill	kg Pb	1.9E-08
8	Disposal, slag, unalloyed electr. steel, to residual material landfill	kg Pb	1.2E-08
9	Disposal, bitumen sheet, to municipal incineration	kg Pb	7.75E-09
10	Ammonia, steam reforming, liquid, at plant	kg Pb	6.55E-09
	Remaining processes	kg Pb	4.98E-08
	Total of all processes	**kg Pb**	**6.67E-06**

B:Untreated wood wastes for MSWI

No	Process	Unit equivalent	Contribution value of HM
1	Disposal, wood untreated, to municipal incineration	kg Pb	3.98E-06
2	Disposal, inert material, to sanitary landfill	kg Pb	2.34E-07
3	Lead, at regional storage	kg Pb	2.14E-07
4	Iron ore, at beneficiation	kg Pb	6.11E-08
5	Disposal, nickel smelter slag, to residual material landfill	kg Pb	5.32E-08
6	Disposal, sludge from steel rolling, to residual material landfill	kg Pb	1.93E-08
7	Disposal, slag, unalloyed electr. steel, to residual material landfill	kg Pb	1.2E-08
8	Disposal, cement, hydrated, to residual material landfill	kg Pb	1.19E-08
9	Disposal, bitumen sheet, to municipal incineration	kg Pb	7.75E-09
10	Ammonia, steam reforming, liquid, at plant	kg Pb	6.55E-09
	Remaining processes	kg Pb	4.83E-08
	Total of all processes	**kg Pb**	**4.65E-06**

Table 30: ER contribution scenario of wood wastes

A: Ttreated wood wastes in MSWI

No	Process	Unit equivalent	Contribution value of ER
1	Natural gas, at production onshore	MJ LHV	0.0296
2	Crude oil, at production onshore	MJ LHV	0.0232
3	Crude oil, at production	MJ LHV	0.0144
4	Crude oil, at production onshore	MJ LHV	0.0142
5	Natural gas, at production onshore	MJ LHV	0.0136
6	Natural gas, at production offshore	MJ LHV	0.0135
7	Natural gas, at production onshore	MJ LHV	0.0131
8	Crude oil, at production offshore	MJ LHV	0.01
9	Uranium natural, at underground mine	MJ LHV	0.00995
10	Crude oil, at production onshore	MJ LHV	0.00835
	Remaining processes	MJ LHV	0.0582
	Total of all processes	**MJ LHV**	**0.208**

B:Untreated wood wastes for MSWI

No	Process	Unit equivalent	Contribution value of ER
1	Natural gas, at production onshore	MJ LHV	0.0296
2	Crude oil, at production onshore	MJ LHV	0.0225
3	Crude oil, at production onshore	MJ LHV	0.0139
4	Crude oil, at production	MJ LHV	0.0139
5	Natural gas, at production onshore	MJ LHV	0.0135
6	Natural gas, at production offshore	MJ LHV	0.0135
7	Natural gas, at production onshore	MJ LHV	0.0131
8	Crude oil, at production offshore	MJ LHV	0.00983
9	Uranium natural, at underground mine	MJ LHV	0.00945
10	Crude oil, at production onshore	MJ LHV	0.0082
	Remaining processes	MJ LHV	0.0563
	Total of all processes	**MJ LHV**	**0.204**

APPENDIX 3

Table 1: Calculation of eco-cost for a kilogram of brick waste to final disposal

Column 1 **Impact category**	**2** **amount**	**3** **characterisation factor**	**4** **(2 x 3)** **kg equivalent**	**5** **damage cost (£)**	**6** **(4 x 5)** **eco-cost (£)**
greenhouse kg CO2 eq.	1.37E-02	1	1.37E-02 kg CO2 eq.	0.01	1.37E-04
acidification kg SO2 eq.	1.12E-04	1	1.12E-04 kg SO2 eq.	7.59	8.50E-04
eutrophication kg PO4 eq.	1.86E-05	0.7	1.30E-05 kg NOx eq.	7.55	9.83E-05
winter smog kg SPM eq.	1.12E-04	1	1.12E-04 kg SPM eq.	35	3.92E-03
summer smog kg C2H4 eq	1.25E-05	1	1.25E-05 kg VOC eq.	1	1.25E-05
heavy metals kg Pb eq.	4.80E-07	1	4.80E-07 kg Pb eq.	1220	5.86E-04
carcinogens kg B(a)P eq.	3.09E-09	0.44	1.36E-09 kg Ni eq.	58	7.89E-08
ozone layer kg CFC11	4.17E-09	1	4.17E-09 kg CFC11	7.5	3.13E-08
energy resources MJ LHV	3.11E-01	1	3.11E-01 MJ LHV	0.07	2.18E-02
				Total eco-cost	2.74E-02

Table 2: Calculation of eco-cost for a kilogram of brick waste to recycling

Column 1 **Impact category**	**2** **amount**	**3** **characterisation factor**	**4** **(2 x 3)** **kg equivalent**	**5** **damage cost (£)**	**6** **(4 x 5)** **eco-cost (£)**
greenhouse kg CO2 eq.	3.22E-03	1	3.22E-03 kg CO2 eq.	0.01	3.22E-05
acidification kg SO2 eq.	3.21E-05	1	3.21E-05 kg SO2 eq.	7.59	2.44E-04
eutrophication kg PO4 eq.	5.43E-06	0.7	3.80E-06 kg NOx eq.	7.55	2.87E-05
winter smog kg SPM eq.	8.89E-05	1	8.89E-05 kg SPM eq.	35	3.11E-03
summer smog kg C2H4 eq	2.47E-06	1	2.47E-06 kg VOC eq.	1	2.47E-06
heavy metals kg Pb eq.	1.38E-08	1	1.38E-08 kg Pb eq.	1220	1.68E-05
carcinogens kg B(a)P eq.	1.42E-09	0.44	6.25E-10 kg Ni eq.	58	3.62E-08
ozone layer kg CFC11	5.39E-10	1	5.39E-10 kg CFC11	7.5	4.04E-09
energy resources MJ LHV	4.95E-02	1	4.95E-02 MJ LHV	0.07	3.47E-03
				Total eco-cost	6.90E-03

Table 3: Calculation of eco-costs for a kilogram of brick to sorting plant

Column 1 Impact category	2 amount	3 characterisation factor	4 (2 x 3) kg equivalent	5 damage cost (£)	6 (4 x 5) eco-cost (£)
greenhouse kg CO2 eq.	1.39E-02	1	1.39E-02 kg CO2 eq.	0.01	1.39E-04
acidification kg SO2 eq.	1.10E-04	1	1.10E-04 kg SO2 eq.	7.59	8.35E-04
eutrophication kg PO4 eq.	1.99E-05	0.7	1.39E-05 kg NOx eq.	7.55	1.05E-04
winter smog kg SPM eq.	1.13E-04	1	1.13E-04 kg SPM eq.	35	3.96E-03
summer smog kg C2H4 eq	1.12E-05	1	1.12E-05 kg VOC eq.	1	1.12E-05
heavy metals kg Pb eq.	1.93E-05	1	1.93E-05 kg Pb eq.	1220	2.35E-02
carcinogens kg B(a)P eq.	2.99E-09	0.44	1.32E-09 kg Ni eq.	58	7.63E-08
ozone layer kg CFC11	3.36E-09	1	3.36E-09 kg CFC11	7.5	2.52E-08
energy resources MJ LHV	3.09E-01	1	3.09E-01 MJ LHV	0.07	2.16E-02
				Total eco-cost	5.02E-02

Table 4: Calculation of eco-costs for a kilogram of non-reinforced concrete to final disposal

Column 1 Impact category	2 amount	3 characterisation factor	4 (2 x 3) kg equivalent	5 damage cost (£)	6 (4 x 5) eco-cost (£)
greenhouse kg CO2 eq.	1.44E-02	1	1.44E-02 kg CO2 eq.	0.01	1.44E-04
acidification kg SO2 eq.	1.19E-04	1	1.19E-04 kg SO2 eq.	7.59	9.03E-04
eutrophication kg PO4 eq.	1.98E-05	0.7	1.39E-05 kg NOx eq.	7.55	1.05E-04
winter smog kg SPM eq.	1.14E-04	1	1.14E-04 kg SPM eq.	35	3.99E-03
summer smog kg C2H4 eq	1.30E-05	1	1.30E-05 kg VOC eq.	1	1.30E-05
heavy metals kg Pb eq.	4.83E-07	1	4.83E-07 kg Pb eq.	1220	5.89E-04
carcinogens kg B(a)P eq.	3.40E-09	0.44	1.50E-09 kg Ni eq.	58	8.68E-08
ozone layer kg CFC11	4.28E-09	1	4.28E-09 kg CFC11	7.5	3.21E-08
energy resources MJ LHV	3.22E-01	1	3.22E-01 MJ LHV	0.07	2.25E-02
				Total eco-cost	2.83E-02

Table 5: Calculation of eco-costs for a kilogram of non-reinforced concrete to recycling

Column 1 Impact category	2 amount	3 characterisation factor	4 (2 x 3) kg equivalent	5 damage cost (£)	6 (4 x 5) eco-cost (£)
greenhouse kg CO2 eq.	3.92E-03	1	3.92E-03 kg CO2 eq.	0.01	3.92E-05
acidification kg SO2 eq.	3.91E-05	1	3.91E-05 kg SO2 eq.	7.59	2.97E-04
eutrophication kg PO4 eq.	6.60E-06	0.7	4.62E-06 kg NOx eq.	7.55	3.49E-05
winter smog kg SPM eq.	9.08E-05	1	9.08E-05 kg SPM eq.	35	3.18E-03
summer smog kg C2H4 eq	3.00E-06	1	3.00E-06 kg VOC eq.	1	3.00E-06
heavy metals kg Pb eq.	1.67E-08	1	1.67E-08 kg Pb eq.	1220	2.04E-05
carcinogens kg B(a)P eq.	1.73E-09	0.44	7.61E-10 kg Ni eq.	58	4.41E-08
ozone layer kg CFC11	6.56E-10	1	6.56E-10 kg CFC11	7.5	4.92E-09
energy resources MJ LHV	6.03E-02	1	6.03E-02 MJ LHV	0.07	4.22E-03
				Total eco-cost	7.79E-03

Table 6: Calculation of eco-costs for a kilogram of non-reinforced concrete to sorting plant

Column 1 Impact category	2 amount	3 characterisation factor	4 (2 x 3) kg equivalent	5 damage cost (£)	6 (4 x 5) eco-cost (£)
greenhouse kg CO2 eq.	1.45E-02	1	1.45E-02 kg CO2 eq.	0.01	1.45E-04
acidification kg SO2 eq.	1.16E-04	1	1.16E-04 kg SO2 eq.	7.59	8.80E-04
eutrophication kg PO4 eq.	2.10E-05	0.7	1.47E-05 kg NOx eq.	7.55	1.11E-04
winter smog kg SPM eq.	1.15E-04	1	1.15E-04 kg SPM eq.	35	4.03E-03
summer smog kg C2H4 eq	1.17E-05	1	1.17E-05 kg VOC eq.	1	1.17E-05
heavy metals kg Pb eq.	1.93E-05	1	1.93E-05 kg Pb eq.	1220	2.35E-02
carcinogens kg B(a)P eq.	3.26E-09	0.44	1.43E-09 kg Ni eq.	58	8.32E-08
ozone layer kg CFC11	3.46E-09	1	3.46E-09 kg CFC11	7.5	2.60E-08
energy resources MJ LHV	3.18E-01	1	3.18E-01 MJ LHV	0.07	2.23E-02
				Total eco-cost	5.10E-02

Table 7: Calculation of eco-costs for a kilogram of bulk iron waste to sorting plant

Column 1 Impact category	2 amount	3 characterisation factor	4 (2 x 3) kg equivalent	5 damage cost (£)	6 (4 x 5) eco-cost (£)
greenhouse kg CO2 eq.	4.28E-03	1	4.28E-03 kg CO2 eq.	0.01	4.28E-05
acidification kg SO2 eq.	2.93E-05	1	2.93E-05 kg SO2 eq.	7.59	2.22E-04
eutrophication kg PO4 eq.	4.88E-06	0.7	3.42E-06 kg NOx eq.	7.55	2.58E-05
winter smog kg SPM eq.	8.36E-06	1	8.36E-06 kg SPM eq.	35	2.93E-04
summer smog kg C2H4 eq	3.15E-06	1	3.15E-06 kg VOC eq.	1	3.15E-06
heavy metals kg Pb eq.	2.88E-07	1	2.88E-07 kg Pb eq.	1220	3.51E-04
carcinogens kg B(a)P eq.	2.76E-10	0.44	1.21E-10 kg Ni eq.	58	7.04E-09
ozone layer kg CFC11	8.86E-10	1	8.86E-10 kg CFC11	7.5	6.65E-09
energy resources MJ LHV	9.08E-02	1	9.08E-02 MJ LHV	0.007	6.36E-04
				Total eco-cost	1.57E-03

Table 8: Calculation of eco-costs for a kilogram of reinforcement steel waste to final disposal

Column 1 Impact category	2 amount	3 characterisation factor	4 (2 x 3) kg equivalent	5 damage cost (£)	6 (4 x 5) eco-cost (£)
greenhouse kg CO2 eq.	6.67E-02	1	6.67E-02 kg CO2 eq.	0.01	6.67E-04
acidification kg SO2 eq.	6.41E-04	1	6.41E-04 kg SO2 eq.	7.59	4.87E-03
eutrophication kg PO4 eq.	1.08E-04	0.7	7.56E-05 kg NOx eq.	7.55	5.71E-04
winter smog kg SPM eq.	1.78E-04	1	1.78E-04 kg SPM eq.	35	6.23E-03
summer smog kg C2H4 eq	5.30E-05	1	5.30E-05 kg VOC eq.	1	5.30E-05
heavy metals kg Pb eq.	7.06E-07	1	7.06E-07 kg Pb eq.	1220	8.61E-04
carcinogens kg B(a)P eq.	2.65E-08	0.44	1.17E-08 kg Ni eq.	58	6.76E-07
ozone layer kg CFC11	1.30E-08	1	1.30E-08 kg CFC11	7.5	9.75E-08
energy resources MJ LHV	1.13E+00	1	1.13E+00 MJ LHV	0.07	7.91E-02
				Total eco-cost	9.23E-02

Table 9: Calculation of eco-costs for a kilogram of reinforcement steel waste to recycling

Column 1 Impact category	2 amount	3 characterisation factor	4 (2 x 3) kg equivalent	5 damage cost (£)	6 (4 x 5) eco-cost (£)
greenhouse kg CO2 eq.	5.62E-02	1	5.62E-02 kg CO2 eq.	0.01	5.62E-04
acidification kg SO2 eq.	5.61E-04	1	5.61E-04 kg SO2 eq.	7.59	4.26E-03
eutrophication kg PO4 eq.	9.46E-05	0.7	6.62E-05 kg NOx eq.	7.55	5.00E-04
winter smog kg SPM eq.	1.55E-04	1	1.55E-04 kg SPM eq.	35	5.43E-03
summer smog kg C2H4 eq	4.30E-05	1	4.30E-05 kg VOC eq.	1	4.30E-05
heavy metals kg Pb eq.	2.40E-07	1	2.40E-07 kg Pb eq.	1220	2.93E-04
carcinogens kg B(a)P eq.	2.48E-08	0.44	1.09E-08 kg Ni eq.	58	6.33E-07
ozone layer kg CFC11	9.40E-09	1	9.40E-09 kg CFC11	7.5	7.05E-08
energy resources MJ LHV	8.64E-01	1	8.64E-01 MJ LHV	0.07	6.05E-02
				Total eco-cost	7.16E-02

Table 10: Calculation of eco-costs for a kilogram of reinforcement steel waste to sorting plant

Column 1 Impact category	2 amount	3 characterisation factor	4 (2 x 3) kg equivalent	5 damage cost (£)	6 (4 x 5) eco-cost (£)
greenhouse kg CO2 eq.	6.07E-02	1	6.07E-02 kg CO2 eq.	0.01	6.07E-04
acidification kg SO2 eq.	5.91E-04	1	5.91E-04 kg SO2 eq.	7.59	4.49E-03
eutrophication kg PO4 eq.	9.95E-05	0.7	6.97E-05 kg NOx eq.	7.55	5.26E-04
winter smog kg SPM eq.	1.63E-04	1	1.63E-04 kg SPM eq.	35	5.71E-03
summer smog kg C2H4 eq	4.62E-05	1	4.62E-05 kg VOC eq.	1	4.62E-05
heavy metals kg Pb eq.	5.36E-07	1	5.36E-07 kg Pb eq.	1220	6.54E-04
carcinogens kg B(a)P eq.	2.51E-08	0.44	1.10E-08 kg Ni eq.	58	6.41E-07
ozone layer kg CFC11	1.03E-08	1	1.03E-08 kg CFC11	7.5	7.73E-08
energy resources MJ LHV	9.70E-01	1	9.70E-01 MJ LHV	0.07	6.79E-02
				Total eco-cost	7.99E-02

Table 11: Calculation of eco-costs for a kilogram of plasterboard waste to final disposal

Column 1 Impact category	2 amount	3 characterisation factor	4 (2 x 3) kg equivalent	5 damage cost (£)	6 (4 x 5) eco-cost (£)
greenhouse kg CO2 eq.	1.37E-02	1	1.37E-02 kg CO2 eq.	0.01	1.37E-04
acidification kg SO2 eq.	1.12E-04	1	1.12E-04 kg SO2 eq.	7.59	8.50E-04
eutrophication kg PO4 eq.	1.86E-05	0.7	1.30E-05 kg NOx eq.	7.55	9.83E-05
winter smog kg SPM eq.	1.12E-04	1	1.12E-04 kg SPM eq.	35	3.92E-03
summer smog kg C2H4 eq	1.25E-05	1	1.25E-05 kg VOC eq.	1	1.25E-05
heavy metals kg Pb eq.	4.80E-07	1	4.80E-07 kg Pb eq.	1220	5.86E-04
carcinogens kg B(a)P eq.	3.09E-09	0.44	1.36E-09 kg Ni eq.	58	7.89E-08
ozone layer kg CFC11	4.17E-09	1	4.17E-09 kg CFC11	7.5	3.13E-08
energy resources MJ LHV	3.11E-01	1	3.11E-01 MJ LHV	0.07	2.18E-02
				Total eco-cost	2.74E-02

Table 12: Calculation of eco-costs for a kilogram of plasterboard waste to recycling

Column 1 Impact category	2 amount	3 characterisation factor	4 (2 x 3) kg equivalent	5 damage cost (£)	6 (4 x 5) eco-cost (£)
greenhouse kg CO2 eq.	3.22E-03	1	3.22E-03 kg CO2 eq.	0.01	3.22E-05
acidification kg SO2 eq.	3.21E-05	1	3.21E-05 kg SO2 eq.	7.59	2.44E-04
eutrophication kg PO4 eq.	5.43E-06	0.7	3.80E-06 kg NOx eq.	7.55	2.87E-05
winter smog kg SPM eq.	8.89E-05	1	8.89E-05 kg SPM eq.	35	3.11E-03
summer smog kg C2H4 eq	2.47E-06	1	2.47E-06 kg VOC eq.	1	2.47E-06
heavy metals kg Pb eq.	1.38E-08	1	1.38E-08 kg Pb eq.	1220	1.68E-05
carcinogens kg B(a)P eq.	1.42E-09	0.44	6.25E-10 kg Ni eq.	58	3.62E-08
ozone layer kg CFC11	5.39E-10	1	5.39E-10 kg CFC11	7.5	4.04E-09
energy resources MJ LHV	4.95E-02	1	4.95E-02 MJ LHV	0.07	3.47E-03
				Total eco-cost	6.90E-03

Table 13: Calculation of eco-costs for a kilogram of construction plasterboard waste to sorting plant

Column 1 Impact category	2 amount	3 characterisation factor	4 (2 x 3) kg equivalent	5 damage cost (£)	6 (4 x 5) eco-cost (£)
greenhouse kg CO2 eq.	2.16E-02	1	2.16E-02 kg CO2 eq.	0.01	2.16E-04
acidification kg SO2 eq.	2.13E-02	1	2.13E-02 kg SO2 eq.	7.59	1.62E-01
eutrophication kg PO4 eq.	2.71E-05	0.7	1.90E-05 kg NOx eq.	7.55	1.43E-04
winter smog kg SPM eq.	2.10E-02	1	2.10E-02 kg SPM eq.	35	7.35E-01
summer smog kg C2H4 eq	1.78E-05	1	1.78E-05 kg VOC eq.	1	1.78E-05
heavy metals kg Pb eq.	8.90E-06	1	8.90E-06 kg Pb eq.	1220	1.09E-02
carcinogens kg B(a)P eq.	4.61E-09	0.44	2.03E-09 kg Ni eq.	58	1.18E-07
ozone layer kg CFC11	5.62E-09	1	5.62E-09 kg CFC11	7.5	4.22E-08
energy resources MJ LHV	5.03E-01	1	5.03E-01 MJ LHV	0.07	3.52E-02
				Total eco-cost	9.43E-01

Table 14: Calculation of eco-costs for a kilogram of treated wood to final disposal

Column 1 Impact category	2 amount	3 characterisation factor	4 (2 x 3) kg equivalent	5 damage cost (£)	6 (4 x 5) eco-cost (£)
greenhouse kg CO2 eq.	1.46E+00	1	1.46E+00 kg CO2 eq.	0.01	1.46E-02
acidification kg SO2 eq.	3.07E-04	1	3.07E-04 kg SO2 eq.	7.59	2.33E-03
eutrophication kg PO4 eq.	2.92E-04	0.7	2.04E-04 kg NOx eq.	7.55	1.54E-03
winter smog kg SPM eq.	3.10E-05	1	3.10E-05 kg SPM eq.	35	1.09E-03
summer smog kg C2H4 eq	3.12E-05	1	3.12E-05 kg VOC eq.	1	3.12E-05
heavy metals kg Pb eq.	6.67E-06	1	6.67E-06 kg Pb eq.	1220	8.14E-03
carcinogens kg B(a)P eq.	1.22E-09	0.44	5.37E-10 kg Ni eq.	58	3.11E-08
ozone layer kg CFC11	1.80E-09	1	1.80E-09 kg CFC11	7.5	1.35E-08
energy resources MJ LHV	2.08E-01	1	2.08E-01 MJ LHV	0.07	1.46E-02
				Total eco-cost	4.23E-02

Table 15: Calculation of eco-costs for a kilogram of untreated wood to final disposal

Column 1 Impact category	2 amount	3 characterisation factor	4 (2 x 3) kg equivalent	5 damage cost (£)	6 (4 x 5) eco-cost (£)
greenhouse kg CO2 eq.	1.47E+00	1	1.47E+00 kg CO2 eq.	0.01	1.47E-02
acidification kg SO2 eq.	3.06E-04	1	3.06E-04 kg SO2 eq.	7.59	2.32E-03
eutrophication kg PO4 eq.	2.92E-04	0.7	2.04E-04 kg NOx eq.	7.55	1.54E-03
winter smog kg SPM eq.	3.00E-05	1	3.00E-05 kg SPM eq.	35	1.05E-03
summer smog kg C2H4 eq	3.11E-05	1	3.11E-05 kg VOC eq.	1	3.11E-05
heavy metals kg Pb eq.	4.65E-06	1	4.65E-06 kg Pb eq.	1220	5.67E-03
carcinogens kg B(a)P eq.	1.20E-09	0.44	5.28E-10 kg Ni eq.	58	3.06E-08
ozone layer kg CFC11	1.70E-09	1	1.70E-09 kg CFC11	7.5	1.28E-08
energy resources MJ LHV	2.04E-01	1	2.04E-01 MJ LHV	0.07	1.43E-02
				Total eco-cost	3.96E-02

APPENDIX 4

1. Eco-costs estimation model parameters of nine environmental indicators for brick to final disposal:

Model Summary and Parameter Estimates

Dependent Variable: VAR00002 (Global warming)

Equation	Model Summary					Parameter Estimates			
	R Square	F	df1	df2	Sig.	Constant	b1	b2	b3
Linear	.867	117.681	1	18	.000	-.527	.056		
Logarithmic	1.000	.	1	18	.	-.863	.434		
Cubic	.993	716.799	3	16	.000	-.996	.226	-.014	.000

The independent variable is VAR00001.

Model Summary and Parameter Estimates

Dependent Variable: VAR00003 (Acidification)

	Model Summary					Parameter Estimates			
Equation	R Square	F	df1	df2	Sig.	Constant	b1	b2	b3
Linear	.867	117.681	1	18	.000	.265	.056		
Logarithmic	1.000	.	1	18	.	-.071	.434		
Cubic	.993	716.799	3	16	.000	-.203	.226	-.014	.000

The independent variable is VAR00001.

Model Summary and Parameter Estimates

Dependent Variable: VAR00004 (Euthrophication)

	Model Summary					Parameter Estimates			
Equation	R Square	F	df1	df2	Sig.	Constant	b1	b2	b3
Linear	.867	117.681	1	18	.000	-.672	.056		
Logarithmic	1.000	.	1	18	.	-1.007	.434		
Cubic	.993	716.799	3	16	.000	-1.140	.226	-.014	.000

The independent variable is VAR00001.

Model Summary and Parameter Estimates

Dependent Variable: VAR00005 (Winter smog)

	Model Summary					Parameter Estimates			
Equation	R Square	F	df1	df2	Sig.	Constant	b1	b2	b3
Linear	.867	117.681	1	18	.000	.929	.056		
Logarithmic	1.000	.	1	18	.	.593	.434		
Cubic	.993	716.799	3	16	.000	.461	.226	-.014	.000

The independent variable is VAR00001.

Model Summary and Parameter Estimates

Dependent Variable: VAR00006 (summer smog)

Equation	Model Summary					Parameter Estimates			
	R Square	F	df1	df2	Sig.	Constant	b1	b2	b3
Linear	.867	117.681	1	18	.000	-1.567	.056		
Logarithmic	1.000	27021597764222960.000	1	18	.000	-1.903	.434		
Cubic	.993	716.799	3	16	.000	-2.036	.226	-.014	.000

The independent variable is VAR00001.

Model Summary and Parameter Estimates

Dependent Variable: VAR00007 (Heavy metal)

	Model Summary					Parameter Estimates			
Equation	R Square	F	df1	df2	Sig.	Constant	b1	b2	b3
Linear	.867	117.681	1	18	.000	.104	.056		
Logarithmic	1.000	.	1	18	.	-.232	.434		
Cubic	.993	716.799	3	16	.000	-.365	.226	-.014	.000

The independent variable is VAR00001.

Model Summary and Parameter Estimates

Dependent Variable: VAR00008 (Carcinogens)

	Model Summary					Parameter Estimates			
Equation	R Square	F	df1	df2	Sig.	Constant	b1	b2	b3
Linear	.867	117.681	1	18	.000	-3.767	.056		
Logarithmic	1.000	.	1	18	.	-4.103	.434		
Cubic	.993	716.799	3	16	.000	-4.236	.226	-.014	.000

The independent variable is VAR00001.

Model Summary and Parameter Estimates

Dependent Variable: VAR00009 (Ozone layer depletion)

	Model Summary					Parameter Estimates			
Equation	R Square	F	df1	df2	Sig.	Constant	b1	b2	b3
Linear	.867	117.681	1	18	.000	-4.169	.056		
Logarithmic	1.000	.	1	18	.	-4.505	.434		
Cubic	.993	716.799	3	16	.000	-4.637	.226	-.014	.000

The independent variable is VAR00001.

Model Summary and Parameter Estimates

Dependent Variable: VAR00010 (Energy resources)

	Model Summary					Parameter Estimates			
Equation	R Square	F	df1	df2	Sig.	Constant	b1	b2	b3
Linear	.867	117.681	1	18	.000	1.674	.056		
Logarithmic	1.000	.	1	18	.	1.338	.434		
Cubic	.993	716.799	3	16	.000	1.205	.226	-.014	.000

The independent variable is VAR00001.

2. Eco-costs estimation model parameters of nine environmental indicators for brick to recycling:

Model Summary and Parameter Estimates

Dependent Variable: VAR00002 (Global warming)

Equation	Model Summary					Parameter Estimates			
	R Square	F	df1	df2	Sig.	Constant	b1	b2	b3
Linear	.867	117.681	1	18	.000	-1.156	.056		
Logarithmic	1.000	27021597764222960.000	1	18	.000	-1.492	.434		
Cubic	.993	716.799	3	16	.000	-1.625	.226	-.014	.000

The independent variable is VAR00001.

Model Summary and Parameter Estimates

Dependent Variable: VAR00003 (Acidification)

Equation	Model Summary					Parameter Estimates			
	R Square	F	df1	df2	Sig.	Constant	b1	b2	b3
Linear	.867	117.681	1	18	.000	-.277	.056		
Logarithmic	1.000	.	1	18	.	-.613	.434		
Cubic	.993	716.799	3	16	.000	-.746	.226	-.014	.000

The independent variable is VAR00001.

Model Summary and Parameter Estimates

Dependent Variable: VAR00004 (Eutrophication)

	Model Summary					Parameter Estimates			
Equation	R Square	F	df1	df2	Sig.	Constant	b1	b2	b3
Linear	.867	117.681	1	18	.000	-1.206	.056		
Logarithmic	1.000	.	1	18	.	-1.542	.434		
Cubic	.993	716.799	3	16	.000	-1.675	.226	-.014	.000

The independent variable is VAR00001.

Model Summary and Parameter Estimates

Dependent Variable: VAR00005 (Winter smog)

	Model Summary					Parameter Estimates			
Equation	R Square	F	df1	df2	Sig.	Constant	b1	b2	b3
Linear	.867	117.681	1	18	.000	.829	.056		
Logarithmic	1.000	.	1	18	.	.493	.434		
Cubic	.993	716.799	3	16	.000	.361	.226	-.014	.000

The independent variable is VAR00001.

Model Summary and Parameter Estimates

Dependent Variable: VAR00006 (Summer smog)

	Model Summary					Parameter Estimates			
Equation	R Square	F	df1	df2	Sig.	Constant	b1	b2	b3
Linear	.867	117.681	1	18	.000	-2.271	.056		
Logarithmic	1.000	.	1	18	.	-2.607	.434		
Cubic	.993	716.799	3	16	.000	-2.740	.226	-.014	.000

The independent variable is VAR00001.

Model Summary and Parameter Estimates

Dependent Variable: VAR00007 (Heavy metal)

	Model Summary					Parameter Estimates			
Equation	R Square	F	df1	df2	Sig.	Constant	b1	b2	b3
Linear	.867	117.681	1	18	.000	-1.438	.056		
Logarithmic	1.000	.	1	18	.	-1.774	.434		
Cubic	.993	716.799	3	16	.000	-1.906	.226	-.014	.000

The independent variable is VAR00001.

Model Summary and Parameter Estimates

Dependent Variable: VAR00008 (Carcinogens)

	Model Summary					Parameter Estimates			
Equation	R Square	F	df1	df2	Sig.	Constant	b1	b2	b3
Linear	.867	117.681	1	18	.000	-4.105	.056		
Logarithmic	1.000	.	1	18	.	-4.441	.434		
Cubic	.993	716.799	3	16	.000	-4.573	.226	-.014	.000

The independent variable is VAR00001.

Model Summary and Parameter Estimates

Dependent Variable: VAR00009 (Ozone layer depletion)

	Model Summary					Parameter Estimates			
Equation	R Square	F	df1	df2	Sig.	Constant	b1	b2	b3
Linear	.867	117.681	1	18	.000	-5.057	.056		
Logarithmic	1.000	.	1	18	.	-5.393	.434		
Cubic	.993	716.799	3	16	.000	-5.526	.226	-.014	.000

The independent variable is VAR00001.

Model Summary and Parameter Estimates

Dependent Variable: VAR00010 (Energy resources)

Equation	Model Summary					Parameter Estimates			
	R Square	F	df1	df2	Sig.	Constant	b1	b2	b3
Linear	.867	117.681	1	18	.000	.876	.056		
Logarithmic	1.000	27021597764222960.000	1	18	.000	.540	.434		
Cubic	.993	716.799	3	16	.000	.407	.226	-.014	.000

The independent variable is VAR00001.

3. Eco-costs estimation model parameters of nine environmental indicators for brick to sorting plant:

Model Summary and Parameter Estimates

Dependent Variable: VAR00002 (Global warming)

Equation	Model Summary					Parameter Estimates			
	R Square	F	df1	df2	Sig.	Constant	b1	b2	b3
Linear	.867	117.681	1	18	.000	-.521	.056		
Logarithmic	1.000	.	1	18	.	-.857	.434		
Cubic	.993	716.799	3	16	.000	-.989	.226	-.014	.000

The independent variable is VAR00001.

Model Summary and Parameter Estimates

Dependent Variable: VAR00003 (Acidification)

Equation	Model Summary					Parameter Estimates			
	R Square	F	df1	df2	Sig.	Constant	b1	b2	b3
Linear	.867	117.681	1	18	.000	.258	.056		
Logarithmic	1.000	.	1	18	.	-.078	.434		
Cubic	.993	716.799	3	16	.000	-.211	.226	-.014	.000

The independent variable is VAR00001.

Model Summary and Parameter Estimates

Dependent Variable: VAR00004 (Eutrophication)

Equation	Model Summary					Parameter Estimates			
	R Square	F	df1	df2	Sig.	Constant	b1	b2	b3
Linear	.867	117.681	1	18	.000	-.642	.056		
Logarithmic	1.000	.	1	18	.	-.978	.434		
Cubic	.993	716.799	3	16	.000	-1.111	.226	-.014	.000

The independent variable is VAR00001.

Model Summary and Parameter Estimates

Dependent Variable: VAR00005 (Winter smog)

Equation	Model Summary					Parameter Estimates			
	R Square	F	df1	df2	Sig.	Constant	b1	b2	b3
Linear	.867	117.681	1	18	.000	.933	.056		
Logarithmic	1.000	.	1	18	.	.597	.434		
Cubic	.993	716.799	3	16	.000	.465	.226	-.014	.000

The independent variable is VAR00001.

Model Summary and Parameter Estimates

Dependent Variable: VAR00006 (Summer smog)

Equation	Model Summary					Parameter Estimates			
	R Square	F	df1	df2	Sig.	Constant	b1	b2	b3
Linear	.867	117.681	1	18	.000	-1.615	.056		
Logarithmic	1.000	27021597764222960.000	1	18	.000	-1.951	.434		
Cubic	.993	716.799	3	16	.000	-2.083	.226	-.014	.000

The independent variable is VAR00001.

Model Summary and Parameter Estimates

Dependent Variable: VAR00007 (Heavy metal)

Equation	Model Summary					Parameter Estimates			
	R Square	F	df1	df2	Sig.	Constant	b1	b2	b3
Linear	.867	117.681	1	18	.000	1.708	.056		
Logarithmic	1.000	.	1	18	.	1.372	.434		
Cubic	.993	716.799	3	16	.000	1.239	.226	-.014	.000

The independent variable is VAR00001.

Model Summary and Parameter Estimates

Dependent Variable: VAR00008 (Carcinogens)

Equation	Model Summary					Parameter Estimates			
	R Square	F	df1	df2	Sig.	Constant	b1	b2	b3
Linear	.867	117.681	1	18	.000	-3.782	.056		
Logarithmic	1.000	.	1	18	.	-4.117	.434		
Cubic	.993	716.799	3	16	.000	-4.250	.226	-.014	.000

The independent variable is VAR00001.

Model Summary and Parameter Estimates

Dependent Variable: VAR00009 (Ozone layer depletion)

	Model Summary					Parameter Estimates			
Equation	R Square	F	df1	df2	Sig.	Constant	b1	b2	b3
Linear	.867	117.681	1	18	.000	-4.263	.056		
Logarithmic	1.000	.	1	18	.	-4.599	.434		
Cubic	.993	716.799	3	16	.000	-4.731	.226	-.014	.000

The independent variable is VAR00001.

Model Summary and Parameter Estimates

Dependent Variable: VAR00010 (Energy resources)

	Model Summary					Parameter Estimates			
Equation	R Square	F	df1	df2	Sig.	Constant	b1	b2	b3
Linear	.867	117.681	1	18	.000	1.671	.056		
Logarithmic	1.000	.	1	18	.	1.335	.434		
Cubic	.993	716.799	3	16	.000	1.203	.226	-.014	.000

The independent variable is VAR00001.

4. Eco-costs estimation model parameters of nine environmental indicators for plasterboard to final disposal:

Model Summary and Parameter Estimates

Dependent Variable: VAR00002(Global warming)

Equation	Model Summary					Parameter Estimates			
	R Square	F	df1	df2	Sig.	Constant	b1	b2	b3
Linear	.867	117.681	1	18	.000	-.527	.056		
Logarithmic	1.000	.	1	18	.	-.863	.434		
Cubic	.993	716.799	3	16	.000	-.996	.226	-.014	.000

The independent variable is VAR00001.

Model Summary and Parameter Estimates

Dependent Variable: VAR00003(Acidification)

Equation	Model Summary					Parameter Estimates			
	R Square	F	df1	df2	Sig.	Constant	b1	b2	b3
Linear	.867	117.681	1	18	.000	.265	.056		
Logarithmic	1.000	.	1	18	.	-.071	.434		
Cubic	.993	716.799	3	16	.000	-.203	.226	-.014	.000

The independent variable is VAR00001.

Model Summary and Parameter Estimates

Dependent Variable: VAR00004 (Eutrophication)

Equation	Model Summary					Parameter Estimates			
	R Square	F	df1	df2	Sig.	Constant	b1	b2	b3
Linear	.867	117.681	1	18	.000	-.672	.056		
Logarithmic	1.000	.	1	18	.	-1.007	.434		
Cubic	.993	716.799	3	16	.000	-1.140	.226	-.014	.000

The independent variable is VAR00001.

Model Summary and Parameter Estimates

Dependent Variable: VAR00005 (Winter smog)

Equation	Model Summary					Parameter Estimates			
	R Square	F	df1	df2	Sig.	Constant	b1	b2	b3
Linear	.867	117.681	1	18	.000	.929	.056		
Logarithmic	1.000	.	1	18	.	.593	.434		
Cubic	.993	716.799	3	16	.000	.461	.226	-.014	.000

The independent variable is VAR00001.

Model Summary and Parameter Estimates

Dependent Variable: VAR00006 (Summer smog)

Equation	Model Summary					Parameter Estimates			
	R Square	F	df1	df2	Sig.	Constant	b1	b2	b3
Linear	.867	117.681	1	18	.000	-1.567	.056		
Logarithmic	1.000	.	1	18	.	-1.903	.434		
Cubic	.993	716.799	3	16	.000	-2.036	.226	-.014	.000

The independent variable is VAR00001.

Model Summary and Parameter Estimates

Dependent Variable: VAR00007 (Heavy metal)

Equation	Model Summary					Parameter Estimates			
	R Square	F	df1	df2	Sig.	Constant	b1	b2	b3
Linear	.867	117.681	1	18	.000	.104	.056		
Logarithmic	1.000	.	1	18	.	-.232	.434		
Cubic	.993	716.799	3	16	.000	-.365	.226	-.014	.000

The independent variable is VAR00001.

Model Summary and Parameter Estimates

Dependent Variable: VAR00008(Carcinogens)

Equation	Model Summary					Parameter Estimates			
	R Square	F	df1	df2	Sig.	Constant	b1	b2	b3
Linear	.867	117.681	1	18	.000	-3.767	.056		
Logarithmic	1.000	.	1	18	.	-4.103	.434		
Cubic	.993	716.799	3	16	.000	-4.236	.226	-.014	.000

The independent variable is VAR00001.

Model Summary and Parameter Estimates

Dependent Variable: VAR00009 (Ozone layer depletion)

Equation	Model Summary					Parameter Estimates			
	R Square	F	df1	df2	Sig.	Constant	b1	b2	b3
Linear	.867	117.681	1	18	.000	-4.169	.056		
Logarithmic	1.000	27021597764222960.000	1	18	.000	-4.505	.434		
Cubic	.993	716.799	3	16	.000	-4.637	.226	-.014	.000

The independent variable is VAR00001.

Model Summary and Parameter Estimates

Dependent Variable: VAR00010 (Energy resources)

	Model Summary					Parameter Estimates			
Equation	R Square	F	df1	df2	Sig.	Constant	b1	b2	b3
Linear	.867	117.681	1	18	.000	1.674	.056		
Logarithmic	1.000	27021597764222960.000	1	18	.000	1.338	.434		
Cubic	.993	716.799	3	16	.000	1.205	.226	-.014	.000

The independent variable is VAR00001.

5. Eco-costs estimation model parameters of nine environmental indicators for plasterboard to recycling:

Model Summary and Parameter Estimates

Dependent Variable: VAR00002 (Global warming)

Equation	Model Summary					Parameter Estimates			
	R Square	F	df1	df2	Sig.	Constant	b1	b2	b3
Linear	.867	117.681	1	18	.000	-.527	.056		
Logarithmic	1.000	.	1	18	.	-.863	.434		
Cubic	.993	716.799	3	16	.000	-.996	.226	-.014	.000

The independent variable is VAR00001.

Model Summary and Parameter Estimates

Dependent Variable: VAR00003 (Acidification)

Equation	Model Summary					Parameter Estimates			
	R Square	F	df1	df2	Sig.	Constant	b1	b2	b3
Linear	.867	117.681	1	18	.000	-.277	.056		
Logarithmic	1.000	.	1	18	.	-.613	.434		
Cubic	.993	716.799	3	16	.000	-.746	.226	-.014	.000

The independent variable is VAR00001.

Model Summary and Parameter Estimates

Dependent Variable: VAR00004 (Eutrophication)

Equation	Model Summary					Parameter Estimates			
	R Square	F	df1	df2	Sig.	Constant	b1	b2	b3
Linear	.867	117.681	1	18	.000	-1.206	.056		
Logarithmic	1.000	.	1	18	.	-1.542	.434		
Cubic	.993	716.799	3	16	.000	-1.675	.226	-.014	.000

The independent variable is VAR00001.

Model Summary and Parameter Estimates

Dependent Variable: VAR00005 (Winter smog)

Equation	Model Summary					Parameter Estimates			
	R Square	F	df1	df2	Sig.	Constant	b1	b2	b3
Linear	.867	117.681	1	18	.000	.829	.056		
Logarithmic	1.000	27021597764222960.000	1	18	.000	.493	.434		
Cubic	.993	716.799	3	16	.000	.361	.226	-.014	.000

The independent variable is VAR00001.

Model Summary and Parameter Estimates

Dependent Variable: VAR00006 (Summer smog)

	Model Summary					Parameter Estimates			
Equation	R Square	F	df1	df2	Sig.	Constant	b1	b2	b3
Linear	.867	117.681	1	18	.000	-2.271	.056		
Logarithmic	1.000	.	1	18	.	-2.607	.434		
Cubic	.993	716.799	3	16	.000	-2.740	.226	-.014	.000

The independent variable is VAR00001.

Model Summary and Parameter Estimates

Dependent Variable: VAR00007 (Heavy metal)

	Model Summary					Parameter Estimates			
Equation	R Square	F	df1	df2	Sig.	Constant	b1	b2	b3
Linear	.867	117.681	1	18	.000	-1.438	.056		
Logarithmic	1.000	.	1	18	.	-1.774	.434		
Cubic	.993	716.799	3	16	.000	-1.906	.226	-.014	.000

The independent variable is VAR00001.

Model Summary and Parameter Estimates

Dependent Variable: VAR00008 (Carcinogens)

	Model Summary					Parameter Estimates			
Equation	R Square	F	df1	df2	Sig.	Constant	b1	b2	b3
Linear	.867	117.681	1	18	.000	-4.105	.056		
Logarithmic	1.000	.	1	18	.	-4.441	.434		
Cubic	.993	716.799	3	16	.000	-4.573	.226	-.014	.000

The independent variable is VAR00001.

Model Summary and Parameter Estimates

Dependent Variable: VAR00009 (Ozone layer depletion)

	Model Summary					Parameter Estimates			
Equation	R Square	F	df1	df2	Sig.	Constant	b1	b2	b3
Linear	.867	117.681	1	18	.000	-5.057	.056		
Logarithmic	1.000	27021597764222960.000	1	18	.000	-5.393	.434		
Cubic	.993	716.799	3	16	.000	-5.526	.226	-.014	.000

The independent variable is VAR00001.

Model Summary and Parameter Estimates

Dependent Variable: VAR00010 (Energy resources)

	Model Summary					Parameter Estimates			
Equation	R Square	F	df1	df2	Sig.	Constant	b1	b2	b3
Linear	.867	117.681	1	18	.000	.876	.056		
Logarithmic	1.000	.	1	18	.	.540	.434		
Cubic	.993	716.799	3	16	.000	.407	.226	-.014	.000

The independent variable is VAR00001.

6. Eco-costs estimation model parameters of nine environmental indicators for plasterboard to sorting plant:

Model Summary and Parameter Estimates

Dependent Variable: VAR00002 (Global warming)

The independent variable is VAR00001.

Equation	Model Summary					Parameter Estimates			
	R Square	F	df1	df2	Sig.	Constant	b1	b2	b3
Linear	.867	117.681	1	18	.000	-.330	.056		
Logarithmic	1.000	.	1	18	.	-.666	.434		
Cubic	.993	716.799	3	16	.000	-.798	.226	-.014	.000

Model Summary and Parameter Estimates

Dependent Variable: VAR00003 (Acidification)

	Model Summary					Parameter Estimates			
Equation	R Square	F	df1	df2	Sig.	Constant	b1	b2	b3
Linear	.867	117.681	1	18	.000	2.545	.056		
Logarithmic	1.000	.	1	18	.	2.209	.434		
Cubic	.993	716.799	3	16	.000	2.076	.226	-.014	.000

The independent variable is VAR00001.

Model Summary and Parameter Estimates

Dependent Variable: VAR00004 (Eutrophication)

	Model Summary					Parameter Estimates			
Equation	R Square	F	df1	df2	Sig.	Constant	b1	b2	b3
Linear	.867	117.681	1	18	.000	-.508	.056		
Logarithmic	1.000	.	1	18	.	-.844	.434		
Cubic	.993	716.799	3	16	.000	-.976	.226	-.014	.000

The independent variable is VAR00001.

Model Summary and Parameter Estimates

Dependent Variable: VAR00005 (Winter smog)

	Model Summary					Parameter Estimates			
Equation	R Square	F	df1	df2	Sig.	Constant	b1	b2	b3
Linear	.867	117.681	1	18	.000	3.202	.056		
Logarithmic	1.000	.	1	18	.	2.866	.434		
Cubic	.993	716.799	3	16	.000	2.734	.226	-.014	.000

The independent variable is VAR00001.

Model Summary and Parameter Estimates

Dependent Variable: VAR00006 (Summer smog)

	Model Summary					Parameter Estimates			
Equation	R Square	F	df1	df2	Sig.	Constant	b1	b2	b3
Linear	.867	117.681	1	18	.000	-1.414	.056		
Logarithmic	1.000	.	1	18	.	-1.750	.434		
Cubic	.993	716.799	3	16	.000	-1.882	.226	-.014	.000

The independent variable is VAR00001.

Model Summary and Parameter Estimates

Dependent Variable: VAR00007 (Heavy metal)

	Model Summary					Parameter Estimates			
Equation	R Square	F	df1	df2	Sig.	Constant	b1	b2	b3
Linear	.867	117.681	1	18	.000	1.372	.056		
Logarithmic	1.000	.	1	18	.	1.036	.434		
Cubic	.993	716.799	3	16	.000	.903	.226	-.014	.000

The independent variable is VAR00001.

Model Summary and Parameter Estimates

Dependent Variable: VAR00008 (Carcinogens)

	Model Summary					Parameter Estimates			
Equation	R Square	F	df1	df2	Sig.	Constant	b1	b2	b3
Linear	.867	117.681	1	18	.000	-3.594	.056		
Logarithmic	1.000	.	1	18	.	-3.929	.434		
Cubic	.993	716.799	3	16	.000	-4.062	.226	-.014	.000

The independent variable is VAR00001.

Model Summary and Parameter Estimates

Dependent Variable: VAR00009 (Ozone layer)

Equation	Model Summary					Parameter Estimates			
	R Square	F	df1	df2	Sig.	Constant	b1	b2	b3
Linear	.867	117.681	1	18	.000	-4.039	.056		
Logarithmic	1.000	.	1	18	.	-4.375	.434		
Cubic	.993	716.799	3	16	.000	-4.508	.226	-.014	.000

The independent variable is VAR00001.

Model Summary and Parameter Estimates

Dependent Variable: VAR00010 (Energy resources)

Equation	Model Summary					Parameter Estimates			
	R Square	F	df1	df2	Sig.	Constant	b1	b2	b3
Linear	.867	117.681	1	18	.000	1.883	.056		
Logarithmic	1.000	.	1	18	.	1.547	.434		
Cubic	.993	716.799	3	16	.000	1.414	.226	-.014	.000

The independent variable is VAR00001.

7. Eco-costs estimation model parameters of three environmental waste disposal options for brick waste:

Model Summary and Parameter Estimates

Dependent Variable: VAR00002 (Final disposal)

Equation	Model Summary					Parameter Estimates			
	R Square	F	df1	df2	Sig.	Constant	b1	b2	b3
Linear	.867	117.681	1	18	.000	1.773	.056		
Logarithmic	1.000	.	1	18	.	1.437	.434		
Cubic	.993	716.799	3	16	.000	1.305	.226	-.014	.000

The independent variable is VAR00001.

Model Summary and Parameter Estimates

Dependent Variable: VAR00003 (Recycling)

Equation	Model Summary					Parameter Estimates			
	R Square	F	df1	df2	Sig.	Constant	b1	b2	b3
Linear	.867	117.681	1	18	.000	1.175	.056		
Logarithmic	1.000	27021597764222960.000	1	18	.000	.839	.434		
Cubic	.993	716.799	3	16	.000	.706	.226	-.014	.000

The independent variable is VAR00001.

Model Summary and Parameter Estimates

Dependent Variable: VAR00004 (Sorting plant)

Equation	Model Summary					Parameter Estimates			
	R Square	F	df1	df2	Sig.	Constant	b1	b2	b3
Linear	.867	117.681	1	18	.000	2.037	.056		
Logarithmic	1.000	.	1	18	.	1.701	.434		
Cubic	.993	716.799	3	16	.000	1.568	.226	-.014	.000

The independent variable is VAR00001.

8. Eco-costs estimation model parameters of three environmental waste disposal options for concrete waste:

Model Summary and Parameter Estimates

Dependent Variable: VAR00002 (Final disposal)

	Model Summary					Parameter Estimates			
Equation	R Square	F	df1	df2	Sig.	Constant	b1	b2	b3
Linear	.867	117.681	1	18	.000	1.787	.056		
Logarithmic	1.000	.	1	18	.	1.451	.434		
Cubic	.993	716.799	3	16	.000	1.319	.226	-.014	.000

The independent variable is VAR00001.

Model Summary and Parameter Estimates

Dependent Variable: VAR00003 (Recycling)

	Model Summary					Parameter Estimates			
Equation	R Square	F	df1	df2	Sig.	Constant	b1	b2	b3
Linear	.867	117.681	1	18	.000	1.227	.056		
Logarithmic	1.000	.	1	18	.	.892	.434		
Cubic	.993	716.799	3	16	.000	.759	.226	-.014	.000

The independent variable is VAR00001.

Model Summary and Parameter Estimates

Dependent Variable: VAR00004 (Sorting plant)

	Model Summary					Parameter Estimates			
Equation	R Square	F	df1	df2	Sig.	Constant	b1	b2	b3
Linear	.867	117.681	1	18	.000	2.043	.056		
Logarithmic	1.000	.	1	18	.	1.707	.434		
Cubic	.993	716.799	3	16	.000	1.575	.226	-.014	.000

The independent variable is VAR00001.

9. Eco-costs estimation model parameters of three environmental waste disposal options for metal waste:

Model Summary and Parameter Estimates

Dependent Variable: VAR00002 (Bulk iron to sorting plant)

	Model Summary					Parameter Estimates			
Equation	R Square	F	df1	df2	Sig.	Constant	b1	b2	b3
Linear	.867	117.681	1	18	.000	.532	.056		
Logarithmic	1.000	.	1	18	.	.196	.434		
Cubic	.993	716.799	3	16	.000	.063	.226	-.014	.000

The independent variable is VAR00001.

Model Summary and Parameter Estimates

Dependent Variable: VAR00003 (Reinforced steel to final disposal)

	Model Summary					Parameter Estimates			
Equation	R Square	F	df1	df2	Sig.	Constant	b1	b2	b3
Linear	.867	117.681	1	18	.000	2.301	.056		
Logarithmic	1.000	.	1	18	.	1.965	.434		
Cubic	.993	716.799	3	16	.000	1.833	.226	-.014	.000

The independent variable is VAR00001.

Model Summary and Parameter Estimates

Dependent Variable: VAR00004 (Reinforced steel to recycling)

	Model Summary					Parameter Estimates			
Equation	R Square	F	df1	df2	Sig.	Constant	b1	b2	b3
Linear	.867	117.681	1	18	.000	2.191	.056		
Logarithmic	1.000	.	1	18	.	1.855	.434		
Cubic	.993	716.799	3	16	.000	1.722	.226	-.014	.000

The independent variable is VAR00001.

Model Summary and Parameter Estimates

Dependent Variable: VAR00005 (Reinforced steel to sorting plant)

Equation	Model Summary					Parameter Estimates			
	R Square	F	df1	df2	Sig.	Constant	b1	b2	b3
Linear	.867	117.681	1	18	.000	2.239	.056		
Logarithmic	1.000	.	1	18	.	1.903	.434		
Cubic	.993	716.799	3	16	.000	1.770	.226	-.014	.000

The independent variable is VAR00001.

10. Eco-costs estimation model parameters of three environmental waste disposal options for plasterboard waste:

Model Summary and Parameter Estimates

Dependent Variable: VAR00002 (Final disposal)

	Model Summary					Parameter Estimates			
Equation	R Square	F	df1	df2	Sig.	Constant	b1	b2	b3
Linear	.867	117.681	1	18	.000	1.773	.056		
Logarithmic	1.000	.	1	18	.	1.437	.434		
Cubic	.993	716.799	3	16	.000	1.305	.226	-.014	.000

The independent variable is VAR00001.

Model Summary and Parameter Estimates

Dependent Variable: VAR00003 (Recycling)

Equation	Model Summary					Parameter Estimates			
	R Square	F	df1	df2	Sig.	Constant	b1	b2	b3
Linear	.867	117.681	1	18	.000	1.175	.056		
Logarithmic	1.000	27021597764222960.000	1	18	.000	.839	.434		
Cubic	.993	716.799	3	16	.000	.706	.226	-.014	.000

The independent variable is VAR00001.

Model Summary and Parameter Estimates

Dependent Variable: VAR00004 (Sorting plant)

	Model Summary					Parameter Estimates			
Equation	R Square	F	df1	df2	Sig.	Constant	b1	b2	b3
Linear	.867	117.681	1	18	.000	3.310	.056		
Logarithmic	1.000	.	1	18	.	2.975	.434		
Cubic	.993	716.799	3	16	.000	2.842	.226	-.014	.000

The independent variable is VAR00001.

11. Eco-costs estimation model parameters of three environmental waste disposal options for wood waste:

Model Summary and Parameter Estimates

Dependent Variable: VAR00002 (treated wood to final disposal)

	Model Summary					Parameter Estimates			
Equation	R Square	F	df1	df2	Sig.	Constant	b1	b2	b3
Linear	.867	117.681	1	18	.000	1.962	.056		
Logarithmic	1.000	.	1	18	.	1.626	.434		
Cubic	.993	716.799	3	16	.000	1.494	.226	-.014	.000

The independent variable is VAR00001.

Model Summary and Parameter Estimates

Dependent Variable: VAR00003(untreated wood to final disposal)

	Model Summary					Parameter Estimates			
Equation	R Square	F	df1	df2	Sig.	Constant	b1	b2	b3
Linear	.867	117.681	1	18	.000	1.934	.056		
Logarithmic	1.000	.	1	18	.	1.598	.434		
Cubic	.993	716.799	3	16	.000	1.465	.226	-.014	.000

The independent variable is VAR00001.