Quantifying the sustainability of the built environment: Model for the determination of the environmental impact of the end-of-life phase

by

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SUMMARY

Due to the global concern over emissions causing global warming and other environmental impacts, it is necessary to determine the effect of the construction sector and devise ways in which to minimise the impact. Low cost housing (LCH) is not the largest sector in terms of energy consumption of the South African residential building industry, however, it is necessary to quantify its impact on the environment. Due to a lack of incentives and legislation, the environmental impact of LCH has been largely neglected. As a result, the potential to reduce the environmental impact of this sector is significant.

Previous research investigated the environmental impact pre-use phase of the building lifecycle specifically for LCH. The aim of this study is thus to continue this research by investigating the impact of the end-of-life phase and to finally suggest a model or method by which the impact can be determined. A model to determine the most appropriate demolition technique is developed by using Multi-Criteria Decision Making (MCDM).

A way in which to quantify the environmental impact of the building lifecycle is by using a Lifecycle Analysis (LCA), which includes the entire building lifecycle and its impacts during its lifetime. A method developed in the previous study of the pre-use phase will be used as a benchmark in order to develop a method for the end-of-life phase. The aim of the method is to simplify the quantification of the environmental impact in a South African context. In the method developed for the end-of-life phase, environmental indicators were chosen in order to quantify the environmental impact, namely: Emissions, Resource Depletion and Waste to Landfill. The objective of the method is to determine the Environmental Impact Index (EII), which is a dimensionless value that combines the chosen indicators by applying normalisation and weighting factors.

A case study on different structural systems of LCH is looked at in order to choose the best alternative. The structural systems considered were the conventional (brick and mortar) design type and the Light Steel Frame Building (LSFB) design type. Two disposal options were also considered as part of the study on the end-of-life phase. These two disposal options included the reference case, which was selected as the landfilling of all waste, and the alternative disposal option, where the waste was landfilled, incinerated, recycled or reused depending on the type of waste. The aim is to demonstrate the difference carefully selected materials in the pre-use phase and carefully considered disposal methods of the waste in the end-of-life phase can make in the final environmental impact of the building lifecycle.

OPSOMMING

As gevolg van die wêreldwye besorgdheid oor besoedeling wat aardverwarming en sekere omgewingsimpakte veroorsaak, is dit nodig om vas te stel wat die omgewingsimpak is wat veroorsaak word deur die konstruksiesektor en om maniere te ontwikkel om die omgewingsimpak te verminder. Laekoste-behuising is nie die grootste sektor in terme van energieverbruik van die Suid-Afrikaanse residensiële boubedryf nie, tog is dit nodig om die omgewingsimpak van laekoste-behuising in Suid-Afrika te bepaal. Die impak van die industrie is grootliks in die verlede afgeskeep, hoofsaaklik as gevolg van die gebrek aan aansporingsvoordele. Gevolglik is die potensiaal om die omgewingsimpak van hierdie sektor te verminder betekenisvol.

Vorige navorsing het die impak van die konstruksiebedryf in die voorgebruik-fase ondersoek. Die doel van hierdie studie is dus om hierdie navorsing voort te sit deur ‘n ondersoek oor die impak van die lewenseinde-fase te doen en uiteindelik 'n model of metode waarvolgens die impak bepaal kan word voor te stel. 'n Model om die mees geskikte slopingstegniek te bepaal is ontwikkel deur gebruik te maak van Multi-kriteria Besluitneming.

'n Manier waarop die omgewingsimpak van ‘n gebou se lewensiklus gekwantifiseer kan word is deur middel van 'n Lewensiklus Analise, wat die hele gebou se lewensiklus en die impak daarvan gedurende die gebou se leeftyd insluit. Die metode wat ontwikkel is in die vorige studie oor die voorgebruik-fase is gebruik as 'n maatstaf om 'n metode te ontwikkel vir die lewenseinde-fase. Die doel van die metode is om ‘n vereenvoudigde kwantifisering van die omgewingsimpak te maak in terme van 'n Suid-Afrikaanse konteks. In die ontwikkelde metode vir die lewenseinde-fase is omgewingsaanwysers gekies om die omgewingsimpak te kwantifiseer. Hierdie omgewingsaanwysers sluit in Emissies, Hulpbronuitputting en Afval na Stortingsterrein. Die einddoel van die metode is om ‘n dimensielose waarde vir die Omgewingsimpak-indeks te bepaal. Die Omgewingsimpak-indeks is 'n kombinasie van die gekose omgewingsaanwysers en word bepaal deur die toepassing van normaliserings- en gewigsfaktore.

'n Gevallestudie is toegepas op verskillende strukturele stelsels van laekoste-behuising om ten einde die beste alternatief te kies. Die strukturele stelsels wat oorweeg is, is die konvensionele (baksteen en pleister) ontwerpstipe en die Ligte Staal Raam Gebou ontwerpstipe. Twee wegdoeningsopsies is ook beskou as deel van die studie op die lewenseinde-fase. Hierdie twee wegdoeningsopsies sluit in die verwysingsgeval, wat gekies is as die storting van alle afval in ‘n stortingsterrein, en die alternatiewe opsie, waar die afval gestort, verbrand, herwin of hergebruik is, afhangende van die tipe afval. Die doel is om die verskil te demonstreer wat noukeurig gekiesde boumateriale in die voorgebruik-fase en weldeurdagte wegdoeningsmetodes van die afval in die lewenseinde-fase mag voortbring en om die verskil aan te dui wat hierdie keuses in die finale omgewingsimpak van die gebou se lewensiklus kan maak.

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LIST OF ABBREVIATIONS

AP	Acidification Potential
BS	British Standard
CDW	construction and demolition waste
CF	Carbon Footprint
CO_{2e}	carbon dioxide equivalent
DPC	damp proof course
EDIP	Environmental Design of Industrial Products
EI	environmental impact
EII	Environmental Impact Index
ELCA	Exergetic Lifecycle Analysis
LCA	Lifecycle Analysis (or Lifecycle Assessment)
LCH	Low-cost Housing
LCIA	Lifecycle Inventory Analysis
LSFB	Light Steel Frame Building
MCDM	Multi-Criteria Decision Making
NO_{3e}	nitrate equivalent
OSB	orientated strand board
RCA	recycled concrete aggregate
SO_{2e}	sulphur dioxide equivalent

Chapter 1

INTRODUCTION

Due to the global concern over emissions causing global warming and other environmental impacts, it is necessary to determine the environmental impact of the construction sector and devise ways in which to minimise the impact.

Research, which was conducted at Stellenbosch University, investigated the impact of the construction industry in the pre-use phase (Brewis, 2011). The aim of this study is to continue this research by investigating the impact of the end-of-life phase and to finally suggest a model or method by which the impact can be determined. Furthermore this study focuses on the impact of the low cost housing (LCH) industry in South Africa. In order to determine the environmental impact of the end-of-life phase it is necessary to determine the best demolition technique. This was determined by using Multi-Criteria Decision Making (MCDM).

LCH is not the largest sector in terms of energy consumption of the South African residential building industry however, it is necessary to quantify its impact on the environment. Due to a lack of incentives and legislation, the environmental impact of LCH has been largely neglected. As a result of this, the potential to reduce the environmental impact of this sector is significant. A case study on different structural systems of LCH was looked at in order to choose the best alternative. As previous research (Brewis, 2011) investigated the environmental impact of the pre-use phase for different models of LCH, this study continued the research by investigating the end-of-life phase for the different systems by looking at different disposal options with a specific focus on the South African construction industry. The considered structural systems were the conventional (brick and mortar) design type and the Light Steel Frame Building (LSFB) design type.

A way in which to quantify the environmental impact of the building lifecycle is using a Lifecycle Assessment (LCA), which includes the entire building lifecycle and its impacts during its lifetime. The analysis of the entire lifecycle is referred to as a cradle-to-grave approach, which means it is assessed from the design of the project to the final demolition and disposal of the project. As only the end-of-life phase is considered a modified cradle-to-gate approach is used.

The method developed in the previous study of the pre-use phase is used as a benchmark in order to develop a method for the end-of-life phase. The method used for the pre-use phase largely remains the same for the end-of-life phase. Minor adjustments and additions were, however, made. The aim of the method is to simplify the quantification of the environmental impact in a South African context. The environmental indicators chosen to quantify the environmental impact are: Emissions, Resource Depletion and Waste to Landfill. The objective of the method is to determine the Environmental Impact Index (EII), which is a dimensionless value that combines the chosen indicators by applying normalisation and weighting factors. The EII is used to compare the different alternatives with regard to their environmental impact.

As mentioned earlier, different disposal methods were investigated. The aim is to demonstrate the difference the selected materials in the pre-use phase and chosen disposal methods of the waste in the end-of-life phase can make in the environmental impact of the building lifecycle. To demonstrate this, a reference case is considered. For the end-of-life phase the reference case is the landfilling of all generated waste in this phase.

Chapter 2 gives an overview of the aspects considered in the development of a model for the end-of-life phase. Sustainability, environmental, demolition and disposal aspects, as well as the end-of-life options for structures are discussed in this chapter. Similarly, in Chapter 3 the aspects of developing a model for the quantification of the environmental impact are discussed.

In Chapter 4 the background of MCDM is explained and the developed MCDM model is applied to the case study in order to determine the most preferred demolition technique. It is also demonstrated how MCDM can be used in order to aid the reduction of the environmental impact of the construction industry.

The developed model for the quantification of the environmental impact of the end-of-life phase is applied to the selected case study of LCH in Chapter 5. In Chapter 6 a sensitivity analysis is carried out on selected assumptions in order to determine their significance and impact on the final results of the study.

Finally Chapter 7 combines the results of the previous study on the pre-use phase and the results of this study on the end-of-life phase to show how the developed model can be used for the building lifecycle. Conclusions and recommendations are then discussed in the final chapter.

Chapter 2

LITERARY OVERVIEW

When considering the sustainability of the end-of-life phase of the building lifecycle many aspects need to be taken into account. Demolition of the structure and waste disposal after demolition, for example, are two important aspects that need to be considered. However, many different methods of demolition and waste disposal exist. This chapter gives an overview of each of the aspects that are considered for the quantification of the sustainability of the end-of-life phase. Sustainability in general and the building lifecycle are discussed first, after which more detail is given on the end-of-life options of buildings, and finally demolition and disposal options are proposed.

2.1. Sustainability and environmental aspects

According to the Brundlandt Report (WCED, 1987), sustainability is defined as development which meets the needs of the current generation without compromising the possibility for future generations to provide for their needs. Sustainability includes ecological, social and economic aspects and in order to achieve sustainability all these aspects need to be addressed. In order to achieve ecological sustainability various changes should be made in the construction industry.

According to McGrath et al. (2000), approximately 40% of all construction and related waste in the United Kingdom has been said to arise from the repair and maintenance of existing buildings. In a three year period in Johannesburg, South Africa (2007-2010), 12.2% of waste was generated from the same activity (City of Johannesburg, 2011). The construction of new domestic buildings is also partly responsible for the generated waste, while the remainder of the waste is generated from other construction activities.

In addition, the construction industry is responsible for 7% of global carbon dioxide emissions, which is mostly due to the production of cement (Mora, 2007). Ecological sustainability in construction will only be possible when renewable energy resources, renewable materials and recycled construction materials are used in new constructions.

According to Mehta (2001), the first step in reducing the energy consumption and greenhouse-gas emissions is by using cement conservatively. Mehta (2001) also states that 4 GJ of energy is needed to produce a ton of Portland cement, while the manufacturing of 1 ton of Portland cement clinker releases about 1 ton of carbon dioxide into the atmosphere. Thus a reduction in the use of Portland cement poses the potential to vastly reduce the environmental impact of the construction industry.

Furthermore the use of virgin aggregate in concrete should also be minimised. A manner in which to minimise the use of virgin aggregate is by using recycled concrete aggregate (RCA). To achieve a given workability of concrete using RCA, high water content is needed due to the higher porosity of the RCA. The high water content can be reduced by adding water reducing admixtures and fly-ash to the concrete mixture which in turn reduces the water requirement (Illston et al., 2001).

The construction industries of developing countries have a significantly larger environmental impact than the construction industries of developed countries, as developing countries have a relatively low degree of industrialisation (Du Plessis, 2002). South Africa thus has the potential to reduce the environmental impact of the construction industry by optimising the construction and demolition processes being used. Since a building's lifecycle consists of three phases there are various ways in which to reduce its environmental impact, but first a general understanding of the building lifecycle is necessary.

2.2. The building lifecycle

In order to determine the environmental impact of a building, a Lifecycle Analysis (LCA) has to be carried out for all three phases of the building lifecycle. The three phases of a building's lifecycle are:

- The pre-use phase: the phase begins when construction is first started and ends when the construction of the building is finished. It also takes into account the production of building materials and the transport of these materials to the site.
- The use phase (operational phase): the phase during which the building is in use. The use of electricity, water, fuels etc. is included in this phase.
- The end-of-life phase: the phase when the building has reached the end of its service life and has to be demolished. This phase also takes into consideration the recycling or disposal of waste generated by demolition and the transport of waste to landfills or recycling depots.

The building lifecycle is shown in Figure 2-1. As shown in the figure, transportation is also included in all of the phases of the building lifecycle, as emissions from transportation also contribute to the total environmental impact of the building or structure.

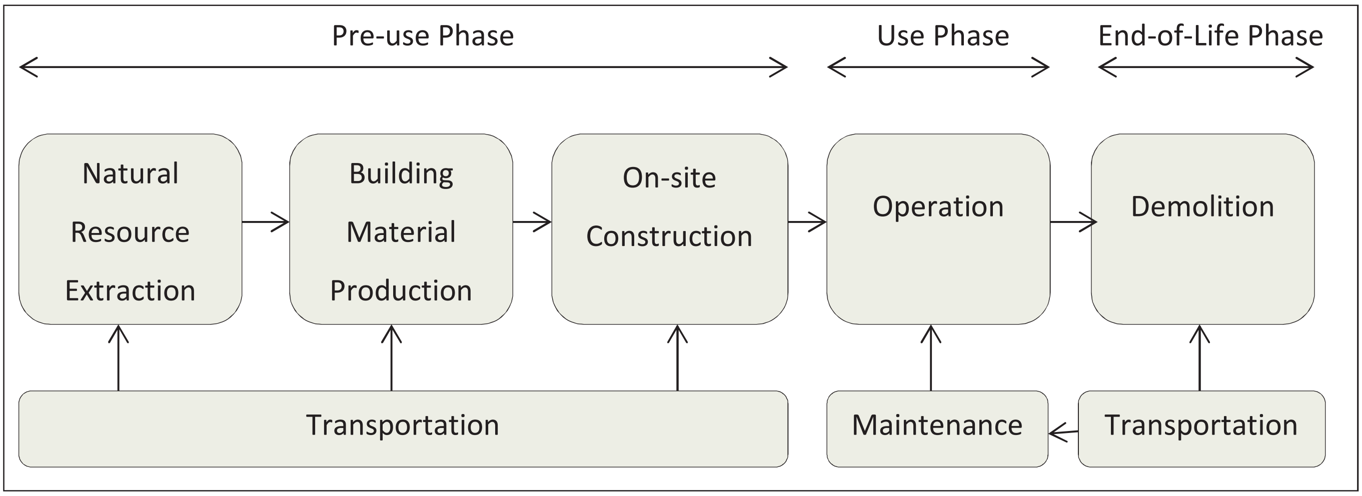

Figure 2-1: Building Life Cycle Theory (Wang et al., 2005)

Each phase of the building lifecycle presents specific problems for sustainability. As the focus of this study is on the end-of-life phase, the challenges of this phase were identified by Hechler (2011) and are discussed below:

- Lack of resources for education on deconstruction;
- Lack of research into demolition;
- Lack of information and tools to implement deconstruction;
- Buildings are typically not designed for deconstruction;
- No standards for the reuse of materials;
- High transportation costs;
- Uses for salvaged materials are undeveloped;
- Low landfill rates encourage waste to be landfilled;
- Time consuming;
- Lack of legislation;
- Construction and demolition waste minimisation is not a priority;
- No incentives to encourage the reuse of materials; and
- Lack of documentation on existing buildings to plan for deconstruction.

The reduction of building material waste has several benefits. These benefits include the reduction of global material consumption, the volume of construction waste and ultimately the volume of demolition waste. The reduction in building material waste also has economic benefits as construction costs are reduced, making the new structure more affordable (Du Plessis, 2002). Wastage rates can be reduced by education, site planning, management and design practices as well as the use of new technologies. New and innovative methods are needed for waste disposal and reuse when the natural degradation processes do not work.

The reuse and recycling of construction and demolition waste need to be investigated, as this is a convenient way to reduce the environmental impact. However, legislation and guidelines on the use of recycled building materials are non-existent in many developing countries. Waste recycling has been implemented to some extent (for example, using fly-ash in concrete mixing), but needs to be extended to add much higher value to the reuse of building waste (Du Plessis, 2002). Waste is created during the construction process, but mostly during the demolition process. Choosing the right end-of-life option for a structure may reduce the generated waste which in turn may also lead to the reduction in the environmental impact of the construction industry.

2.3. End-of-life options for structures

It is first necessary to understand the difference between deconstruction and demolition, before the end-of-life options of a structure are discussed. When a building is deconstructed, it is taken apart and certain parts are reused as structural members in new buildings. Demolition, on the other hand, is when a building is completely torn down by blasting or wrecking.

When demolishing a building it is important to look at different factors that may influence the choice of demolition method. For example, older buildings typically have a less complex structural system which is generally simpler to demolish. However, they often have antiquarian value due to components that are salvaged and reused. On the other hand, the complexity and size of buildings have greatly increased in recent years and therefore more technical expertise are needed in order to demolish them safely (McGrath et al., 2000).

Alternatives to the demolition of a building include refurbishment, retrofitting and adaptive building. These options are not considered in this study; however, they can be seen as possible alternatives to the demolition of a structure. It is also necessary to mention that in some cases these options will form part of the use phase of the building.

When a building’s performance is improved the term refurbishment is used to describe the action being taken. Retrofitting refers to the structure being adapted in order to fulfil a different purpose than what was originally intended. An example of this can be seen in Figure 2-2. An old wine storage tank was retrofitted and changed into a cooling room for fruit (Brümmer, [s.a.]). A few years later it was retrofitted again and changed into a house. Adaptive building thus refers to when a building is used for multiple functions and can easily be changed and put to different use. The different demolition options and techniques are discussed in the following section.

Figure 2-2: An old wine tank (left, Brümmer, [s.a.]) retrofitted and now used as a house (right).

2.4. Demolition

Standards on the demolition process are lacking in South Africa. A small provision for demolition is made in Part E of the National Building Regulations and Building Standards Act (103 of 1977). This act states that permission for demolition work should first be obtained from the local authorities before demolition can commence. It states further that the demolition work must meet the requirements for health and safety as stated in Part F of the same act. No guidelines or requirements are given specifically for the demolition process, therefore British Standard (BS) 6187 (2000) is used in this study in order to obtain more detail about the demolition process.

BS 6187 (2000) suggests various demolition methods or techniques. These methods can be used in combination with each other or individually. It is proposed that the demolition technique should promote reuse and recycling of waste materials arising from demolition activities. BS 6187 (2000) suggests that demolition can either be done by:

- hand;
- machine;
- remotely controlled machines and robotic devices;
- compact machines;
- high reach machines;

- tower and high-reach cranes;
- hydraulic attachments;
- mechanical (non-hydraulic) attachments;
- cutting by drilling and sawing;
- chemical agents;
- explosives;
- hot cutting; and
- by high pressure water jetting.

BS 6187 (2000) recommends that the demolition process be started with the removal of hazardous materials (e.g. asbestos) after which soft stripping of doors, windows, door frames, fittings, ceilings and partitions should commence. Soft stripping can be done by hand or hand-tools and compact machines can be used.

Before starting the demolition all building plans (as-built, as-designed) need to be perused before a demolition method can be chosen. Precast units should preferably be removed from the structure before demolition by using a combination of hand or machine-mounted breaker and hot cutting. Impact hammers, hydraulic shears or explosives can be used on structures containing separately stressed precast units. For structures having post-tensioned members or monolithic structures, expert advice needs to be obtained in order to determine the best demolition method. Timber structures can be demolished by deliberate collapse or by deconstruction. Some older buildings may contain asbestos in wall fittings or as roof sheeting. Extra care and health and safety measures need to be implemented in the case of removing and disposing of hazardous materials (BS 6187, 2000).

In addition to the methods mentioned above, different options and extents of demolition exist. The various options of building demolition are discussed in the following sections (McGrath et al., 2000).

2.4.1. Disassembly

Disassembly refers to the action of taking the building apart without damaging any of the components. Care is taken not to damage any of the components even though the components may not necessarily be reused in other structures.

2.4.2. Destruction

The process of intentional destruction is often referred to as demolition. As demolition is the name also given to the industry it should not confused with the process of demolition. In order to avoid confusion the term destruction will be used when referring to the demolition process. Destruction refers to the complete removal of a structure without the intention of reusing or recycling any components. Destruction can be carried out by machine, by hand or by explosion.

2.4.3. Deconstruction

Deconstruction is the term used when a building is taken apart in the opposite order it was built. The intent of deconstruction is to reuse as many of the components as possible. In some cases a deconstructed building will be rebuilt on a different site, for example movable classrooms for schools.

2.4.4. Progressive demolition

Progressive demolition is the removal of certain components (which are non-essential to the structural system) while maintaining the stability of the building. After this the structure is demolished by destruction. Progressive demolition can be carried out by hand, machine and explosives (in the destruction part) (Abdullah & Anumba, 2000) and is useful in confined and constricted areas (BS 6187, 2000).

When a building is demolished waste is generated. This waste needs to be removed from site and disposed of in a proper and legal manner. The following section will discuss the various disposal options for the waste materials arising during the end-of-life phase and demolition.

2.5. Waste disposal

According to Emery et al. (2010), clean builder's rubble is waste consisting of broken bricks, sand, stone, cement, plaster and similar inert materials. However, it excludes paper, plastic, wood, glass and metal, some of which is also generated with the demolition of low-cost housing (LCH). If the waste is contaminated by more than 10% it is regarded as mixed waste.

The disposal option for the waste that is generated during the demolition process depends on the type of waste. Some waste can be reused in other applications, while other can be recycled. Some of the generated waste will also be unusable or hazardous and should thus be disposed of properly. Various waste disposal options exist for construction and demolition waste (CDW). The various waste disposal options for CDW are discussed below (Ortiz, 2010).

2.5.1. Landfill

According to Bokalders and Block (2010), landfill sites in Europe are being phased out rapidly. This may be due to the fact that they are harmful to the environment and require large areas of land. Furthermore, one of the biggest concerns regarding landfills is that they leach harmful substances into the ground which may contaminate ground water. Landfills are also responsible for polluting the environment and pollutants may spread to nearby ecosystems. Transportation of waste to landfills also has an impact on the environment. However, transportation is a factor not only limited to landfills.

Unfortunately the use of landfills cannot be eradicated completely as a certain amount of waste cannot be incinerated, reused or recycled. The remaining waste, which could not be classified as incinerable or recyclable, is then landfilled. However, Bokalders and Block (2010) suggest that all hazardous waste be removed and taken to special disposal facilities in order to reduce the environmental impact of landfills. They also suggest that waste is sorted, reused or destroyed in order to prevent the waste spreading to ecosystems.

2.5.2. Incineration

Incineration is an easy solution to dispose of waste, however not all waste can be incinerated. Incineration also leads to air pollution as this process leads to emissions of waste products. Some of the emissions include acidifying substances, which when combined with water, form acid rain which in turn causes damage to buildings and concrete structures. Heavy metals and dioxins are also emitted, both which are harmful to human health (Bokalders and Block, 2010).

In order to reduce the emissions caused by incineration of waste, proper incineration facilities are needed and gasses emitted should be filtered before they are released into the environment (Bokalders and Block, 2010). It is also necessary to sort waste before incineration as this will prevent the incineration of waste which may emit harmful substances.

In 2009 the South African Government released a policy on the high temperature incineration of hazardous waste (DEAT, 2009). The policy included incineration as well as co-processing in cement-kilns. However, some waste types are not allowed to be received, stored, handled or co-processed in cement kilns (DEAT, 2009). These products include:

- anatomical, infectious or biologically active medical waste;
- asbestos containing waste;
- unsorted electronic waste;
- bio-hazardous waste;
- entire batteries;
- explosives;
- mineral acids and corrosives;
- radioactive waste;
- unsorted municipal waste; and
- unknown or unidentified waste.

Before any incineration process can be carried out in an incinerator or cement-kiln the relevant approval must be obtained in terms of South African environmental legislation, which includes the National Environmental Management: Waste Act (NEMA) and compliance to national, provincial and local regulations (DEAT, 2009).

AfriSam was the first cement producer in South Africa to start using alternative fuels in its cement-kilns (AfriSam, 2011). This was mainly due to Holcim being an international stakeholder in AfriSam. Holcim uses waste materials as fuel in the cement production process as sustainable construction is regarded as one of their environmental priorities (Holcim, [s.a.]). In 2010 Holcim used various types of alternative fuels in its cement-kilns. Figure 2-3 shows the distribution of these fuels.

The waste types that can be incinerated in a cement-kiln are shown in Figure 2-3. However, incineration should only be considered if the waste cannot be recycled or reused.

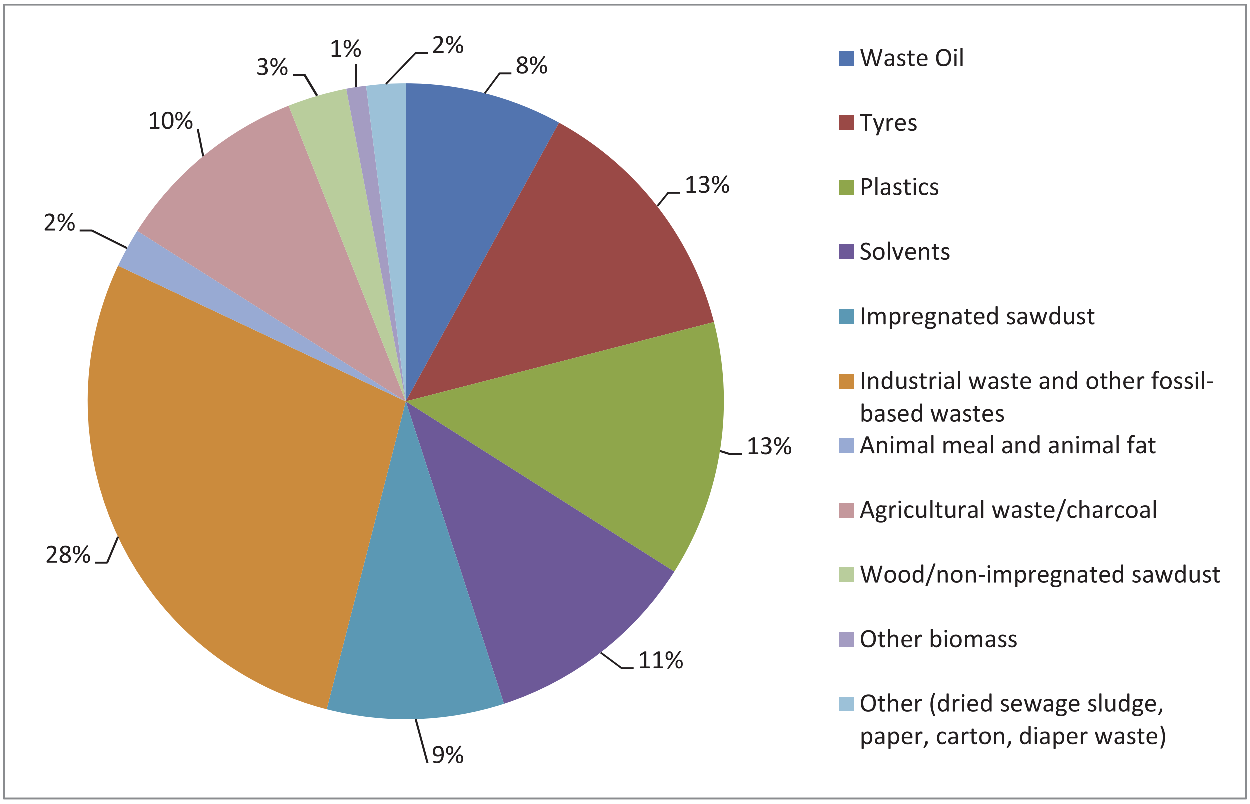

Figure 2-3: Typical waste types used for alternative fuel by relative volume (Holcim, 2010)

2.5.3. Reuse and recycling

After prevention of waste, reuse and recycling is the preferred disposal option for general waste, but especially for CDW. However, in order to optimise reuse and recycling, waste sorting is imperative. Sorting waste leads to easier reuse possibilities, can reduce disposal cost and can aid the removal and safe disposal of hazardous materials from site.

Bokalders and Block (2010) suggest that bins and skips for different waste types be set up on site in order to aid waste sorting. By doing this recyclable and reusable waste can easily be removed from site to other sites (for reuse) or to recycling depots. Furthermore it is suggested to find recycling depots and landfills as close as possible to the site in order to reduce transportation cost of waste.

Economic, environmental, technical and social impacts need to be taken into consideration when assessing recycling as a viable option for the disposal or reduction of demolition waste (Björklund et al., 2005). Tam and Tam (2006) suggest three major benefits of recycling:

- it reduces the demand for new resources;
- it lowers transportation and production costs; and
- it uses waste that would otherwise have ended up in a landfill site.

It is important to realise that the recycling of building materials is only a viable option if the recycled materials can compete with natural resources with regard to cost and quantity. Three areas need to be taken into account when considering recycling a material and using a recycled material:

- economy;
- its compatibility with other materials; and
- its material properties.

For optimum recycling results in the end-of-life phase, special attention needs to be given to the selection of building materials during the design phase (which is part of the pre-use phase of the building lifecycle). The selection of the right materials during the pre-use phase will also reduce the carbon dioxide (CO_2) emissions for the entire lifecycle of a building (Gonzalez et al., 2006).

Four categories of recycling exist namely (De Belie, 2012):

- primary recycling: the waste material is remade into the original material;
- secondary recycling: the waste material is used for another purpose;
- tertiary recycling: an example is the depolymerisation of plastics; and
- quaternary recycling: the conversion of waste material into energy.

This study focused mostly on primary and secondary recycling. For example, in the case of reinforcing steel primary recycling would be that the steel recovered from the building would be melted and formed into another element or new reinforcing steel, while the reuse of steel in other applications, such as art, would be secondary recycling.

Currently, in South Africa, CDW can either be recycled at landfills equipped with recycling equipment, or at recycling depots. Nagataki et al. (2004) describe the concrete recycling process as follows: first the source concrete is crushed with a combination of an impact crusher and a jaw crusher. After this, crushed concrete goes through a mechanical grinding process twice in order to minimise the amount of adhered mortar. Figure 2-4 illustrates the recycling process.

In order to promote the use of recycled CDW it is necessary to create a balance between safety, quality, cost-effectiveness and environmental impact. The current South African legislation on waste does not make enough provision for the recycling of CDW and should be extended to include this aspect. Guidelines or standards on the disposal and reuse of the recycled CDW is also currently lacking in South Africa. The development of such guidelines or standards is a necessity in the successful application of recycling of CDW in South Africa. The people involved in the recycling process also need to be educated to understand the recycling process.

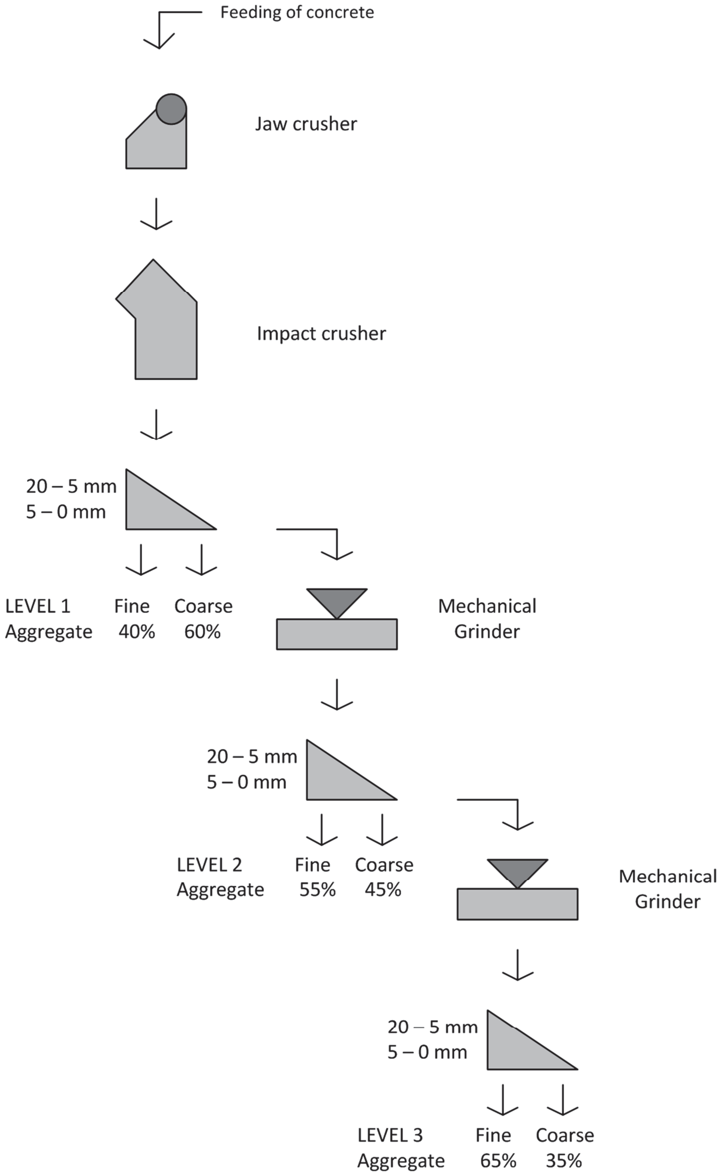

Figure 2-4: The recycling process of concrete (Nagataki et al., 2004)

By taking all the information discussed in this chapter into account and by evaluating the environmental impact of a structure's lifecycle, it is possible to identify aspects and points in the building lifecycle where processes can be optimised in order to reduce the environmental impact. However, before the processes can be optimised it is first necessary to develop a model by which the environmental impact can be evaluated. Brewis (2011) developed a model for the pre-use phase of a building in South Africa. In the following chapter a developed model for the determination of the environmental impact of the end-of-life phase is discussed.

Chapter 3

MODELLING ENVIRONMENTAL SUSTAINABILITY

In order to model the environmental sustainability of the end-of-life phase of the building lifecycle a Lifecycle Analysis (or Assessment) (LCA) has to be carried out. The LCA is a technique to assist the assessment of the environmental impacts associated with a product, or in this case, a structure's life from cradle-to-grave. LCA addresses the environmental impact aspect of sustainability and thus the economic and social aspects have to be evaluated separately. To aid the use of LCA the ISO 14040 standards series can be used. According to the ISO standards the LCA consists of four phases (ISO 14040, 2006), namely the:

- Goal and scope definition phase;
- Inventory analysis phase;
- Impact assessment phase; and
- the Interpretation phase.

In order to carry out the LCA of a building all the phases of the building lifecycle should be considered, however, as a study on the pre-use phase was carried out previously by Brewis (2011), this study focused on the end-of-life phase and the four phases of the LCA process are applied to the end-of-life phase only. Since no specific method for conducting a LCA exists, this study develops a case specific method for determining the environmental impact of the end-of-life phase. The LCA is performed in accordance with ISO 14044 (2006) and the aspects of the different phases of the LCA are discussed in this chapter.

3.1. Goal and scope definition

The goal and scope of the LCA analysis depends on the subject and intention of the study. System boundaries are also included in this phase. Since a LCA study is relative, it is important to identify the functional unit of the system and study (ISO 14040, 2006).

3.1.1. Goal

This study was intended to aid the determination of the environmental impact of the end-of-life phase of a building or structure lifecycle in South Africa by using a cradle-to-gate approach. A cradle-to-gate approach was chosen as it looks at a specific action in the building lifecycle and not the entire lifecycle (which would lead to a cradle-to-grave approach). In collaboration with a previous study carried out on the pre-use phase, conclusions were drawn about the environmental impact of a building or structure by combining both phases, leading to a modified cradle-to-gate approach. This study was intended to aid the construction industry in South Africa in lowering the environmental impact due to construction and demolition activities. It was intended to help designers and construction managers to develop and build structures with minimal impact on the environment by selecting certain products and minimising waste, but also to minimise the impact of demolition activities as well as minimising the impact of the waste generated during these activities. For the purpose of this study, the focus was specifically on low cost housing (LCH).

3.1.2. Scope

The system to be studied depends on the type of structure. For each type of structure the engineer or designer will have to develop a product system and identify the system boundaries and functional unit for that specific case. For the purpose of this study the functional unit was one housing unit or one structure. In Figure 3-1, the product system for the end-of-life phase is shown. The system boundary is also shown in Figure 3-1. Transport is included in the system as it plays a big role in waste removal and thus will contribute to the environmental impact.

For the purpose of this study only the ecological sustainability is modelled. Due to all processes emitting some sort of gas or substance, emissions was identified to be an impact. Complete landfilling of waste is used as a reference case and thus land-use is also considered as an impact. Waste, in this case, is defined in a traditional sense where it is assumed that the material is disposed of as it is no longer useful in its current form. Finally, resource depletion was considered as the use of fuels requires extraction of natural resources. Cement production and concrete also use natural resources and thus in the reuse and recycling of the waste materials, some resources was saved and thus decreased the environmental impact of the pre-use phase. This was however not included in the study of the end-of-life phase as it fell outside the system boundary. The recycling process was also considered as part of the pre-use phase in the new lifecycle of the material and was thus not included in the system boundary.

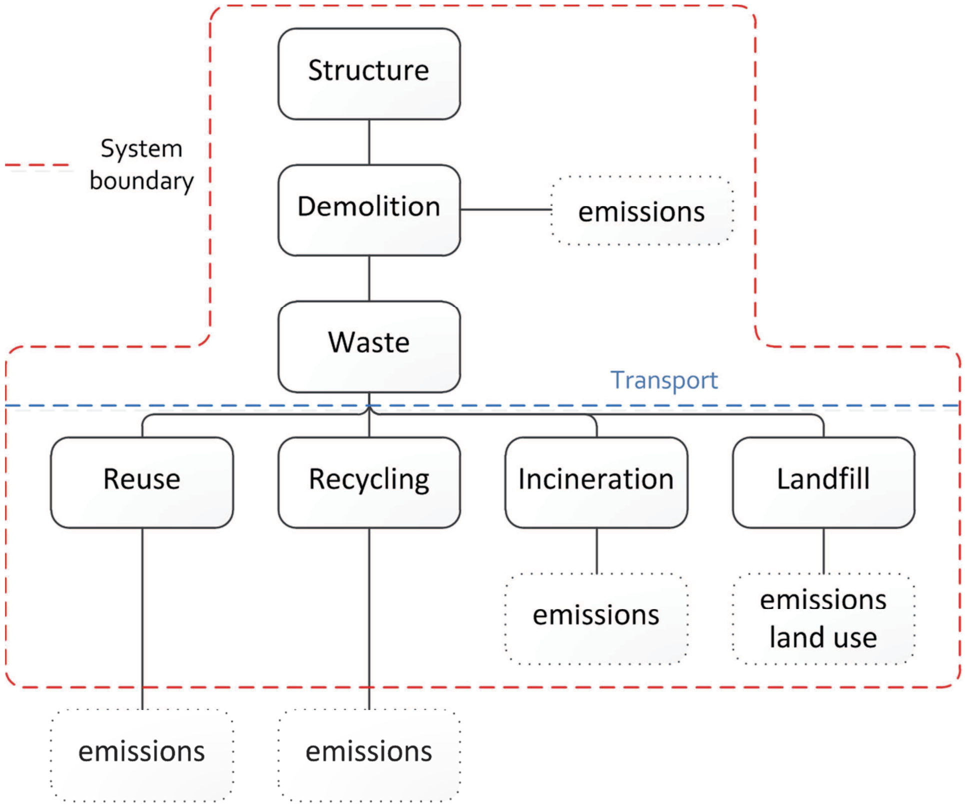

Figure 3-1: Demolition system and system boundary

3.2. Inventory analysis

An inventory analysis has to be carried out in order to ensure that all processes included in the lifecycle of the building are taken into account in the LCA of the building. If a product system has one or more end-products, the impact caused by the product system need to be allocated to different end-products by choosing one of three different approaches:

- no allocation;
- allocation by mass/volume; and
- allocation by economic value.

The allocation depends on the product system under evaluation. If the product is seen as waste only no allocation is necessary for avoided waste, however, if there are by-products involved, allocation can be done by mass/volume or economic value. For this case allocation by mass/volume is used as the respective mass and volume of all products are known and set. The following formula is used when using mass allocation (Equation 1):

$$C_m = \frac{mass_{by-product}}{mass_{main\ product} - mass_{by-product}} \qquad (1)$$

where C_m is the mass allocation coefficient. No allocation is used in the reference case of regarding all material as waste. In the alternative disposal option allocation is already included in the emission factor of the material.

The emission data currently available in the Ecoinvent 2.2 database (Ecoinvent, 2010) is lacking for the South African context. Thus, in the majority of the cases or unless otherwise stated, global data was used or, in the case where the specific global data is not available, the Swiss factors were used as these are the original values calculated as environmental factors.

3.3. Impact assessment

Two types of assessment methods exist for the determination of the environmental impact. The first of the two is an application-oriented method. Application-oriented methods use checklists compiled from basic building lifecycle theory and assign relative scores to different aspects of a building's environmental impact in order to determine the environmental rating of the building. An example of application-oriented methods are the Green Star Rating Tool in South Africa and Australia, as well as the BREEAM method used in the United Kingdom and the LEED method used in the United States of America (World Green Building Council, [s.a.]).

The second type of assessment method is of an analytical nature. The analytical-oriented assessment methods are also based on the building lifecycle but use quantitatively measured environmental impacts. The system aims at quantifying the environmental impact of a building by applying a weighting system to the environmental impacts and finally calculating the impact by simple calculations. Some of the analytic-oriented methods include the CML 2001 method developed and published by Leiden University (Guineé et al., 2001), as well as Goedkoop and Spriensma's Eco-indicator 99 method (Goedkoop & Spriensma, 2001). The analytical oriented methods can further be divided into two categories. The first of these categories is the problem related methods. These types of methods (e.g. CML 2001) merely quantify the emissions that contribute to the problem. It does not, however, calculate the actual damage caused to the environment by these emissions. The second category is the damage related methods. These are the methods that also quantify the damage caused to the environment, ecosystems and human health (e.g. Eco-indicator 99). The difference between the two categories is that the problem related methods usually provide a more reliable representation of the results, but it is difficult to compare these results with each other, while the damage related methods' results are not as reliable but allow easier interpretation of the results.

Damage related methods, however, are complicated to use and require the use of large databases and expensive software. The need thus exists to create a user-friendly model, specific to the South African context. Such a method for the pre-use phase was created by

Brewis (2011). The method used for this study continues Brewis' (2011) study and expands the developed method with specific focus on LCH units. A short description of the developed model is discussed in Section 0

Brewis' suggested model

Brewis (2011) developed a model in order to aid the determination of the environmental impact of the pre-use phase of a building lifecycle. The model developed is a guideline or tool which can be used to objectively improve the environmental impact of the pre-use phase and ultimately the whole building lifecycle. The model was developed to specifically quantify the environmental impact of low-cost housing units in South Africa by looking at more than just the carbon footprint calculations.

Three environmental indicators were used as part of the model of the pre-use phase, namely Emissions, Waste Generation and Resource Depletion. The indicators were chosen and explained by Brewis (2011) due to their specific relevance in the local (South African) context. The Ecoinvent database (version 2.2, 2010) was used in order to obtain the lifecycle impact assessment (LCIA) factors of the various materials in the inventory. The Ecoinvent database implements the first step, namely the environmental impact assessment. However, weighting and normalisation should be implemented by the user.

In order to distinguish between the different environmental indicators, variables were selected and defined as EI_i (*i*th environmental impact). In order to determine the final environmental impact, each indicator needed to be quantified. Brewis suggested that the Emissions indicator be quantified as follows:

The amount of gas (kg) emitted can be calculated with:

$$E_i = e_i m_i \tag{2}$$

where e_i is the emission factor associated with the material or energy and m_i is the related mass or flow. The Emissions indicator was further divided into different gasses that are produced and emitted during the processes involved, namely Carbon Footprint (CF) (EI_1) and

Acidification Potential (AP) (EI_2). The following equations were used by Brewis to calculate EI_1 and EI_2 respectively:

$$EI_1 = CF = \sum_{i=1}^{n} GWP_i E_i \tag{3}$$

$$EI_2 = AP = \sum_{i=1}^{n} f_i E_i \tag{4}$$

where GWP_i is the global warming potential (GWP) factor obtained from literature, f_i is the acidification potential factor also obtained from literature and E_i is the amount of gas (kg) as calculated in Equation 2.

In order to quantify the Resource Depletion indicator, the concept of exergy was used to quantify the amount of resources used in the pre-use phase. According to Cornelissen et al. (2000), exergy is defined as the maximum work potential (or energy flow) in relation to the environment. In order to determine the amount of resource depletion that occurs, it was recommended that the conventional LCA be extended to include an Excergetic Lifecycle Analysis (ELCA). Using an ELCA will lead to a more detailed inventory analysis. In order to determine the Cumulative Exergy Extraction from the Natural Environment (CEENE) in MJ_{ex} conversion factors, called X-factors (in MJ_{ex}/unit), were used. These factors are defined in the Ecoinvent database. The Resource Depletion indicator (EI_3) was then calculated as follows:

$$EI_3 = CEENE_j = \sum_{i=1}^{n} X_i a_{ij} \tag{5}$$

where X_i is the factor of the *i*th resource flow and a_{ij} is the amount of resource flow *i* needed to produce product *j* (Dewulf et al., 2007). As can be seen the CEENE was calculated by summing over all the reference flows considering the appropriate X-factor.

Finally the last indicator, Waste Generation, was quantified. This was done by determining the mass of waste ending up in landfills as follows:

$$\begin{aligned} EI_4 &= M - M_r \\ &= M_d \end{aligned} \tag{6}$$

where M is the total mass of the quantified waste, M_r is the waste recovered by recycling or reuse and finally M_d is the mass of the waste that is disposed at a landfill.

The next step according to the method is to apply normalisation and weighting factors to each indicator or EI_i. By then summing all the normalised and weighted impacts the final environmental impact (relative to the associated impact) was determined using:

$$EII = \sum_{i=1}^{n} c_i \frac{EI_i}{EI_{i,ref}} \tag{7}$$

where c_i is the weighting factor related to EI_i, $EI_{i,ref}$ is the normalisation reference factor and *n* is the final amount of impacts considered. The EDIP '97 method was used to obtain the weighting factors as this method has similar impact indicators to those chosen for the study.

A method similar to the one developed by Brewis (2011) was used to quantify the environmental impact of the end-of-life phase and is discussed in Section 3.5.

3.4. Interpretation

The interpretation phase is the final phase in the LCA of a product. In this phase the significant issues are identified based on the results from the LCIA phase of the LCA. Sensitivity and consistency checks are also included in this phase and finally conclusions, limitations and recommendations are discussed based on the results obtained from the LCA (ISO 14044, 2006).

Interpretation of the case study will be discussed in Chapter 5 and Chapter 8 of this report.

3.5. Proposed method for quantifying the environmental impact of the end-of-life phase

The first step in developing a model for the determination of the end-of-life phase is to choose the indicators that need to be considered. Since most processes emit gasses which have a negative impact on the environment, Emissions was the first selected indicator.

Furthermore Resource Depletion was also considered as the distance of transportation in the end-of-life phase leads to high usage of fuels. Land usage was also considered as some waste was landfilled, which required a certain area of land. Land use formed part of the Resource Depletion indicator. The final indicator was Waste to Landfill, as waste disposal is an integral part in the end-of-life phase. The flow of the model development process is demonstrated in Figure 3-2. Each indicator has certain characteristics which justify the decision of including them in the model. These characteristics and quantification methods are discussed in the following sections.

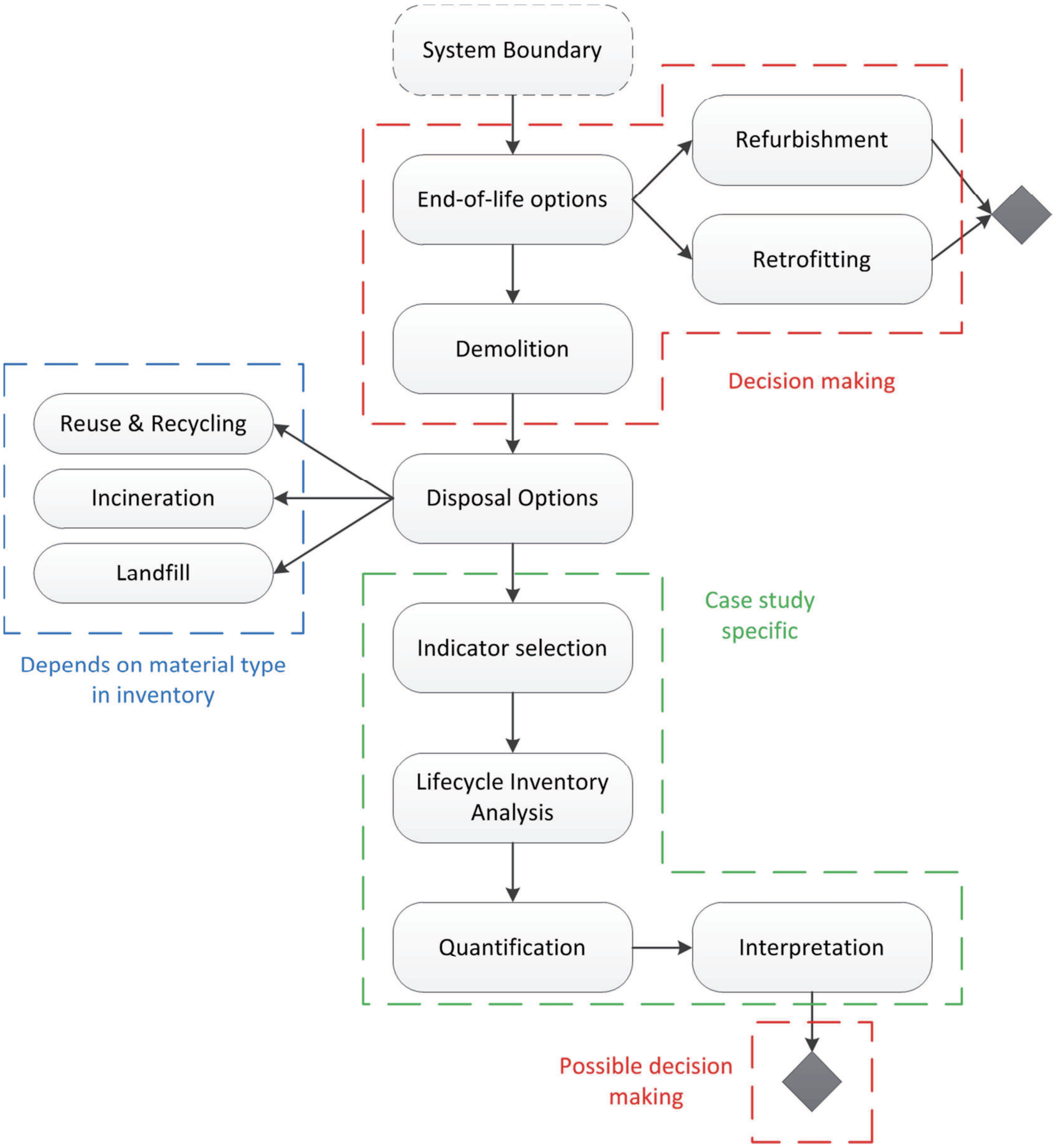

Figure 3-2: Methodical flow of model development

3.5.1. Emissions

In the case of emissions it is necessary to establish which gasses need to be considered and quantified in each possible disposal method. Various types of Greenhouse Gasses (GHG) exist and have different impacts on the environment. It is thus necessary to identify the gasses relevant to this study.

For landfilling, methane (CH_4) and CO_2 are the two most important emissions to air (Doka, 2009). CO_2 emissions from landfilling equipment used were considered if applicable. CO_2 emissions also apply to all transportation activities arising in the end-of-life phase, as well as from recycling and reuse activities and the use of machinery. It is necessary to note that by reusing or recycling certain products, other gas emissions - such as nitrogen oxides (NO_x), nitrous oxide (N_2O), carbon monoxide (CO) and sulphur dioxide (SO_2) - are avoided. In the case of landfilling emissions to land and emissions to water was also considered. The two most important emissions to land associated with landfills are those of dioxins and ammoniacal nitrogen which form part of leachate resulting from rain water draining through the landfill and causing eutrophication.

In the case of incineration emissions to air were considered as the incineration of waste lead to the emission of gasses into the earth’s atmosphere. Since concrete and cement cannot be incinerated, there were no emissions to air due to incineration of these products. However, the incineration of treated wood products, plastics and rubber may lead to harmful emissions into the atmosphere. In South Africa there is a general push towards the incineration of hazardous waste in cement kilns. Some hazardous wastes that are suggested to be incinerated in landfills are: solvents, varnishes, plastic, rubber, textile, contaminated plastic, packaging material, waste oils, paint, glue, tar, tyres, paper and wood waste such as saw dust and wood shavings. Unfortunately the incineration of these hazardous products results in the release of toxic emissions into the air. Some of the toxic emissions include dioxin and furan (by-products of Persistent Organic Pollutants (POPs)), as well as heavy metals (GroundWorks, 2006). Furthermore, incineration of waste also releases CO_2, N_2O, NO_x, NH_3 (ammonia) and organic carbon (C). CH_4 is also released, but to such a small extent that it is not regarded as climate-relevant (Johnke et al., 2000). From the abovementioned information it is evident that emissions to air, land and water need to be considered as part of the model to accurately quantify the impact on the environment.

In order to quantify the gas emissions, all gasses were converted to CO_2-equivalents (CO_{2e}) with the following conversion factors (Johnke et al., 2000) in order to determine the CF:

Table 3-1: GWP conversion factors (Johnke et al., 2000)

Substance	Chemical formula	GWP (100 years) [kg CO_2/kg emission]
Carbon dioxide	CO_2	1
Nitrous oxide	N_2O	310
Ammonia	NH_3	Not defined
Oxides of nitrogen	NO_x	8
Methane	CH_4	21

The quantification of gas emission E_i (in kg) was done by using the following equation:

$$E_i = e_i m_i \tag{8}$$

where e_i is the emission factor (in kg CO_{2e}/unit) of the material or substance and m_i is its mass or flow.

The first calculated environmental impact for Emissions was Carbon Footprint (EI_1). In order to determine the environmental impact of the emissions to air it is necessary to quantify it in terms of its GWP by using the following equation to calculate the carbon footprint (Azapagic et al., 2004):

$$EI_1 = CF = \sum_{i=1}^{n} GWP_i \, E_i \tag{9}$$

where the GWP of an emission *i* (from Table 3-1) is multiplied by the amount of gas emitted as calculated in Equation 8. EI_1 is then obtained by summing all the impacts. CF was chosen as CO_2 and CO_{2e} emissions two of the biggest contributors to global warming and thus have a significant impact on the environment.

Acidification Potential (AP) was considered as the second indicator (EI_2). Acidification of soil and water happens mainly when gases such as SO_x and NO_x transform to form acids. Nitric acid (HNO_3) and sulphuric acid (H_2SO_4) increase the acidity of water and soil which leads to corrosion of manmade structures (Azapagic et al., 2004). It is for the abovementioned reason that AP was also included in the model. AP was determined as follows:

$$EI_2 = AP = \sum_{i=1}^{n} f_i \, E_i \tag{10}$$

where AP will be the amount of gas emitted in kg SO_{2e}, f_i is the acidification factor of gas *i* (see Table 3-2) and E_i is the emitted amount of gas in kg.

Table 3-2: Acidification Potential Factors (Azapagic et al., 2003)

Substance	Chemical formula	AP factor (kg SO_2 equivalents/kg)
Oxides of nitrogen	NO_x	0.7
Sulphur dioxide	SO_2	1
Ammonia	NH_3	1.88

Finally Eutrophication Potential (EP) was also considered as an indicator as the use of landfills for waste disposal may cause the over fertilisation of water and soil due to nutrients being leached from the landfill (Azapagic et al., 2004). This may lead to further consequences, such as foul odours, death or poisoning of fish and other water animals and intake of toxins by humans or livestock (Norris, 2003). The two most important nutrients in the case of eutrophication are nitrogen and phosphates. As this study has a specific focus on waste and waste disposal in the end-of-life phase, the quantification and inclusion of EP in the model is important. The following equation was used to determine the EP:

$$EI_3 = EP = \sum_{i=1}^{n} k_i \, E_i \tag{11}$$

where EP is the amount of gas emitted in kg NO_{3e}, k_i is the eutrophication factor of substance *i* (see Table 3-3) and E_i is the emitted amount of substance *i* (in kg).

Table 3-3: Eutrophication Potential factors (Heijungs *et al*., 1992)

Substance	**EP factor (kg NO_3 equivalents/kg)**
NO_x	1.35
NH_3	3.64
NH_4^+	3.6
NO_3^-	1
PO_4^{3-}	10.45
P_2O_5	14.09

3.5.2. Resource Depletion

The biggest contributor to resource depletion in the end-of-life phase is the transportation of waste to landfills or recycling depots. Fuel and electricity are also needed to run the machines used in the demolition and recycling processes. In Figure 3-3 the energy demand of the South African transport sector in 2006 (DME, 2009) is shown.

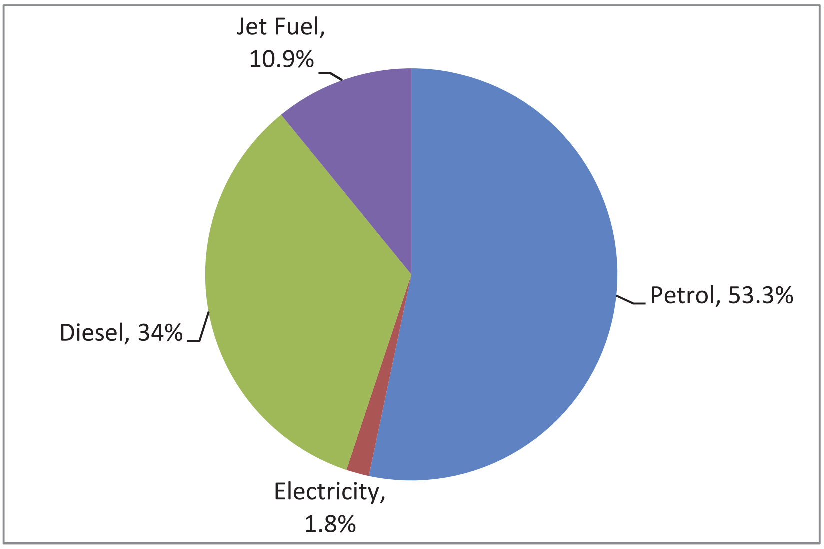

Figure 3-3: Energy demand of the transport sector in 2006 (DME, 2009)

It can be concluded that high amounts of resources are needed to manufacture the petrol, diesel and electricity needs of the transportation requirements in the end-of-life phase.

Furthermore, waste disposal requires large areas of land for landfills. About 95% of urban waste is disposed of on land, which leads to about 1200 landfills that are controlled by local authorities in South Africa. Households contribute about 15 million tons of waste per year, while industries contribute 25 million tons of waste per year (Enviro-info, [s.a.]). Construction and demolition waste occupy about 10-20% of landfills (DEAT, 2005). There is thus a potential to reduce landfill space by reducing the volume of construction and demolition waste ending up in landfills. Therefore it is clear that the Resource Depletion indicator should include land use for landfills and that resource use due to transport need to be quantified and considered.

In order to quantify resource depletion an Exergetic Lifecycle Analysis (ELCA) was carried out. As mentioned previously, Cornelissen et al. (2000) defined exergy as the maximum work potential (or energy) that can be extracted from a material in relation to its environment. According to the first law of thermodynamics, energy cannot be created or destroyed; it can only be transformed from one state to another. However, some energy is lost during this transformation as heat, which thus reduces the worth of the useful energy. It is on this principle that exergy is based. Exergy is measured in Joule (J_{ex}) and when a system is in equilibrium with the environment the exergy of that system is zero (Rosen et al., 2008).

The ELCA works on the same principle as a normal LCA, however the inventory phase of the ELCA is more detailed. The amount of exergy that is destroyed during the use of a resource gives the irreversible amount of the product – thus the amount of the resource that was depleted. Conversion factors are used to quantify the cumulative exergy extraction from the resource. The following equation was used to determine the cumulative exergy extraction from the natural environment (CEENE) in MJ_{ex}:

$$EI_4 = CEENE_j = \sum_{i=1}^{n} X_i a_{ij} \tag{12}$$

where X_i is the conversion factor (or X-factor) of the energy or flow needed for *i* and a_{ij} is the amount of energy or flow *i* needed to produce product *j*. X-factors are obtainable from the Ecoinvent database and are given in MJ_{ex}/unit of energy or flow where "unit" is defined in the Ecoinvent database. EI_4 is then obtained by summing over all the energy or flows.

3.5.3. *Waste Generation*

In the reference case all waste was landfilled and thus it was not necessary to be sorted, however for all other cases all waste was sorted into different categories in order to fully determine the amount of waste that was generated as well as the amount of energy saved due to reuse and recycling. Waste was grouped into four categories:

- reuse;
- recycling;
- incineration; and
- landfill.

It was thus necessary to have a detailed bill of quantities for the housing unit that should be demolished. By expanding the bill of quantities to include a column for Waste Disposal Scenario the mass of waste that was landfilled was calculated by a simple calculation. The following equation was used to determine the mass of waste to be landfilled:

$$EI_5 = M_L = \sum_{i=1}^{n} m_i M_i \tag{13}$$

where M_L is the mass of waste to be landfilled (in kg), m_i is the waste fraction factor obtained from Ecoinvent (in kg/kg) and M_i is the total mass of waste arising from the demolition (in kg). The amount of waste landfilled was considered as the fifth and final environmental indicator (EI_5) and depended on the chosen waste disposal option. The importance of the inclusion of the Waste to Landfill indicator is proven by the amount of waste that is landfilled in the end-of-life phase.

Five environmental indicators were thus chosen to determine the environmental impact of demolition and disposal activities in the construction industry and are shown in Table 3-4.

Table 3-4: Summary of environmental indicators considered

EI_x	Name	Unit
EI_1	Global Warming Potential	kg CO_{2e}
EI_2	Acidification Potential	kg SO_{2e}
EI_3	Eutrophication Potential	kg NO_{3e}
EI_4	Resource Depletion	MJ_{ex}
EI_5	Waste to Landfill	Kg

3.5.4. Weighting and normalisation

In order to determine the final environmental impact per unit the Environmental Impact Index (EII) was calculated by applying weighting and normalisation factors.

A normalisation reference factor ($EI_{i,ref}$) and a weighting factor (c_i) was applied to each environmental impact and corresponded to the relative importance of the impact. The dimensionless value for the EII was then calculated by summing the weighted impacts of all five indicators (EI_i) using the following equation:

$$EII = \sum_{i=1}^{5} c_i \frac{EI_i}{EI_{i,ref}} \qquad (14)$$

The normalisation and weighting factors of the EDIP ‘97 method was used (seeTable 3-5). Global, European and Danish factors were used as South African factors are non-existent. This method was chosen as it has similar impact categories to the indicators chosen in the developed method. According to Stranddorf et al. (2005) these factors are based on political targets. Brewis (2011) also chose the EDIP ’97 method to determine the environmental impact of the pre-use phase. As this study on the end-of-life phase is a continuation of the pre-use phase, the same methods were used in order to add the different impacts of all phases and eventually calculate the impact of the entire building lifecycle.

Table 3-5: EDIP normalisation and weighting factors (Stranddorf et al., 2005 & Goedkoop et al., 2008)

Impact	Normalisation	Weighting	Origin
Global warming (GWP 100)	8700 kg CO_{2e}/capita/yr	1.12	Global
Acidification	59 kg SO_{2e}/capita/yr	1.27	Europe
Eutrophication	95 kg NO_{3e}/capita/yr	1.22	Europe
Bulk waste	1350 kg/capita/yr	1.1	Denmark
Resources		1	

The developed model was applied to a case study of two different LCH systems, namely the conventional brick and mortar type as well as a Light Steel Frame Building system. The case study and all relevant assumptions are discussed in Chapter 5. However, before the model could be implemented it was first necessary to develop a model to determine the best demolition method for the case study.

Chapter 4

END-OF-LIFE PHASE AND DEMOLITION: A MCDM MODEL

In order to model the environmental sustainability of the end-of-life phase, as discussed in the previous chapter, it is first necessary to determine how the structure will be demolished and what impact this demolition will have on the environment. Thus a model was developed which will aid the decision making process when choosing the best demolition method for the project. This decision can be made by using Multi-Criteria Decision Making (MCDM). This chapter gives an overview of what needs to be considered when developing a model for the determination of the most suitable demolition method. Demolition methods discussed in Chapter 2 were used as possible choices for demolition which was evaluated according to certain criteria. The developed model was applied to a specific case of low cost housing (LCH).

4.1. Multi-criteria decision making methods

MCDM methods are methods used to identify and choose between alternatives (the different choices of actions available to the decision maker) by starting from several criteria (the different dimensions from which the alternatives can be viewed). Weights of importance are assigned to each criterion in order to calculate which alternative will be most desired according to the chosen combination of criteria. Various types of MCDM methods exist of which the most traditional methods are (Triantaphyllou, 2000):

- Weighted sum models (WSM);
- Weighted product models (WPM);
- Analytical hierarchy process (AHP);
- Revised AHP;

- Eliminate and choice translating reality (ELECTRE); and
- Technique for order preference by similarity to ideal solution (TOPSIS).

In order to choose the right method for the decision making process, it is necessary to identify what the aspects of the decision are and what method best suits those aspects. Each method evaluates the problem either by ranking, weighting, rating or pairwise comparison. For complicated decision models the ELECTRE and TOPSIS methods can be used as they make use of intricate mathematical calculations, whereas the WSM and WPM methods are more simplistic and make use of the addition or multiplication of each alternative. These methods also take into account the dimensions of each of the criteria, thus if the problem is multi-dimensional some methods are not suitable for the decision making model. Triantaphyllou (2000) discussed these methods in a comparative study.

For the purpose of this study the AHP method was chosen. This method can be applied to single or multi-dimensional problems. The AHP method decomposes a complex decision-making model into a system of hierarchies descending from a goal to the criteria, sub-criteria and alternatives in levels (Saaty, 1990). Constructing a hierarchy helps to give an overview of the problem and provides the decision maker with a way in which to identify what the importance of each level is. According to Saaty (1990) it is important to construct the hierarchy as thoroughly as possible, but not so thorough that it unnecessarily complicates the problem.

First the characteristics that contribute to the solution are identified, and then the contributors to the problem are noted – these are the alternatives, criteria and sub-criteria of the decision model. After the criteria, sub-criteria and alternatives are chosen, a matrix of the relative importance of each criterion to the others are constructed, then matrices are constructed using the relative importance of each alternative in terms of each criterion (Saaty, 1990). Since the model has sub-criteria, each alternative's relative importance is compared in terms of each sub-criterion. After this the AHP score of each alternative is calculated and the best alternative is the one with the highest score.

For the purpose of this study the relative importance were subjectively evaluated by the researcher. This method is thus suitable for this study as it takes into account human judgement. It is also suited for this study as it structures the problem into levels and then uses a step-by-step approach to find the best alternative. A study done by Abdullah and Anumba (2002) was used as a benchmark for this study and this study thus followed the same steps.

4.2. Hierarchy study

The goal of this study (situated at Level 0) was for the decision maker to determine the most appropriate demolition method, which also has as the least possible impact on the environment. This was done by evaluating all demolition alternatives according to a certain set of criteria. The hierarchy structure is shown in Figure 4-1.

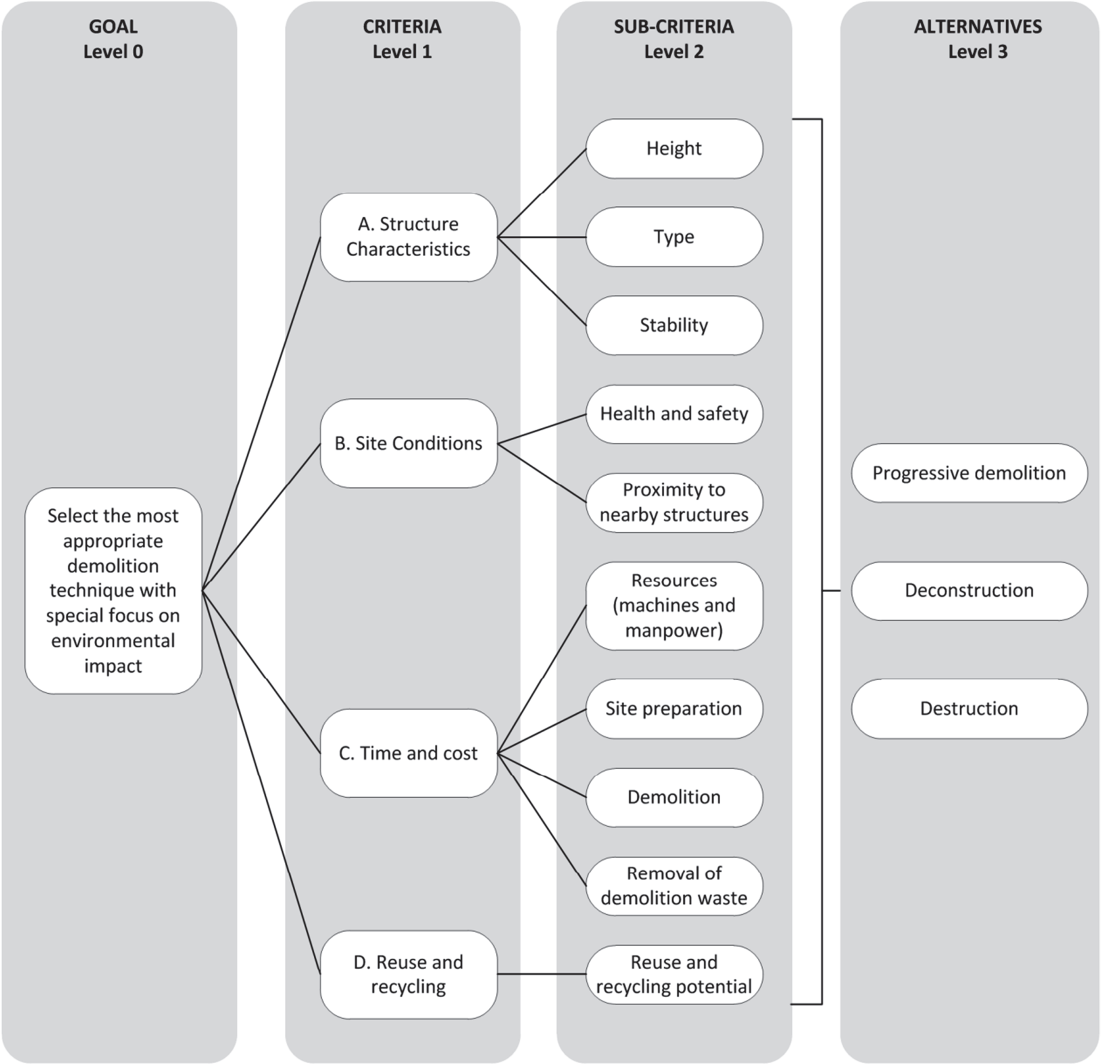

Figure 4-1: Hierarchy structure of MCDM model

4.2.1. Criteria (Level 1)

The purpose was to determine a demolition technique that has an environmental impact that is as low as possible and the most suitable for each scenario. Therefore it was first necessary to determine the project characteristics before any criteria can be chosen. As this model will be applied to a specific case of demolition the characteristics and criteria used for this study may not necessarily be suitable for other studies, as each study and case are unique.

The developed MCDM model was applied to LCH in South Africa. The site chosen was that of the Kayamandi Watergang Housing Project near Stellenbosch. This study focused on the environmental impact of the end-of-life phase, thus one of the most important criteria was the recycling and reusing component. To keep sustainability in mind, it was also necessary to evaluate time and monetary cost. Finally it was also necessary to evaluate the type of structure, as well as its location.

Keeping in mind all the above mentioned points, the characteristics of the chosen demolition project were the following:

- Type of structure: single or duplex, semi-detached housing units, constructed from brick and mortar and containing a wooden first storey floor. The structures are typically demolished due to poor durability and building quality.
- Location: Since the structures are semi-detached and each building is built in close proximity to the other, it was necessary to take into account damage that may be caused to nearby buildings. Since the site can be closed off and evacuated for the demolition, the main concern was that of keeping nearby buildings out of danger, but health and safety should not be neglected.
- Reuse and recycling: many of the components can be reused in other building projects. Examples of reusable components are door frames, wash basins, toilets, roof trusses, roof sheeting and in some cases the bricks used for the building can also be cleaned and reused. Bricks and the concrete in the floor slab can also be recycled.

- Time and cost: the time allocated to the project will depend on the extremity of the demolition to be done. In this case the most time effective solution was considered, but reuse and recycling still had priority.

Finally, according to the characteristics of the project the following criteria (Level 1) were chosen to evaluate the alternatives:

- Structure characteristics;
- Site conditions;
- Time and cost; and
- Reuse and recycling.

These criteria were further divided into sub-criteria (Level 2), according to the project characteristics as discussed previously, and are shown in the hierarchy structure in Figure 4-1.

4.2.2. Alternatives (Level 3)

In the case of MCDM, alternatives are described as the different choices of actions available to the decision maker. For this study alternatives were defined as the different demolition methods or options available to the decision maker and are situated in Level 3. Three demolition alternatives, which are discussed in Chapter 2, were chosen. These methods are discussed below as they are applied to the specific case:

- Progressive demolition: first the structure is stripped of all removable elements after which the remaining structure is demolished using a bulldozer.
- Deconstruction: all elements are removed without being damaged, walls left standing are demolished in a way that will be most optimal for recycling and will generate the least waste. This demolition can be done by hand or with hand-operated machinery.
- Destruction: the whole structure is demolished with a bulldozer.

4.3. Prioritisation of criteria

In order to prioritise the criteria, Saaty's (1990) scale of relative importance was used (see Table 4-1). Each criterion (in Level 1 of the hierarchy structure) were compared to all the other criteria according to this scale and then assigned a value. After this all the sub-criteria (Level 2) of each criterion were compared to each other. Finally each alternative (Level 3) was compared to the other alternatives according to each sub-criterion (Level 2). The hierarchy of importance is thus formed in this way.

Table 4-1: Scale of relative importance (Saaty, 1990)

Intensity of importance	Definition	Explanation
1	Equal importance	Two activities contribute equally to the objective
3	Weak importance of one over the other	Experience and judgement slightly favour one activity over the other
5	Essential or strong importance	Experience and judgement strongly favour one activity over the other
7	Demonstrated importance	An activity is strongly favoured and its dominance demonstrated in practice
9	Absolute importance	The evidence favouring one activity over the other is of the highest possible order of affirmation
2, 4, 6, 8	Intermediate values between two adjacent judgements.	
Reciprocals of above non-zero	If activity *i* has one of the above non-zero numbers assigned to it when compared to activity *j*, then activity *j* has the reciprocal value when compared with activity *i*.	

A matrix was formed of the comparisons by using the following method: when a criterion was compared to itself a value of 1 was assigned and when two different criteria were compared and a value assigned, the reciprocal value was entered in the opposite comparison of the two. For example, criterion *i* is compared to criterion *j* and assigned a value of *n*: in position *ij* of the matrix the value *n* is entered, while in position *ji* of the matrix the value *1/n* is entered. In the matrix, according to Saaty (1990), the element appearing in the left-hand column is compared to the element appearing in the top row. For less favourable comparisons, a fraction is entered.

For the purpose of this study the following relative importance values were assigned to the criteria:

Table 4-2: Matrix of pairwise comparisons

Criteria for goal	Structure characteristics (A)	Site conditions (B)	Time and cost (C)	Reuse and recycling (D)
Structure characteristics(A)	1	2	1/5	1/9
Site conditions (B)	1/2	1	1/7	1/9
Time and cost (C)	5	7	1	1/4
Reuse and recycling (D)	9	9	4	1

The relative importances were assigned according to the values given in Table 4-1 and the reasons for the chosen values are discussed below.

- **Comparing (A) Structure characteristics and (B) Site conditions:** more favour was given to structure characteristics, as this played a role in the type of demolition done. Thus a value of 2 was assigned when comparing (A) to (B) and a value of 1/2 was assigned when comparing (B) to (A).
- **Comparing (A) Structure characteristics and (C) Time and cost:** Time and cost were highly valued in this study as it was also necessary to find the most time- and cost-effective solution, thus (C) was more important than (A). A value of 1/5 was assigned to the importance of comparing (A) to (C) and a value of 5 was assigned to the importance of comparing (C) to (A).
- **Comparing (A) Structure characteristics to (D) Reuse and recycling:** Reuse and recycling potential was the highest valued criterion in this study, thus a high importance value was assigned. When comparing (A) to (D) the value of 1/9 was given, while when comparing (D) to (A), a value 9 was assigned.

- **Comparing (B) to (C):** a value of 1/7 was assigned to the comparison of (B) to (C), and a value of 7 was assigned to the comparison of (C) to (B).
- **Comparing (B) to (D):** for the same reason as comparing (A) to (D) a value of 1/9 was given when comparing (B) to (D) and a value of 9 was given when comparing (D) to (B).
- **Comparing (C) to (D):** Reuse and recycling potential was still favoured over time and cost, but to a certain extent, therefore an intermediate value of 4 was assigned when comparing (D) to (C) and the reciprocal value of 1/4 was assigned when comparing (C) to (D).

This leads to the matrix previously shown in Table 4-2. The matrix was then normalised by taking each entry in a column and dividing it by the sum of the column. After this, the average of the rows was taken, leading to the weight of each criterion. The weights of importance calculated for each criterion are shown in Table 4-3.

Table 4-3: Weights of importance as calculated in Appendix A

Criteria for goal	Weight
Structure characteristics (A)	0.071
Site conditions (B)	0.047
Time and cost (C)	0.262
Reuse and recycling (D)	0.621
sum	1.000

As can be seen the weights add up to 1.000, which is the desired value. Next all the sub-criteria of each criterion were compared in order to prioritise them.

4.3.1. Pairwise comparisons of sub-criteria for each criterion

The pairwise comparison of the sub-criteria for each criterion was prioritised as shown in Table 4-4 where the sub-criterion in the shaded cell of the table has a higher priority. The intensity refers to the relative importance that the higher prioritised sub-criterion has over the one it is compared to. The intensity was assigned according to Table 4-1.

Table 4-4: Pairwise comparison of sub-criteria

Criterion	Comparison of sub-criteria		Intensity
Structure Characteristics	Height	Type	1
Site Conditions	Health & safety	Proximity	3
Time and cost	Resources	Site preparation	2
	Resources	Demolition	3
	Resources	Waste removal	2
	Site preparation	Demolition	2
	Site preparation	Waste removal	1
	Demolition	Waste removal	2

In the case where there are only two sub-criteria and they are regarded to be equal, the intensity is equal to one and they each contribute 50% locally to the specific criterion. This is seen in the comparison for *Structure Characteristics* and one of the comparisons for *Time and cost*. For the local weighting, all weights must add up to 1.000. In order to determine the global weights, the local weight of the sub-criterion was multiplied by the weight of its criterion as shown in Table 4-3 and all global weights of the sub-criteria added up to the weight of their criterion. Thus the global weights for both sub-criteria (height and type) were 0.035.

In the case of *Site conditions* proximity to other structures was regarded as more important than health and safety as the site was evacuated for demolition. This lead to proximity having a local weight of 0.75 and a global weight of 0.035, while health and safety had a local weight of 0.25 and a global weight of 0.012.

For the comparisons of *Time and cost*, demolition was regarded as the most important as the type of demolition will determine the cost, number of resources needed, the amount of waste generated and the time needed to complete the demolition project. Waste removal and site preparation are more important than resources as the extent of waste removal and site preparation determines the number of resources needed. This leads to the local and global weights shown in Table 4-5.

Table 4-5: Weights for sub-criteria of time and cost

Sub-criteria	Local weight	Global weight
Resources	0.123	0.032
Site preparation	0.227	0.060
Demolition	0.423	0.111
Waste removal	0.227	0.060
sum	1.000	0.262

The final step in the prioritisation procedure is to evaluate each alternative according to each sub-criterion. All calculations can be found in Appendix A.

4.3.2. Pairwise comparison of alternatives for each sub-criterion

In Table 4-6 the importance of each alternative over the other was chosen when evaluated according to each sub-criterion. Once again, the alternative in the shaded cell is the alternative with the higher priority.

Table 4-6: Pairwise comparison of alternatives

Sub-criterion	Comparison of alternatives		Intensity
Height	Progressive Demolition	Deconstruction	2
	Progressive Demolition	Destruction	4
	Deconstruction	Destruction	6
Type	Progressive Demolition	Deconstruction	3
	Progressive Demolition	Destruction	3
	Deconstruction	Destruction	7
Health and safety	Progressive Demolition	Deconstruction	3
	Progressive Demolition	Destruction	7
	Deconstruction	Destruction	9
Proximity	Progressive Demolition	Deconstruction	3
	Progressive Demolition	Destruction	7
	Deconstruction	Destruction	9
Resources	Progressive Demolition	Deconstruction	3
	Progressive Demolition	Destruction	5
	Deconstruction	Destruction	7
Site Preparation	Progressive Demolition	Deconstruction	2
	Progressive Demolition	Destruction	4
	Deconstruction	Destruction	7
Demolition	Progressive Demolition	Deconstruction	3
	Progressive Demolition	Destruction	7
	Deconstruction	Destruction	9
Waste removal	Progressive Demolition	Deconstruction	5
	Progressive Demolition	Destruction	3
	Deconstruction	Destruction	9
Reuse and recycling	Progressive Demolition	Deconstruction	6
	Progressive Demolition	Destruction	3
	Deconstruction	Destruction	9

In the case of the sub-criterion, *Height*, the alternative that would most easily demolish the double storey building was favoured. All weights calculated for each sub-criterion can be found in Table 4-7.

When assigning an importance value according to the sub-criterion, *Type*, the alternative that would most easily demolish any type of structure was favoured. In the importance evaluation of *Health and Safety*, a higher importance was assigned to the safer alternative, which in this case would be deconstruction as no big machines are used and the building is demolished in an orderly manner. According to the importance rating of *Proximity*, alternatives that would have the potential to cause the least damage to nearby structures were favoured. When *Resources* (as a sub-criterion) was considered, the alternative using the least resources was rated as more important. For the *Site Preparation* sub-criterion, the alternative that needs the least site preparation was favoured. For this case deconstruction needed the least site preparation as it follows an orderly manner of demolition. The alternative with the least complex demolition method was favoured in the case of *Demolition* as sub-criterion, which is shown in Table 4-7 as Destruction. Destruction makes sense as the least complex demolition method as it only requires a bulldozer to be used during the demolition process. In the case of *Waste Removal*, the alternative requiring the lowest amount of waste removal from site after demolition was favoured. Finally, for *Reuse and Recycling*, the alternative with the highest reuse and recycling potential was regarded as more important.

Table 4-7: Calculated weights for each sub-criterion

Sub-criterion	Alternative	Local Weight	Global Weight
Height	Progressive Demolition	0.194	0.007
	Deconstruction	0.107	0.004
	Destruction	0.700	0.025
Type	Progressive Demolition	0.243	0.009
	Deconstruction	0.088	0.003
	Destruction	0.669	0.024
Health and safety	Progressive Demolition	0.295	0.003
	Deconstruction	0.649	0.008
	Destruction	0.057	0.001
Proximity	Progressive Demolition	0.295	0.010
	Deconstruction	0.649	0.023
	Destruction	0.057	0.002
Resources	Progressive Demolition	0.193	0.006
	Deconstruction	0.083	0.003
	Destruction	0.724	0.023
Site Preparation	Progressive Demolition	0.315	0.019
	Deconstruction	0.602	0.036
	Destruction	0.082	0.005
Demolition	Progressive Demolition	0.155	0.017
	Deconstruction	0.069	0.008
	Destruction	0.777	0.086
Waste removal	Progressive Demolition	0.180	0.011
	Deconstruction	0.748	0.045
	Destruction	0.071	0.004
Reuse and recycling	Progressive Demolition	0.166	0.103
	Deconstruction	0.764	0.474
	Destruction	0.070	0.043

The sum of the local and global weights of each sub-criterion is shown in Table 4-8. As is expected all local weights add up to 1.000.

Table 4-8: Sum of weights for each sub-criterion

Sub-criterion	ΣGlobal weight	ΣLocal weight
Height	0.035	1.000
Type	0.035	1.000
Health & Safety	0.012	1.000
Proximity	0.035	1.000
Resources	0.032	1.000
Site preparation	0.060	1.000
Demolition	0.111	1.000
Waste removal	0.060	1.000
Reuse and recycling	0.621	1.000

It is acknowledged that all of these comparisons are subjective and have been chosen in order to meet the needs of this study. This, however, gives a good indication of how a MCDM model can be used to determine the most suitable demolition method. The final table is set up to show all weighting factors (Table 4-9):

Table 4-9: Table of all weights

	Structure Characteristics		Site conditions		Time & Cost				Reuse & Recycling	Total *
Alternative	Height	Type	Health & safety	Proximity	Resources	Site prep	Demolition	Waste removal	Reuse & recycling potential	
Progressive demolition	0.007	0.009	0.003	0.010	0.006	0.019	0.017	0.011	0.103	0.185
Deconstruction	0.004	0.003	0.00	0.023	0.003	0.036	0.008	0.045	0.474	0.602
Destruction	0.025	0.024	0.001	0.002	0.023	0.005	0.086	0.004	0.043	0.213
Totals	0.035	0.035	0.012	0.035	0.032	0.060	0.111	0.060	0.621	1.000
	0.071		0.047		0.262				0.621	1.000
	1.000									

*Values in this column are the overall AHP score of each alternative

As can be seen in Table 4-9, deconstruction was the most favoured demolition technique as it received the highest AHP score (0.602) after all the criteria were considered. All global weights of sub-criteria add up to the global weights of their criteria and finally all the weights of the criteria add up to 1.000. The AHP scores of the alternatives also add up to 1.000, which is the desired effect. Thus the developed model was done correctly.

4.4. Consistency Indices

Consistency indices are used in order to determine what degree of inconsistency occurs between the decisions made by the decision maker (Abdullah & Anumba, 2002). A consistency index (or CI) is generally considered to be acceptable if it is less than 0.10. To calculate the consistency index the following equation is used:

$$CI = \frac{(\lambda - n)}{(n - 1)}$$

where n is the matrix size and λ is the eigenvalue of the matrix.

Table 4-10 shows the calculated consistency indices for the pairwise comparison of the criteria as well as for all the pairwise comparisons of the alternatives according to the sub-criteria.

All CI calculations can be found in Appendix B. As can be seen from the values in Table 4-10, all of the CI values are below the desired 0.10.

Table 4-10: Consistency indexes for matrices

Matrix of:	CI
Criteria	0.053
Height	0.0046
Type	0.0035
Health & safety	0.041
Proximity to nearby structures	0.041
Resources	0.033
Site preparation	0.001
Demolition	0.041
Removal of demolition waste	0.015
Reuse & recycling	0.027

It can be concluded that the best demolition method for the Watergang Housing Project in Kayamandi, is deconstruction. Deconstruction aids reuse and recycling of waste materials arising from demolition activities and is thus the desired option.

This method can be used to determine the best demolition option of a specific demolition case. The developed model demonstrated how MCDM can be incorporated in the environmental impact calculations in order to have the lowest environmental impact. By making use of a detailed inventory of processes in the LCA, the selected demolition method can be evaluated accurately as part of the environmental impact calculation and an accurate value for the environmental impact can be obtained. The following chapter applies the developed environmental impact model to calculate the environmental impact of the end-of-life phase for the LCH project used in the MCDM model application.

Chapter 5

IMPLEMENTATION TO LOW COST HOUSING

Low cost housing (LCH) is not the largest sector in terms of energy consumption of the South African residential building industry. However, due to a lack of incentives and legislation, the environmental impact of LCH has been largely neglected. As a result of this the potential to reduce the environmental impact of this sector is significant.

Durability and quality issues are two of the most influential factors influencing the success of LCH in South Africa. Many problems exist with the durability of LCH. Some of these problems include structural problems, inferior quality of building materials and poor construction practice. According to Siti (2005) several factors influence the service life of a building, namely:

- weather;
- environment;
- workmanship;
- building materials;
- usage; and
- the level of maintenance

The severity by which these factors influence the quality or durability of a building depends on the condition of each factor. If the condition of these factors is poor, the lifespan of a building will be shortened.

According to Mr Tokyo Sexwale (South African Minister of Human Settlements) R400 million was spent repairing poorly built LCH since 2002 (Molatlhwa, 2012). Maintenance on the houses should be done in order to improve the durability. At the hand-over of the house to the new owner, the maintenance of the house becomes the owner’s responsibility. A low level of or no maintenance is experienced in some cases. This may be due to the owner lacking funds to properly maintain the house.

From 1994 to 2009 houses consisting mostly of brick and mortar were built in South Africa. These houses were of poor quality as it was mostly a shell with nothing inside (Dutlow, 2010). When LCH of poor quality and durability becomes too dangerous to live in or too expensive to repair, the building will be demolished and rebuilt.

A case study on different structural systems of LCH was looked at in order to choose the best environmentally sustainable alternative. The two chosen structural systems were the conventional brick and mortar design type and the Light Steel Frame Building (LSFB) design type. As previous research investigated the environmental impact of the pre-use phase for different models of LCH (Brewis, 2011), this study continued the research by investigating the end-of-life phase for the different structural systems by looking at various waste disposal options.

5.1. Model calculations

For calculation and comparison purposes the structure was broken down into further building elements, according to Brewis' model (2011). These elements were also used in the calculation sheets to separate the materials used for each part of the structural system. The building elements include the following:

- foundations;
- floor slab;
- external walls;
- internal walls;
- ceiling and insulation;
- roofing; and
- roof covering.

All materials included in the Bill of Quantities are as chosen by Brewis (2011) for the pre-use phase. The Bill of Quantities was used as a template to calculate the environmental impact of the pre-use phase, thus the environmental impact of the end-of-life phase was calculated on the same template, however, without the rate and cost columns found in a standard Bill of Quantities. An extra column for the waste disposal option was included. All design specifications used by Brewis (2011) were maintained for the purpose of this study. Where applicable, assumptions made by Brewis (2011) in order to aid calculations were also maintained in addition to the assumptions made for the end-of-life phase.

5.2. Assumptions

In order to quantify the environmental impact, the following assumptions were made for both the conventional design type as well as the LSFB design type housing units:

- Project duration was taken at one year in order to easily normalise impact potentials. As impact potentials have a unit per year, this means that dimensionless normalised values were obtained, which were easily comparable.
- Ecoinvent uses a value of 15 km in its calculation of transport emissions included in the disposal of building materials (Doka, 2009). Distances to dismantling facilities are also included. Since the factors used are from Swiss origin, an additional transport value of waste to final disposal was chosen as 10 km. Switzerland has a population density of 191 people/km^2 while South Africa has 41 people/km^2 (Population Reference Bureau, 2012). This means that there are larger distances in South Africa than in Switzerland which need to be accounted for in the calculations. It is acknowledge that this assumption is not scientifically based, therefore the sensitivity of the additional transport value is investigated in Chapter 6 of this report.
- A truck size of 3.5 to 7.5 t was selected for transport.
- The mass of waste to be transported was estimated as the total mass of one housing unit according to the amount of materials used.
- Galvanised steel was considered to be recycled as normal non-galvanised steel and thus galvanisation did not have an impact in the end-of-life phase.
- Energy for dismantling and demolition were included in all material impact factors in the Ecoinvent database and was thus not added separately.

- When using materials from the building demolition dataset, land use is included in the inventory of processes for each material in the cases where landfilling is involved.

5.3. Ecoinvent information

Three types of disposal options exist for building products in the Ecoinvent database. The system boundaries for each of these options are shown in Figure 5-1. All the processes included in the boundary are included in the inventory analysis for the building product. The disposal options available in the Ecoinvent database (Doka, 2009) are:

- Direct recycling: materials are separated at the building site and are recycled without prior sorting, only dismantling impacts are inventoried, environmental impact from transport and the actual recycling process are not included as these are assigned to the recyclate (referring to the recycled product) consumer.
- (Partial) recycling after sorting: sorting applies if the building material cannot be separated at site, transport to sorting facilities and final disposal are included, burdens from the waste sorting process are included.
- Direct disposal (landfilling or incineration) without sorting or recycling: burdens for dismantling and transport to final disposal are included.

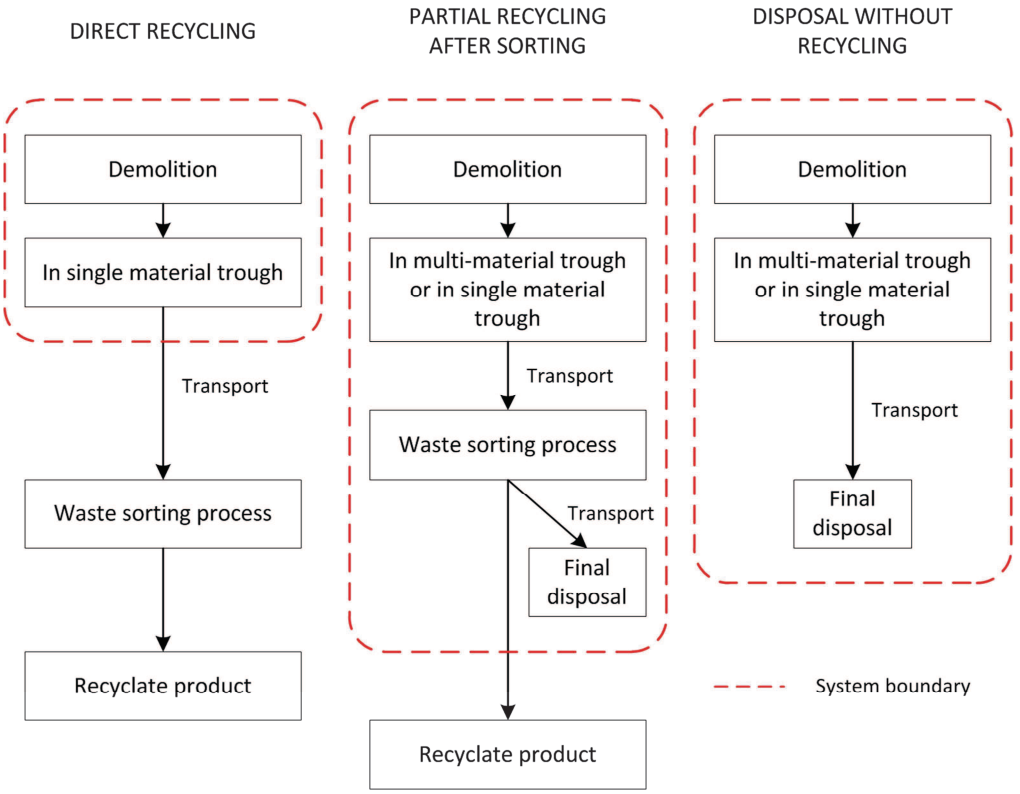

Figure 5-1: Disposal options according to the Ecoinvent database (Doka, 2009)

As can be seen from Figure 5-1 as well as the explanation on the different disposal options, dismantling burdens are included in the system boundary of the disposal processes. It is thus necessary to discuss what exactly the dismantling process used in the Ecoinvent database entails. Ecoinvent uses tearing with hydraulic devices as its dismantling method. Manual dismantling is not included as its environmental impact is negligible. Emissions and transport impacts are included in the inventory for the dismantling process. In the Ecoinvent database a distinction between the different disposal options are made in the descriptive name of the material that is considered. The general name for the disposal of building materials is "*disposal, building, NAME, to final disposal*", where *NAME* is the name of the material under consideration (e.g. concrete). The disposal option is indicated at the end as "*to final disposal*", which shows that there will be no sorting or recycling included in the disposal system and that the material will be landfilled or incinerated. The indication for sorting (reuse) and recycling are indicated as "*to sorting plant*" and "*to recycling*", respectively.

As mentioned previously, the environmental impact of two LCH design types was investigated and is discussed in the following sections of this chapter.

5.4. Conventional design

The conventional design type for a housing unit (seen in Figure 5-2) refers to a brick and mortar house. The substructure of the conventional unit is made up of the foundation and floor slab; whereas the top structure includes the walls and roof system.

Figure 5-2: A conventional design type building

5.4.1. Environmental Assessment

The reference case was firstly assessed. The reference case states that all waste is landfilled (where landfilling is available). In Table 5-1 the different materials used in the impact assessment can be seen with a description of the environmental burdens included in the material system. These items are closely related to the item on the Bill of Quantities and, where available, the same materials as used in the pre-use phase were selected.

Table 5-1: Waste materials to be landfilled (unless otherwise stated) selected for the conventional design type (Ecoinvent)

Item on Bill	Ecoinvent Name	Unit	Description
Concrete	Disposal, building, concrete, not reinforced, to final disposal	kg	System includes energy for dismantling, particulate matter emissions from dismantling and handling, transport to dismantling facilities and final disposal of waste material. Waste contains 1 kg inert material with density of 2200 kg/m^3.
Blockwork	Same as above	kg	Same as above
Reinforcement	Disposal, building, reinforcement steel, to final disposal	kg	System includes energy for dismantling, transport to dismantling facilities and final disposal of waste material. Waste contains 1 kg of steel with density of 7900 kg/m^3.
Steel Mesh	Same as above	kg	Same as above
Gypsum Plasterboard	Disposal, building, plaster board, gypsum plaster, to final disposal	kg	System includes energy for dismantling, particulate matter emissions from dismantling and handling, transport to dismantling facilities and final disposal of waste material. Waste contains 1 kg gypsum with density of 1000 kg/m^3.
Brickforce	Disposal, building, bulk iron (excluding reinforcement), to sorting plant	kg	System includes machines for handling in sorting plant, electricity demand for sorting plant, transport to dismantling facilities. Waste contains 1 kg steel with density of 7900 kg/m^3.
Roof sheeting	Same as above	kg	Same as above

Damp proof membrane	Disposal, building, polyurethane sealing, to final disposal	kg	System includes transport to dismantling facilities and final disposal of waste. Waste contains 1 kg polyurethane with density of 1200 kg/m^3.
Plaster	Disposal, building, mineral plaster, to final disposal	kg	System includes particulate matter emissions from dismantling and handling, transport to dismantling facilities and final disposal of waste material. Waste contains 1 kg inert material with density of 2000 kg/m^3.
Howe Truss (Roofing)	Disposal, building, waste wood, untreated, to final disposal	kg	System includes transport to dismantling facilities and final disposal of waste. Waste contains 1 kg of untreated wood with density of 720 kg/m^3. Total burden allocated to waste disposal function of waste incinerator in incineration process.
Glass Wool Insulation	Disposal, building, mineral wool, to final disposal	kg	System includes particulate matter emissions from dismantling and handling, transport to dismantling facilities, final disposal of waste material. Waste contains 1 kg of inert material with density of 50 kg/m^3.

As can be noted from Table 5-1, all materials were selected from the dataset for landfilling, except brickforce which was treated as bulk iron. The Ecoinvent database does not make provision for landfilled iron and thus it was assumed that all bulk iron items are reused and sent to a sorting plant as the next alternative to landfilling. Alternatively, different disposal options were chosen for the waste in the second case. In Table 5-2 the materials and their respective disposal options are shown.

Table 5-2: Waste materials and their alternative disposal scenario selected for the conventional design type (Ecoinvent)

Item on Bill	Ecoinvent Name	Unit	Description
Concrete	Disposal, building, concrete, not reinforced, to recycling	kg	System includes energy for dismantling, particulate matter emissions from dismantling and handling. Waste contains 1 kg inert material with density of 2200 kg/m^3.
Blockwork	Same as above	kg	Same as above
Reinforcement	Disposal, building, reinforcement steel, to recycling	kg	System includes energy for dismantling. Waste contains 1 kg of steel with density of 7900 kg/m^3.
Steel Mesh	Same as above	kg	Same as above
Gypsum Plasterboard	Disposal, building, plaster board, gypsum plaster, to recycling	kg	System includes energy for dismantling, particulate matter emissions from dismantling and handling. Waste contains 1 kg gypsum with density of 1000 kg/m^3.
Brickforce	Disposal, building, bulk iron (excluding reinforcement), to sorting plant	kg	System includes machines for handling in sorting plant, electricity demand for sorting plant, transport to dismantling facilities. Waste contains 1 kg steel with density of 7900 kg/m^3.
Roof sheeting	Same as above	kg	Same as above
Damp proof membrane	Disposal, building, polyurethane sealing, to final disposal	kg	System includes transport to dismantling facilities and final disposal of waste. Waste contains 1 kg polyurethane with density of 1200 kg/m^3.
Plaster	Disposal, building, mineral plaster, to final disposal	kg	System includes particulate matter emissions from dismantling and handling, transport to dismantling facilities and final

			disposal of waste material. Waste contains 1 kg inert material with density of 2000 kg/m^3.
Howe Truss (Roofing)	Disposal, building, waste wood, untreated, to final disposal	kg	System includes transport to dismantling facilities and final disposal of waste. Waste contains 1 kg of untreated wood with density of 720 kg/m^3. Total burden allocated to waste disposal function of waste incinerator in incineration process.
Glass Wool Insulation	Disposal, building, mineral wool, to recycling	kg	System includes particulate matter emissions from dismantling and handling. Waste contains 1 kg inert material with density of 50 kg/m^3.

From the above table it is evident that most of the building materials can be recycled, which was the favoured disposal option. Plaster, the damp proof membrane and the wooden truss for the roof are landfilled. It is possible to recycle or reuse the wooden truss, but it is not recommended by Ecoinvent (Doka, 2009). The influence of the disposal option of the wooden truss on the final environmental impact was investigated in a sensitivity analysis. Brickforce (or bulk iron) was sent to a sorting plant for reasons mentioned previously. Calculations, to determine the environmental impact, were based on the materials used in the previous two tables and are discussed in the next section.

5.4.2. Assessment calculations and results

Calculations were done, similar to Brewis (2011), on a calculation sheet which was an expansion of the Bill of Quantities. The five chosen environmental indicators, namely Carbon Footprint, Acidification Potential, Eutrophication Potential, Resource Depletion, and Waste to Landfill, were evaluated using the equations and method mentioned in Section 3.5. Where units differed from those used in Ecoinvent a conversion factor was used which was either the density of the waste material or a factor used by Brewis (2011) (obtained from literature – CMA, 2007). The full Bill of Quantities, all Ecoinvent factors used and the environmental impact calculation sheets can be found in Appendix C.

In order to quantify the impacts it was necessary to multiply the amount of material (converted to Ecoinvent units if necessary) with the factors obtained from the Ecoinvent database. Examples of calculations for each environmental indicator of concrete blockwork to landfill are shown below:

$$\begin{aligned}\text{Ecoinvent amount [kg]} &= \text{Bill amount [m}^2\text{] x conversion factor}\\ &= 14.90 \text{ x } 160\\ &= 2384 \text{ kg}\end{aligned}$$

$$\begin{aligned}\text{Carbon Footprint} &= \text{mass [kg] x factor [kg CO}_{2e}\text{/kg]}\\ &= 2384 \text{ x } 0.014122\\ &= 33.667 \text{ kg CO}_{2e}\end{aligned}$$

$$\begin{aligned}\text{Acidification Potential} &= \text{mass [kg] x factor [kg SO}_{2e}\text{/kg]}\\ &= 2384 \text{ x } 0.00011201\\ &= 0.267 \text{ kg SO}_{2e}\end{aligned}$$

$$\begin{aligned}\text{Eutrophication Potential} &= \text{mass [kg] x factor [kg NO}_{3e}\text{/kg]}\\ &= 2384 \text{ x } 0.00021401\\ &= 0.510 \text{ kg NO}_{3e}\end{aligned}$$

$$\begin{aligned}\text{Resource Depletion} &= \text{mass [kg] x factor [MJ}_{ex}\text{/kg]}\\ &= 2384 \text{ x } 0.332053\\ &= 791.614 \text{ MJ}_{ex}\end{aligned}$$

$$\begin{aligned}\text{Waste to Landfill} &= \text{mass [kg] x factor [kg/kg]}\\ &= 2384 \text{ x } 0.9997632\\ &= 2383.435 \text{ kg}\end{aligned}$$

To determine the final environmental indicator amount the sum of all the individual amounts for each material was taken leading to the results shown in Figure 5-3. The results for the alternative disposal were calculated in the same manner and are also shown in Figure 5-3.

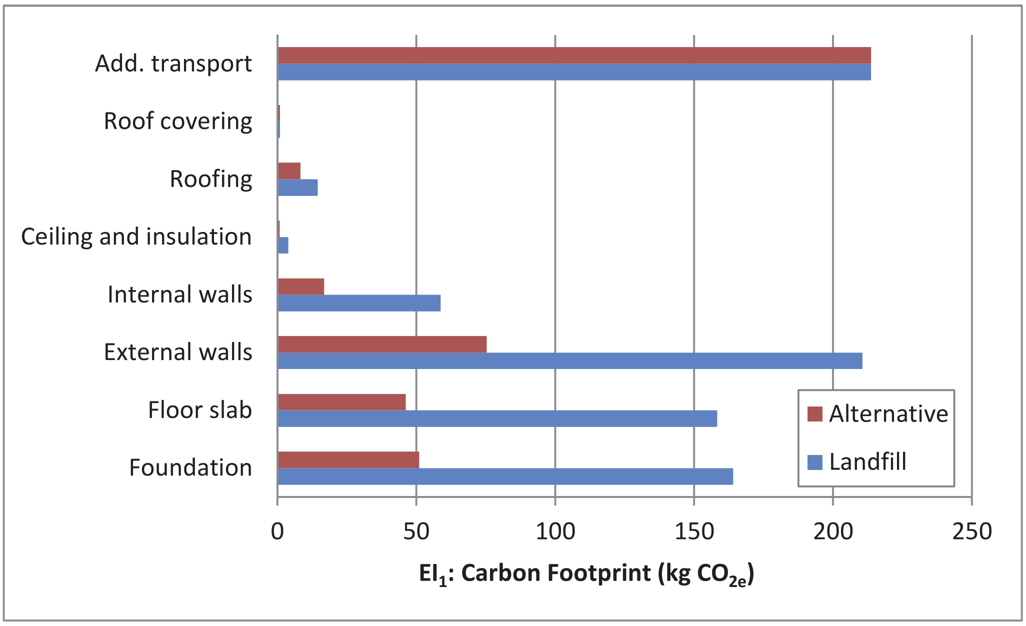

Figure 5-3: Carbon Footprint results from disposal of the conventional design type

As was expected, the landfill disposal option had a higher carbon footprint outcome for the building elements than the alternative disposal option. The external walls, floor slab, foundation and transport were the elements that contribute the most to the carbon footprint of the housing unit for both disposal options. Transport contributed a high amount due to the mass of the concrete materials that had to be transported to the disposal facilities. Furthermore, the walls, floor slab and foundation contributed due to the high carbon footprint impact factor for concrete, since these elements mostly consist of concrete.

From Figure 5-4 it is evident that, once again transport, the external walls, the floor slab and the foundations had the largest acidification potential when landfilled. This was due to the large amounts of concrete used in these elements. Reinforcement also had a significant acidification potential factor, but since the amount of reinforcing was not as large, its impact was less. For the alternative disposal options the same elements had the largest impact, however, as seen previously, the alternative disposal option had a significantly lower acidification potential than landfilling.

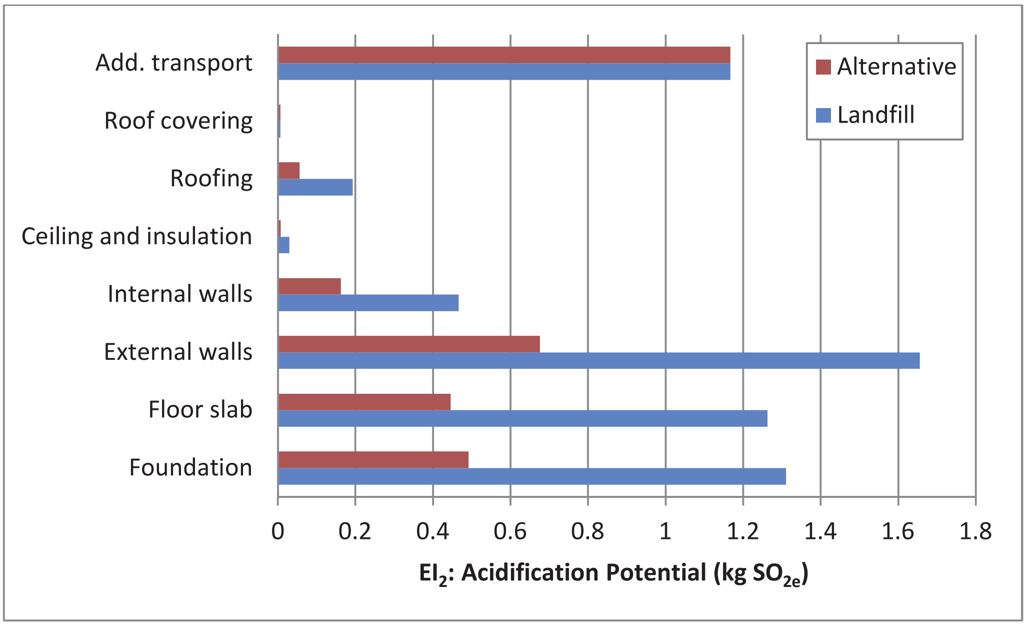

Figure 5-4: Acidification Potential results for disposal of the conventional design type

It is once again evident that transport, the external walls, the floor slab and the foundation were the elements that contributed the most to the eutrophication potential (as seen in Figure 5-5), however, it also shows that the impact from roofing and internal walls was also making a contribution. The amount of concrete used in the largest contributors was once again the reason for their high impact. It was, however, the use of purlins and wood in the roofing that was contributing to its significant impact.

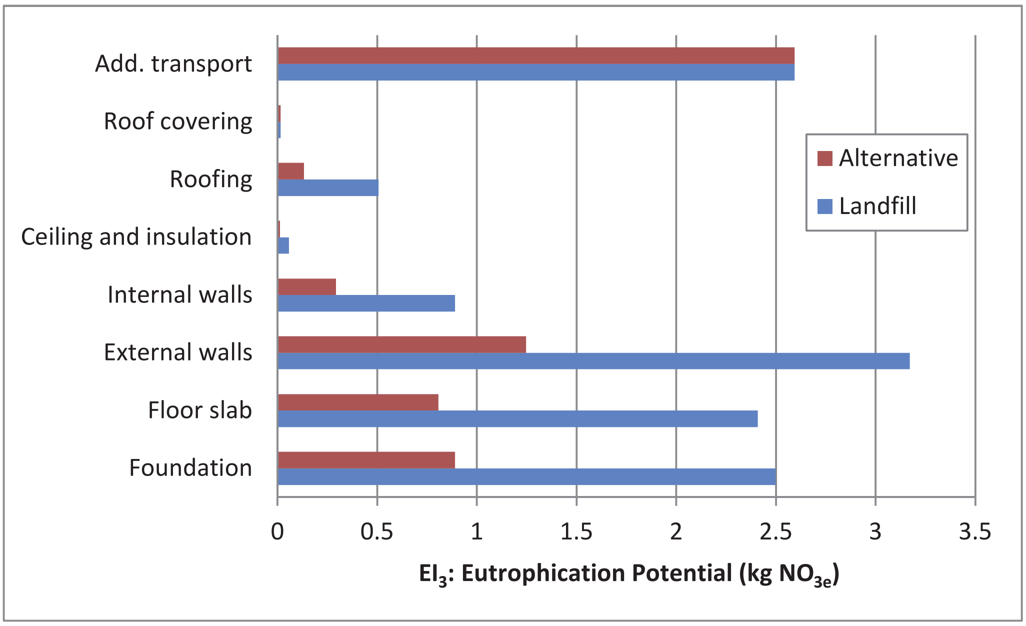

Figure 5-5: Eutrophication Potential results for disposal of the conventional design type

The results for the fourth indicator, namely Resource Depletion, are shown in Figure 5-6.

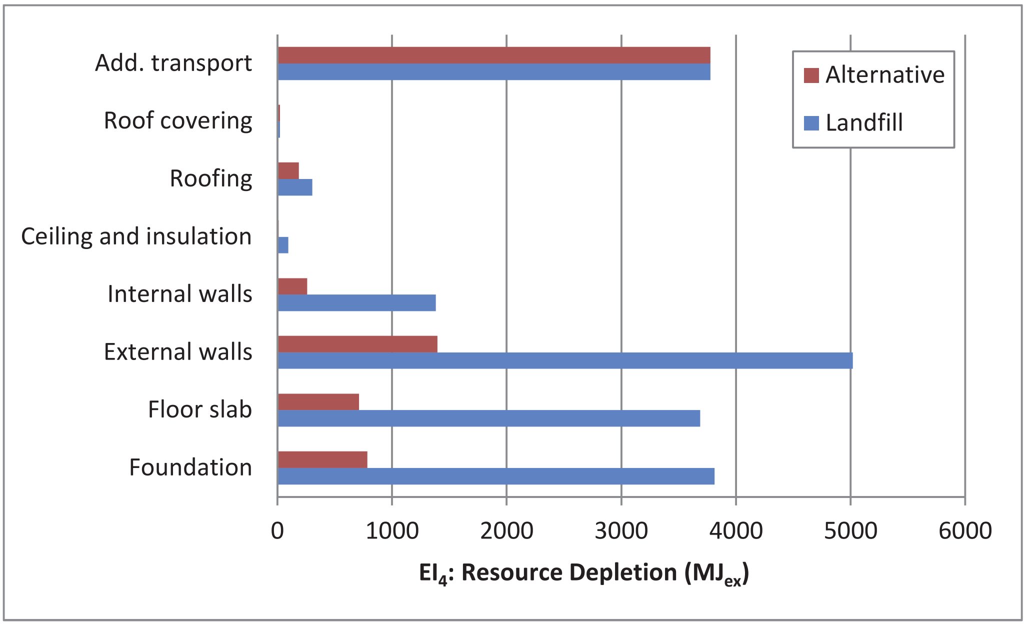

Figure 5-6: Resource Depletion results for disposal of the conventional design type

The resource depletion of landfilled materials was higher than that of materials disposed of with the alternative disposal option. This is indicated in Figure 5-6. A possible reason for the higher resource depletion of landfilled materials was that Ecoinvent includes transport of these waste materials to final disposal, whereas recycling and reuse options do not include any transport of waste. Transport has a high resource depletion due to its use of non-renewable fossil fuel resources to operate the trucks. Even though this was the case, there was still a significant impact from the external walls, floor slab and foundation in the case of the alternative disposal option. This can be due to the larger impact factor of reinforcing and the large amounts of concrete used in these elements.

From Figure 5-7 it is evident that the landfill disposal option had the largest amount of waste landfilled, as all waste was landfilled unless otherwise indicated. The reason for the amount of waste to landfill for the external walls, the floor slab and the foundation was the large amount of concrete that these elements contain. Contrary to the other indicators, transport had little waste to landfill, which is to be expected as transportation does not produce much waste that can be landfilled.

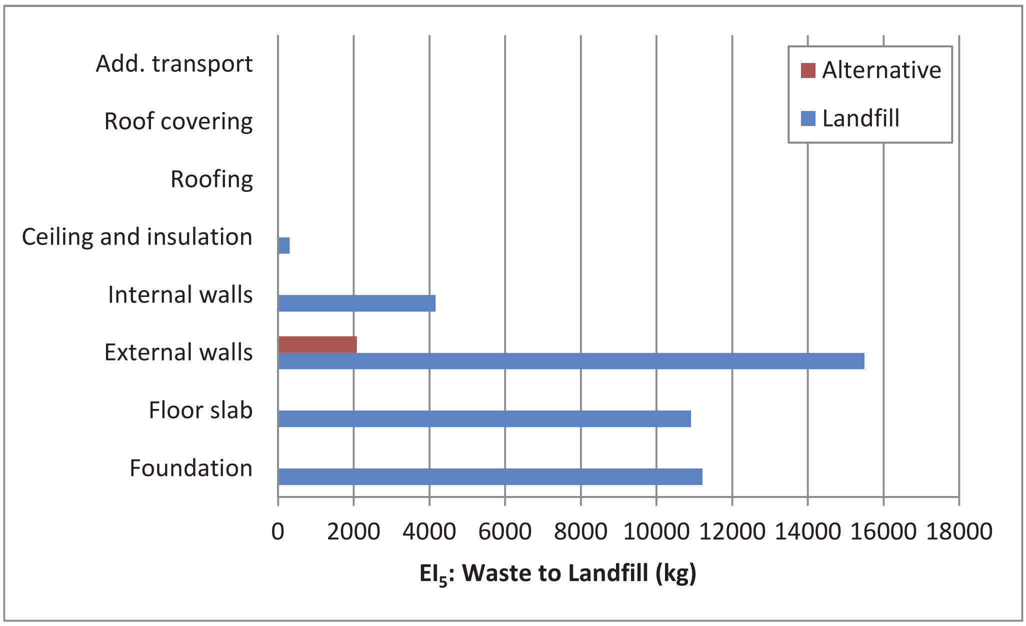

Figure 5-7: Waste to Landfill results for disposal of the conventional design type

5.4.3. Concluding summary and remarks

A summarisation of the calculated indicators is shown below in Table 5-3.

Table 5-3: Summary of results for conventional design type

Indicator	Landfill Disposal Amount	Alternative Disposal Amount	Unit
EI_1: Carbon Footprint	824.810	415.199	kg CO_{2e}
EI_2: Acidification Potential	6.092	3.033	kg SO_{2e}
EI_3: Eutrophication Potential	12.144	6.033	kg NO_{3e}
EI_4: Resource Depletion	18098.353	7177.679	MJ_{ex}
EI_5: Waste to Landfill	42117.53	2099.767	kg

It was noted that the external walls, the floor slab and the foundation made the largest contribution to all the indicators in both the cases of landfilling and alternative disposal. This was due to the large amounts of concrete being used in this design type. Transport was the other indicator that had a significant contribution to the first four indicators due to the large amounts of concrete that was transported to landfill. The additional transport distance also contributed to the results of the first four indicators. As mentioned previously the effect of the amount of transport was assessed by means of a sensitivity analysis in Chapter 6.

As a conventional design type was only one of the two design types chosen to be assessed, the second design type, namely LSFB, was also assessed.

5.5. LSFB design

The structural system of the LSFB design type consists of a substructure – comprising of foundations and a floor slab – and a top structure, consisting of a steel frame structure, a roof structure, as well as cladding and insulation. The structure was further divided into additional building elements in order to aid computation. These building elements are the same as those discussed in Section 5.1.

5.5.1. Environmental assessment

Calculations were made for the reference case (landfilling of all waste) using the materials given in Table 5-4. Included burdens for each material are discussed in the description of the material.

Table 5-4: Waste materials to be landfilled (unless otherwise stated) selected for the LSFB design type (Ecoinvent)

Item on Bill	Ecoinvent Name	Unit	Description
Concrete	Disposal, building, concrete, not reinforced, to final disposal	kg	System includes energy for dismantling, particulate matter emissions from dismantling and handling, transport to dismantling facilities and final disposal of waste material. Waste contains 1 kg inert material with density of 2200 kg/m^3.
Blockwork	Same as above	kg	Same as above
Mortar	Disposal, building, cement (in concrete) and mortar, to final disposal	kg	System includes energy for dismantling, particulate matter emissions from dismantling and handling, transport to dismantling facilities, final disposal of waste material. Waste contains 1 kg inert material with density of 3150 kg/m^3.
Brick (clay)	Disposal, building, brick, to final disposal	kg	System includes energy for dismantling, particulate matter emissions from dismantling and handling, transport to dismantling facilities, final disposal of waste materials. Waste contains 1 kg of inert material with density of 1600 kg/m^3.

Reinforcement	Disposal, building, reinforcement steel, to final disposal	kg	System includes energy for dismantling, transport to dismantling facilities and final disposal of waste material. Waste contains 1 kg of steel with density of 7900 kg/m^3.
Steel Mesh	Same as above	kg	Same as above
Gypsum Plasterboard	Disposal, building, plaster board, gypsum plaster, to final disposal	kg	System includes energy for dismantling, particulate matter emissions from dismantling and handling, transport to dismantling facilities and final disposal of waste material. Waste contains 1 kg gypsum with density of 1000 kg/m^3.
Fibre-cement board	Disposal, building, cement-fibre slab, to final disposal	kg	System includes energy for dismantling, particulate matter emissions from dismantling and handling, transport to dismantling facilities, final disposal of waste material. Waste contains 0.64 kg inert material and 0.36 kg untreated wood with density of 1200 kg/m^3. Total burden allocated to waste disposal function of waste incinerator.
Brickforce	Disposal, building, bulk iron (excluding reinforcement), to sorting plant	kg	System includes machines for handling in sorting plant, electricity demand for sorting plant, transport to dismantling facilities. Waste contains 1 kg steel with density of 7900 kg/m^3.
Roof sheeting	Same as above	kg	Same as above
Roofing	Same as above	kg	Same as above

Steel frame	Same as above	kg	Same as above
Damp proof membrane	Disposal, building, polyurethane sealing, to final disposal	kg	System includes transport to dismantling facilities and final disposal of waste. Waste contains 1 kg polyurethane with density of 1200 kg/m^3.
Blass Wool Insulation	Disposal, building, mineral wool, to final disposal	kg	System includes particulate matter emissions from dismantling and handling, transport to dismantling facilities, final disposal of waste material. Waste contains 1 kg of inert material with density of 50 kg/m^3.
OSB Thermal Break	Disposal, building, waste wood, untreated, to final disposal	kg	System includes transport to dismantling facilities and final disposal of waste. Waste contains 1 kg of untreated wood with density of 720 kg/m^3. Total burden allocated to waste disposal function of waste incinerator in incineration process.

For reasons corresponding to those of the conventional design type, brickforce and roof sheeting (referred to in Ecoinvent as bulk iron) were sent to a sorting plant. Materials shown in Table 5-5 were used to determine the environmental impact of the alternative disposal option.

Table 5-5: Waste materials and their alternative disposal scenario selected for the conventional design type (Ecoinvent)

Item on Bill	Ecoinvent Name	Unit	Description
Concrete	Disposal, building, concrete, not reinforced, to	kg	System includes energy for dismantling, particulate matter emissions from dismantling and handling. Waste contains 1

	recycling		kg inert material with density of 2200 kg/m^3.
Blockwork	Same as above	kg	Same as above
Mortar	Disposal, building, cement (in concrete) and mortar, to final disposal	kg	System includes energy for dismantling, particulate matter emissions from dismantling and handling, transport to dismantling facilities, final disposal of waste material. Waste contains 1 kg inert material with density of 3150 kg/m^3.
Brick (clay)	Disposal, building, brick, to recycling	kg	System includes energy for dismantling, particulate matter emissions from dismantling and handling. Waste contains 1 kg of inert material with density of 1600 kg/m^3.
Reinforcement	Disposal, building, reinforcement steel, to recycling	kg	System includes energy for dismantling. Waste contains 1 kg of steel with density of 7900 kg/m^3.
Steel Mesh	Same as above	kg	Same as above
Gypsum Plasterboard	Disposal, building, plaster board, gypsum plaster, to recycling	kg	System includes energy for dismantling, particulate matter emissions from dismantling and handling. Waste contains 1 kg gypsum with density of 1000 kg/m^3.
Fibre-cement board	Disposal, building, cement-fibre slab, to recycling	kg	System includes energy for dismantling, particulate matter emissions from dismantling and handling. Waste contains 0.64 kg inert material and 0.36 kg untreated wood with density of 1200 kg/m^3.Total burden allocated to waste disposal function

			of waste incinerator.
Brickforce	Disposal, building, bulk iron (excluding reinforcement), to sorting plant	kg	System includes machines for handling in sorting plant, electricity demand for sorting plant, transport to dismantling facilities. Waste contains 1 kg steel with density of 7900 kg/m^3.
Roof sheeting	Same as above	kg	Same as above
Roofing	Same as above	kg	Same as above
Steel frame	Same as above	kg	Same as above
Damp proof membrane	Disposal, building, polyurethane sealing, to final disposal	kg	System includes transport to dismantling facilities and final disposal of waste. Waste contains 1 kg polyurethane with density of 1200 kg/m^3.
Glass Wool Insulation	Disposal, building, mineral wool, to recycling	kg	System includes particulate matter emissions from dismantling and handling. Waste contains 1 kg of inert material with density of 50 kg/m^3.
OSB Thermal Break	Disposal, waste wood, untreated, to final disposal	kg	System includes transport to dismantling facilities and final disposal of waste. Waste contains 1 kg of untreated wood with density of 720 kg/m^3. Total burden allocated to waste disposal function of waste incinerator in incineration process.

As was the case with the conventional design type, most of the materials in the LSFB design type can also be recycled, except for wood and polyurethane materials. These are not recommended to be recycled by Ecoinvent. Bulk iron was in the case of LSFB also sent to a sorting plant. Calculations and results based on the LSFB design type and the materials used are discussed in the next section.

5.5.2. Assessment calculations and results

The quantification of impacts for the case of the LSFB design type was the same as for the conventional design type done in Section 5.4.2. The same equations were used and where applicable conversion factors were used to convert units to those of Ecoinvent. The results obtained for each indicator are graphically represented and discussed below. All numerical results are given in Appendix D.

The first indicator, Carbon Footprint, yielded the results shown in Figure 5-8.

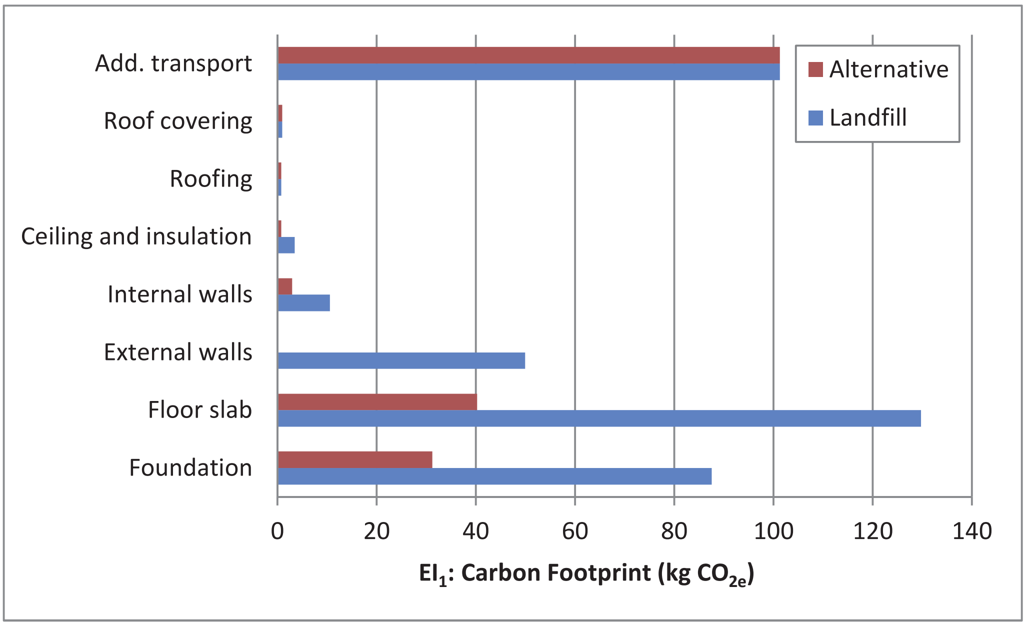

Figure 5-8: Carbon Footprint results for disposal of the LSFB design type

Similar to the conventional design type results, landfilling of waste had a bigger carbon footprint than the alternative waste disposal option. Transport, the external walls, the floor slab and the foundation are the building elements that contributed the most to the carbon footprint of landfilling of the LSFB design type, however, when looking at the alternative disposal option, the external walls make the smallest contribution to the carbon footprint. This may be due to the fact that the most used building materials in the external walls (light steel profiles, OSB thermal break, gypsum plasterboard) were reused or recycled. The high contribution of transport may be due to the transportation of large amounts of concrete, which was also the reason for the high contributions of the floor slab and the foundation.

The largest contributors to acidification potential in the LSFB design type was the same as for the conventional design type, for both the landfilling and the alternative disposal option scenarios. Internal walls had a lower contribution in the case of the LSFB design type mainly due to a much lower impact factor for steel. The results obtained from the assessment of the acidification for the LSFB case are shown in Figure 5-9.

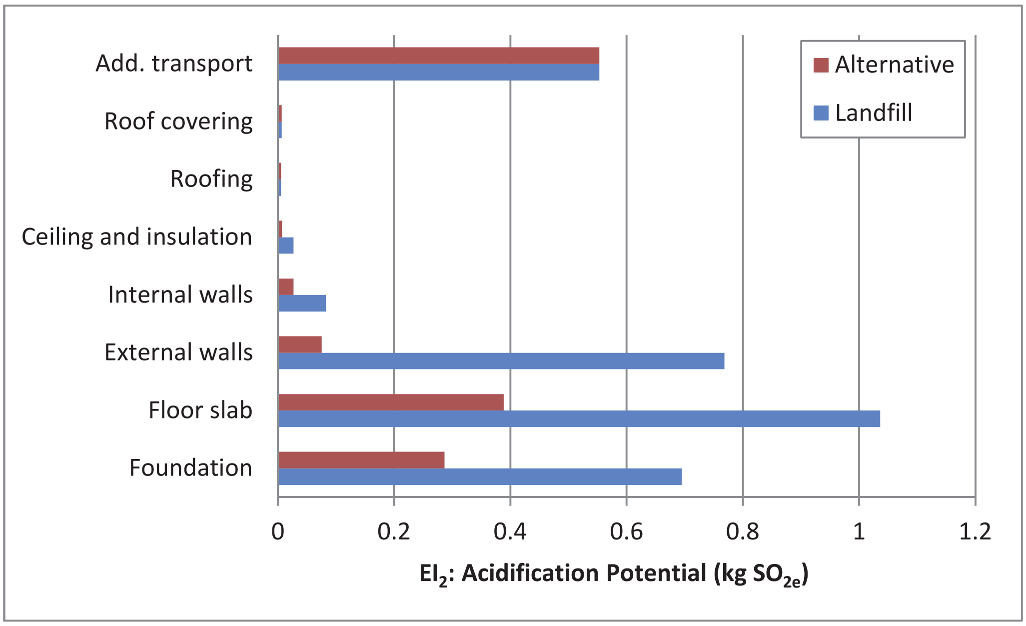

Figure 5-9: Acidification Potential results for disposal of the LSFB design type

In the case of the Eutrophication Potential of the LSFB design type (see Figure 5-10) it can be seen that transport, the external walls, the floor slab and the foundation are the largest contributors in the landfilling disposal scenario. In the case of the floor slab and foundations this may be due to the high amounts of concrete used in these elements, while in the case of the external walls the use of gypsum plasterboard, OSB for thermal break and fibre cement board cladding had the largest eutrophication potential. It is evident, however, that when these building materials were disposed of alternatively, the impact was greatly reduced.

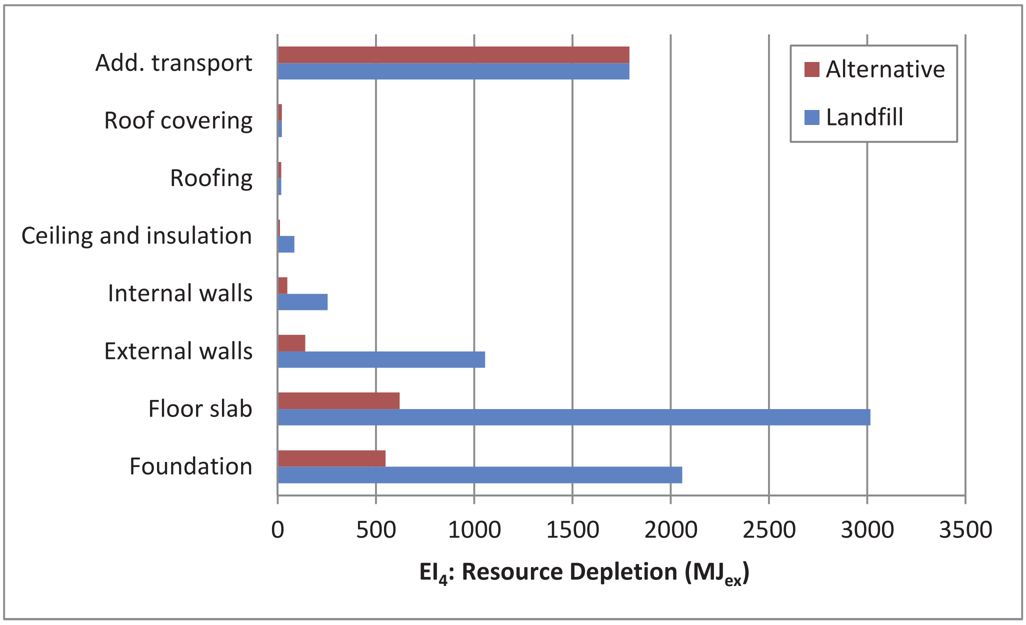

Figure 5-11: Resource Depletion results for disposal of the LSFB design type

Landfilling of waste lead to a larger resource depletion than the alternative disposal scenario, as shown in Figure 5-11. This can be due to the inclusion of transport of waste materials to final disposal in the Ecoinvent database, however, in the case of reuse or recycling, transport is not included. The more transportation of waste that is necessary, the more non-renewable fossil fuel resources are used, leading to a bigger depletion of resources. Resource depletion of the floor slab and foundation in the case of alternative disposal, however, still remain relatively high.

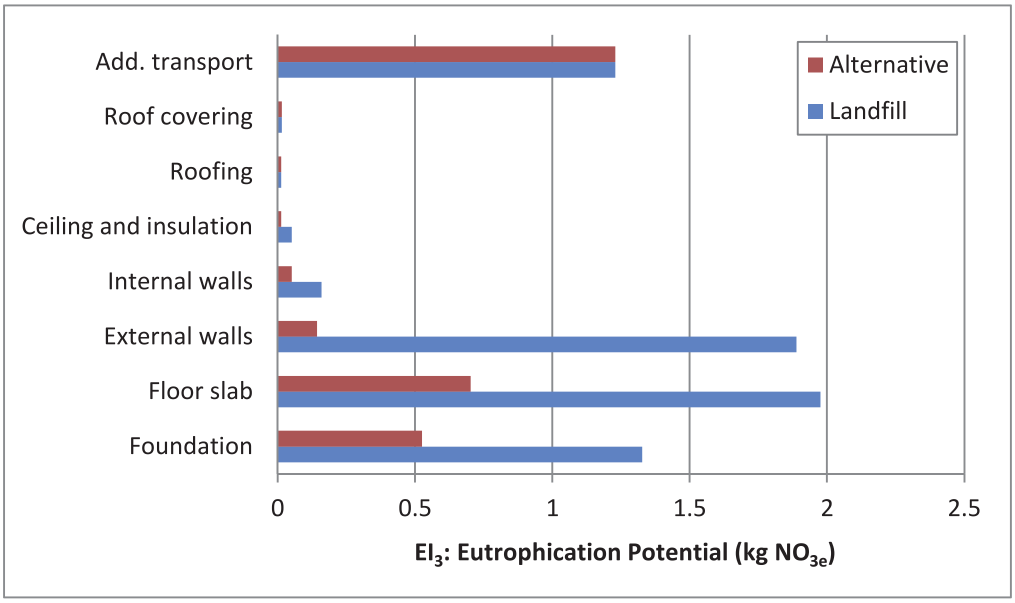

Figure 5-10: Eutrophication Potential results for disposal of the LSFB design type

As can be expected more waste goes to landfill in the case of the landfill disposal option (from Figure 5-12), due to the disposal of most of the generated waste in landfills. Due to the large amounts of concrete in the floor slab and the foundation a larger amount of waste is landfilled. The reason for the low amount of waste that goes to landfill in the case of transport is due to the same reasons mentioned in the case of the conventional design type.

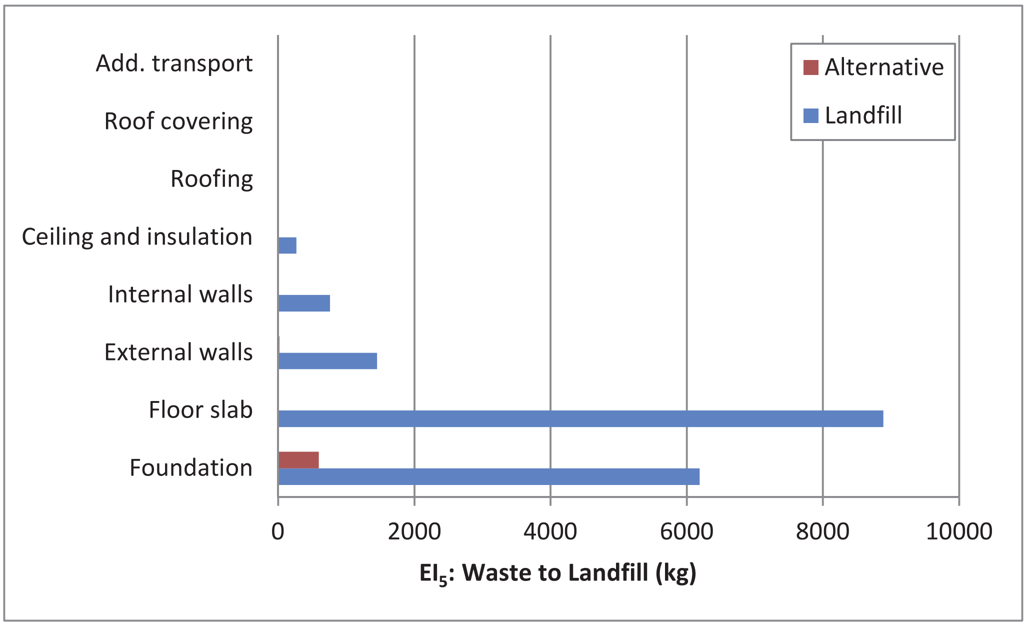

Figure 5-12: Waste to Landfill results for disposal of the LSFB design type

5.5.3. Concluding summary and remarks

A summarisation of the calculated indicators is shown in Table 5-6:

Table 5-6: Summary of results for LSFB design type

Indicator	Landfill Disposal Amount	Alternative Disposal Amount	Unit
EI$_1$: Carbon Footprint	384.326	186.565	kg CO_{2e}
EI$_2$: Acidification Potential	3.173	1.350	kg SO_{2e}
EI$_3$: Eutrophication Potential	6.661	2.696	kg NO_{3e}
EI$_4$: Resource Depletion	8296.075	3198.866	MJ_{ex}
EI$_5$: Waste to Landfill	17563.210	634.376	kg

As was the case with the conventional design type, it was noted that the external walls, the floor slab and the foundation make the largest contribution to all the indicators in both the cases of landfilling and alternative disposal. The contribution of the external walls, in some cases, was much lower than for the case of the conventional design type, due to the lower concrete content. Transport also had a significant contribution to the first four indicators due to the large amounts of waste being transported to landfill and in the case of the floor slab and the foundation large amounts of concrete had to be transported. The effect of the amount of transport was assessed by means of a sensitivity analysis in Chapter 6.

A comparison of the two disposal scenarios for both the conventional and LSFB design types is discussed in the next section.

5.6. Design type indicator results comparison

A comparison for all the chosen indicators was made for both design types and disposal scenarios and is shown graphically in Figure 5-13.

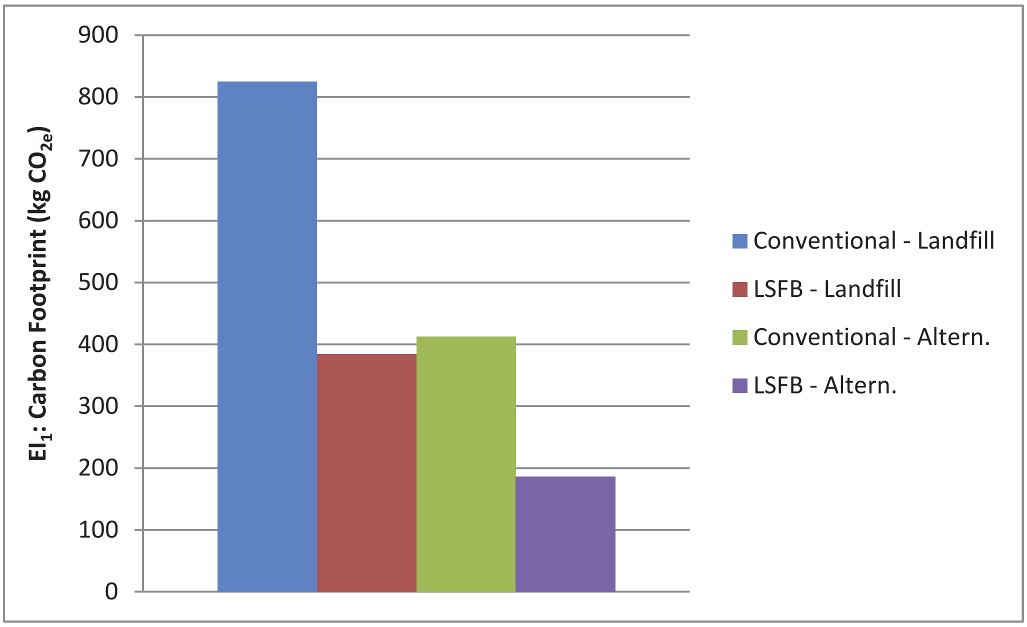

Figure 5-13: Results comparison for Carbon Footprint

From Figure 5-13 it is evident that the landfilling of the conventional design type had the largest carbon footprint due to the high amounts of concrete used in this design type. In the case of the alternative disposal option there was a significant difference between the conventional and LSFB design types. It is, however, interesting that the Carbon Footprint for the alternative disposal of the conventional design type is higher than that of the landfilling of the LSFB design type.

The conventional design type has a higher acidification potential and eutrophication potential than the LSFB design type for both disposal scenarios as shown in Figure 5-14 and Figure 5-15 respectively.

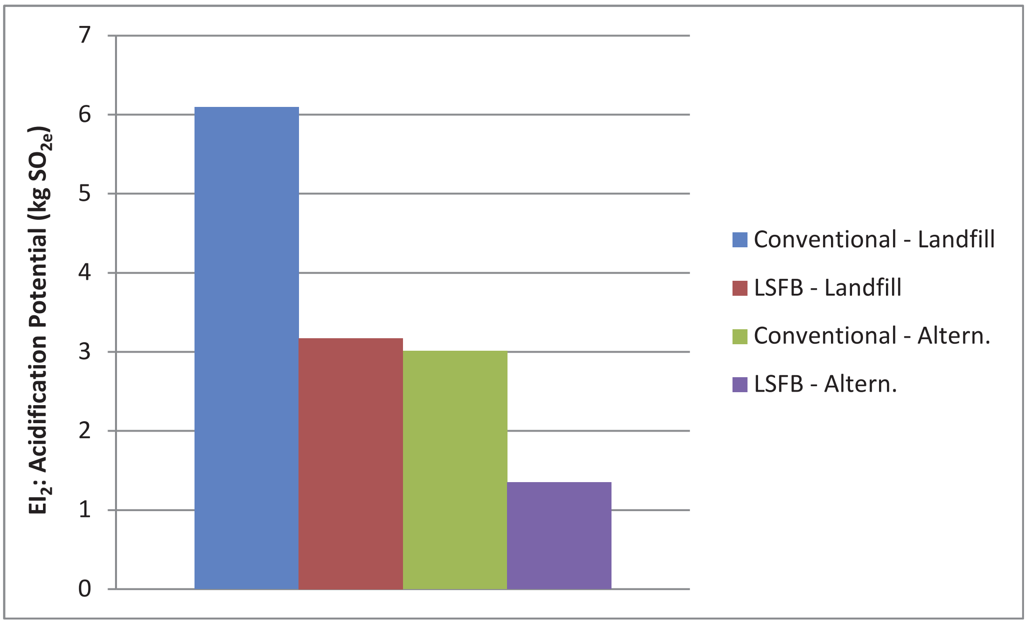

Figure 5-14: Results comparison for Acidification Potential

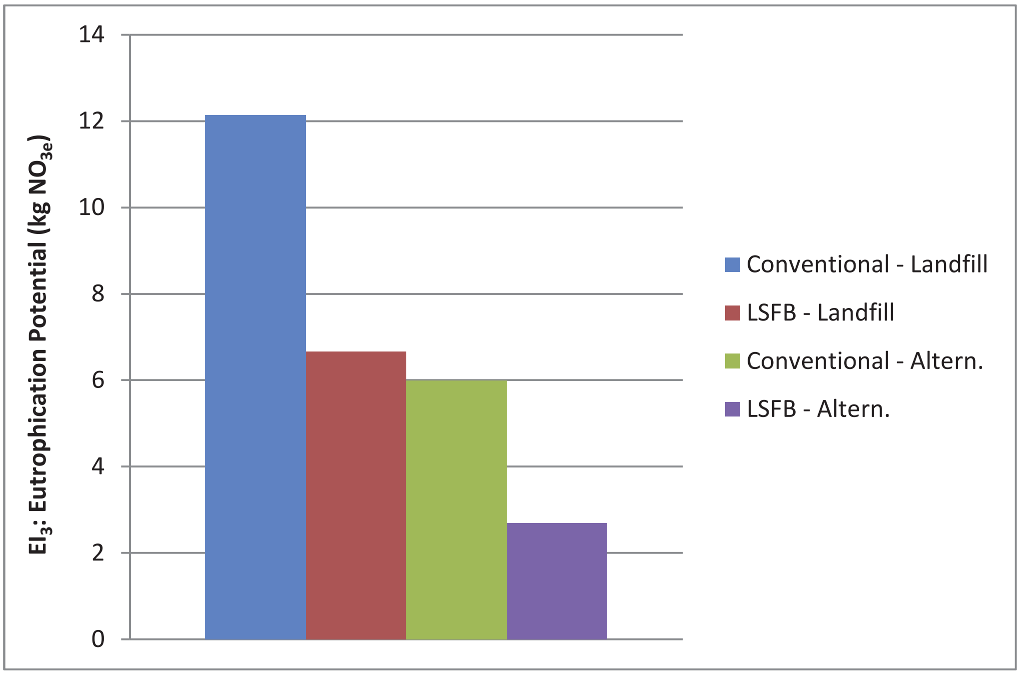

Figure 5-15: Results comparison for Eutrophication Potential

Similar to the carbon footprint indicator, Resource Depletion (shown in Figure 5-16) was highest for the landfilling scenario of the conventional design type. However, in the case of the alternative disposal option of the conventional design type, the resource depletion was much lower than for the landfilling disposal option.

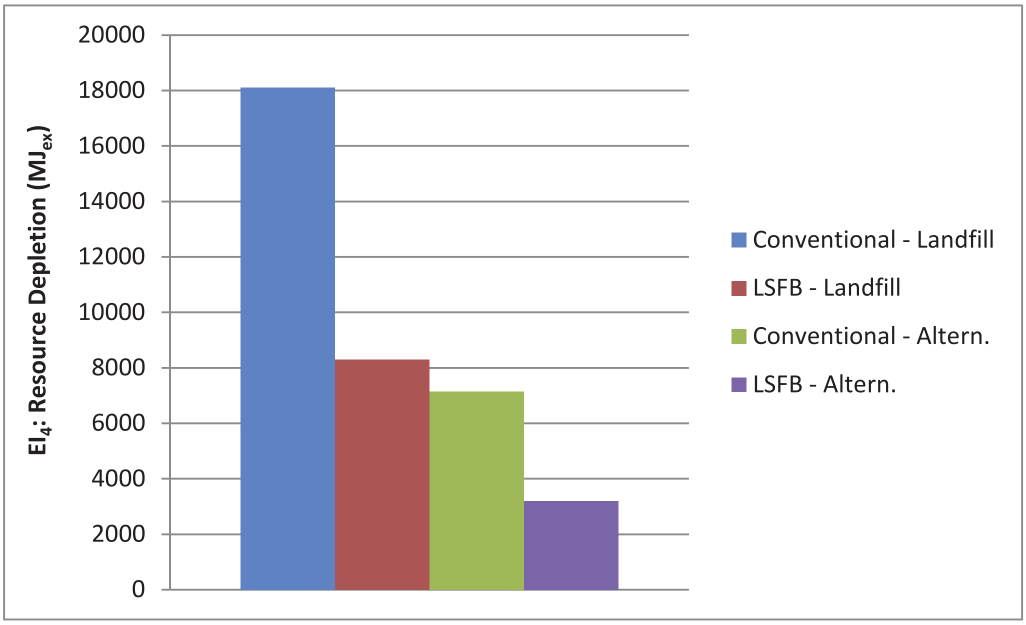

Figure 5-16: Results comparison for Resource Depletion

As was expected the conventional design type had a higher amount of waste sent to landfill in both disposal scenarios due to the large amounts of concrete used in this design. However, in the case of the alternative disposal option the amount of waste being landfilled was much lower than for the case of the landfilling disposal option. These results are shown in Figure 5-17.

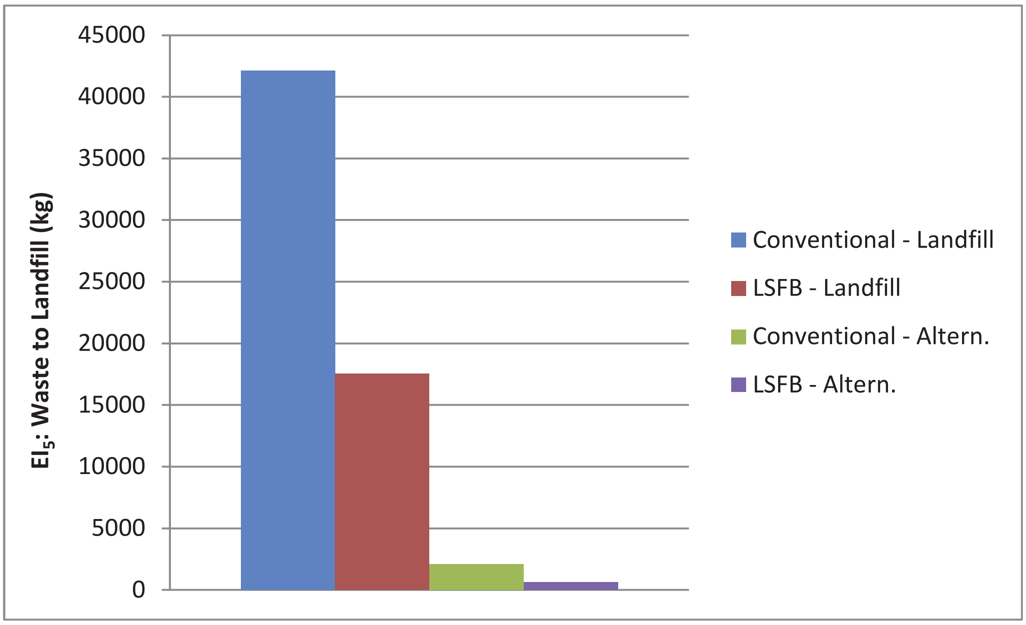

Figure 5-17: Results comparison for Waste to Landfill

Normalisation and weighting factors were applied to the environmental indicators (EI) next to determine the final impact of each design type by using the following general equations:

Normalisation: $EI_{i\text{norm}} = EI_i\,[\text{kg equivalents}] / EI_{i\text{NF}}$ (15)

Weighting: $EI_{i\text{weighted}} = EI_{i\text{norm}} \times EI_{i\text{WF}}$ (16)

where $EI_{i\text{norm}}$ is the normalised factor for *i*, EI_i is the equivalent amount obtained in the impact analysis, $EI_{i\text{NF}}$ is the normalisation factor corresponding to *i*, $EI_{i\text{weighted}}$ is the dimensionless weighted value of *i* and $EI_{i\text{WF}}$ is the corresponding weighting factor for *i*. All normalisation and weighting factors are shown previously in Table 3-5.

5.7. Final assessment results

In order to obtain the final results for the two design types, normalisation and weighting factors were applied.

Normalised values were obtained by dividing the obtained value for each indicator by its corresponding normalisation factor. An example for the normalisation of the CF is shown below:

$$\begin{aligned} CF_{normalised} &= CF\ [\text{kg } CO_{2e}] \,/\, CF_{NF}\ [\text{kg } CO_{2e}] \\ &= 824.81 / 8.7 \times 10^{3} \\ &= 0.095\ [-] \end{aligned}$$

where $CF_{normalised}$ is the normalised value of the CF, CF is the value obtained in the impact analysis for carbon footprint and CF_{NF} is the normalisation factor for the CF. The normalised values for the other indicators were done using the same equation and the corresponding normalisation factors. Following the normalisation, the corresponding weighting factor was also applied to each indicator as shown below:

$$\begin{aligned} CF_{weighted} &= CF_{normalised} \times CF_{WF} \\ &= 0.095 \times 1.12 \\ &= 0.106\ [-] \end{aligned}$$

where $CF_{weighted}$ is the normalised and weighted dimensionless value for the CF and CF_{WF} is the corresponding CF weighting factor. Similarly, the weighted values for the remaining indicators were determined using the above calculation and the appropriate weighting factors.

After normalisation and weighting were done, the different impacts were dimensionless and could be summed to get the Environmental Impact Index (EII) of the two design types. Normalisation and weighting factors given previously in Table 3-5 were applied and yielded the results for the landfilling and alternative disposal scenarios shown in Table 5-7 and Table 5-8 respectively:

Table 5-7: Weighted results for landfill disposal

		Environmental Impact	**Normalised value**	**Weighted value**
Carbon Footprint [kg CO_{2e}]	Conv. Design	824.810	0.095	0.106
	LSFB	384.326	0.044	0.049
Acidification Potential [kg SO_{2e}]	Conv. Design	6.092	0.103	0.131
	LSFB	3.173	0.054	0.068
Eutrophication Potential [kg NO_{3e}]	Conv. Design	12.144	0.128	0.156
	LSFB	6.661	0.070	0.086
Waste to Landfill [kg]	Conv. Design	42117.526	31.198	34.318
	LSFB	17563.207	13.010	14.311

Table 5-8: Weighted results for alternative disposal scenario

		Environmental Impact	**Normalised value**	**Weighted value**
Carbon Footprint [kg CO_{2e}]	Conv. Design	415.199	0.048	0.053
	LSFB	186.565	0.021	0.024
Acidification Potential [kg SO_{2e}]	Conv. Design	3.034	0.051	0.065
	LSFB	1.350	0.023	0.029
Eutrophication Potential [kg NO_{3e}]	Conv. Design	6.033	0.064	0.077
	LSFB	2.694	0.028	0.035
Waste to Landfill [kg]	Conv. Design	2099.767	1.555	1.711
	LSFB	634.376	0.470	0.517

Since a different method was used to determine Resource Depletion it is shown separately. The landfill disposal scenario yielded a resource depletion of 18098.353 MJ_{ex} and 8296.075 MJ_{ex} for the conventional design and the LSFB design respectively. The calculated Resource

Depletion for the alternative disposal scenario was 7177.679 MJ_{ex} for the conventional design type and 3198.866 MJ_{ex} for the LSFB design type.

In order to better compare the values, Waste to Landfill was drawn on a separate graph as the values were much greater than those of the other considered impacts.

As can be seen from Figure 5-18 and Figure 5-19 Waste to Landfill has, by far, the largest environmental impact, followed by Eutrophication Potential, Acidification Potential and Carbon Footprint for both the cases of the conventional and LSFB design types and also for both disposal scenarios. In some cases it was also noticed that the alternative disposal of the conventional type design lead to a larger impact value than the landfilling disposal scenario for the LSFB design type.

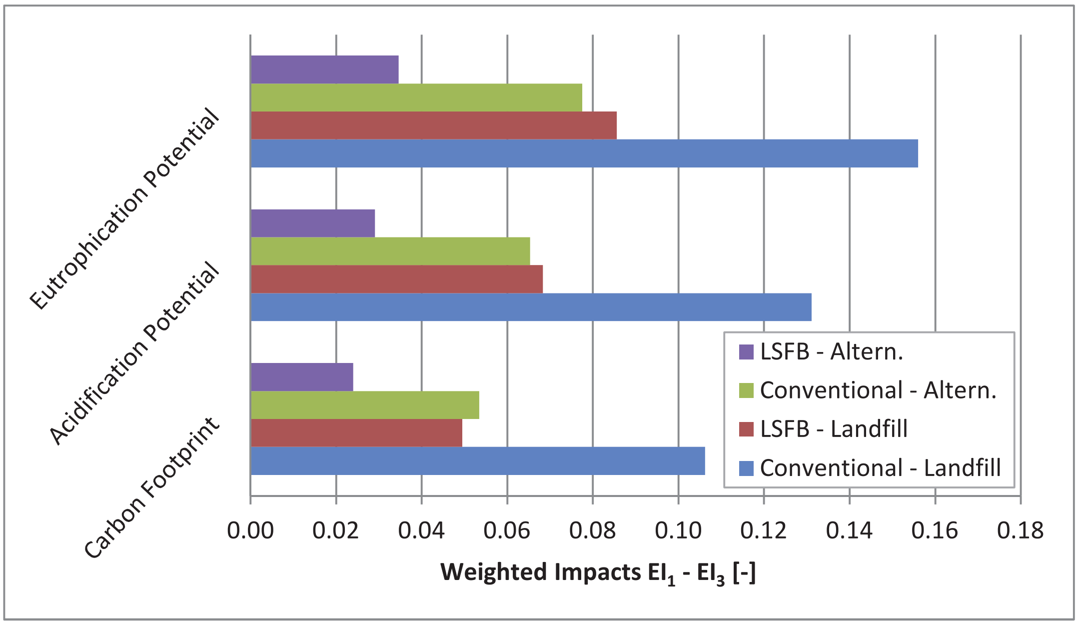

Figure 5-18: Weighted results for different design types and disposal scenarios

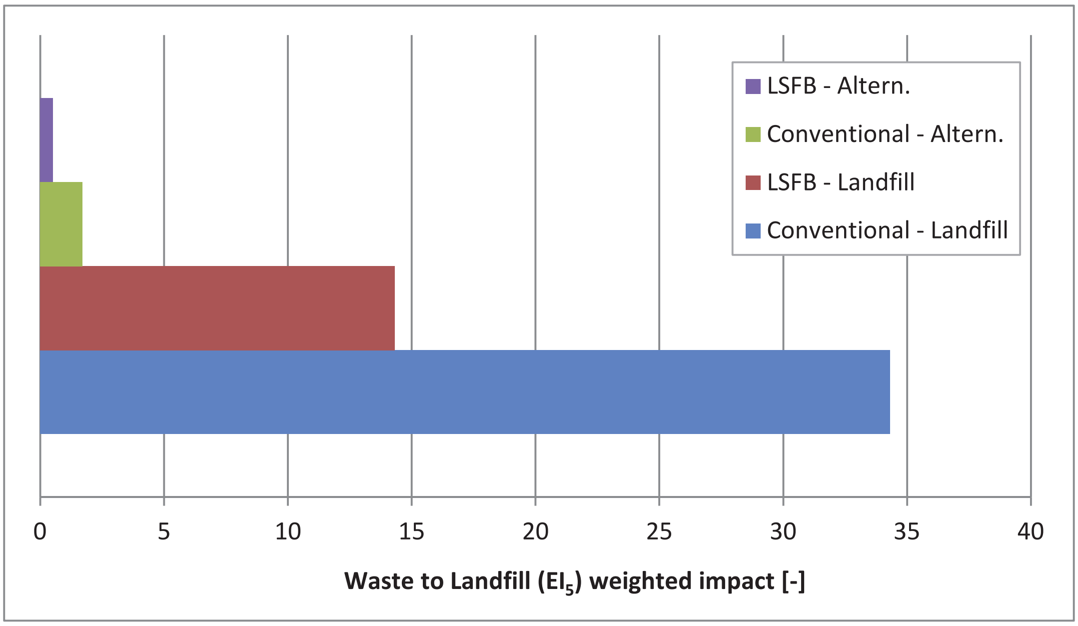

Figure 5-19: Weighted results for Waste to Landfill

From Figure 5-20 it is concluded that the conventional design type and the landfill disposal option had a larger resource depletion. It is evident that the conventional design type had a larger environmental impact than the LSFB design type across the board for the end-of-life phase.

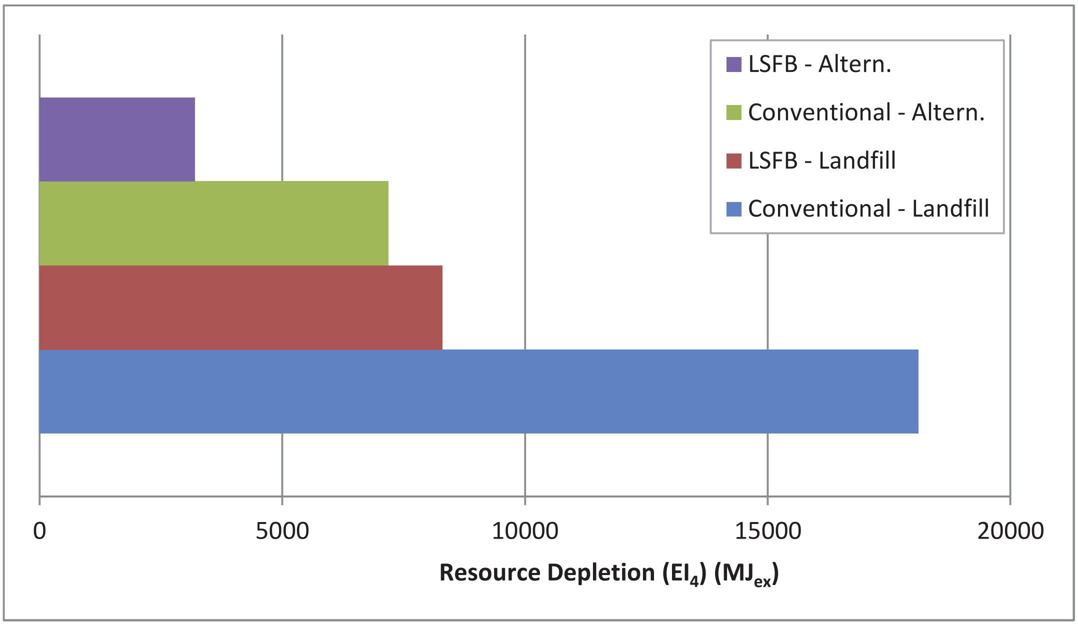

Figure 5-20: Resource Depletion impact results

The final environmental impact for each alternative was calculated as the sum of the weighted impacts of Carbon Footprint, Acidification Potential, Eutrophication Potential and Waste to Landfill. Resource Depletion was not included as a different impact method was used for its calculation. The Environmental Impact Index was calculated, in the case of landfilling, as 34.711 for the conventional design type, which is 2.39 times larger than the EII of 14.514 calculated for the LSFB design type. An EII of 1.907 was calculated for the conventional design type in the alternative disposal scenario. This value is 3.16 times larger than the calculated value of 0.605 for the LSFB design type. These results are shown in Figure 5-21.

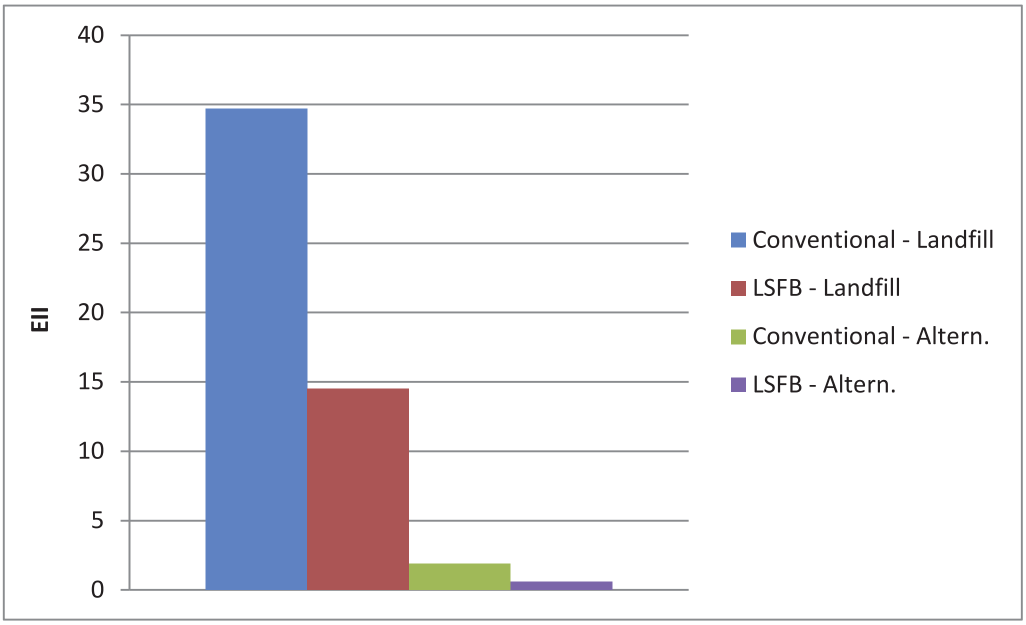

Figure 5-21: EII for both design types and disposal scenarios

It is evident from these results that the alternative disposal options of all building types hold great advantages for the environment and the environmental impact of the end-of-life phase. It is also clear that the largest contributing indicator is Waste to Landfill. These results also indicate that Eutrophication Potential is an important indicator to consider in the case where waste is landfilled.

Due to the variable nature of some aspects of this study a sensitivity analysis was done in order to determine the influence these variables have on the eventual results of such a study. The sensitivity analysis is explained in the following chapter.

Chapter 6

SENSITIVITY ANALYSIS

Due to the variable nature of some of the assumed values for the selected impacts, a sensitivity analysis was performed to investigate whether the assumptions had a significant effect on the outcome of the environmental assessment. One of the most variable assumptions was that of transport distances for waste. Transport was thus the first impact considered in the sensitivity analysis. Furthermore, weighting values differ for certain areas and since there is no specific South African values for weighting, the different available weighting factors needed to be investigated to determine how they will affect the outcome of the final impact. Lastly, the difference between the impacts of landfilling and incineration was investigated.

6.1. Transport

As was discussed in Chapter 5, the additional transport distance has a relatively large impact on the results of this study. The impact of transport depends on two factors, namely the amount of material (or waste) being transported (in ton) and secondly the distance travelled during the transportation of the materials (in km). The multiplication of these two factors leads to the unit of transport, tkm.

In this case the amount of waste being transported was set, therefore the variable distance was the distance travelled. The distance of the additional transportation was thus varied. It was assumed that a 3.5 to 7.5 t truck was used for transporting the waste materials. A value for the additional transport distance was assumed as 10 km. The sensitivity analysis thus considered a variation in the additional transportation distance between 0 and 20 km. The assessment was carried out for the calculations used in Chapter 5 and the varied EII values were plotted in Figure 6-1 for the landfill disposal option and Figure 6-2 for the alternative disposal option.

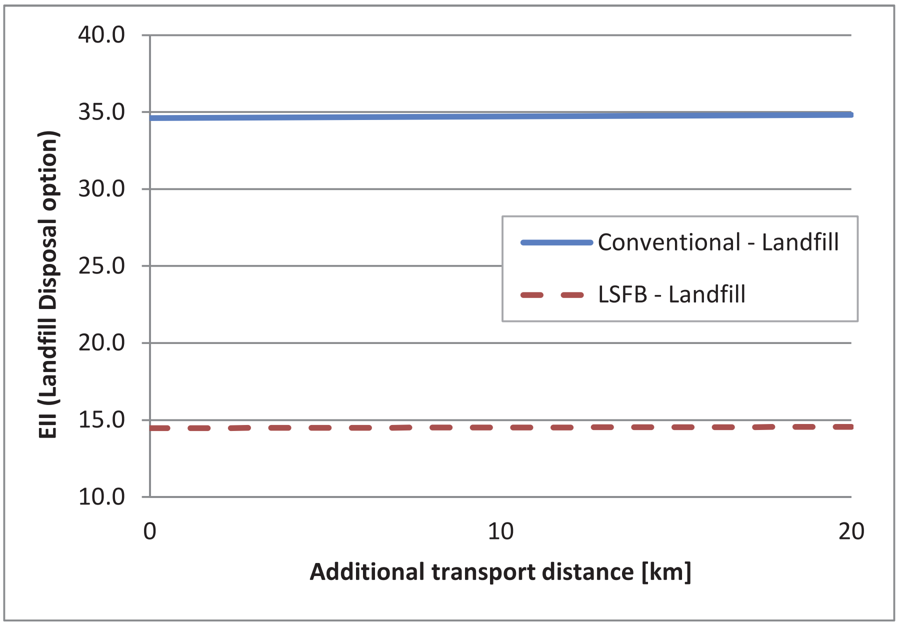

Figure 6-1: The effect of varying transportation distances on the EII of the landfill disposal option

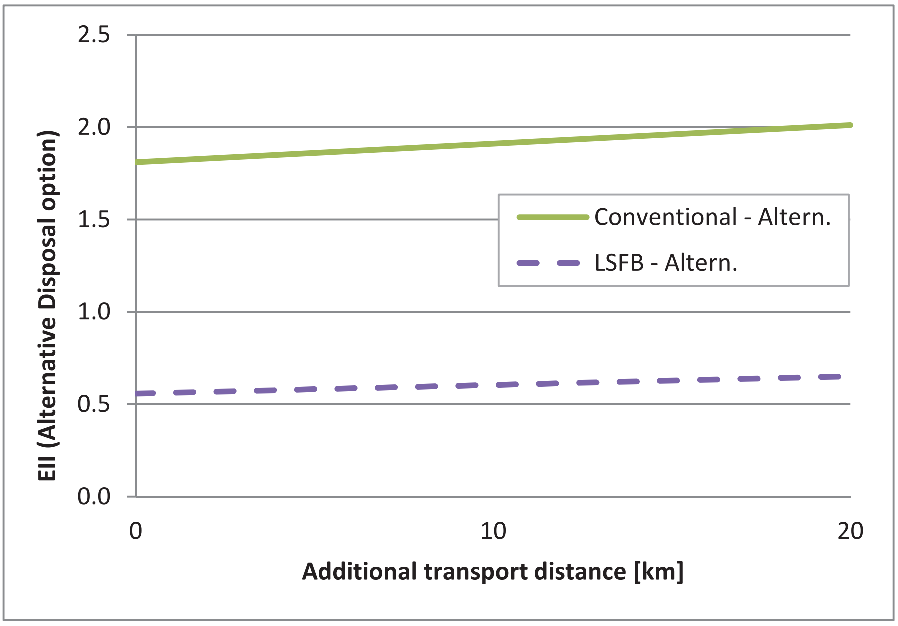

Figure 6-2: The effect of varying transportation distances on the EII of the alternative disposal option

As can be seen from the graphical representations, the distance in transport had a more significant impact on the alternative disposal option than on the landfill disposal option. The reason is that the impact for this disposal option was already low and the increase in the travelled distance lead to an increase in the EII which was high in relation to the EII if there was no additional transport, whereas the increase in the landfill option's EII was small in relation to the EII when no additional transport was included. It is evident that the EII was sensitive to additional transportation distances, however it was not sensitive when the EII was used for the comparison of the two design types as the gradient of the two curves was similar. This was expected due to the results of the EII calculation and is confirmed by the sensitivity analysis.

The same calculation was done in order to assess the sensitivity of the Resource Depletion indicator to the transport distances. The results are shown graphically below in Figure 6-3.

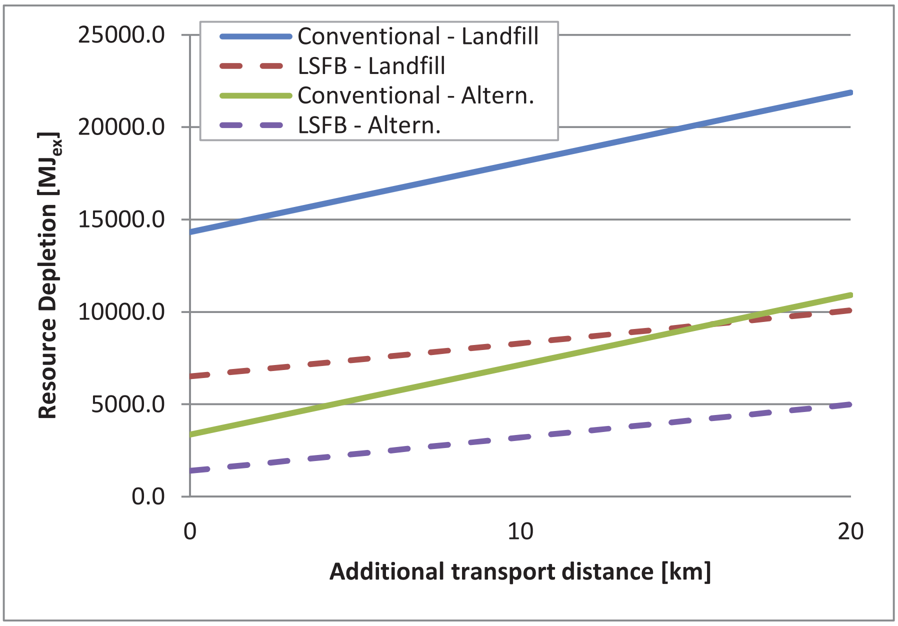

Figure 6-3: The effect of varying transportation distances on the Resource Depletion

For the landfill disposal option both the conventional and the Light Steel Frame Building (LSFB) design types had more or less the same increase in their Resource Depletion as the additional transport distance increased. The same was true for the alternative disposal option. However, the graph for the alternative disposal of the conventional design intersects the graph of the landfill disposal of the LSFB design at 15.80 km. This means that after an additional transportation distance of 15.80 km the resource depletion of the alternative disposal of the conventional design will be larger than that of the landfilling of the LSFB design type. This is due to the larger volume of waste that was transported in the case of the conventional design type than in the case of the LSFB design type. From this it can thus be concluded that the main influencing factor is not transportation distances, but rather the volume of waste being transported.

6.2. Weighting factors

Many different weighting factors exist in literature. From Stranddorf et al. (2005) weighting factors for the original EDIP '97 method can be obtained, but also more recent global and European factors. The Danish factors are also included by Stranddorf et al. (2005). Since Stranddorf et al. (2005) suggested that the European factors be used for developing countries, the weighting factors that were extracted from literature are shown in Table 6-1. Weighting factors are calculated based on actual emissions or by extrapolating emission data for one region. Furthermore weighting factors are often set to achieve political targets (Stranddorf et al., 2005)

Table 6-1: Different weighting factors obtained (Stranddorf et al., 2005 & Goedkoop et al., 2008)

Indicator	Original EDIP '97	Europe	Denmark
Carbon Footprint (CF)	1.3	1.05	1.11
Acidification Potential (AP)	1.3	1.27	1.34
Eutrophication Potential (EP)	1.2	1.22	1.31
Waste to Landfill	-	-	1.1

From Table 6-1 it is noted that the different weighting factors vary between 1.05 and 1.34, this range was thus used to determine the sensitivity of the EII to the weighting factor used in the calculation. The results were obtained for the landfilling disposal scenario (Figure 6-4) and the alternative disposal scenario (Figure 6-5).

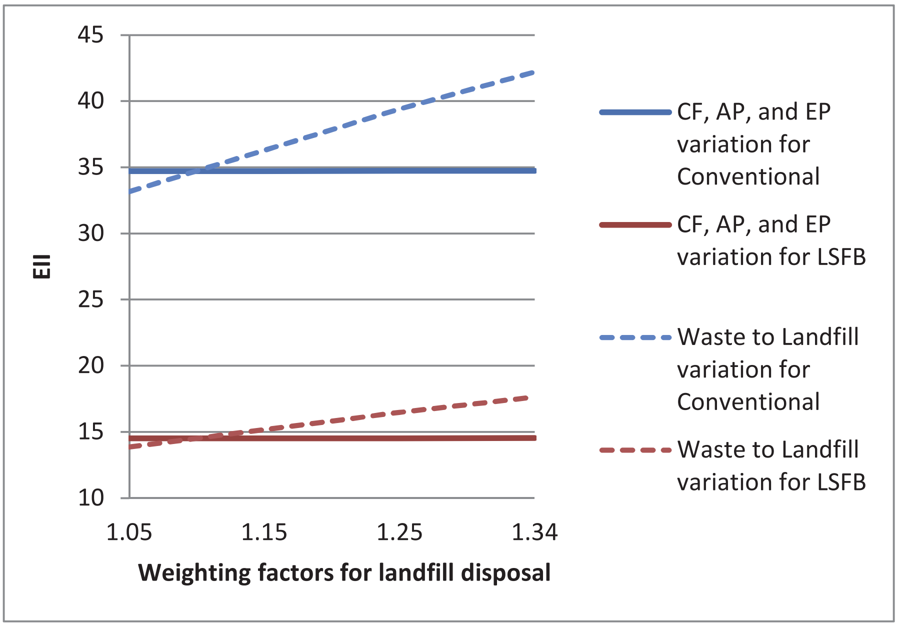

Figure 6-4: The effect of varying weighting factors on the EII of the landfill disposal option

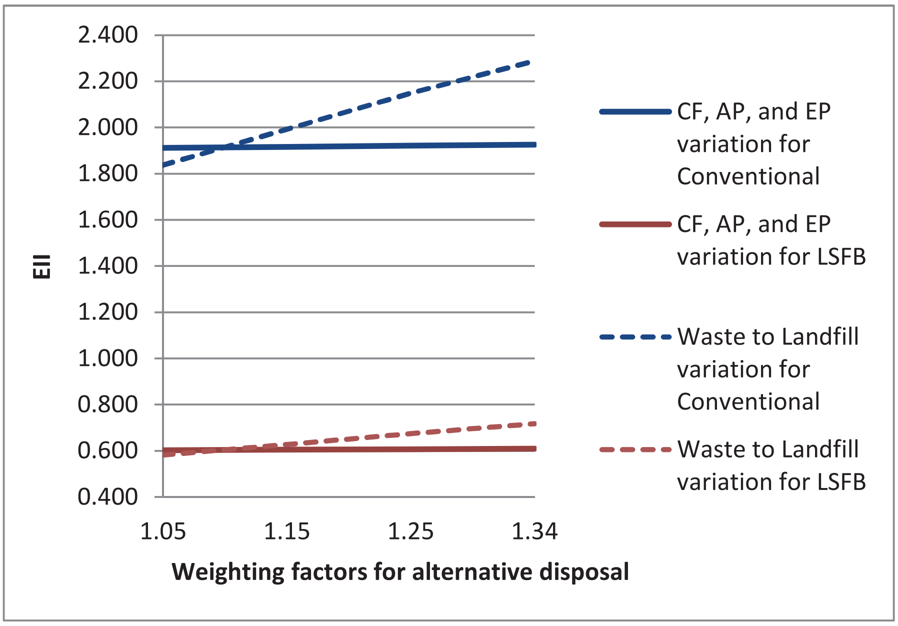

Figure 6-5: The effect of varying weighting factors on the EII of the alternative disposal option

From Figure 6-4 and Figure 6-5 it was concluded that the variation in weighting factors for Carbon Footprint (CF), Acidification Potential (AP) and Eutrophication Potential (EP) had negligible effect on the EII and does not influence the consideration of the design types. It is clear that the selection of weighting factors for these indicators in the end-of-life phase was not influential in the outcome of the EII. This is evident from the small difference shown on the graphs in Figure 6-4 and Figure 6-5. The variation of the EII due to the varied weighting factors for CF, AP and EP is so small that the graphs for these three indicators lie on the same line and are difficult to distinguish.

The varying weighting factor for Waste to Landfill, however, had a significant impact on the final result of the EII for both design types and disposal options. This confirms the statement made in the previous chapter on the significant influence that transportation distances have on the final environmental impact results. It is thus necessary to choose the weighting factor for this indicator carefully. It is assumed that the weighting factor for Waste to Landfill for Denmark is higher due to the smaller area of land available for landfills, whilst South Africa has a much larger area of land that can be used as landfill space. South Africa has a total land area of 1 219 090 km^2 (StatsSA, [s.a.]) which is 28.3 times larger than Denmark's land area of 43 098 km^2 (Visit Copenhagen, [s.a.]). It can thus be argued that the weighting factor that is used for South Africa should be much lower than the currently applied factor of 1.1. Due to a lack of environmental data for South Africa, however, it is difficult to estimate an appropriate and scientifically viable weighting factor that can be used.

6.3. Incineration

In the case of the alternative disposal option analysis, no incineration of waste materials was selected as a possible disposal option. Two materials were included in the Bill of Quantities for both the conventional and the LSFB design type that can be either landfilled or incinerated. In the analysis both these materials were landfilled. A sensitivity analysis was carried out on these materials by choosing incineration as the disposal option instead of landfilling. The two materials incinerated were the damp proof membrane and the wooden roof truss. In Table 6-2 the description of each item selected in Ecoinvent are shown.

Table 6-2: Description of materials chosen for incineration in Ecoinvent (Ecoinvent)

Item	Ecoinvent name	Unit	Description
Damp proof membrane	Disposal, PE sealing sheet, 4% water, to municipal incineration	kg	System includes waste-specific air and water emissions from incineration, auxiliary material consumption for flue gas cleaning. Short-term emissions to river water and long-term emissions to ground water from slag compartment (from bottom slag) and residual material landfill (from solidified fly ashes and scrubber sludge).
Roof truss	Disposal, wood, untreated, 20% water, to municipal incineration	kg	System includes waste-specific air and water emissions from incineration, auxiliary material consumption for flue gas cleaning. Short-term emissions to river water and long-term emissions to ground water from slag compartment (from bottom slag) and residual material landfill (from solidified fly ashes and scrubber sludge).

The adjusted results for the impacts and the EII were obtained and are shown graphically in Figure 6-6. The sensitivity analysis was only carried out on the alternative disposal scenario of the two design types. The first was landfilling the waste which was the same as the original results obtained in the assessment, while the second was the results obtained by incinerating the two waste materials instead of landfilling them.

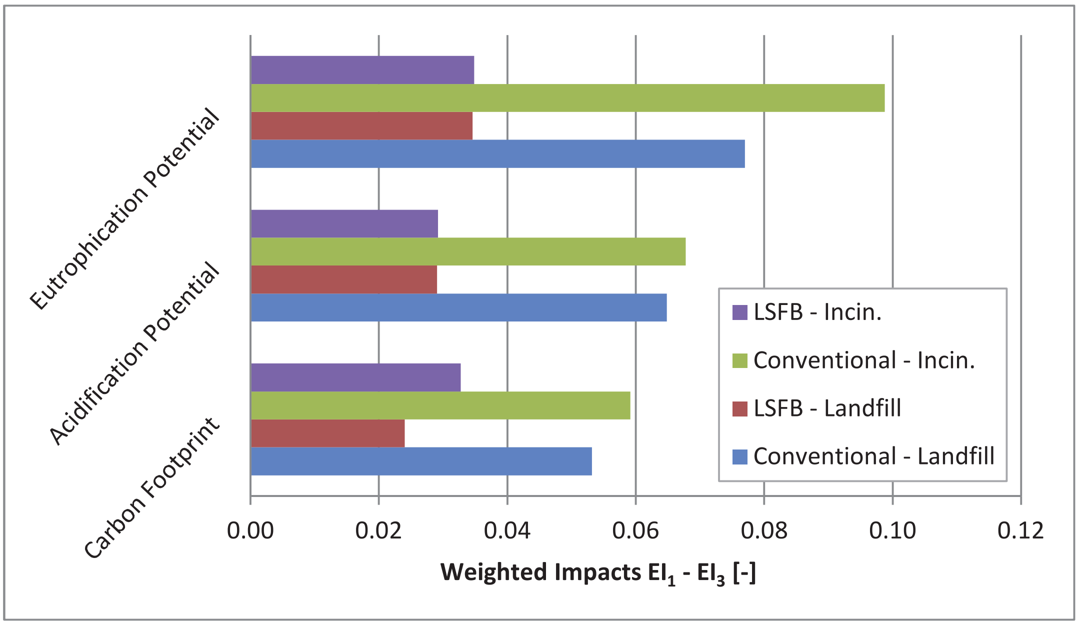

Figure 6-6: Adjusted weighted impacts when using incineration instead of landfilling

It can be seen that in the case of the LSFB design type, incineration of the waste did not have less eutrophication and acidification potential than landfilling, however a higher carbon footprint was calculated for incineration than for landfill. This is due to higher emissions to air in the case of incineration.

Similar to the previous results, Figure 6-7 shows that there was no significant difference in Resource Depletion between landfilling and incineration of the selected materials for the LSFB design type. For the conventional design type the Resource Depletion of landfilling the waste was only slightly lower than that of incineration. Thus the difference in disposal does not make much of a difference on the Resource Depletion indicator.

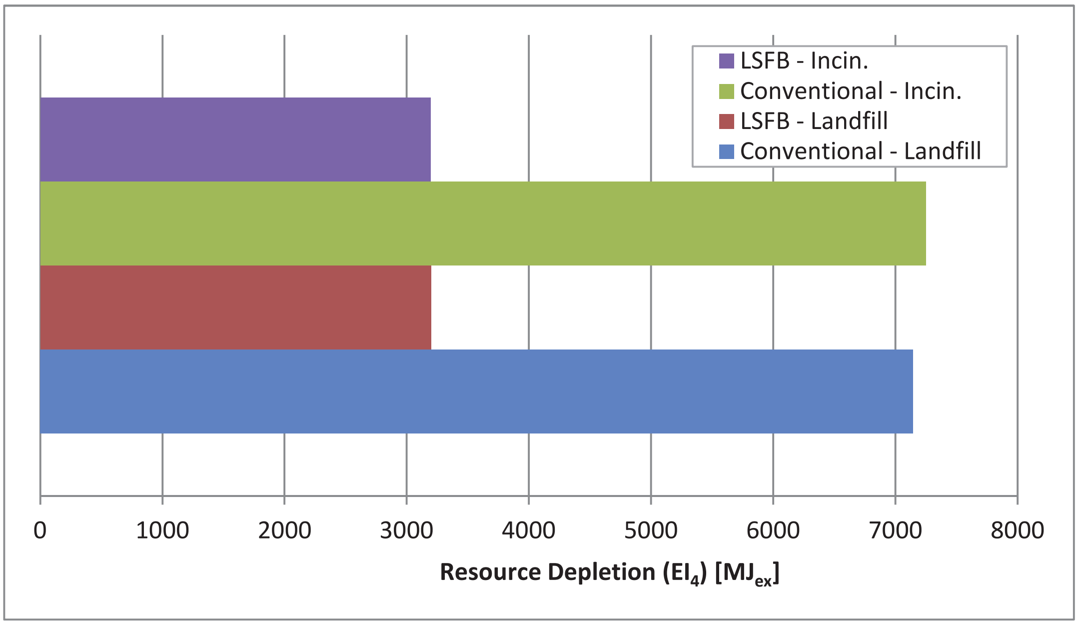

Figure 6-7: The difference in Resource Depletion between landfilling and incinerating the selected waste materials

As was expected, the Waste to Landfill indicator was much lower for the conventional design type in the case of incineration. However, Figure 6-8 shows that there was not much difference between the two disposal options in the case of the LSFB design type.

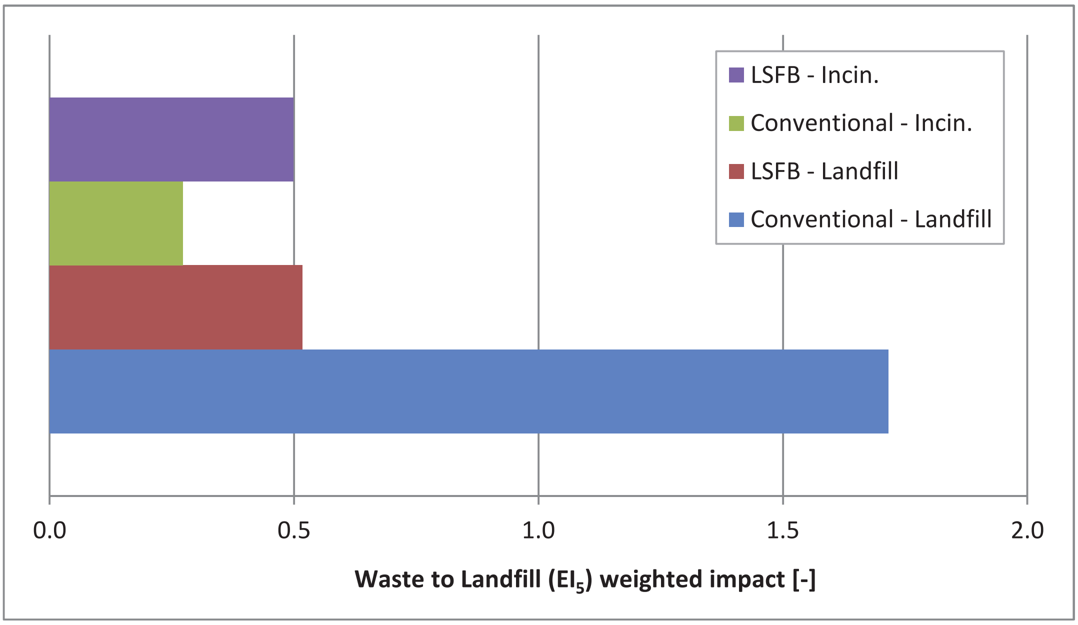

Figure 6-8: Effect of different disposal option of Waste to Landfill

The graph in Figure 6-9 shows the effect of the disposal option on the EII of both designs.

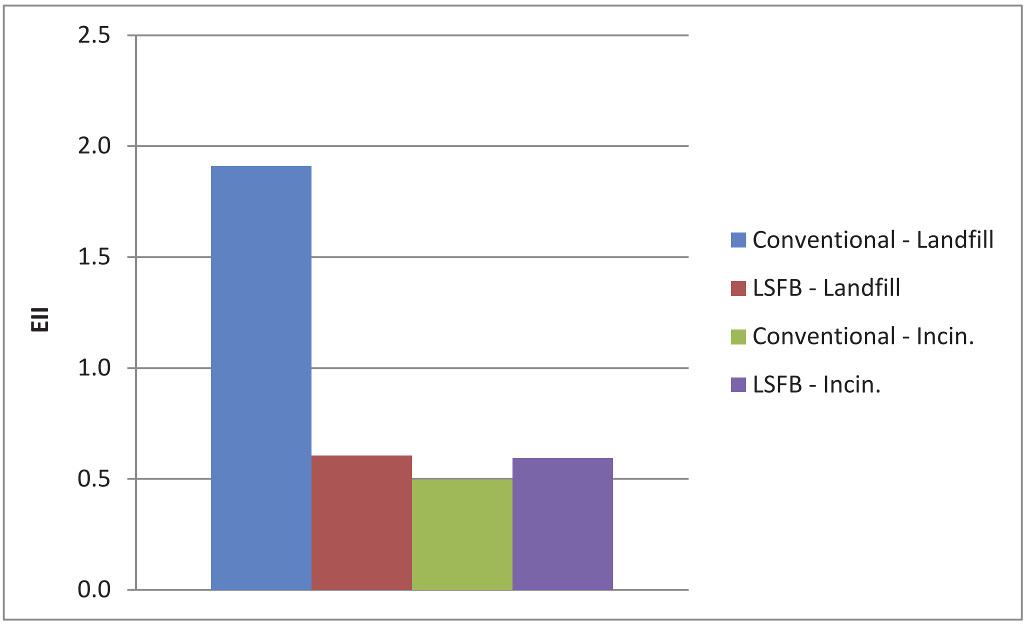

Figure 6-9: The effect of different disposal options on the EII

As is also shown in the previous graph, incineration had the biggest effect on the impacts of the conventional design type in the sense that it more than halved the impact. This is due to the smaller mass that was landfilled in the case of the wooden roof truss, as mostly ash remains from the incineration process which was then landfilled. In the case of the LSFB design type, the impacts remained more or less the same. The reason for this is that the LSFB design type only had one of the materials, which was incinerated instead of landfilled, and there was not much of a difference in impacts between the two disposal options of this material.

6.4. Summary and observations

From the performed sensitivity analysis it was evident that the Waste to Landfill indicator was the indicator with the most influence on the EII of the design types and disposal options. This was, however, expected from the results shown in the calculation of the EII in Chapter 5. In the case of varying the weighting factors, the change in the weighting factor of the Waste to Landfill indicator had the biggest impact on the EII, while the change in weighting factors of the other indicators had negligible effect on the EII. The change in disposal option, in Section 6.3., led to a large difference between the amounts of waste going to landfill in the conventional design type analysis, once again indicating that the Waste to Landfill indicator affected the EII the most of all the indicators. Finally, the EII of alternative disposal was most sensitive to the changes in the transportation distances; however Resource Depletion was also affected largely by this change. It is noted that, even though the transportation distances have a significant influence on the outcome of the EII results, the volume of waste that is landfilled still has an even more significant influence on the final results as larger volumes of waste that is transported leads to a higher resource depletion.

The results of this study indicate the importance of the selection of the disposal option and weighting factors. It also indicates the influence of transportation distances and the volume of landfilled waste on the selected indicators. This study was of high importance, as it indicated which assumptions influence the outcome of the results significantly.

Chapter 7

THE EII OF THE PRE-USE AND END-OF-LIFE PHASES COMBINED

As discussed earlier a previous study on the pre-use phase of the building lifecycle was conducted by Brewis (2011). The purpose of this chapter is to combine the results obtained from the analysis of the pre-use phase with the results obtained in this study on the alternative disposal option of the end-of-life phase. The final result is thus a combination of both the pre-use and end-of-life phases with a discussion on the combined results.

7.1. Pre-use phase and end-of-life phase results

The results obtained for each indicator in the analysis of the conventional design type is shown in Table 7-1.

Table 7-1: Results for the conventional design type

No.	Environmental Impact	Pre-use Total (Brewis, 2011)	End-of-life Total	Unit
EI_1	Carbon Footprint	8736	415.199	kg CO_{2e}
EI_2	Acidification Potential	43	3.034	kg SO_{2e}
EI_3	Eutrophication Potential	0*	6.033	kg NO_{3e}
EI_4	Resource Depletion	92434	7177.679	MJ_{ex}
EI_5	Waste to Landfill	4375	2099.767	kg

*EI_3 was not considered by Brewis, thus a value of 0 is assigned.

The results obtained for the Light Steel Frame Building (LSFB) design type is shown in Table 7-2.

Table 7-2: Results for the LSFB design type

No.	Environmental Impact	Pre-use Total (Brewis, 2011)	End-of-life Total	Unit
EI_1	Carbon Footprint	9207	186.56	kg CO_{2e}
EI_2	Acidification Potential	113	1.35	kg SO_{2e}
EI_3	Eutrophication Potential	0*	2.69	kg NO_{3e}
EI_4	Resource Depletion	113943	3198.87	MJ_{ex}
EI_5	Waste to Landfill	2933	634.38	kg

*EI_3 was not considered by Brewis, thus a value of 0 is assigned.

As can be seen from Table 7-1 and Table 7-2, EI_5 was named “Waste to Landfill”. Brewis considered waste to be landfilled and named EI_5 “Waste Generation” which is the same as the “Waste to Landfill” indicator used in this study.

For easier comparison the normalised and weighted values for the conventional and LSFB design types are shown in Table 7-3 and Table 7-4.

Table 7-3: Normalised and weighted results for the conventional design type (dimensionless)

No.	Environmental Impact	Pre-use impact (Brewis, 2011)	End-of-life impact
EI_1	Carbon Footprint	1.12	0.053
EI_2	Acidification Potential	0.92	0.065
EI_3	Eutrophication Potential	0*	0.077
EI_5	Waste to Landfill	3.56	1.711

*EI_3 was not considered by Brewis, thus a value of 0 is assigned.

Table 7-4: Normalised and weighted results for the LSFB design type (dimensionless)

No.	Environmental Impact	Pre-use impact (Brewis, 2011)	End-of-life impact
EI_1	Carbon Footprint	1.19	0.024
EI_2	Acidification Potential	2.44	0.029
EI_3	Eutrophication Potential	0*	0.035
EI_5	Waste to Landfill	2.39	0.517

*EI_3 was not considered by Brewis, thus a value of 0 is assigned.

The final EII for the pre-use phase of the conventional design type was calculated as 5.61 and as 6.00 for the LSFB design type. The study was then expanded to include the end-of-life phase in the final results. The EII obtained for the end-of-life phase of the conventional design type was 1.907 and 0.605 for the end-of-life phase of the LSFB design type. The results for the pre-use and end-of-life phase were combined in order to obtain one value for each indicator of each design type and also the combined EII of each design type.

7.2. Combined results

By combining the results obtained in the analysis of the pre-use and end-of-life phases the combined weighted impacts were obtained for each indicator (Table 7-5) and graphically represented in Figure 7-1 and Figure 7-2.

Table 7-5: Combined normalised and weighted impacts

No.	Environmental Impact	Conventional Total	LSFB Total	Unit
EI_1	Carbon Footprint	1.173	1.214	[-]
EI_2	Acidification Potential	0.985	2.469	[-]
EI_3	Eutrophication Potential	0.077	0.035	[-]
EI_4	Resource Depletion	99611.68	117141.9	[MJ_{ex}]
EI_5	Waste to Landfill	5.271	2.907	[-]

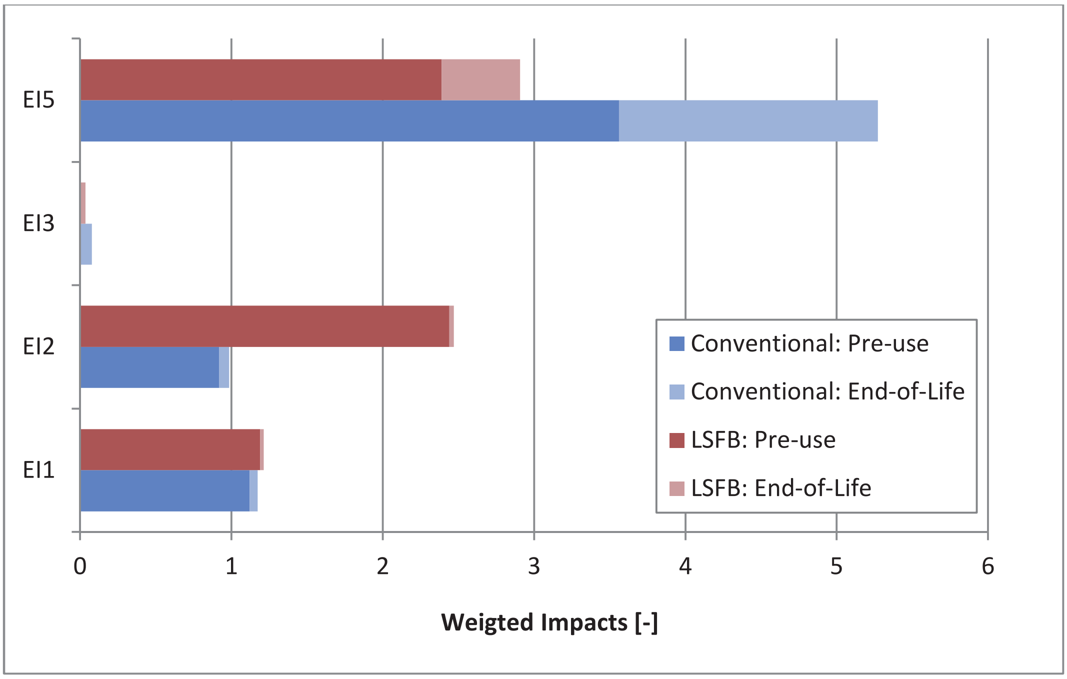

Figure 7-1: Weighted impacts for both design types

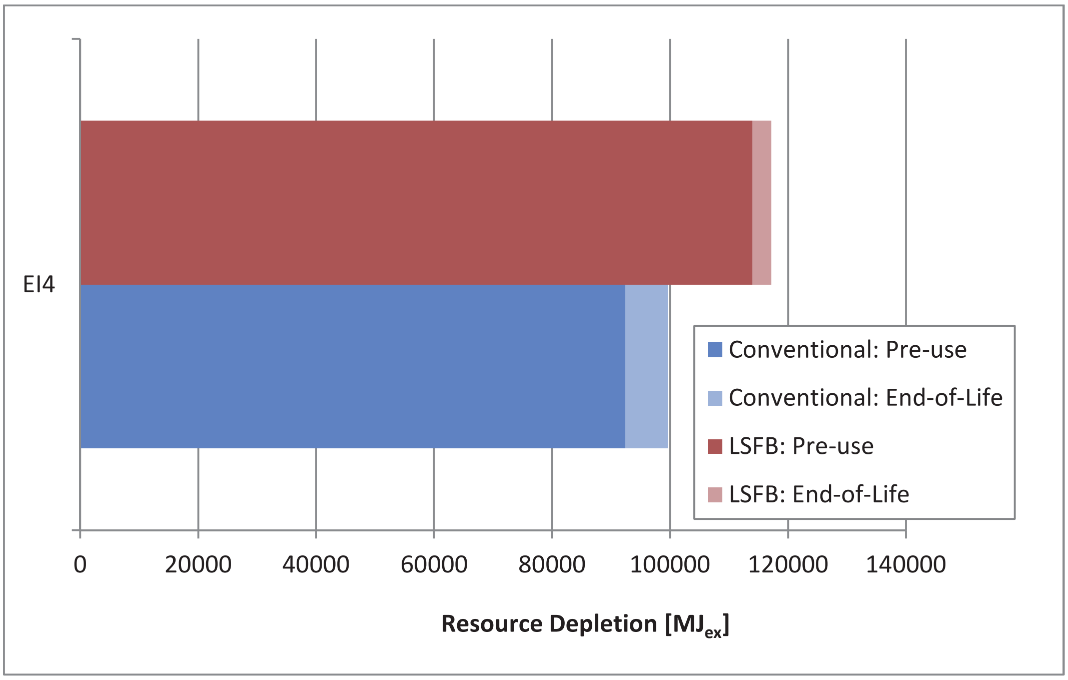

Figure 7-2: Combined Resource Depletion for both design types

The combined EII for both design types were calculated as 7.521 for the conventional design type and 6.605 for the LSFB design type. The results are shown in Figure 7-3. From this figure it is concluded that the LSFB design type has the least combined environmental impact when considering the pre-use and end-of-life phases.

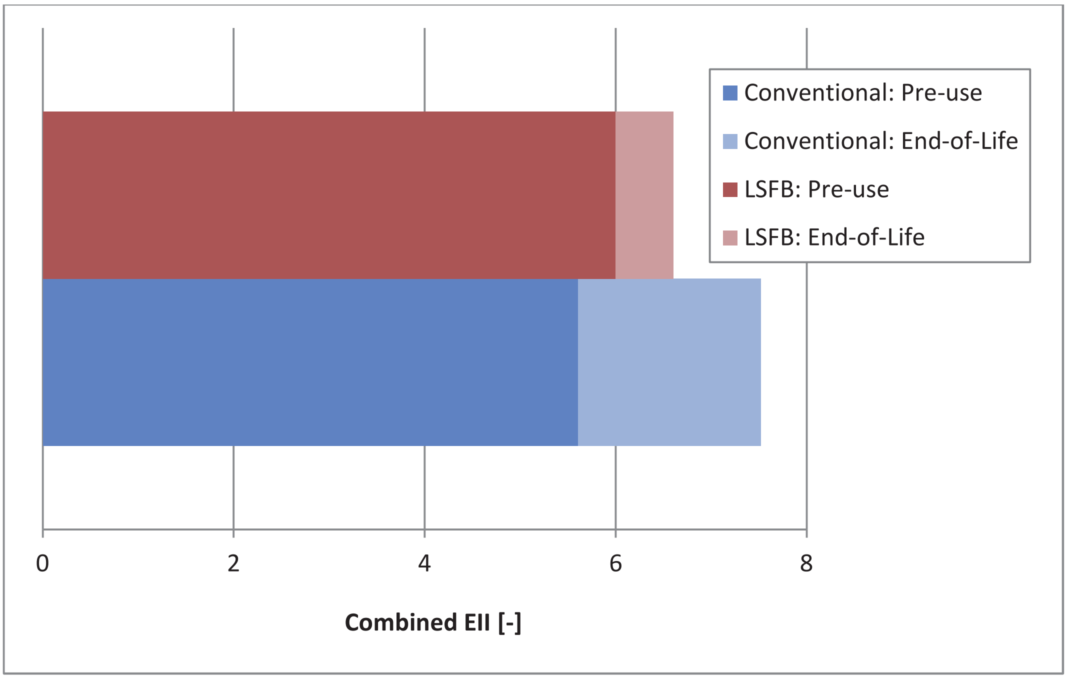

Figure 7-3: Combined EII results for both design types

By perusing the graphs shown in Figure 7-1 to Figure 7-3 it is clear that the pre-use phase has a much more significant environmental impact than the end-of-life phase. This is due to the higher environmental burdens associated with the production of the selected building materials. It should be noted, however, that a reduction in the environmental impact of the pre-use phase can be possible when reused or recycled materials are used for the construction of new structures.

In the case of only considering the end-of-life phase, Waste to Landfill had a significant influence on the outcome of the EII results. In combination with the pre-use phase, however, the influence of this factor is less significant due to the much larger environmental impacts of the pre-use phase. It is thus evident that even though large volumes of landfilled waste in the end-of-life phase have a significant environmental impact on this phase, it becomes less significant when the structure’s whole lifecycle is considered. It should, however, not be overlooked as a possible way in which to minimise the environmental impact of the end-of-life phase.

Chapter 8

CONCLUSIONS AND RECOMMENDATIONS

The aim of this project was to determine the environmental impact of the end-of-life phase of the building lifecycle by developing a model which was applied to a case study of using two different low-cost housing (LCH) structural systems, namely the conventional and Light Steel Frame Building (LSFB) design types. LCH was chosen as a case study due to the significant potential it has in reducing the environmental impact of the construction industry in South Africa. However, due to the lack of normalisation and weighting factors for the South African context, global, European and, in some cases, Danish and Swiss factors were used in order to determine the Environmental Impact Indicator (EII) of each LCH design alternative.

The EII of the end-of-life phase of both design types were determined and combined with the results of the pre-use phase to get more thorough results. From the conducted sensitivity analysis it was evident that transport distances will need to be set in order to determine the most accurate representation of the environmental impact. Varying transport distances had a significant impact on the EII of each alternative in both the pre-use and the end-of-life phase. The most influential factor, however, was the volume of waste that is landfilled. Waste to Landfill and the disposal method of waste thus had a major impact on the EII in the end-of-life phase. The amount of waste being landfilled should be kept as low as possible in order to keep the environmental impact of the end-of-life phase as low as possible. In the context of the pre-use and end-of-life phases combined, however, the influence of the Waste to Landfill indicator on the EII was significantly lower due to the overshadowing impacts of the production of construction materials in the pre-use phase.

The proposed model can be used in order to optimise the design of the structure it is applied to by substituting materials, with large impacts, with alternative materials, with lower impacts, thus lowering the EII of the design. In the end-of-life phase the model can also be used as an optimisation tool. Together with the case specific Multi-Criteria Decision

Making (MCDM) model, the end-of-life phase can be optimised to include the most environmentally viable demolition method and the disposal options with the least environmental impact can be used.

Even though this model is comprehensive and includes all materials used in the structural systems, its accuracy for the South African context is arguable. A proper model for the South African construction industry can only be developed once emission, normalisation and weighting factors have been obtained for South Africa, or at least Africa. Once these factors are obtained the model will deliver a greater accuracy for the South African context.

Furthermore the model of the pre-use phase should be extended to include Eutrophication Potential. Waste Generation was considered as an impact indicator in this model and the generated waste was assumed to be landfilled, thus the waste may cause eutrophication of land and water resources. As Eutrophication Potential was the largest of the emission impacts in the end-of-life phase it is important to be included in models that consider landfilling of waste. By including Eutrophication Potential in the pre-use phase, a more accurate representation of the emission indicators will be achieved.

The combination of the two studies only covered two phases of the building lifecycle, thus the model can also be developed even further in order to include the use phase of the building lifecycle. In this phase the refurbishment of the building, demolition during refurbishment and replacement of structural elements can be included, to name a few. This refurbishment process in the use phase will also lead to waste, further emissions and resource depletion. Thus by extending the study and including the use phase an even more accurate representation of the environmental impact of each structural system will be achieved which will also influence the environmental impact of the construction industry. When considering the use phase a service life should be assigned to the structure in order to determine how many times the structure will be refurbished and at what stage it is demolished. A decision making model can also be developed in order to determine whether or not a building should be refurbished or demolished. By including these elements the durability of each alternative will also be determined which has a direct influence on the final environmental impact of each structural system alternative.

Due to the lack of incentives and legislation on waste disposal and alternative disposal options in South Africa most role players in the construction industry are ignoring disposal alternatives and merely landfill waste as it is the cheapest and quickest option. In order to address this issue the cost of landfilling construction and demolition waste should be raised and companies landfilling waste should receive penalties in the form of increased taxes or a reduction in green building credits. Companies who do comply to using alternative disposal methods should be rewarded through a reduction in taxes and the awarding of green building credits which will be considered in the tender process of new projects. Legislation should be put in place in order to aid the use of recycled materials in new applications and at some stage also to make recycling of certain materials compulsory.

Studies on the social and economic aspects of sustainability are also recommended for future studies in order to have a comprehensive model for sustainable construction.

Finally, in order to best implement the developed models, a software package should be developed in order to eradicate the tedious process of transferring impact factors from the Ecoinvent databases to spreadsheets in order to calculate the impacts. A software package for the South African industry using South African factors should be developed in order to best model the South African situation.

By applying all these recommendations to the existing models as well as considering them in future developments, the environmental impact of the South African construction industry can be calculated easily and the final impact lowered immensely.

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APPENDIX A

MCDM EVALUATION CALCULATIONS

Abbreviations

SC	Site characteristics
S. cond.	Site conditions
TC	Time and cost
RR	Reuse and recycling
H&S	Health and safety
Prox.	Proximity to other structures
Site prep.	Site preparation
Demol.	Demolition
Waste rem.	Waste removal
PD	Progressive demolition
DC	Deconstruction
DS	Destruction
L. Weight	Local weight
G. Weight	Global weight

Criteria Evaluation

Criteria	SC	S. cond.	TC	RR
SC	1	2	0.20	0.111
S. cond.	0.5	1	0.14	0.111
TC	5	7	1	0.25
RR	9	9	4	1
sum	15.5	19	5.34	1.472

Criteria	SC	S. cond.	TC	RR	**Weight**
SC	0.065	0.105	0.04	0.075	**0.071**
S. cond.	0.032	0.053	0.03	0.075	**0.047**
TC	0.323	0.368	0.19	0.170	**0.262**
RR	0.581	0.474	0.75	0.679	**0.621**
				sum	1.000

Structure Characteristics

Sub-criteria	Height	Type
Height	1	1
Type	1	1
sum	2	2

Criteria	Height	Type	**L.Weight**	**G.Weight**
Height	0.500	0.500	**0.500**	**0.035**
Type	0.500	0.500	**0.500**	**0.035**
		sum	1.000	0.071

Site Conditions

Sub-criteria	H&S	Prox.
H&S	1	0.333
Prox.	3	1
sum	4	1.333

Sub-criteria	H&S	Prox.	**L.Weight**	**G.Weight**
H&S	0.250	0.250	**0.250**	**0.012**
Prox.	0.750	0.750	**0.750**	**0.035**
		sum	1.000	0.047

Time and Cost

Sub-criteria	Resources	Site prep.	Demol.	Waste rem.
Resources	1	0.5	0.333	0.5
Site prep.	2	1	0.5	1
Demolition	3	2	1	2
Waste removal	2	1	0.5	1
sum	8	4.5	2.333	4.500

Sub-criteria	Resources	Site prep.	Demol.	Waste rem.	**L.Weight**	**G.Weight**
Resources	0.125	0.111	0.143	0.111	**0.123**	**0.032**
Site prep.	0.25	0.222	0.214	0.222	**0.227**	**0.060**
Demolition	0.375	0.444	0.429	0.444	**0.423**	**0.111**
Waste removal	0.25	0.222	0.214	0.222	**0.227**	**0.060**
				sum	1.000	0.262

Height Evaluation

Criteria	PD	DC	DS
PD	1	2	0.25
DC	0.5	1	0.167
DS	4	6	1
sum	5.5	9	1.417

Criteria	PD	DC	DS	**L.Weight**	**G.Weight**
PD	0.182	0.222	0.18	**0.194**	**0.007**
DC	0.091	0.111	0.12	**0.107**	**0.004**
DS	0.727	0.667	0.71	**0.700**	**0.025**
			sum	1.000	0.035

Type Evaluation

Criteria	PD	DC	DS
PD	1	3	0.333
DC	0.333	1	0.143
DS	3	7	1
sum	4.333	11	1.476

Criteria	PD	DC	DS	**L.Weight**	**G.Weight**
PD	0.231	0.273	0.23	**0.243**	**0.009**
DC	0.077	0.091	0.10	**0.088**	**0.003**
DS	0.692	0.636	0.68	**0.669**	**0.024**
			sum	1.000	0.035

Health and Safety Evaluation

Criteria	PD	DC	DS
PD	1	0.333	7
DC	3	1	9
DS	0.143	0.111	1
sum	4.143	1.444	17

Criteria	PD	DC	DS	**L.Weight**	**G.Weight**
PD	0.241	0.231	0.41	**0.295**	**0.003**
DC	0.724	0.692	0.53	**0.649**	**0.008**
DS	0.034	0.077	0.06	**0.057**	**0.001**
			sum	1.000	0.012

Proximity to nearby structures Evaluation

Criteria	PD	DC	DS
PD	1	0.333	7
DC	3	1	9
DS	0.143	0.111	1
sum	4.143	1.444	17

Criteria	PD	DC	DS	**L.Weight**	**G.Weight**
PD	0.241	0.231	0.41	**0.295**	**0.010**
DC	0.724	0.692	0.53	**0.649**	**0.023**
DS	0.034	0.077	0.06	**0.057**	**0.002**
			sum	1.000	0.035

Resources Evaluation

Criteria	PD	DC	DS
PD	1	3	0.2
DC	0.333	1	0.143
DS	5	7	1
sum	6.333	11	1.343

Criteria	PD	DC	DS	**L.Weight**	**G.Weight**
PD	0.158	0.273	0.15	**0.193**	**0.006**
DC	0.053	0.091	0.11	**0.083**	**0.003**
DS	0.789	0.636	0.74	**0.724**	**0.023**
			sum	1.000	0.032

Site Preparation Evaluation

Criteria	PD	DC	DS
PD	1	0.5	4
DC	2	1	7
DS	0.25	0.143	1
sum	3.25	1.643	12

Criteria	PD	DC	DS	**L.Weight**	**G.Weight**
PD	0.308	0.304	0.33	**0.315**	**0.019**
DC	0.615	0.609	0.58	**0.602**	**0.036**
DS	0.077	0.087	0.08	**0.082**	**0.005**
			sum	1.000	0.060

Demolition Evaluation

Criteria	PD	DC	DS
PD	1	3	0.143
DC	0.333	1	0.111
DS	7	9	1
sum	8.333	13	1.254

Criteria	PD	DC	DS	**L.Weight**	**G.Weight**
PD	0.120	0.231	0.11	**0.155**	**0.017**
DC	0.040	0.077	0.09	**0.069**	**0.008**
DS	0.840	0.692	0.80	**0.777**	**0.086**
			sum	1.000	0.111

Removal of Demolition Waste Evaluation

Criteria	PD	DC	DS
PD	1	0.2	3
DC	5	1	9
DS	0.333	0.111	1
sum	6.333	1.311	13

Criteria	PD	DC	DS	**L.Weight**	**G.Weight**
PD	0.158	0.153	0.23	**0.180**	**0.011**
DC	0.789	0.763	0.69	**0.748**	**0.045**
DS	0.053	0.085	0.08	**0.071**	**0.004**
			sum	1.000	0.060

Reuse and Recycling Potential Evaluation

Criteria	PD	DC	DS
PD	1	0.167	3
DC	6	1	9
DS	0.333	0.111	1
sum	7.333	1.278	13

Criteria	PD	DC	DS	**L.Weight**	**G.Weight**
PD	0.136	0.130	0.23	**0.166**	**0.103**
DC	0.818	0.783	0.69	**0.764**	**0.474**
DS	0.045	0.087	0.08	**0.070**	**0.043**
			sum	1.000	0.621

APPENDIX B

CONSISTENCY INDECES

Abbreviations

SC	Site characteristics
S. cond.	Site conditions
TC	Time and cost
RR	Reuse and recycling
PD	Progressive demolition
DC	Deconstruction
DS	Destruction
CI	Consistency Index
λ	Eigenvalue

Criteria

	SC	**S. cond.**	**TC**	**RR**
SC	1	2	0.2	0.111
S. cond.	0.5	1	0.14	0.111
TC	5	7	1	0.25
RR	9	9	4	1

Relative priority
0.071
0.047
0.262
0.621

Eigenvector
4.037
4.022
4.187
4.390

λ	4.159
CI	**0.053**

Alternatives

Height

	PD	**DC**	**DS**
PD	1	2	0.25
DC	0.5	1	0.167
DS	4	6	1

Relative priority
0.194
0.107
0.700

Eigenvector
3.0056295
3.0027881
3.0192417

λ	3.01
CI	**0.0046**

Type

	PD	DC	DS
PD	1	3	0.333
DC	0.333	1	0.143
DS	3	7	1

Relative priority
0.009
0.003
0.024

Eigenvector
3.005
3.002
3.014

λ	3.007
CI	**0.0035**

Health & Safety

	PD	DC	DS
PD	1	0.333	7
DC	3	1	9
DS	0.143	0.111	1

Relative priority
0.003
0.008
0.001

Eigenvector
3.082
3.150
3.012

λ	3.081
CI	**0.041**

Proximity to nearby structures

	PD	DC	DS
PD	1	0.333	7
DC	3	1	9
DS	0.143	0.111	1

Relative priority
0.010
0.023
0.002

Eigenvector
3.082
3.150
3.012

λ	3.081
CI	**0.041**

Resources

	PD	DC	DS
PD	1	3	0.2
DC	0.333	1	0.143
DS	5	7	1

Relative priority
0.006
0.003
0.023

Eigenvector
3.043
3.014
3.141

λ	3.066
CI	**0.033**

Site preparation

	PD	DC	DS
PD	1	0.5	4
DC	2	1	7
DS	0.25	0.143	1

Relative priority
0.019
0.036
0.005

Eigenvector
3.002
3.004
3.000

λ	3.002
CI	**0.0010**

Demolition

	PD	DC	DS
PD	1	3	0.143
DC	0.333	1	0.111
DS	7	9	1

Relative priority
0.017
0.008
0.086

Eigenvector
3.043
3.013
3.190

λ	3.082
CI	**0.041**

Removal of demolition waste

	PD	DC	DS
PD	1	0.2	3
DC	5	1	9
DS	0.333	0.111	1

Relative priority
0.011
0.045
0.004

Eigenvector
3.017
3.065
3.006

λ	3.029
CI	**0.015**

Reuse & recycling potential

	PD	DC	DS
PD	1	0.167	3
DC	6	1	9
DS	0.333	0.111	1

Relative priority
0.103
0.474
0.043

Eigenvector
3.030
3.124
3.009

λ	3.054
CI	**0.027**

APPENDIX C

Conventional Design: Environmental impacts for reference (landfill) disposal scenario

Materials			Disposal	Ecoinvent			Carbon Footprint EI_1		Acidification Potential EI_2		Eutrophication Potential EI_3		Resource Depletion EI_4		Waste to Landfill EI_5	
Item	Unit	Quantity	Type	Unit	Conversion	Quantity	[kg CO_{2eq}/unit]	per item	[kg SO_{2eq}/unit]	per item	[kg $NO_3^-{}_{eq}$/unit]	per item	[MJ_{ex}/unit]	per item	[kg]	per item
Foundations																
Excavation	m^3	8.94														
10 MPA concrete foundation (600x200mm)	m^3	3.00	Landfill	kg	2200	6600	0.014122	93.2052	0.00011201	0.739266	0.00021401	1.412466	0.332053	2191.5499	0.9997632	6598.437
Reinforcing (4 x Y12)	kg	103.00	Landfill	kg			0.068015	7.005545	0.00063196	0.0650919	0.0011553	0.1189959	1.15988	119.46763	1.0030048	103.3095
190 mm blockwork including	m^2	14.90	Landfill	kg	160 ^{1}	2384	0.014122	33.66685	0.00011201	0.2670318	0.00021401	0.5101998	0.332053	791.61438	0.9997632	2383.435
brickforce (75x2.8mm)	m	125.00	Reuse	kg	0.11 ^{2}	13.75	0.0038784	0.053328	2.64E-05	0.0003624	6.28E-05	0.0008636	0.0873171	1.2006103	0.0004163	0.005724
galvanised	m^2	2.45														
filled with concrete	m^3	0.97	Landfill	kg	2200	2134	0.014122	30.13635	0.00011201	0.2390293	0.00021401	0.4566973	0.332053	708.60113	0.9997632	2133.495
Floor slab																
Damp proof membrane 250 micron	m^2	41.00	Landfill	kg	0.23 ^{3}	9.43	0.010078	0.095036	7.30E-05	0.0006883	0.00014337	0.001352	0.2699254	2.5453964	0.9997331	9.427483
25 MPa concrete (power floated)	m^3	4.92	Landfill	kg	2200	10824	0.014122	152.8565	0.00011201	1.2123962	0.00021401	2.3164442	0.332053	3594.1418	0.9997632	10821.44
Steel mesh ref 193	m^2	41.00	Landfill	kg	1.93 ^{4}	79.13	0.068015	5.382027	0.00063196	0.050007	0.0011553	0.0914189	1.15988	91.7813	1.0030048	79.36777
External walls 140 mm																
Two top courses of brickwork to be filled with 10 MPa concrete	m^3	0.65	Landfill	kg	2200	1430	0.014122	20.19446	0.00011201	0.1601743	0.00021401	0.3060343	0.332053	474.83581	0.9997632	1429.661
Blockwork, mortar &	m^2	75.00	Landfill	kg	160 ^{5}	12000	0.014122	169.464	0.00011201	1.34412	0.00021401	2.56812	0.332053	3984.6361	0.9997632	11997.16
brickforce as NHBRC standard	m	125.00	Reuse	kg	0.11 ^{6}	13.75	0.0038784	0.053328	2.64E-05	0.0003624	6.28E-05	0.0008636	0.0873171	1.2006103	0.0004163	0.005724
galvanised	m^2	2.45														
Plaster externally (12 mm thick)	m^2	75.00	Landfill	kg	27.6 ^{7}	2070	0.010078	20.86146	7.30E-05	0.1510893	0.00014337	0.2967759	0.2699254	558.74555	0.9997331	2069.447
Bagged internally	m^2	75.00														
DPC (110mm width) - 375 micron	m	29.00	Landfill	kg	0.03 ^{8}	0.87	0.010078	0.008768	7.30E-05	6.35E-05	0.00014337	0.0001247	0.2699254	0.2348351	0.9997331	0.869768
Internal walls 90mm																
Blockwork, mortar	m^2	26.00	Landfill	kg	160	4160	0.014122	58.74752	0.00011201	0.4659616	0.00021401	0.8902816	0.332053	1381.3405	0.9997632	4159.015
Bagged	m^2	52.00														
Ceiling and thermal insulation																
6.4 mm gypsum plaster board	m^2	40.00	Landfill	kg	5.7 ^{9}	228	0.0134	3.0552	0.00010505	0.0239514	0.0002014	0.0459192	0.320963	73.179574	0.9997632	227.946
50mm glass wool laid to manufacturers specification, finished with coverstrips (incl cornices)	m^2	40.00	Landfill	kg	2	80	0.010078	0.80624	7.30E-05	0.0058392	0.00014337	0.0114696	0.2699254	21.594031	0.9997331	79.97865
Roofing																
Howe type truss to be designed by supplier for 7 m span	m^3	0.63	Landfill	kg	720	453.6	0.013872	6.292339	0.00030172	0.1368602	0.0008225	0.373086	0.259551	117.73233	0.0134416	6.097118
114x38mm wall plate including beam filling	m^3	0.05	Reuse	kg	7900	395	0.0038784	1.531968	2.64E-05	0.0104098	6.28E-05	0.0248092	0.0873171	34.49026	0.0004163	0.164443
50x76 mm purlins on edge at maximum 12 m spacing	m^3	0.22	Reuse	kg	7900	1738	0.0038784	6.740659	2.64E-05	0.0458033	6.28E-05	0.1091603	0.0873171	151.75714	0.0004163	0.72355
Roof covering																
0.54 mm Fielders corrugated Colorbond G550 AZ150 anti-corrosive	m^2	46.00	Reuse	kg	5.03 ^{10}	231.38	0.0038784	0.897384	2.64E-05	0.0060978	6.28E-05	0.0145325	0.0873171	20.203434	0.0004163	0.096326
"Zincalume" based steel sheeting	m^2	46.00														
Ridge cappings 450 mm girth	m2	6.00	Reuse	kg	2.26	13.56	0.0038784	0.052591	2.64E-05	0.0003574	6.28E-05	0.0008517	0.0873171	1.1840201	0.0004163	0.005645
galvanised	m^2	2.70														
Additional transport (10 km)	tkm	439.43		tkm			0.48632	213.7036	0.0026554	1.1668624	0.0059029	2.5939113	8.5936702	3776.3165	0.0396913	17.44153
Total impact								824.8104		6.0918255		12.144378		18098.353		42117.53

Conventional Design: Environmental impacts for alternative disposal scenario

Materials			Disposal	Ecoinvent			Carbon Footprint EI_1		Acidification Potential EI_2		Eutrophication Potential EI_3		Resource Depletion EI_4		Waste to Landfill EI_5	
Item	Unit	Quantity	Type	Unit	Conversion	Quantity	[kg CO_{2eq}/unit]	per item	[kg SO_{2eq}/unit]	per item	[kg $NO_3^-{}_{eq}$/unit]	per item	[MJ_{ex}/unit]	per item	[kg]	per item
Foundations																
Excavation	m^3	8.94														
10 MPA concrete foundation (600x200mm)	m^3	3.00	Recycle	kg	2200	6600	0.0040446	26.69436	3.90E-05	0.2575386	7.06E-05	0.4662306	0.0621286	410.04893	3.732E-05	0.246301
Reinforcing (4 x Y12)	kg	103.00	Recycle	kg			0.057938	5.967614	0.00055897	0.0575739	0.0010119	0.1042257	0.8899947	91.669457	0.0005346	0.055062
190 mm blockwork including	m^2	14.90	Recycle	kg	160 [1]	2384	0.0040446	9.642326	3.90E-05	0.0930261	7.06E-05	0.1684081	0.0621286	148.11464	3.732E-05	0.088967
brickforce (75x2.8mm)	m	125.00	Reuse	kg	0.11 [2]	13.75	0.0038784	0.053328	2.64E-05	0.0003624	6.28E-05	0.0008636	0.0873171	1.2006103	0.0004163	0.005724
galvanised	m^2	2.45														
filled with concrete	m^3	0.97	Recycle	kg	2200	2134	0.0040446	8.631176	3.90E-05	0.0832708	7.06E-05	0.1507479	0.0621286	132.58249	3.732E-05	0.079637
Floor slab																
Damp proof membrane 250 micron	m^2	41.00	Landfill	kg	0.23 [3]	9.43	0.010078	0.095036	7.30E-05	0.0006883	0.00014337	0.001352	0.2699254	2.5453964	0.9997331	9.427483
25 MPa concrete (power floated)	m^3	4.92	Recycle	kg	2200	10824	0.0040446	43.77875	0.000039021	0.4223633	0.000070641	0.7646182	0.0621286	672.48024	3.732E-05	0.403933
Steel mesh ref 193	m^2	41.00	Recycle	kg	1.93 [4]	79.13	0.057938	4.584634	0.00055897	0.0442313	0.0010119	0.0800716	0.8899947	70.425282	0.0005346	0.042302
External walls 140 mm																
Two top courses of brickwork to be filled with 10 MPa concrete	m^3	0.65	Recycle	kg	2200	1430	0.0040446	5.783778	0.000039021	0.0558	0.000070641	0.1010166	0.0621286	88.843935	3.732E-05	0.053365
Blockwork, mortar &	m^2	75.00	Recycle	kg	160 [5]	12000	0.0040446	48.5352	0.000039021	0.468252	0.000070641	0.847692	0.0621286	745.54351	3.732E-05	0.44782
brickforce as NHBRC standard	m	125.00	Recycle	kg	0.11 [6]	13.75	0.0038784	0.053328	2.64E-05	0.0003624	6.28E-05	0.0008636	0.0873171	1.2006103	0.0004163	0.005724
galvanised	m^2	2.45														
Plaster externally (12 mm thick)	m^2	75.00	Landfill	kg	27.6 [7]	2070	0.010078	20.86146	7.30E-05	0.1510893	0.00014337	0.2967759	0.2699254	558.74555	0.9997331	2069.447
Bagged internally	m^2	75.00														0
DPC (110mm width) - 375 micron	m	29.00	Landfill	kg	0.03 [8]	0.87	0.010078	0.008768	7.30E-05	6.35E-05	0.00014337	0.0001247	0.2699254	0.2348351	0.9997331	0.869768
Internal walls 90mm																
Blockwork, mortar	m^2	26.00	Recycle	kg	160	4160	0.0040446	16.82554	0.000039021	0.1623274	0.000070641	0.2938666	0.0621286	258.45508	3.732E-05	0.155244
Bagged	m^2	52.00														
Ceiling and thermal insulation																
6.4 mm gypsum plaster board	m^2	40.00	Recycle	kg	5.7 [9]	228	0.0033226	0.757553	3.21E-05	0.0073088	5.80E-05	0.0132315	0.0510399	11.637106	3.066E-05	0.00699
50mm glass wool laid to manufacturers specification, finished with coverstrips (incl cornices)	m^2	40.00	Recycle	kg	2	80	0	0	0.00E+00	0	0	0	0	0	0	0
Roofing																
Howe type truss to be designed by supplier for 7 m span	m^3	0.63	Reuse	kg	720	453.6	0	0	0	0	0	0	0	0	0	0
114x38mm wall plate including beam filling	m^3	0.05	Reuse	kg	7900	395	0.0038784	1.531968	2.64E-05	0.0104098	6.28E-05	0.0248092	0.0873171	34.49026	0.0004163	0.164443
50x76 mm purlins on edge at maximum 12 m spacing	m^3	0.22	Reuse	kg	7900	1738	0.0038784	6.740659	2.64E-05	0.0458033	6.28E-05	0.1091603	0.0873171	151.75714	0.0004163	0.72355
Roof covering																
0.54 mm Fielders corrugated Colorbond G550 AZ150 anti-corrosive	m^2	46.00	Reuse	kg	5.03 [10]	231.38	0.0038784	0.897384	2.64E-05	0.0060978	6.28E-05	0.0145325	0.0873171	20.203434	0.0004163	0.096326
"Zincalume" based steel sheeting	m^2	46.00														
Ridge cappings 450 mm girth	m2	6.00	Reuse	kg	2.26	13.56	0.0038784	0.052591	2.64E-05	0.0003574	6.28E-05	0.0008517	0.0873171	1.1840201	0.0004163	0.005645
galvanised	m^2	2.70														
Additional transport (10 km)	tkm	439.43					0.48632	213.7036	0.0026554	1.1668624	0.0059029	2.5939113	8.5936702	3776.3165	0.0396913	17.44153
Total impact								415.199		3.0337886		6.0333537		7177.679		2099.767

References

1. CMA Masonry Manual 2007 Table 7.3
2. lorraine@impiwire.co.za
3. www.sigscp.co.uk
4. www.steeldalemesh.com
5. CMA Masonry Manual 2007 Table 7.3
6. lorraine@impiwire.co.za
7. SANS 10160-2 Table A.1
8. CMA Masonry Manual 2007 Table 7.3
9. www.gyproc.co.za
10. www.clotansteel.co.za

APPENDIX D

LSFB: Environmental impacts for reference (landfill) disposal scenario

Materials			Disposal	Ecoinvent			Carbon Footprint EI_1		Acidification Potential EI_2		Eutrophication Potential EI_3		Resource Depletion EI_4		Waste to Landfill EI_5	
Item	Unit	Quantity	Type	Unit	Conversion	Quantity	[kg CO_{2eq}/unit]	per item	[kg SO_{2eq}/unit]	per item	[kg $NO_3^-{}_{eq}$/unit]	per item	[MJ_{ex}/unit]	per item	[kg]	per item
Foundation																
Excavation	m^3	4.06														
Concrete (400x150 mm) - 25 MPa	m^3	1.54	Landfill	kg	2200	3388	0.014122	47.84534	0.00011201	0.3794899	0.00021401	0.7250659	0.332053	1124.9956	0.9997632	3387.198
Reinforcing (2-Y10)	kg	31.35	Landfill	kg			0.068015	2.13227	0.00063196	0.0198119	0.0011553	0.0362187	1.15988	36.362236	1.0030048	31.4442
Brickwork (clay) - double layer cavity wall	m^2	12.70	Landfill	kg	171 [1]	2171.7	0.0134	29.10078	0.00010505	0.2281371	0.0002014	0.4373804	0.3209634	697.0362	0.9997632	2171.186
Mortar	m^3	0.19	Landfill	kg	3150	598.5	0.014122	8.452017	0.00011201	0.067038	0.00021401	0.128085	0.3320901	198.75593	0.9997632	598.3583
Brickforce	m	76.20	Reuse	kg	0.11 [2]	8.382	0.0038784	0.032509	2.64E-05	2.21E-04	6.28E-05	5.26E-04	0.0873171	0.7318921	0.0004163	0.00349
Floor slab																
Concrete (100 mm - 25 MPa)	m^3	4.00	Landfill	kg	2200	8800	0.014122	124.2736	0.00011201	0.985688	0.00021401	1.883288	0.332053	2922.0665	0.9997632	8797.916
Reinforcing - Mesh ref 193	m^2	41.00	Landfill	kg	1.93 [3]	79.13	0.068015	5.382027	6.32E-04	0.050007	0.0011553	0.0914189	1.15988	91.7813	1.0030048	79.36777
Damp proof membrane	m^2	41.00	Landfill	kg	0.23 [4]	9.43	0.010078	0.095036	7.30E-05	0.0006883	0.00014337	0.001352	0.2699254	2.5453964	0.9997331	9.427483
Anchor bolts																
External walls																
Light steel profiles	m	357.00	Reuse	kg		386.1	0.0038784	1.49745	2.64E-05	1.02E-02	6.28E-05	2.43E-02	0.0873171	33.713138	0.0004163	0.160738
galvanised	m^2	134.95														
Fasteners: #10-16x16 wafer screws	sum	530.00														
Cladding - 9 mm fibre cement board	m^2	75.00	Landfill	kg	12.6 [5]	945	0.02014	19.0323	3.49E-04	0.3294365	8.38E-04	0.7916549	0.4120712	389.40731	0.3062078	289.3664
Vapour permeable membrane	m^2	75.00	Landfill	kg	0.23	17.25	0.010078	0.173846	7.30E-05	0.0012591	0.00014337	0.0024731	0.2699254	4.6562129	0.9997331	17.2454
Thermal break -OSB	m^3	1.43	Landfill	kg	720	1029.6	0.013872	14.28261	0.00030172	0.3106509	0.0008225	0.846846	0.259551	267.23369	0.0134416	13.83949
Bulk insulation - 25 mm glass wool	m^2	75.00	Landfill	kg	1 [6]	75	0.010078	0.75585	7.30E-05	0.0054743	0.00014337	0.0107528	0.2699254	20.244404	0.9997331	74.97998
Gypsum plasterboard lining - 15 mm	m^2	75.00	Landfill	kg	14.1 [7]	1057.5	0.0134	14.1705	0.00010505	0.1110904	0.0002014	0.2129805	0.320963	339.41842	0.9997632	1057.25
Internal walls																
Light steel profiles	m	125.00	Landfill			133.8	0.0038784	0.51893	2.64E-05	0.0035262	6.28E-05	0.0084037	0.0873171	11.68303	0.0004163	0.055703
galvanised	m^2	47.25														
Fasteners: #10-16x16 wafer screws	sum	224.00														
Gypsum plasterboard lining - 15 mm	m^2	52.00	Landfill	kg	14.1	733.2	0.0134	9.82488	0.00010505	0.0770227	0.0002014	0.1476665	0.320963	235.3301	0.9997632	733.0264
Bulk insulation - 25 mm glass wool	m^2	26.00	Landfill	kg	1 [8]	26	0.010078	0.262028	7.30E-05	0.0018977	0.00014337	0.0037276	0.2699254	7.01806	0.9997331	25.99306
Ceiling and insulation																
Gypsum plasterboard - 6.4 mm	m^2	40.00	Landfill	kg	5.7 [9]	228	0.0134	3.0552	0.00010505	0.0239514	0.0002014	0.0459192	0.320963	73.179574	0.9997632	227.946
Bulk insulation - glass wool mat 25 mm	m^2	40.00	Landfill	kg	1 [10]	40	0.010078	0.40312	7.30E-05	0.0029196	0.00014337	0.0057348	0.2699254	10.797015	0.9997331	39.98932
Roofing																
Light steel profiles	m	131.00	Reuse	kg		141.38	0.0038784	0.548328	2.64E-05	0.0037259	6.28E-05	0.0088798	0.0873171	12.344894	0.0004163	0.058858
galvanised	m^2	49.52														
Fasteners: #10-16x16 TEK	sum	390.00														
Purlins	m	57.00	Reuse	kg	1.07	60.99	0.0038784	0.236544	2.64E-05	0.0016073	6.28E-05	0.0038307	0.0873171	5.3254708	0.0004163	0.025391
galvanised	m^2	22.06														
Covering																
Sheeting	m^2	46.00	Reuse	kg	5.03 [11]	231.38	0.0038784	0.897384	2.64E-05	0.0060978	6.28E-05	0.0145325	0.0873171	20.203434	0.0004163	0.096326
galvanised	m^2	46.00														
Ridge cappings 450 mm girth	m	6.00	Reuse	kg	2.26	13.56	0.0038784	0.052591	2.64E-05	0.0003574	6.28E-05	0.0008517	0.0873171	1.1840201	0.0004163	0.005645
galvanised	m^2	2.70														
Additional transport (10 km)	tkm	208.30					0.48632	101.3005	0.0026554	0.5531198	0.0059029	1.2295741	8.5936702	1790.0615	0.0396913	8.267689
Total impact								384.3256		3.1733932		6.6614132		8296.0753		17563.21

LSFB: Environmental impacts for alternative disposal scenario

Materials			Disposal	Ecoinvent			Carbon Footprint EI_1		Acidification Potential EI_2		Eutrophication Potential EI_3		Resource Depletion EI_4		Waste to Landfill EI_5	
Item	Unit	Quantity	Type	Unit	Conversion	Quantity	[kg CO_{2eq}/unit]	per item	[kg SO_{2eq}/unit]	per item	[kg $NO_3^-{}_{eq}$/unit]	per item	[MJ_{ex}/unit]	per item	[kg]	per item
Foundation																
Excavation	m^3	4.06														
Concrete (400x150 mm) - 25 MPa	m^3	1.54	Recycle	kg	2200	3388	0.0040446	13.7031	3.90E-05	0.1322031	7.06E-05	0.2393317	0.0621286	210.49178	3.732E-05	0.126434
Reinforcing (2-Y10)	kg	31.35	Recycle	kg			0.057938	1.816356	0.00055897	0.0175237	0.0010119	0.0317231	0.8899947	27.901335	0.0005346	0.016759
Brickwork (clay) - double layer cavity wall	m^2	12.70	Recycle	kg	171[1]	2171.7	0.0033226	7.21569	3.21E-05	0.069616	5.80E-05	0.1260303	0.0510399	110.84343	3.066E-05	0.066578
Mortar	m^3	0.19	Landfill	kg	3150	598.5	0.014122	8.452017	0.00011201	0.067038	0.00021401	0.128085	0.3320901	198.75593	0.9997632	598.3583
Brickforce	m	76.20	Reuse	kg	0.11[2]	8.382	0.0038784	0.032509	2.64E-05	2.21E-04	6.28E-05	5.26E-04	0.0873171	0.7318921	0.0004163	0.00349
Floor slab																
Concrete (100 mm - 25 MPa)	m^3	4.00	Recycle	kg	2200	8800	0.0040446	35.59248	0.000039021	0.3433848	0.000070641	0.6216408	0.0621286	546.7319	3.732E-05	0.328401
Reinforcing - Mesh ref 193	m^2	41.00	Recycle	kg	1.93[3]	79.13	0.057938	4.584634	5.59E-04	0.0442313	0.0010119	0.0800716	0.8899947	70.425282	0.0005346	0.042302
Damp proof membrane	m^2	41.00	Landfill	kg	0.23[4]	9.43	0.010078	0.095036	7.30E-05	0.0006883	0.00014337	0.001352	0.2699254	2.5453964	0.9997331	9.427483
Anchor bolts																
External walls																
Light steel profiles	m	357.00	Reuse	kg		386.1	0.0038784	1.49745	2.64E-05	1.02E-02	6.28E-05	2.43E-02	0.0873171	33.713138	0.0004163	0.160738
galvanised	m^2	134.95														
Fasteners: #10-16x16 wafer screws	sum	530.00														
Cladding - 9 mm fibre cement board	m^2	75.00	Recycle	kg	12.6[5]	945	0.0033226	3.139857	3.21E-05	0.0302929	5.80E-05	0.0548412	0.0510399	48.23274	3.066E-05	0.028971
Vapour permeable membrane	m^2	75.00	Landfill	kg	0.23	17.25	0.010078	0.173846	7.30E-05	0.0012591	0.00014337	0.0024731	0.2699254	4.6562129	0.9997331	17.2454
Thermal break -OSB	m^3	1.43	Reuse	kg	720	1029.6	0	0	0.00E+00	0	0	0	0	0	0	0
Bulk insulation - 25 mm glass wool	m^2	75.00	Recycle	kg	1[6]	75	0	0	0.00E+00	0	0	0	0	0	0	0
Gypsum plasterboard lining - 15 mm	m^2	75.00	Recycle	kg	14.1[7]	1057.5	0.0033226	3.51365	3.21E-05	0.0338992	5.80E-05	0.0613699	0.0510399	53.974733	3.066E-05	0.03242
Internal walls																
Light steel profiles	m	125.00	Reuse			133.8	0.0038784	0.51893	2.64E-05	0.0035262	6.28E-05	0.0084037	0.0873171	11.68303	0.0004163	0.055703
galvanised	m^2	47.25														
Fasteners: #10-16x16 wafer screws	sum	224.00														
Gypsum plasterboard lining - 15 mm	m^2	52.00	Recycle	kg	14.1	733.2	0.0033226	2.43613	0.000032056	0.0235035	0.000058033	0.0425498	0.0510399	37.422482	3.066E-05	0.022478
Bulk insulation - 25 mm glass wool	m^2	26.00	Recycle	kg	1[8]	26	0	0	0.00E+00	0	0	0	0	0	0	0
																0
Ceiling and insulation																
Gypsum plasterboard - 6.4 mm	m^2	40.00	Recycle	kg	5.7[9]	228	0.0033226	0.757553	0.000032056	0.0073088	0.000058033	0.0132315	0.0510399	11.637106	3.066E-05	0.00699
Bulk insulation - glass wool mat 25 mm	m^2	40.00	Recycle	kg	1[10]	40	0	0	0.00E+00	0	0	0	0	0	0	0
Roofing																
Light steel profiles	m	131.00	Reuse	kg		141.38	0.0038784	0.548328	2.64E-05	0.0037259	6.28E-05	0.0088798	0.0873171	12.344894	0.0004163	0.058858
galvanised	m^2	49.52														
Fasteners: #10-16x16 TEK	sum	390.00														
Purlins	m	57.00	Reuse	kg	1.07	60.99	0.0038784	0.236544	2.64E-05	0.0016073	6.28E-05	0.0038307	0.0873171	5.3254708	0.0004163	0.025391
galvanised	m^2	22.06														
Covering																
Sheeting	m^2	46.00	Reuse	kg	5.03[11]	231.38	0.0038784	0.897384	2.64E-05	0.0060978	6.28E-05	0.0145325	0.0873171	20.203434	0.0004163	0.096326
galvanised	m^2	46.00														
Ridge cappings 450 mm girth	m	6.00	Reuse	kg	2.26	13.56	0.0038784	0.052591	2.64E-05	0.0003574	6.28E-05	0.0008517	0.0873171	1.1840201	0.0004163	0.005645
galvanised	m^2	2.70														
Additional transport (10 km)	tkm	208.30					0.48632	101.3005	0.0026554	0.5531198	0.0059029	1.2295741	8.5936702	1790.0615	0.0396913	8.267689
Total impact								186.5645		1.3497793		2.693549		3198.8657		634.3763

References

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