QUANTIFYING THE ENVIRONMENTAL DIMENSION OF SUSTAINABLILTY FOR THE BUILT ENVIRONMENT: WITH A FOCUS ON LOW-COST HOUSING IN SOUTH AFRICA

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Thesis presented in fulfilment of the requirements for the degree of Master of Science in Engineering in the Engineering Faculty at Stellenbosch University

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March 2012

DECLARATION

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SUMMARY

Sustainability is difficult to achieve in a world where population and economic growth leads to increased production of greenhouse gases, resource depletion and waste generation. Today, the environmental dimension of sustainability, which is more commonly known as the natural environment, and the construction industry are two terms often mentioned together. In Europe, 12.4 % of greenhouse gas emissions are induced by the construction and manufacturing industry (Maydl, 2004). Also, 50 % of the resources extracted are used in the construction industry and more than 25 % of waste generated is construction and demolition waste. In South Africa, the building sector accounts for approximately 23 % of the total greenhouse gas emissions (Milford, 2009). Furthermore, 60 % of investment is made in the residential sector where 33 % of the building stock is the focus of the government's Housing Programme. It is seen that the construction industry significantly impacts the natural environment and the aim should be to reduce this negative impact.

Within the local residential sector, the low-cost housing sector presents potential when it comes to sustainable improvements. Each of the three spheres of sustainability, namely economy, natural environment and society, plays a crucial role in this sector. Various studies have been done on the economical and social fields, but little information exists on the impact low-cost houses have on the environment. A need arises to scientifically quantify the environmental impact hereof, therefore it is chosen as the focus of this study.

Various methods in order to determine the environmental impact of the built environment exist globally, but they tend to be complex, are used in conjunction with difficult to understand databases and require expensive software. A need for a local quantification method with which to determine the environmental impact of the built environment, more specifically low-cost housing, has been identified. A simple and easy-to-use analysis-orientated quantification method is proposed in this study. The quantification method is compiled with indicators related to the local conditions; these include Emissions, Resource Depletion and Waste Generation. The end objective is to provide the user with an aggregated total value called the Environmental Impact Index to ease comparison of possible alternatives.

The quantification method is developed as a mathematical tool in the form of a partial Life Cycle Assessment which can aid in objective decision making during the conception and design phase of a specific project. Note that only the Pre-Use Phase of the building life cycle is considered during the assessment, but can be extended to include the Use Phase and End-of-Life Phase. The proposed method has the capability of calculating and optimising the environmental impact of a building.

Regarding low-cost housing, different housing unit designs can be compared in order to select the best alternative.

The quantification method is implemented for two low-cost house design types in this study. Firstly, the conventional brick and mortar design is considered whereafter a Light Steel Frame Building is viewed as an alternative. The model implementation demonstrates that the model operates in its supposed manner. Also, Light Steel Frame Building housing units are shown to be worth investigating as an alternative to the conventional brick and mortar design but should be confirmed with a more accurate Life Cycle Assessment.

OPSOMMING

In ’n wêreld waar toenemende ekonomiese en bevolkingsgroei veroorsaak dat al hoe meer kweekhuisgasse voortgebring word, hulpbronne uitgeput word en groter hoeveelhede rommel geproduseer word, is dit ’n bykans onbegonne taak om volhoubaarheid te probeer bereik.

Volhoubaarheid rakende die natuurlike omgewing en konstruksie is twee terme wat vandag dikwels saam genoem word. Ongeveer 12.4 % van die kweekhuisgasse wat in Europa vrygestel word kom uit die konstruksie- en vervaardigingbedrywe (Maydl, 2004). Die konstruksiebedryf gebruik ook bykans die helfte van hulpbronne wat ontgin word en meer as 25 % van rommel word deur konstruksie of sloping produseer. Die Suid-Afrikaaanse boubedryf is verantwoordelik vir 23 % van die totale hoeveelheid kweekhuisgasse wat die land vrystel. Die behuisingsektor, waar die regering aan die hoof van 33 % van eenhede staan, ontvang 60 % van bestaande beleggings (Milford, 2009). Dit is dus duidelik dat die boubedryf ’n negatiewe impak op die natuurlike omgewing het en dat dit van groot belang is om dié situasie te verbeter.

In die behuisingsektor het lae-koste-behuising groot potensiaal as dit kom by volhoubaarheid. Volhoubaarheid bestaan uit drie sfere: ekonomie, natuurlike omgewing en sosiaal, en al drie speel ’n betekenisvolle rol in lae-koste-behuising. Daar is reeds verskeie studies aangepak om die ekonomiese en sosiale sfere te beskryf, maar daar is steeds min inligting beskikbaar oor die omgewingsimpak van ’n lae-koste-huis. Dit laat die behoefte ontstaan om hierdie impak te kwantifiseer.

Bestaande metodes wat wêreldwyd gebruik word om ’n omgewingsimpak te bepaal is dikwels besonder kompleks en benodig duur sagteware tesame met ingewikkelde databasisse om dit te implementeer. ’n Behoefte aan ’n plaaslike kwantifiseringsmetode is geïdentifiseer. Hierdie studie stel ’n eenvoudige, gebruikersvriendelike kwantifiseringsmetode bekend. Dit word saamgestel uit faktore wat verband hou met die plaaslike omgewing: Uitlaatgasse, Hulpbronuitputting en Rommelvervaardiging. Uiteindelik word ’n saamgestelde waarde, wat die Omgewingsimpak-indeks genoem word, bereken om vergelyking te vergemaklik.

Hierdie kwantifiseringsmetode word aan die hand van ’n gedeeltelike lewenssiklus-analise as ’n wiskundige hulpmiddel ontwikkel. Slegs die eerste fase van ’n gebou se lewenssiklus word beskou tydens hierdie studie, maar dit is moontlik om die ander twee fases in te sluit. Die voorgestelde metode het die vermoë om die omgewingsimpak te bereken en ook te optimeer. Tydens die ontwerpsfase, wanneer belangrike besluite geneem moet word, kan so ’n hulpmiddel van enorme waarde wees om die beste opsie uit verskillende alternatiewe te help identifiseer.

Die studie beskou twee tipes behuisingseenhede vir die doel van implementering van die kwantifiseringsmetode: die konvensionele baksteen en mortel metode en alternatiewelik ’n ligte staalraamwerk-gebou.

Tydens implementering van die voorgestelde metode, demonstreer die model dat dit werk soos dit veronderstel is om te funksioneer. Verder is getoon dat ’n ligte staalraamwerk-gebou ’n waardevolle alternatief is om te ondersoek, maar dit moet liefs met ’n meer akkurate lewenssiklus-analise bevestig word.

ACKNOWLEDGEMENTS

I wish to thank the following people who never hesitated to assist me with any queries and who were always willing to share their knowledge with me.

Prof. W.P Boshoff, I sincerely thank you for your guidance and enthusiastic interest in my research. This thesis would not have been completed without your input. I dearly appreciate all your effort. You always challenged my thoughts and helped me to gain perspective and see the bigger picture.

Wibke de Villiers, your caring interest and availability for questions did not go unseen. Thank you for always being prepared to help or listen to my process of thought.

The LSFB section of this thesis would not exist without Craige During. I cannot thank you enough for your willingness to design the LSFB house for me. Your time and effort is greatly appreciated.

Plans and details of the Watergang Kayamandi Housing Project were provided by Darren Allen. Thank you for your interest in my work.

Norman van der Merwe supplied the Bill of Quantities for the Watergang Kayamandi Housing Project. This was used as a template for most of the calculations done. Thank you for sharing the sensitive information for academic purposes.

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LIST OF ABBREVIATIONS

CO_{2e}	carbon dioxide equivalent
SO_{2e}	sulphur dioxide equivalent
GHG	greenhouse gas
GWP	global warming potential
LCA	Life Cycle Assessment
ELCA	Exergetic Life Cycle Analysis
LCIA	Life Cycle Impact Assessment
CF	Carbon Footprint
AP	Acidification Potential
EDIP	Environmental Design of Industrial Products
EI	environmental impact
EII	Environmental Impact Index
SANS	South African National Standards
SABS	South African Bureau of Standards
NHBRC	National Home Builders' Registration Council
ABT	Alternative Building Technology
LSFB	Light Steel Frame Building
EPS	expanded polystyrene
OSB	orientated strand board
DPC	damp proof course
CDW	construction and demolition waste

Chapter 1

INTRODUCTION

Sustainable development is defined according to the Brundtland Report (WCED, 1987) published by the World Commission on Environment and Development in 1987, as development that "meets the needs of the present generation without compromising the ability of the future generation to meet their own needs". However, sustainability is difficult to achieve in a world where population and economic growth lead to increased production of greenhouse gases (GHG), resource depletion and waste generation.

Today, the environmental dimension of sustainability, which is more commonly known as the natural environment, and the construction industry are two terms often mentioned together. In Europe, 12.4 % of GHG emissions are induced by the construction and manufacturing industry (Maydl, 2004). Also, 50 % of the resources extracted are used in the construction industry and more than 25 % of waste generated is construction and demolition waste. In South Africa, the building sector accounts for approximately 23 % of the total GHG emissions (Milford, 2009). Furthermore, 60 % of investment is made in the residential sector where 33 % of the building stock is the focus of the government's Housing Programme. It can be seen that the construction industry significantly impacts the natural environment, from here onwards named the environment, and the aim should be to reduce this negative impact.

Within the local residential sector, the low-cost housing sector presents potential when it comes to sustainable improvements. Sustainability consists of three spheres, namely economy, environment and society. Each of these areas plays a crucial role within this sector. Various studies have been done on the economical and social fields, but little information exists on the impact low-cost houses have on the environment. A need arises to scientifically quantify the environmental impact hereof, therefore it is chosen as the focus of this study.

Various methods in order to determine the environmental impact of the built environment exist globally, but they tend to be complex, are used in conjunction with difficult to understand databases and require expensive software. A simple and easy-to-use analysis-orientated quantification method is proposed in this study to be used locally. The quantification method is compiled applying indicators related to the local conditions; these include Emissions, Resource Depletion and Waste Generation. The end objective of the method is to provide the user with an aggregated total value called the Environmental Impact Index (EII) to ease comparison of possible alternatives. All indicators contribute to the final EII.

The quantification method is developed as a mathematical tool in the form of a partial Life Cycle Assessment (LCA) which can aid in objective decision making during the conception and design phase of a specific project. Note that only the Pre-Use Phase is considered during this study, but it can be extended to include the Use Phase and End-of-Life Phase. The proposed model has the capability of calculating and optimising the environmental impact of a building. Different housing unit designs can be compared in order to select the best option.

The quantification method is implemented for two low-cost house design types in this study. Firstly the conventional brick and mortar design is considered whereafter a Light Steel Frame Building (LSFB) is viewed as an alternative. Results are produced in various formats: environmental impacts of the chosen indicators separately, the EII and the cost of the unit for both design types.

Furthermore, alternative materials were substituted as input to investigate the effect on the environmental impacts, possibly leading to an optimised design. The proposed model shows to be useful as an optimisation tool. Lastly, a sensitivity analysis is performed on certain assumptions in order to quantify their significance.

Chapter 2 sheds light on the current situation with regards to construction and low-cost housing in South Africa. Topics such as design types, legislation, the economical impact, social factors and challenges within this sector are addressed. The next chapter explains the proposed environmental impact quantification method in full. Chapter 4 provides the framework wherein the quantification method is implemented for low-cost housing types specifically.

Chapters 5 and 6 demonstrate in detail how the environmental impact is determined for the conventional design type and LSFB alternative respectively and provides graphical results. The following chapter compares the results for both design types.

Chapter 8 presents the proposed model as an optimisation tool whereafter Chapter 9 provides a sensitivity analysis on assumptions made to determine the significance thereof. Finally, conclusions are made and recommendations for future studies are put forward.

Chapter 2

BACKGROUND ON CONSTRUCTION AND LOW-COST HOUSING IN SOUTH AFRICA

Data is readily available on the environmental, economical and social impacts of the construction industry globally, but little information exists on the impacts in South Africa. Firstly, the current position of the local building sector is described whereafter the residential sector becomes the particular focus. More specifically, low-cost housing is studied from a sustainability viewpoint.

2.1 Economical and environmental impact of the building sector

The United Nations Environment Programme Sustainable Buildings & Climate Initiative (UNEP-SBCI) commissioned a report titled *Greenhouse Gas Emission Baselines and Reduction Potentials from Buildings in South Africa: A Discussion Document* (Milford, 2009). This report was the first of its kind aiming to quantify and provide tangible information on the impact of the construction industry in South Africa. This section aims to provide a broad view on this topic with the aid of statistical and graphical extracts from the mentioned document.

Figure 1 shows the ratio of investment in the various building sectors for the year 2007. It can be deduced that the residential sector plays the biggest role in this regard with a total investment of 63 %.

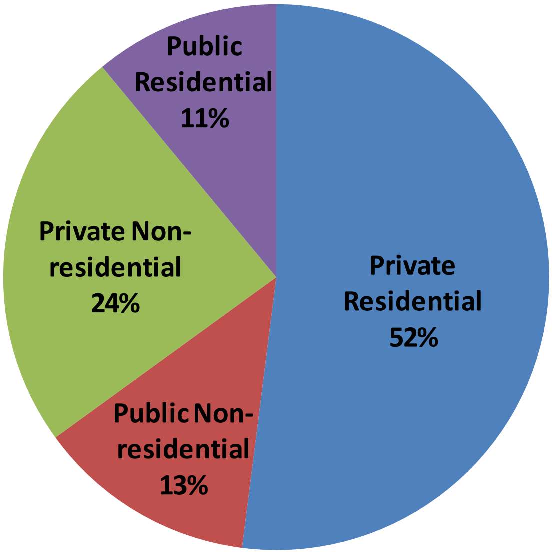

Figure 1: Investment in building by sector in 2007 (Milford, 2009)

In 2006, stock was taken of the residential sector. The outcome can be seen in Figure 2 with divisions for Flats and Townhouses, Dwelling units either larger or smaller than 80 m^2 and also a part labelled Other which includes backyard properties, informal or squatter units and traditional or rural housing. This part, contributing 33 % to the total building stock, is the focus of the government's Housing Programme.

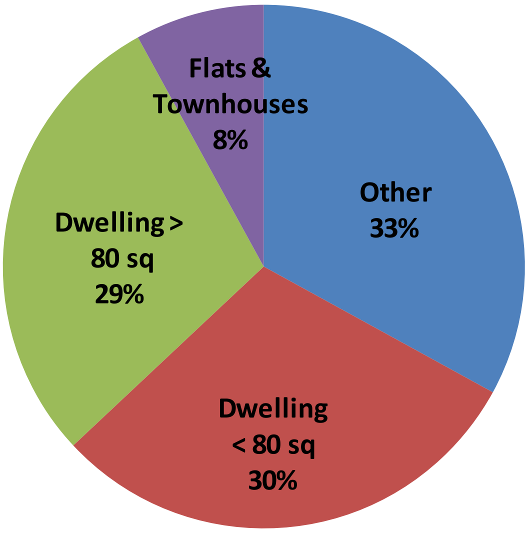

Figure 2: Total residential building stock in 2006 (Milford, 2009)

Even though a large proportion of residential units in South Africa form part of programmes established by the government to facilitate the process of providing all inhabitants with adequate housing, Figure 3 shows that insufficient finances are invested in the public residential sector if compared to the private sector. This may relate to reasons why South Africa suffers such a large housing backlog.

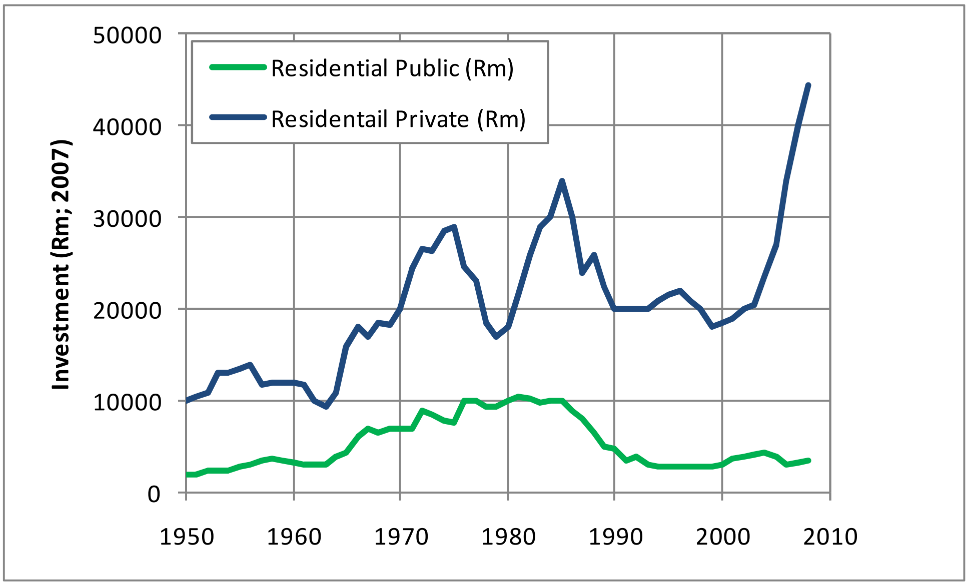

Figure 3: Investment in residential buildings (Milford, 2009)

The UNEP-SBCI document does not only focus on the economical impact of the building industry in South Africa, but goes further into quantifying equivalent carbon emissions in order to portray the environmental impact thereof. Note that only the operation phase was included in the compilation of this data for each contributing sector. Figure 4 shows the percentage of equivalent carbon dioxide emissions (CO_{2e}) per sector in the year 2007. The building sector comprises the residential and commercial sections and it can be seen in Figure 4 that after manufacturing, the building sector plays the second largest role in South Africa considering CO_{2e} emissions.

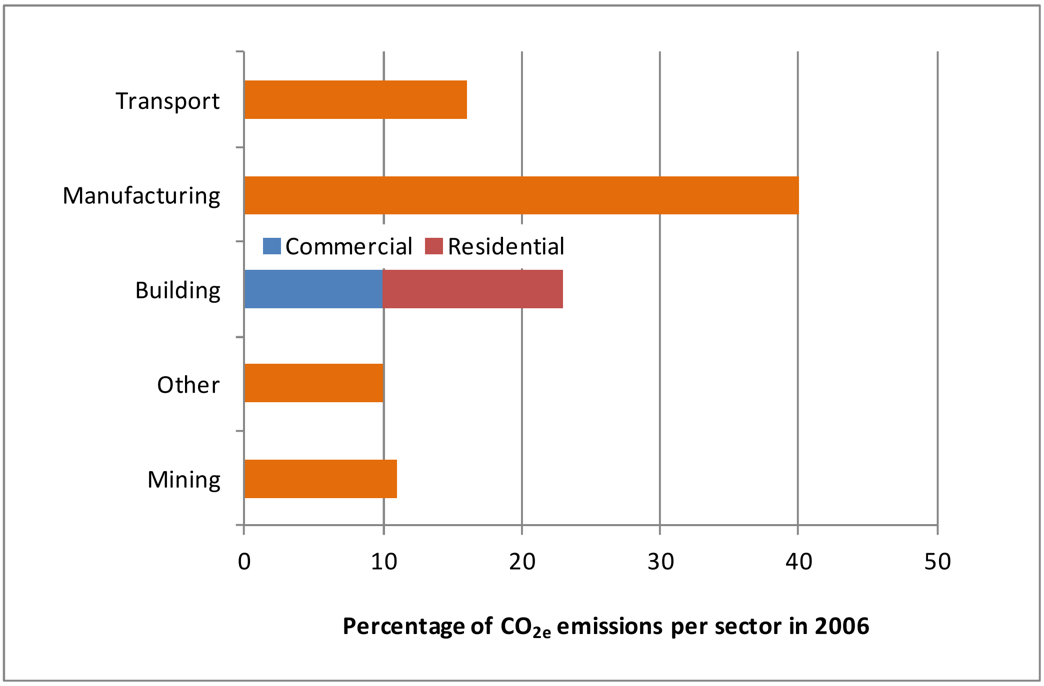

Figure 4: CO_{2e} emissions per sector (Milford, 2009)

It is therefore clear that the building sector in South Africa strongly impacts the economy and environment. As mentioned before, the residential sector plays a large role, but for the purpose of this study, the focus is on the low-cost housing sector specifically since it presents potential for improvement within a sustainability framework considering the economy, environment and society.

2.2 Economical context of low-cost housing

South Africa is ranked as one of the ten countries with the highest inequality rate in terms of income. Income inequality can be measured by the Gini-coefficient (Gini, 1912) and currently stands at 0.72 for South Africa. This number increases from the 0.72 to 0.80 for the whole country if taxes and grants are excluded (Statistics South Africa, 2008). The coefficient can be described as 0.0 being absolute income equality and 1.0 absolute income inequality. It is possible that this unacceptable rate of inequality contributes to the large number of poor people with inadequate housing and living conditions.

According to the Banking Council of South Africa, it is estimated that approximately 80 % of new households are unable to gain access to mortgage loans or non-mortgage finance in order to procure housing opportunities (Tonkin, 2008).

Quantifying the large housing backlog is a difficult task as there is no final agreement on the definition of inadequate housing. The lack of reliable statistics also adds to this problem. The poor levels of housing delivery and increasing backlog may be due to insufficient resources being assigned to the housing problem, skills shortages and a lack of capacity in government (Tonkin, 2008).

The Housing White Paper (New Housing Policy and Strategy for South Africa: White Paper, 1994) provides the National Housing Goal which states that the budget of the housing sector should be increased to 5 % of the total government expenditure in order to obtain a decent delivery rate of 350 000 houses per annum; this number is calculated to reduce the housing backlog over the next years. Unfortunately, the government has cut state expenditure in order to reduce the budget deficit resulting in housing expenditure decreasing to below 2 % of the total budget (Tonkin, 2008). Table 1 provides the actual expenditure per financial year of the Department of Human Settlements as extracted from Annual Reports. This value includes the amount of money spent by each of the participating programmes within the Department of Human Settlements, namely Administration, Housing Policy, Research and Monitoring, Housing Planning and Delivery Support, Housing Development Finance and Strategic Relations and Governance. The number of houses completed or in process of completion is given in the adjacent column. Accounting for inflation, the expenditure increases exponentially as the number of housing units delivered remains relatively steady.

Table 1: Actual annual expenditure and number of housing units delivered (Tonkin, 2008 & Department of Human Settlements, Annual Reports)

Year	Expenditure [mil R]	Housing Units Delivered
2003/2004	4 520	193 615
2004/2005	4 808	217 348
2005/2006	5 256	216 133
2006/2007	7 165	271 219
2007/2008	8 586	248 850
2008/2009	10 920	245 082
2009/2010	13 370	226 425

Typically, households earning below R 3 500 per month collectively qualify for a state subsidy (Breaking New Ground, 2004). The government subsidy for the top structure of a standard 40 m^2 house is R 55 706 effective 1 April 2009 (van der Merwe, 2011). Also, if the project features difficult soil conditions an additional 15 % of this value may be applied for. Furthermore, if the site is located within the Southern Cape Coastal Condensation Area (SCCCA), an extra R 10 803 is added to the subsidy amount summing to a total of approximately R 75 000 per house. Municipal engineering services may be financed from a further R 22 162 subsidy per stand and the cost of raw land is financed from the annual allocation to Provincial Governments of R 6 000 per stand (Department of Human Settlements, 2009). The various subsidy programmes which may be applied for include the Integrated Residential Development Programme, Individual Housing Subsidy and the Enhanced People's Housing Process among others.

The annual budget of the Department of Human Settlements and grants contributed by government is established and driven by relevant legislation and policies. The following section provides short descriptions of regulations considered.

2.3 Housing legislation, policies and regulations

In order to understand the workings of the Housing Sector in South Africa, background information is given on the various applicable policies and legislation.

Section 26 of the South African Constitution states the following:

> (1) "Everyone has the right to have access to adequate housing.
>
> (2) The State must take reasonable legislative and other measures, within its available resources, to achieve the progressive realisation of this right" (Constitution of the Republic of South Africa, 1996).

After the first democratic election in 1994, various policies and strategies have been implemented in support of the new approach to the Housing Sector. These include the Reconstruction and Development Programme (RDP) of 1994, the Growth, Employment and Redistribution (GEAR) Strategy of 1996, the Accelerated and Shared Growth Initiative – South Africa (ASGI-SA) of 2005 as well as the Housing Act No. 107 of 1997. There are two documents which constitute the National Department of Human Settlements' directive, namely the New Housing Policy and Strategy for South Africa: White Paper 1994 and the Comprehensive Plan for the Development of Sustainable Human

Settlements, also known as “Breaking New Ground” of 2004 (Department of Human Settlements, 2010). Both of these documents will be discussed in more detail hereafter.

2.3.1 New Housing Policy and Strategy for South Africa, 1994

The vision of this Policy (New Housing Policy and Strategy for South Africa: White Paper, 1994) is to establish integrated communities who are situated in close proximity of job or other economical opportunities, health and educational services along with social facilities. All South Africans will have access to:

(1) “A permanent residential structure with secure tenure, ensuring privacy and providing adequate protection against the elements, and
(2) Potable water, adequate sanitary facilities including waste disposal and domestic electricity supply.”

The approach to implementation of this Policy (New Housing Policy and Strategy for South Africa: White Paper, 1994) follows 7 key strategies:

(1) Stabilising the housing environment, in other words motivating private sector investments in the low-income housing sector whilst ensuring optimum benefit of governmental expenditure.
(2) Mobilising housing credit. Ultimately this strategy promotes saving by beneficiaries so that they can establish creditworthiness and maintain their own housing.
(3) Providing subsidy assistance.
(4) Supporting the Enhanced People’s Housing Process (EPHP) entailing greater input from beneficiaries in housing delivery – at least the top structure.
(5) Rationalising institutional capacities thus creating an environment where regulators and implementers could fulfil their respective roles effectively and efficiently whether it be at national, provincial or local municipality level.
(6) Facilitating the speedy release and servicing of land.
(7) Coordinating government investment in development by integrating the public and private sector.

It is important to note that the Policy strongly emphasises the fact that special needs of the youth, disabled, the aged and single-parent families should be considered carefully (Department of Human Settlements, 2010).

2.3.2 Breaking New Ground: Comprehensive Plan for the Development of Sustainable Human Settlements, 2004

The Comprehensive Plan (Breaking New Ground, 2004) is based on the principles of the Housing White Paper of 1994, although the focus now shifts to the integration of communities and sustainable human settlements by improving the quality of the housing environments. Another important focal point is the Upgrading of Informal Settlements to improve the lives of people living in slums - in line with the United Nations Millennium Goals (Department of Human Settlements, 2010). Target 11 of Goal 7 says that a substantial improvement in the lives of at least 100 million inhabitants should be achieved by the year 2020 (United Nations, 2001).

With the broader vision of providing integrated sustainable human settlements, the objectives of the National Department of Human Settlements are poverty alleviation, job creation, wealth creation and empowerment, economical growth and improving the quality of life of poor citizens. A variety of literature proposes that increased access to low-income housing has little impact on poverty alleviation (Department of Human Settlements, 2010).

Sustainable human settlements actuates sustainable development, creates wealth, reduces poverty and results in equity owing to the balance in the economic growth, social upliftment along with the natural systems being in equilibrium with its carrying capacity required for its existence (Breaking New Ground, 2004).

In order to achieve these objectives of government, nine strategies are implemented and are listed. More detailed information on each strategy can be found in the *National Housing Policy and Subsidy Programmes of 2010* (Department of Human Settlements, 2010).

(1) Supporting the entire residential housing market.
(2) Moving from housing to sustainable human settlements.
(3) Applying existing housing instruments.
(4) Adjusting institutional arrangements with government.
(5) Building institutions and capacity.
(6) Enhancing financial arrangements.
(7) Creating jobs and providing housing.
(8) Building awareness and enhancing information communication.
(9) Implementing systems for monitoring and evaluation.

2.3.3 National Building Regulations

The purpose of Building Regulations is to ensure socially acceptable levels of health, safety, welfare and agreement between the inhabitants and community in which the building is located. These objectives can be achieved by rendering rules on the design, construction and operation of the building. Certificates reporting on the adequacy of a system or material can be obtained from the South African Bureau of Standards (SABS), Council for Scientific and Industrial Research (CSIR) or Agrément Board South Africa. SANS 10400 of 2004 provide a revised interpretation of the National Building Regulations of 1990 (Tonkin, 2008).

2.3.4 National Home Builders' Registration Council (NHBRC)

The NHBRC was set up as a Section 21 company in 1995 and now operates as a statutory body. All home builders are obliged to register with this body and have to enrol all new houses built under the Defect Warranty Scheme. Housing consumers are protected from dishonest and corrupt builders, contractors and developers through the Product Defect Warranty Scheme and a Code of Conduct for Home Builders effective 16 March 2007. Registration fees constitute most of the Warranty Scheme's funding which is then used to pay for repairs and structural defects when claims are made (Tonkin, 2008).

Furthermore, the NHBRC provides minimum ethical and technical standards to be adhered to and requires a five year standard home builders warranty from the builder for each bondable new home built. These norms and requirements can be found in the Home Builders Manual (NHBRC, 1999). Spot check inspections are carried out on enrolled homes under construction to verify that the builder complies with the NHBRC's building standards and guidelines. The NHBRC also acts in an arbitrative capacity between consumers and home builders if major structural defects occur after hand-over of the completed, enrolled unit (Tonkin, 2008).

Concluding this section on applicable regulations, no guidelines depicted in mentioned policies or legislation exist with regard to the environmental impact of the low-cost housing unit.

2.4 Social aspects of low-cost housing

Apart from the political and economical aspects influencing the Housing Sector, inevitable social impacts exist which may not be ignored. The following section provides information regarding the living conditions of inhabitants and also touches on the topic of public participation during project development.

2.4.1 Housing conditions

Poverty alleviation often hides behind a false sense created by statistics on access to water, electricity, housing and education facilities. A variety of literature proposes that an increased access to low-income housing has little impact on decreasing the state of poverty. Furthermore, governmental expenditure on this sector does not necessarily improve the quality of living (Charlton *et al.*, 2006).

Provision of shelter and security are two main intentions of housing. The accelerated need for adequate housing and the lack of efficient delivery, has forced some inhabitants to live in backyard dwellings of new housing developments as seen in Figure 5. These shacks provide a source of income for the owners of the low-cost house (Govender *et al.*, 2010). According to the South African Institute of Race Relations, the percentage of people living in backyard dwellings is increasing more rapidly than the number of people living in informal settlements (South African Institute of Race Relations, 2008). Allowing these backyard dwellings may result in a decrease in the quality of living conditions.

Figure 5: Backyard dwelling (Govender *et al.*, 2010)

Shack dwellings are considered shameful by most; however, people still tend to live here due to the shortage in job opportunities and inner-city housing along with overcrowding elsewhere. Alcohol misuse, noisiness (including domestic violence) and the lack of privacy in shack dwellings are expressed as some of the main problems by inhabitants (Ross, 2010). Formal housing is considered relief from forced close living conditions.

Beneficiaries do not necessarily realise that the maintenance of their home is their own responsibility and that if they do not look after the unit, it will degenerate structurally over time causing further problems (Ross, 2010). Most consider the government responsible for maintenance. Some even approach the local municipality when something is broken – this burden may only fall on them in the case of rental stock, not ownership (van Stavel, 2011). Fire risk is one important point to bear in mind. On the other hand, most beneficiaries cannot afford to live in new houses considering water and electricity bills, maintenance etc. that has to be paid (Ross, 2010).

Structurally, these houses tend to show large cracks after a certain period of time while damp is visible on the walls of many dwellings (Govender *et al*., 2010). The inadequate indoor air quality may lead to inhabitants falling ill. TB (Tuberculosis) is especially prevalent in these overcrowded communities. Poor waste disposal and removal create unhealthy living conditions and cases of diarrhoea attacks are frequently reported.

During a survey in the City of Cape Town Metropole, it was discovered that many housing units do not have an outside drain connected to the sewerage system. Inhabitants dispose of waste water by flushing it down a toilet which is a terrible waste of potable water (Govender *et al*., 2010).

2.4.2 Public participation

Community participation is commonly related to a bottom-up approach whereas the conventional top-down approach requires less input and resources from the local area. There is a belief that community participation is the only way leading to sustainable development, but little information exists on the negative aspects and disadvantages of this approach (Lizarralde *et al*., 2007). Negative outcomes may include restricted integration of economic opportunities, low typology densities, urban fragmentation, limited possibilities for extensions on the housing unit and little variety of models used.

Lizarralde *et al.* (2007) argues that in some housing project instances the wrong decisions are justified by the desires of the community. For example, the residents of a certain township demanded single detached units as this was the norm of typology being built in upmarket areas. This was not the optimised solution for this particular area, but the developers built what the residents wanted. The desires of the community should be taken into account but not at the cost of negatively affecting neighbouring communities or even the environment.

The complex interaction between participants, interests, objectives, resources and processes ultimately determines the performance of low-cost housing projects (Lizarralde *et al*., 2007). Participants include the three spheres of government, civil society, the private sector and other important role players (Tonkin, 2008). Community participation is in fact crucial in these developments, but the value of their input with regard to the decision making process should be managed effectively. In the end, developing countries should aim at producing sustainable environments that further develop and improve the quality of living of its residents (Lizarralde *et al.*, 2007).

2.5 Design types of low-cost housing

Diverse design types for low-cost housing exist although only a few will be discussed in more detail in the following sections. Even though the building systems explained differ greatly in construction method and materials used, the final products are not easily distinguishable from one another. Generally, social acceptance plays a crucial role in the choice of design type. Firstly the conventional brick and mortar design is presented where after certain alternative building technologies are shared.

2.5.1 Conventional design

The conventional design is known to most contractors locally and is usually selected as a design type for its low cost and the fact that it complies with the National Home Builders' Registration Council (NHBRC) Home Building Manual (NHBRC, 1999). Variations on some material items are possible and will be explained next.

Depending on the soil conditions as specified by a geotechnical report, an appropriate foundation type is chosen. If a raft foundation is required, it has to be designed and certified by a structural engineer. For stable soil conditions, a strip-footing foundation is adequate. According to the NHBRC Home Building Manual (NHBRC, 1999), the minimum depth of the foundation must be 200 mm; for external walls the minimum foundation width is 500 mm and for internal walls a minimum width of 400 mm is required. At least 10 MPa concrete should be used for the foundations. A damp proof course (DPC) layer is necessary beneath the reinforced floor slab which should be of at least 25 MPa and power floated to a smooth finish.

Typically, external walls are at least 140 mm in thickness and constructed with concrete hollow masonry units whereas internal walls are similar but only 90 mm thick. Internal load bearing walls should also have a thickness of 140 mm. External walls are usually plastered to avoid rain penetration, while the minimum requirement for internal masonry walls is that it should be neatened and smoothed, also known as bagged walls or bag-washing. The brickforce is normally galvanised when used in coastal areas.

Concrete lintels are generally placed across all door and window frame openings for crack prevention. Normally steel window and door frames are used. Figure 6 shows typical doors and windows used during low-cost housing construction.

Figure 6: Completed semi-detached 40 m^2 house

A more economical way of roof construction, compared to a timber truss system, entails placing timber rafters in the length of the house with sheeting used as covering. This method requires the gable walls to be built up to the required height of the roof. Figure 7 depicts this method of construction. If corrugated or IBR roof sheeting is used rather than clay roof tiles, it should be at least 0.5 mm thick. Note that the roof design should be done by a specialist according to the specific area conditions. The NHBRC Home Building Manual specifies the minimum roof pitch. This depends on the type of roof covering used and whether an underlay is considered or not. For example, corrugated iron roof covering requires a pitch of at least 11° whereas a roof covered without an underlay and clay tiles should be pitched at a minimum of 26° (NHBRC, 1999). A framework of the construction process is provided in Section 4.1.

Figure 7: Typical roof construction of the conventional design

2.5.2 Alternative Building Technologies (ABT's)

The current Human Settlements Minister, Tokyo Sexwale, stated in October 2010 that of the 2.5 milllion houses built since 1994, only 17 000 were constructed using ABT's – this is a mere 0.68 % of the total housing units delivered (Moladi, [s.a.]). He is determined to increase this ratio in future in order to eradicate the 2.1 million housing backlog South Africa still faces.

Three alternative building technologies applicable to the low-cost housing sector are discussed. It is believed that these are currently the most widely implemented alternative building systems in the low-cost housing sector although other building systems exist on the market.

Light Steel Frame Building (LSFB)

Although Light Steel Frame design has widely been in use in the United States, Europe and Australia for decades, it has only recently been introduced in South Africa. LSFB is a system offering various benefits including cost-efficiency, quality products, durability, minimal wastage, low mass panels with ease of handling and reduced construction time (SASFA, [s.a.]).

Depending on the soil conditions, foundation types can vary from a raft foundation, strip-footings, slab-on-ground and pad-and-pier configurations. The Light Steel Frame Building code, SANS 517:2009, has a guide to foundation design for these structures. Conditions permitting, strip-footings would be chosen since contractors are familiar with the method of construction. It is important that the slab be power floated to an exact level ensuring accurate erection of the pre-fabricated wall panels.

The steel elements used are cold formed and manufactured from high strength, thin (typically 0.5 – 1.0 mm thick) galvanised steel sheets. The design yield strength is 550 MPa. Wall frames and roof trusses are assembled in a factory with fasteners connecting the elements through pre-punched holes.

Wall panels consisting of various different material layers can be designed according to the specifications and layouts provided in the code (SANS, 2009). External walls comprise of an external cladding, waterproof membrane, a thermal break, bulk insulation between the steel elements (minimum thickness of 25 mm) and internal lining. Cladding includes brick veneer, fibre cement board panels or weatherboard whereas lining generally refers to gypsum board. Internal walls simply consist of gypsum board, with a minimum thickness of 15 mm, on either side of the bulk insulation in the wall panel.

Furthermore, the LSFB design code (SANS, 2009) provides information on roofs and ceilings. Insulation is an important element which should be considered carefully. A DPC layer is placed onto the truss followed by wooden or steel purlins. Any type of sheeting or clay/cement tiles may be used as roof covering but should be designed for accordingly. Gypsum board acts sufficiently as ceiling material.

Similar doors and windows as for the conventional method are used and are placed into the pre-fabricated positions in the wall panels.

Figure 8 shows a simple, schematic diagram of the construction process of a light steel frame unit.

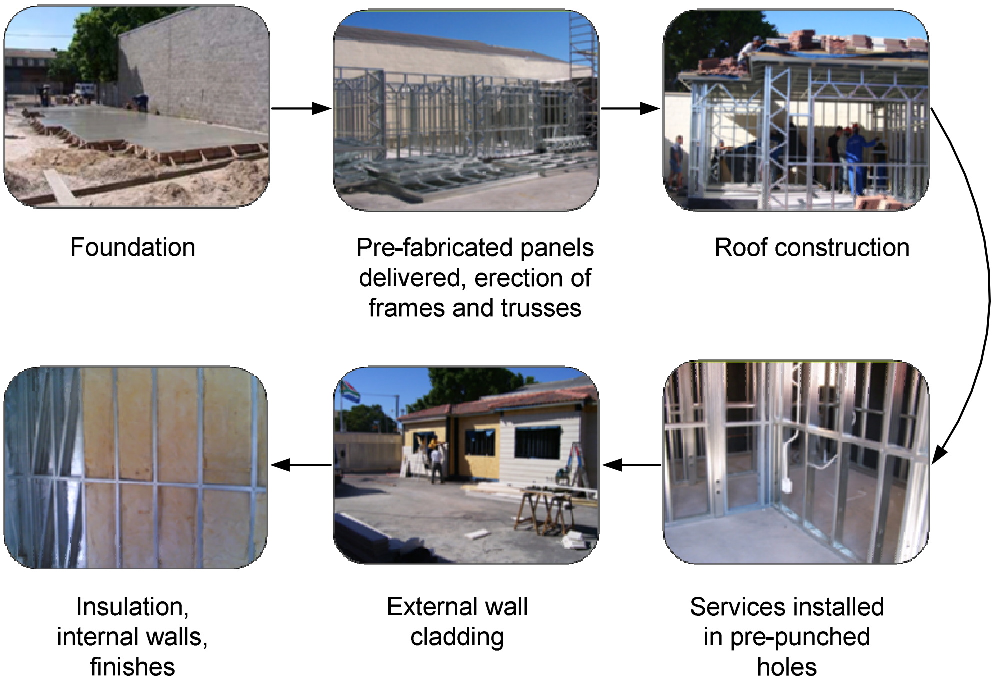

Figure 8: LSFB building process (Light Frame Homes, [s.a.])

Imison

The Imison building system is similar to LSFB construction. A housing unit typically consists of a galvanized light-gauged, cold formed structural steel frame erected on a concrete surface bed. Different to the various layers required for wall panels in LSFB units, infill panels comprise of an expanded polystyrene (EPS) core sprayed externally with Fibrecote, a special fibre reinforced plaster. The roof structure can be designed as a timber or light steel frame truss with conventional roof covering and optional insulation (Agrément, 2009).

This ABT was the winner of the ABSA Bank International Innovation Housing and Sustainable Energy Efficiency competition in 2010 held (Imison wins ABSA housing competition, [s.a.]). The building system also holds an Agrément certificate, 2008/342 (Agrément, 2009). More than a thousand homes were built in Zola, Soweto, using the Imison system (Department of Human Settlements, 2009). Other housing projects have been completed in Attredgeville and Mamelodi, Gauteng, as well as in the Western Cape.

Moladi© building system

The Gauteng Department of Housing commissioned the construction of 17 houses in the Innovation Hub in Soshanguve near Pretoria in 2006 (Delivering low-cost housing using alternative technology, [s.a.]). Various non-conventional building technologies were tested in the hope of complementing the conventional design and accelerating the delivery process. The Housing Technology Innovation Hub is jointly sponsored by the NHBRC and ABSA Bank (Dlamini, 2006). A competition emerged from this initiative, and of the 17 houses built, the Moladi building system was the winner.

Moladi© patented a building system comprising a lightweight, reusable and recyclable plastic formwork filled with an aerated mortar. The formwork can be easily handled, assembled and transported as it only weighs 8 kg/m^2. The modular formwork components are fully interlocking and any desired dimensional structure can be designed for. Typically the wall cavity is either 100 mm or 150 mm wide with any safe specified wall length or height. Also, the formwork panels can be re-used up to 50 times, providing a cost effective solution (Moladi, [s.a.]).

All internal and external walls are designed to have steel reinforcing as specified by an independent, certified engineer. The reinforcement, window frames, doors, electrical conduits, plumbing and other fittings are positioned before the wall cavity is filled with the mortar mix. The aerated mortar consists of sand, cement, water and a non-toxic, water based chemical called MoladiCHEM. The mortar mix, or more specifically the chemical additive, holds an Agrément Certificate number 94/231. No plastering is necessary after the formwork is removed as the formwork and mortar fill system results in a smooth wall finish. Lastly, the roof is constructed according to engineering design specifications. Typically the roof system comprises purlins with IBR sheeting as cover. Figure 9 shows a photo of a 40 m^2 house constructed with the Moladi system (Moladi, [s.a.]).

Figure 9: A typical 40 m^2 house constructed with the Moladi building system (Moladi, [s.a.])

The top structure, that is everything erected above the completed foundation, of a single house can typically be constructed within two days granted enough labour is provided. Figure 10 lists the steps completed over the course of two days. Once the formwork is removed, it can immediately be used for the construction of a unit on the adjacent plot further reducing project construction time.

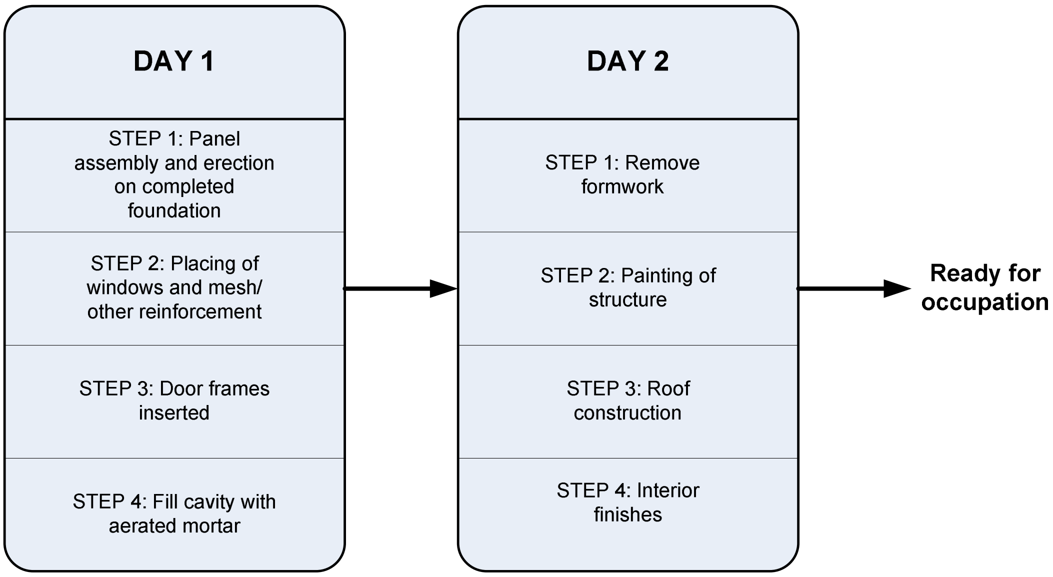

Figure 10: Construction flow of the Moladi building system (Moladi, [s.a.])

The Moladi system has been used in housing projects in Gauteng and the Western Cape, specifically the Morgen's Village development in Mitchell's Plain (Social Housing Trends, 2010).

2.6 Housing challenges and incentives

It is often argued that South Africa's housing problem originates from the Apartheid era (Tonkin, 2008). More than 80 % of the population was denied housing and land rights. Most of the people had to reside in informal settlements, backyard shacks and hostels as a result of the Apartheid laws controlling where they could live. Today, South African cities still have a similar typology since the racial structure of the past is now replaced by hard class lines.

Due to population growth, the large increase in the number of households, continuing high rates of urbanisation, and South Africa’s high unemployment rate (ever increasing), the demand for government assisted housing has changed greatly over the last couple of years (Department of Human Settlements, 2010). Since 1994, approximately 2.5 million houses have been built, but the current backlog of over 2 million still faces the following challenges, impeding the progressive supply and delivery of housing (Tonkin, 2008):

(1) The lack of affordable, well-located land causes these developments to form on urban peripheries with weak prospects of integration. Slow release of land further complicates the process.
(2) The slow response of funding allocated by government.
(3) The number of subsidies required is increasing as pointed out by President Thabo Mbeki in the 2004 State of the Nation Address (Mbeki, 2004).
(4) Insufficient capacity of the Housing Sector, especially common in local municipalities (Department of Human Settlements, 2010).
(5) The withdrawal of large construction groups. This commenced after the announcement that as from April 2002 local authorities will become the developers of low-income housing projects (Charlton *et al*., 2006).

Residents have different needs and housing might not be an equal priority for all. Providing the same solution to different types of users is not a sustainable answer. It should be taken into account that there are different household sizes of dissimilar economic levels (Lizarralde *et al*., 2007).

With political elections every five years, the structure of municipalities changes along with the Integrated Development Plan (IDP). The IDP is one of the main motivators in industry as this document summarises the priorities of each municipality/ward (van Stavel, 2011). It is important that politicians look beyond a five-year horizon and sacrifice the short-term self gain for the long-term benefit of all citizens (Tonkin, 2008). Instead of delivering a large number of poorly planned houses within a short time, the government should incorporate health and safety of the inhabitants when planning such projects (Govender *et al*., 2010).

Achieving sustainability within the low-cost housing sector is a challenge itself. Various incentives are provided with the goal of sustainable human settlements in mind. Densification of housing typologies is one of the main motivators along with improving the location of new housing developments. It is advised that subsidies be increased accordingly in order to provide better quality housing units (Charlton *et al*., 2006). The subsidy amount has not been increased with inflation over the years since its inception in 1994. Charlton *et al*. (2006) furthermore argues that funding for land should be done separately from the housing subsidy trusting this would accelerate the process and provide adequate finances for the housing unit itself. Keeping the lack of skills in municipalities in mind, accreditation of municipalities should be put in place in order to quantify the capacity of the institution. Catering for the unemployed, labour intensive construction methods are to be used with on-site production of building materials and training of local contractors (Department of Human Settlements, 2010).

Generally, information on the low-cost housing sector is concerned with the political, economical and social aspects only. Only a few reviews on the environmental impact of this sector exist, therefore a need arises for a scientifically based quantification model which can be applied locally in order to calculate the environmental impact of low-cost housing projects or units.

Chapter 3

QUANTIFYING THE ENVIRONMENTAL DIMENSION OF SUSTAINABILITY

Several environmental impact quantification methods are available globally but these methods are often complex, require expensive software for implementation and are not easy to use. This chapter proposes an easy-to-use analysis-orientated method which is inexpensive to implement and based on environmental indicators applicable to local conditions.

3.1 Defining sustainability

According to the Brundtland Report of 1987 (WCED, 1987), sustainable development is defined as development that "meets the needs of the present generation without compromising the ability of the future generation to meet their own needs". In order to achieve sustainability, the following three dimensions need to be considered: economy, society and the natural environment. Figure 11 represents the interaction between these three dimensions. Sustainability is achieved when the three spheres overlap and are in balance.

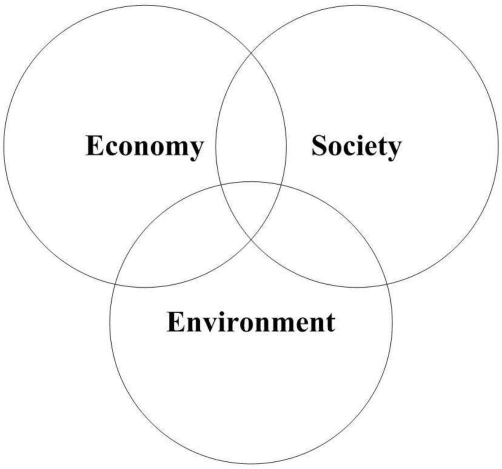

Figure 11: Dimensions of sustainability

The economical sphere includes elements such as economic growth, job creation and efficient resource use (Moldan *et al.*, 2011). The ultimate objective is decoupling economic growth from environmental degradation as there is a tendency towards a decline in the latter as development increases.

Aspects describing the social dimension of sustainability are the following: health and human well-being, security, nutrition, shelter or housing, education and freedom of cultural expression (Moldan *et al*., 2011). Tonkin (2008) further states that the aim should be to improve the quality of living in general.

Lastly, the dimension labelled environment entails aspects that impact on the ecological sphere, including climate change, land use, efficient transport systems, energy conservation, food systems, water security, waste generation and maintenance of ecosystem integrity through resource management (Moldan *et al*., 2011).

Sustainability does not consist of three independent spheres, rather the integration of economy, environment and society. Technically, a single dimension cannot be isolated even though this research does consider the environmental dimension separately. Future research should consider quantification of the economical and social dimensions resulting in full integration and achievement of sustainability. Integrated criteria possibly include the use of local materials stimulating the local economy and reducing the environmental impact due to transportation distances. Another example is local job creation which influences the local economy and benefits society.

As the focus of this study is on the environmental dimension of sustainability only, the environmental impact is elaborated in the following sections.

3.2 Current assessment methods

Two types of assessment methods currently exist in an effort to quantify the environmental impact of a building:

(1) *The application-oriented method:* A basic assessment system which uses a checklist compiled from building life cycle theory and comparing qualitative and quantitative aspects of a building's environmental impact by relative scores given. Existing methods include the UK BREEAM and the US Leadership in Energy and Environmental Design, LEED (Liu *et al*., 2010). The Green Star SA Rating Tool is also included in this category.

(2) *The analysis-oriented method:* Also based on building life cycle theory but in addition includes all accumulated environmental impacts measured quantitatively. The main functionality of this method lies in a database of building materials and their associated environmental impacts together with a weighting system aiming to quantify the overall environmental impact of a

building with simple calculations. Known examples include the Building for Environmental and Economic Sustainability (BEES) in the US and the Canadian Athena (Liu *et al.*, 2010). The method proposed in this study falls under this category as the analysis-orientated method is believed to be more scientific and comprehensive. Also, a local method already exists regarding the application-orientated method.

Within the analysis-orientated category, various Life Cycle Impact Assessment (LCIA) methods exist. This includes the CML 2001 method published by the Center of Environmental Science of Leiden University; the Environmental Design of Industrial Products (EDIP) 1997 and 2003 from collaboration in Denmark and the Eco-indicator 99 method produced by Goedkoop and Spriensma in 1999. All these methods are based on a similar framework considering three steps. The first step entails calculating the environmental impact potentials where the contribution of each emission to the different impact categories, as defined by the method considered, is computed with the use of characterisation factors also known as equivalency factors. The next step is normalising these potentials in order to compare their impact with a common reference. Lastly, to be able to compare the impacts in relation to one another, weighting factors are applied (Hischier *et al.*, 2010).

The mentioned methods are complex to use and require the utilisation of large databases implemented with expensive software. Also, it generally relates to global factors. Within a South African context, a scientifically based analysis-orientated method is needed which is easy to use, inexpensive to implement and is region specific. The purpose of this study is to create such a model using different indicators as explained in the following sections.

3.3 Proposed method for quantifying the Environmental Impact

This proposed method of quantifying the environmental impact of the built environment covers a broader scope than the conventional carbon footprint calculation. The goal is to provide a guideline or tool which can be used in order to objectively improve the environmental impact of the built environment. Even though this proposed model may be applied to the built environment in general, it will be implemented to quantify the environmental impact of low-cost housing units specifically.

3.3.1 Selected indicators

Three different environmental indicators are proposed namely Emissions, Waste Generation and Resource Depletion to assist with the quantification process. Indicators are typically identified and applied over a certain period of time in order to determine a trend and may be measured between an established baseline and set targets (Moldan *et al*., 2011). The three indicators are selected as they are relevant to the current local context and believed to induce the greatest impact on the environment in relation with various other environmental impacts considered globally.

Emissions

In Figure 4, representing the CO_{2e} emissions per sector, it is seen that the manufacturing sector contributes 40 % of the total emissions whereas the building sector is responsible for a further 23 % (Milford, 2009). Emissions due to the built environment link with both these sectors since the percentage applicable to the building sector only includes operation of buildings. Production of construction materials also has a significant impact on the environment and this is classified under the manufacturing sector.

Furthermore, in line with international trends, President Jacob Zuma's address at the UN Climate Change Conference in Copenhagen on 18 December 2009 pledged the following:

> "With financial and technological support from developed countries, South Africa for example will be able to reduce emissions by 34 % below 'business as usual' levels by 2020 and by 42 % by 2025" (Address by President Jacob Zuma, [s.a.]).

To be able to reach such a level of emissions in 2020, a significant reduction in the total contribution of 63 % from both the building and manufacturing sectors will lead to a substantial decrease in the overall emissions. Emissions is thus an important environmental indicator which needs to be considered.

Resource Depletion

It is estimated that the total global combustion of fossil energy during the 20th century amounts to 500 Gt (Krausmann *et al*., 2009). Furthermore, it is believed to have greatly contributed to the amount of greenhouse gas emissions in turn accelerating climate change. South Africa supplies almost 90 % of its energy by using non-renewable fossil fuels as energy resources. This is evident in Figure 12.

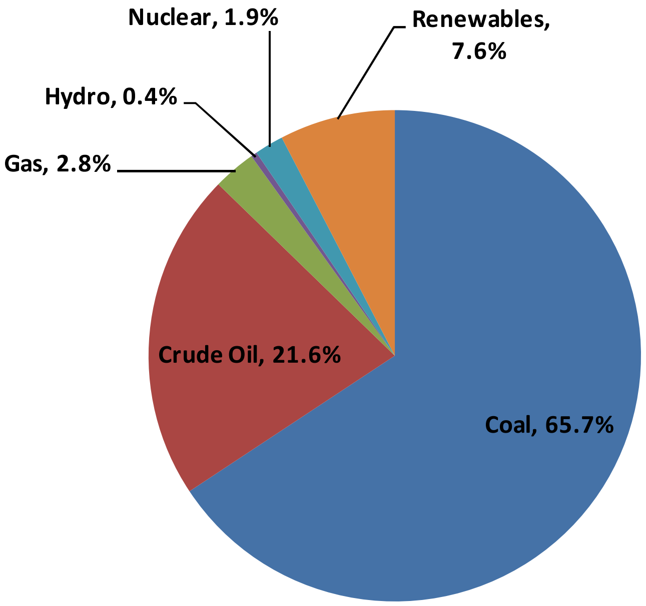

Figure 12: Primary energy supply in 2006 (DoE, 2010)

Also, energy consumption per sector is shown in Figure 13. It can be seen that the building sector consumes 27.2 % of the total energy whereas the manufacturing industry uses 32.2 % of the energy supplied. Once again, similar to the case of emissions, the building and manufacturing sectors are responsible for the largest energy consumption, a total of 59.4 %. Note that apart from resources being used to supply energy, other mineral and metal resources are extracted to manufacture products.

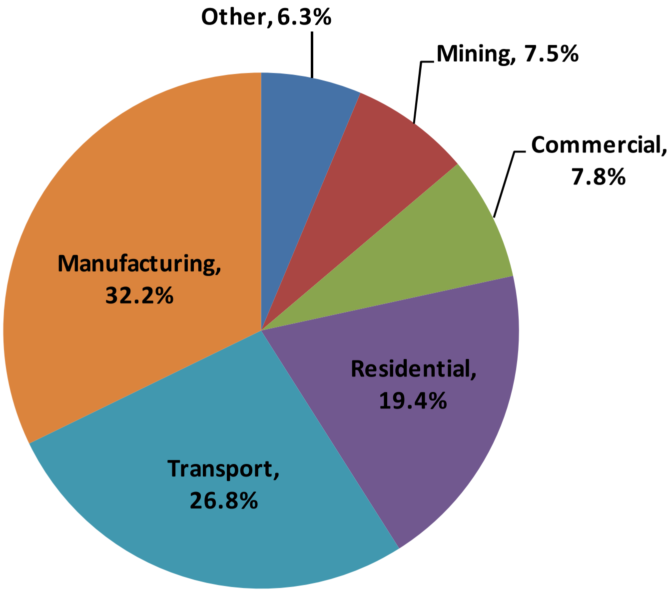

Figure 13: Sectoral consumption of energy in 2006 (DoE, 2010)

At the beginning of the 21th century, the global amount of materials extracted was approximated between 47 and 59 billion metric tons per annum (Krausmann *et al*., 2009). Also, 70 % of the resources extracted are non-renewable resources and this proportion is ever increasing. The predominant increase in material resource use is ascribed to population growth. This complex process is furthermore driven by the global economy (Krausmann *et al*., 2009).

The amount of resources extracted has increased significantly since 1980 as seen in Figure 14. The total resource extraction escalated from 40 billion tons to 55 billion tons in 2002. It is clear from the figure that industrial and construction materials are the greatest contributor to the total amount of resources extracted. An increase in this category is also evident.

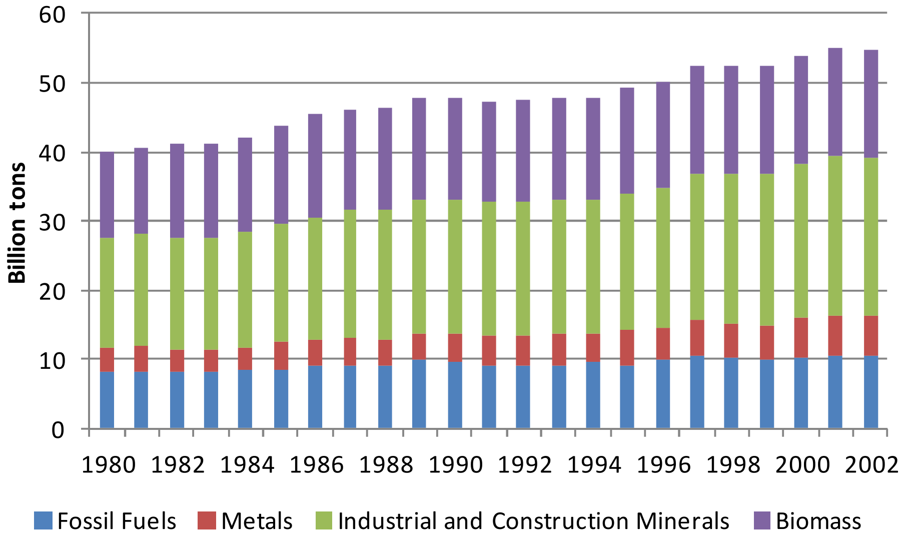

Figure 14: Global used resource extraction by material category (Behrens *et al*., 2007)

If resources are not managed effectively, whether it is on a global level or in South Africa, a possibility of exhausting them emanates. It is therefore important to be able to quantify the impact of Resource Depletion as it significantly influences the environmental impact of the built environment.

Waste Generation

The choice of Waste Generation as an indicator relates to the fact that South Africa suffers from limited landfill space and the consequent occurrence of widespread illegal dumping.

The following sites and activities typically generate solid waste: households, offices, shops, markets, restaurants, public institutions, industries, water works and sewage facilities, construction and demolition, and agricultural practices (Pipatti *et al*., 2006). Also, of the total municipal solid waste generated in South Africa, 90 % thereof is disposed at solid waste sites. South Africa suffers from limited land which can serve as space for the development of new landfill sites (DEAT, 2005). Several landfills have been closed or will be closed in the near future as capacities have been reached.

Widespread illegal dumping occurs possibly due to the shortage of landfill sites, long transportation distances, dumping fees, the lack of education on recycling options and enforcement measures not managed well (Katz *et al*., 2011).

Construction and demolition waste contributes 10 - 20 % of landfill space and is currently an untapped resource in South Africa (DEAT, 2005). Construction and demolition waste includes defective items, leftover materials, wastage and packaging (Katz *et al*., 2011). Various useful recycled or re-used forms of construction and demolition waste exist, therefore it is important to be able to quantify the amount of waste generated from construction and demolition activities.

3.3.2 Indicators across building life cycle

Each of the above mentioned environmental indicators is quantified using one or more variables, defined as EI_i (*i*th environmental impact). In order to simplify this complex procedure, a typical building life cycle is divided into three phases, namely the Pre-Use Phase, the Use Phase and the End-of-Life Phase.

The Pre-Use Phase typically includes resource extraction, production of materials and construction on and off site while the Use Phase is synonymous with the operation of the building. The End-of-Life Phase comprises of demolition of the building. Figure 15 shows a concise graphical representation of the life cycle of a building.

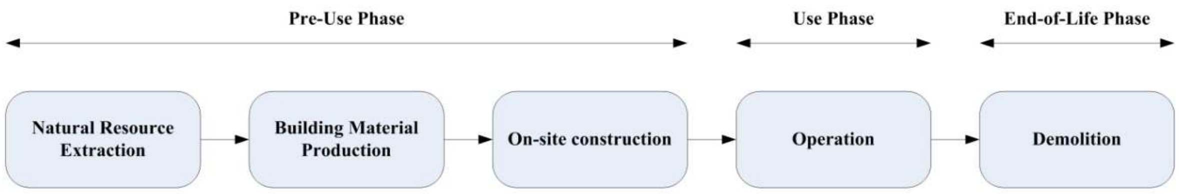

Figure 15: Building life cycle (Wang *et al*., 2005)

A great amount of gasses emitted into the atmosphere as a result of the built environment are from production of building materials and transport thereof as acquired in the Pre-Use Phase. Energy required for building operation in the Use Phase also contributes significantly to Emissions. Resources can be defined to include raw materials, fuels, water and land mostly acquired during the

Pre-Use Phase of a building. Most waste accumulates as demolition waste during the End-of-Life Phase of a structure although construction waste is generated in the Pre-Use Phase.

Life Cycle Assessment (LCA) is a system analysis method that is useful in evaluating resource consumption and waste emissions across the whole life cycle of products or processes (Wang *et al.*, 2005).

According to ISO 14040:2006, a LCA consists of the following four phases: goal and scope definition, inventory analysis, impact assessment and interpretation of results. During the first phase, audience and system boundaries are determined. Secondly, the inventory analysis requires quantifying relevant inputs and outputs whereafter evaluation of the significance of the environmental impact based on the inventory is done during the assessment phase. Finally, based on the results, conclusions can be reached and recommendations for improvements can be made (Schreuer *et al.*, 2003).

The following sections discuss the chosen indicators, namely Emissions, Resource Depletion and Waste Generation which each have negative impacts on the environment. Methods for quantifying these impacts in each phase of a building's life cycle are proposed.

3.3.3 Quantification of Emissions

Cement production contributes between 3 % and 6 % of global equivalent carbon dioxide (CO_{2e}) emissions annually (Marland *et al.*, 2007, Jegatheesan *et al*. 2009). Even if zero emission cement production technology is used, 0.44 tons of CO_2 will still be emitted per ton of pure limestone used due to calcination. Two possible solutions exist to this problem: reduce consumption – in a world with a growing population and demand it is not readily possible – or develop new materials producing less CO_{2e} emissions (Chaturvedi *et al.*, 2004).

The international steel industry often affirms that steel is a more environmentally friendly material than concrete as it is highly recyclable. Steel also has a higher modulus of elasticity compared to concrete and can carry a greater load with less material being used when slenderness issues are overcome (Chaturvedi *et al.*, 2004). It is however difficult to justify these statements without taking an objective holistic approach of the environmental impact for each application. These arguments should also not be based on a single environmental indicator, e.g. only on the carbon footprint.

Nitrogen oxides (NO_x), sulphur dioxide (SO_2), carbon monoxide (CO) and carbon dioxide (CO_2) are the primary emissions in the cement manufacturing process while CO_2, CO, SO_x and NO_x are the principal gas emissions during steel production (TFEIP, 2006). It is thus important to quantify these emissions as the environmental impact of cement and steel production is substantial.

Quantification method

For each process or material flow under study, different emissions are emitted due to the constituent materials and energy needed. Various emission factors exist for each material or energy used. Emission factors usually occur in the form of kg CO_2/unit (Carbon Trust, 2008). Furthermore, the amount of gas (kg) emitted can be calculated as follows:

$$E_i = e_i m_i \tag{1}$$

where e_i is the emission factor associated with the material or energy considered and m_i its related mass or flow.

Associated with the gasses emitted during the production of steel and cement, two Environmental Impacts (EI's) are proposed for the quantification of the emissions of the built environment, namely Carbon Footprint and Acidification Potential.

Carbon Footprint

Certain gasses in the earth's atmosphere trap the energy from the sun in turn warming the earth's surface. These gasses, better known as greenhouse gasses (GHG's), form part of the natural greenhouse effect and without it life on earth would not be possible. However, an enhanced greenhouse effect will have negative consequences. GHG's as listed in the Kyoto Protocol (United Nations, 1998) include carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), hydrofluorocarbons (HFC's), perfluorocarbons (PFC's) and sulphur hexafluoride (SF_6). All these emissions are used in calculating the carbon footprint of a system although only the first three mentioned are applicable to the built environment.

Quantifying a carbon footprint requires all components to be of CO_{2e} form (Azapagic *et al.*, 2004). This facilitates the comparison procedure. Once the CO_{2e} for all the components has been determined, the sum of these kg CO_{2e} values produces the carbon footprint of the system. It may be obtained as follows:

$$EI_1 = CF = \sum_{i=1}^{n} GWP_i \, E_i \tag{2}$$

where the global warming potential (GWP) associated to a certain emission *i* is obtained from Table 2 and E_i the amount of gas emitted as calculated earlier. EI_1 is the first environmental impact considered.

Table 2: GWP factors (Pachauri *et al*., 2007)

GHG Name	**Chemical Formula**	**GWP for a 100-year time horizon**
Carbon dioxide	CO_2	1
Methane	CH_4	25
Nitrous Oxide	N_2O	310

Acidification Potential

The acidification of soils and water resources through acids such as HNO_3 and H_2SO_4 occurs mainly by way of transformation of air pollutants, including SO_2 and NO_x, into the mentioned acids. The acidification potential is given in sulphur dioxide equivalents (SO_{2e}). Increased acidity of water and soil can consequently increase corrosion of manmade structures (Azapagic *et al*., 2004). The Acidification Potential value in kg, the second EI, is determined as follows:

$$EI_2 = AP = \sum_{i=1}^{n} f_i E_i \tag{3}$$

where f_i represents the acidification factor of gas *i* found in Table 3 and E_i the emitted amount in kg. Note that other emissions causing acidification are not considered here since only emissions typically related to the built environment are taken into account.

Table 3: Acidification factors (Azapagic *et al*., 2004)

Name	**Chemical name**	**Acidification factor (f)**
Sulphur dioxide	SO_2	1
Oxides of nitrogen	NO_x	0.7

3.3.4 Quantification of Resource Depletion

It is rather complex to quantify resource depletion using indexes or reserve-to-use ratios; therefore it is advised that exergy be incorporated into a life cycle analysis (Wang *et al*., 2005). There exists a direct relation between the exergy use of fossil fuels and minerals and the environmental impact of natural resource depletion (Cornelissen *et al*., 2000).

Definition of Exergy

A resource, whether natural or artificial, is defined as a material which is in a state of disequilibrium with the environment, consequently possessing exergy. Processes such as purification increase the value and exergy of resources (Rosen *et al*., 2008).

Exergy is defined as the maximum obtainable work potential of a material or energy flow in relation to the environment (Cornelissen *et al*., 2000). Exergy is thus the maximum theoretical work or available energy which can be extracted from a combined system, including its environment, as the system passes from a given state of energy to equilibrium with the environment (Wang *et al*., 2005).

The first law of thermodynamics states that energy is conserved in all processes even if energy conversions take place. The quality or usefulness of energy can however be reduced in worth and this concept is formulated by the second law of thermodynamics concerned with the non-conservation of entropy (De Meester *et al*., 2009). Exergy comprehends this quality concept and is also a measure of its potential to cause change. When in equilibrium with the reference environment, the exergy of a system is zero (Rosen *et al*., 2008). The unit of exergy is Joule (J_{ex}).

This environment can be a local or global average, more often referred to as the reference conditions. These conditions have been defined as a temperature of 298 K and atmospheric pressure of 101,325 Pa (De Meester *et al*., 2009).

Exergetic Life Cycle Analysis

In order to accommodate resource depletion as an environmental impact, it is suggested that the conventional LCA be extended to an Exergetic Life Cycle Analysis (ELCA). The framework of assessment remains similar. The first phase, the goal and scope definition, is identical but the inventory analysis of the ELCA is more detailed. A simplified input-output approach could be used to quantify material mass and energy flow balances of processes taken into account. The impact assessment phase represents the calculation of exergy flows and the phase where exergy destruction of the processes is determined. The accumulation of exergy destruction over the entire life cycle gives the irreversibility of the product. Important to note is that the ELCA points out places in the life cycle where exergy destruction takes place. Aiming to minimise exergy destruction, objective improvement possibilities may be presented (Cornelissen, 2000).

Quantification of Cumulative Exergy

Calculation of cumulative annual exergy demand can be done as follows (De Meester *et al*., 2009):

1. Draw up an inventory of all materials and energy per annum for the full life cycle.
2. Calculate embodied energy of materials using Ecoinvent database for the Swiss Centre for Life Cycle Inventories.
3. Quantify above in terms of exergy by using the eXoinvent method developed by De Meester *et al*. (2009) in conjunction with earlier research by Dewulf *et al*. (2007).

In Step 3 conversion factors called X-factors are introduced which quantify the cumulative exergy extraction from the natural environment (Dewulf *et al*., 2007). The factor X is defined as the exergy content in MJ_{ex}/unit of reference flow for units defined in the Ecoinvent database. The CEENE (Cumulative Exergy Extraction from the Natural Environment) in MJ_{ex} for a product *j*, can be calculated as the sum over all reference flows considering the appropriate X-factor. This results in the third EI and is defined as follows:

$$EI_3 = CEENE_j = \sum_{i=1}^{n} X_i a_{ij} \tag{4}$$

where X_i is the factor of the *i*th reference flow and a_{ij} the amount of reference flow *i* needed to produce product *j* (Dewulf *et al*., 2007).

3.3.5 Quantification of Waste Generation

The construction and building industry is responsible for a large amount of waste or building rubble also referred to as CDW (construction and demolition waste). Furthermore, the volume of CDW is depleting available land space in landfills and causes illegal dumping to a considerable extent (dos Santos *et al*., 2004).

From construction and demolition activities, concrete, bricks and blocks are currently commonly disposed of at landfill sites because little demand exists for their recycled forms. These materials have the potential to be crushed and used as secondary aggregates in road base and sub-base construction. Other uses for recycled aggregates include bulk fill or concrete. Making use of recycling and other initiatives reduces the volume of resource extraction and the number of new quarries required (Duran *et al*., 2005).

Proposed Waste Minimisation Strategy

The following strategy is proposed for the demolition of any part of the built environment. Firstly, prior to demolition, an inventory of materials in a building needs to be made. This includes the estimation of the volume, separability and composition in order to determine the feasibility of the exercise. Secondly, suitable areas on site where materials can be separated into the following different categories are required. The categories include hazardous waste, construction materials which can be reused, building materials sufficient for recycling (e.g. aggregates for concrete), materials which can be used to provide energy and finally the material disposed of at a solid waste site (Bokalders *et al*., 2010). Only after the above mentioned preparation is done should the demolition commence. Figure 16 shows the proposed order of dealing with CDW. Note that construction waste is typically generated during the Pre-Use Phase and demolition waste during the End-of-Life Phase.

The reduced environmental impact due to waste treatment can be measured in two ways: the reduced mass of waste ending up in landfills, or quantifying the avoided production and extraction of virgin resources. The latter mentioned requires initiatives or strategies such as recycling, re-use, recovery, incineration etc. Once the best strategies have been selected, the implementation thereof will include a study of the economical viability.

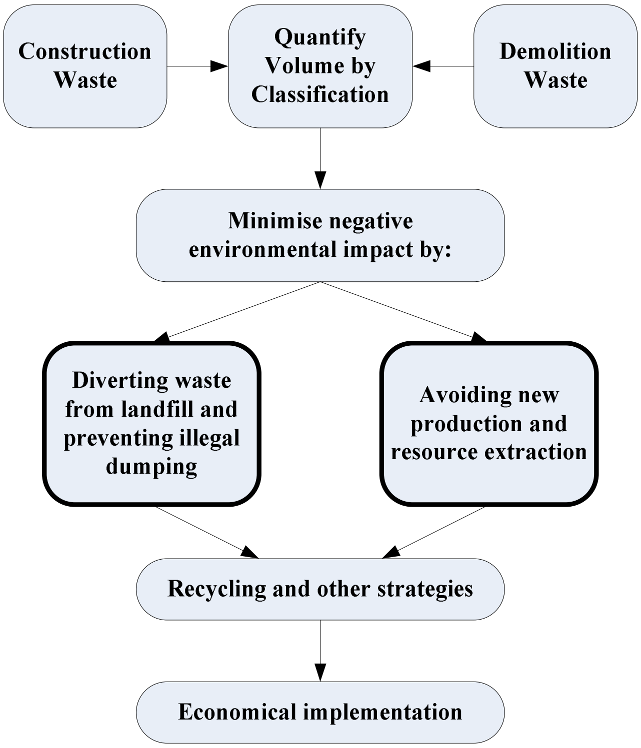

Figure 16: Quantification and minimisation of the environmental impact of waste

Quantification of Classified Waste Volumes

A method for quantifying the volume of construction and demolition waste expected has been proposed by Solís-Guzmán *et al*. (2009), but it only relates to dwelling type buildings in Spain. This quantification model has been developed by studying 100 dwelling projects, particularly their Bill of Quantities, and defining three coefficients, associated with the three sources of waste, to estimate the demolished volume, wreckage volume and the packaging volume.

Proposed procedure of waste quantification (Solís-Guzmán *et al*., 2009):

(1) Classification system – put together similar materials of same unit.
(2) Determine quantity of each item per m^2 of the building.
(3) Calculate the expected waste.

Although the coefficients and quantities determined by Solís-Guzmán *et al.* (2009) have not yet been determined for the South African context, the Spanish values will be used for the purpose of this study. These coefficients can easily be calibrated once a study of the South African context has been done. Note that even though this method calculates the volume of waste generated, the mass can be determined by multiplying with the respective material density factors.

The following sections explain two means of minimising the negative environmental impact of waste once the volume has been quantified, namely Waste Diversion and Production Avoidance. Furthermore, methods of evaluating these impacts are presented.

Waste Diversion

Without recycling initiatives, the volume of waste may increase at an alarming rate. Consequential increase in landfill costs could encourage waste producers to find new methods of diverting waste from landfills. Recycling initiatives are likely to be implemented without any enforcing regulations when the cost of landfilling exceeds the cost of transporting waste to a recycling station and also when the cost of using primary aggregates exceeds the cost of using recycled aggregates. Strategies such as taxes and or the use of subsidies would however accelerate the implementation (Duran *et al*., 2005).

In order to monitor the state of landfill sites, it is necessary to quantify the mass (kg) of waste disposed. Considering recycling, re-use and so forth, the following equation provides a way with which to determine the mass of waste ending up in landfill:

$$\begin{aligned} EI_4 &= M - M_r \\ &= M_d \end{aligned} \tag{5}$$

where M is the total mass of waste quantified after classification, M_r the waste mass recovered by implementing recycling strategies in turn corresponding to M_d, the reduced mass of waste disposed at the landfill site. M_d is proposed as the fourth EI.

Production Avoidance

Waste material recovered from the demolition phase as the 'avoided product' is quantifiable as 'avoided cumulative exergy consumption'. The cumulative exergy consumption (J_{ex}) can be calculated with the eXointvent tool as mentioned before.

If a product is merely disposed of, an extra amount of cumulative exergy will be required for its disposal, CE_xC_{disp}. However, if a waste product is recovered for secondary use, two new cumulative exergy factors need to be considered. Firstly, natural virgin resources are preserved noted as CE_xC_{av}. Secondly, other processes for example transport and incineration requirements involve some cumulative exergy, CE_xC_{rec}. The natural resource savings that are earned when a disposal scenario is replaced by a recovery scenario can be labelled the net avoided virgin resource consumption or the net avoided cumulative exergy consumption, $CE_xC_{net.av}$ (Dewulf *et al.*, 2009). The last mentioned can be determined as follows and is proposed as the fifth EI:

$$EI_5 = CE_xC_{net.av} = CE_xC_{av} + CE_xC_{disp} - CE_xC_{rec} \tag{6}$$

If resulting $CE_xC_{net.av}$ values are positive, it indicates that for whichever scenario and waste fraction considered, it results in net virgin natural resource savings. Note that when a shorter lifetime is assumed for the building, the relative importance of the End-of-Life Phase naturally increases (Dewulf *et al.*, 2009).

3.3.6 Proposed Environmental Impact Index

In order to obtain a holistic view of the environmental impact of the built environment, it is proposed that environmental impacts defined are to be combined into a final index called the Environmental Impact Index (EII). Table 4 shows a summary of the proposed environmental impacts along with the unit of measurement.

Table 4: Summary of Environmental Impacts

No.	**Name**	**Unit**
EI_1	Carbon Footprint	kg CO_{2e}
EI_2	Acidification Potential	kg SO_{2e}
EI_3	Resource Depletion	J_{ex}
EI_4	Waste Diversion	kg
EI_5	Production Avoidance	J_{ex}

Each environmental impact is divided by a normalisation reference EI_{ref} in order to obtain dimensionless units for all impacts which then make them comparable. Also, a weighting factor is assigned to each environmental impact corresponding to the relative importance of the associated impact. The EII can thus be calculated as:

$$EII = \sum_{i=1}^{5} c_i \frac{EI_i}{EI_{refi}} \tag{7}$$

where c_i is the weighting factor related to EI_i, the environmental impacts and EI_{refi} the associated normalisation reference.

Agreement has not been reached with current research as how to aggregate environmental impacts into a single index as proposed above. Various techniques exist such as expert decision and analytical studies, but the decision remains which selection would be the best. Some scholars argue that while trying to combine these impacts into one comparative index, it obscures the relative contribution of each. Transparency of decision making over the building life cycle may thus be enhanced in a disaggregated form (Azapagic *et al.*, 2004).

LCIA methods mentioned in Section 3.2 include Eco-Indicator 99 and the EDIP 1997 or 2003 version. Weighting factors for the three damage categories defined in the Eco-Indicator method is determined by an expert panel survey (Hischier *et al.*, 2010) whereas for the EDIP method, these weighting factors are based on political targets set in accordance with selected reference values (Stranddorf *et al.*, 2005).

As mentioned previously, this quantification method may be applied to the built environment in general, but this study focuses on low-cost housing specifically for which the proposed model will be implemented in the following chapters.

Chapter 4

IMPLEMENTATION FRAMEWORK OF PROPOSED MODEL

The proposed quantification method will be implemented within a certain framework following three main assumptions and for two low-cost housing design types. This chapter provides information on the chosen framework along with the methodology used when implementing the quantification method.

4.1 Framework

This section provides background information on the reference housing project selected to simplify calculations and decrease material and design assumptions. In order to implement the proposed method, three assumptions are made related to the phase of the building life cycle selected, impact assessment factors required in order to determine the impact potentials and proportion waste volumes expected due to construction activities.

4.1.1 Reference housing project

For the quantification method to be implemented, an existing housing project was used as a reference, namely the Kayamandi Watergang Housing Project near Stellenbosch. The project consisted of two phases. Phase 1A went to out tender in November 2006 for the construction of 534 low-cost houses whereas the second phase concluded the construction of 113 housing units at the end of April 2011. The project consisted of nine different types of unit combinations ranging from single units, duplex units and two or more semi-detached single or duplex units (Allen, 2011). Figure 17 shows two types of unit combinations. The functional unit used for the implementation of the quantification process is a single housing unit of 40 m^2.

Soil conditions were classified according to the NHBRC Home Building Manual (NHBRC, 1999). One half of the site was classified as H/S founding material whereas the rest was found to be H1/S1 material (van der Merwe, 2011). Residential site class designations mentioned refer to expansive and compressible soils typically fine grained clays, silts and sandy material.

Figure 17: a) Semi-detached duplex units, and b) Semi-detached single units (Allen, 2011)

The Master Plan of the area showing the layout and orientation of the different housing units can be found in Appendix A.

Furthermore, for the purpose of implementing the proposed environmental impact quantification method, two of the three mentioned design types as described in Section 2.5 are chosen. The conventional design type is widely used in low-cost housing projects, well-known by contractors and the NHBRC Building Manual (NHBRC, 1999) assists during the design stage. Along with the advantages mentioned when constructing a Light Steel Frame Building, a design code SANS 517:2009 has been published recently. Light Steel Frame design hence presents itself as a building system with potential increase in popularity locally as opposed to alternative building systems run on a small scale by an individual or small group.

4.1.2 Pre-Use Phase and system boundary

For the purpose of this study only the Pre-Use Phase is considered. It is believed that the conceptual and design phase, which is included in the Pre-Use Phase, may prove to have an important influence on the impact of the building across the whole life cycle. Also, it is during the Pre-Use Phase where the structural engineer possibly has the most influence as the Use Phase is concerned with the operation of the building and the End-of-Life Phase the demolition thereof. Variables such as building orientation, material selection, construction methods and so forth influence the sustainability of the building; therefore the Pre-Use Phase entails important choices affecting society and the environment in the long term (Wang *et al.*, 2005). Llatas (2011) mentions that several studies have identified the reasons for the substantial amount of construction waste generated as poor decisions and design concepts submitted during the design stage. Keep in mind that conclusions regarding the better alternative should not be based on the Pre-Use Phase only as it does not provide a holistic view. For such results it is advised to incorporate the other building life cycle phases.

Following the choice of building life cycle phase, it is furthermore important to define the system boundary. A system boundary is a set of criteria specifying which unit processes are part of a system (BS EN ISO 14040, 2006). The exclusion of certain elements of the phase may have a significant effect on the outcome; it is thus crucial that the most accurate system boundary be selected for the study undertaken. Figure 18 shows the system boundary of the Pre-Use Phase for a conventional designed low-cost house whereas Figure 19 is similar but for a Light Steel Frame Building as an alternative to the brick and mortar design. Note that the finishes and services are excluded from the system boundary for both cases as the same elements or processes are used for both design types. In this instance, the EII will increase by the same amount for both cases and can been seen as a common factor.

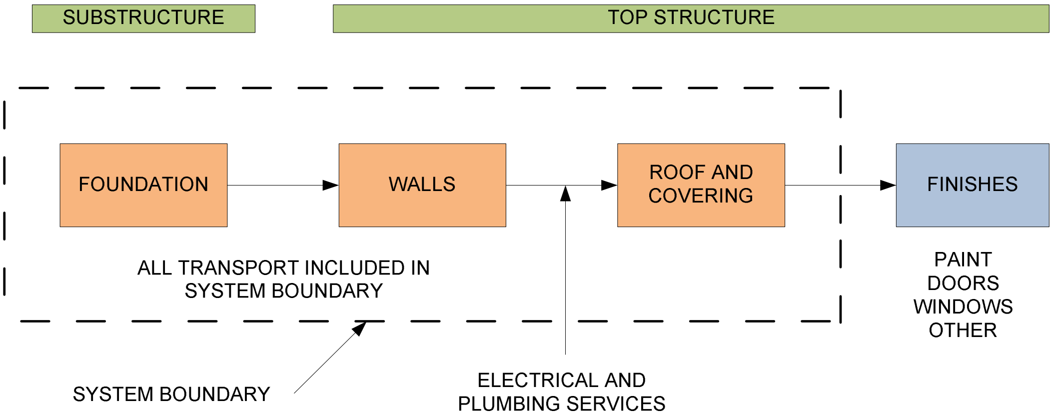

Figure 18: System boundary for conventional brick and mortar design

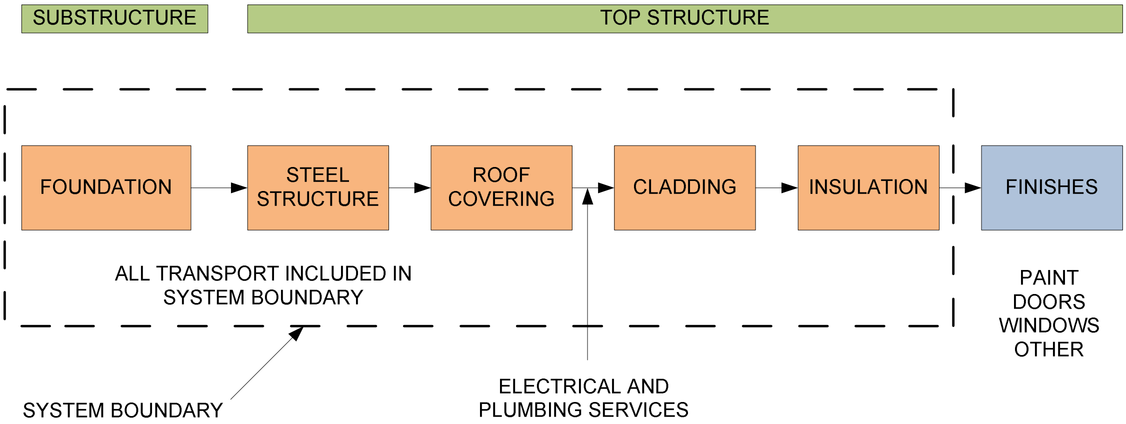

Figure 19: System boundary for LSFB as an alternative

Once the system boundary has been clearly defined, the quantification method can be applied.

4.1.3 Ecoinvent database

The Ecoinvent project was initiated early in the 1990's. Swiss Centre for Life Cycle Inventories developed the database which accommodates approximately 4000 datasets for products, services and processes. These datasets are often used in Life Cycle Assessments and case studies. The Ecoinvent Centre functions as collaboration between the following institutes: Swiss Federal Institute of Technology Zürich (ETHZ), Swiss Federal Institute of Technology Lausanne (EPFL), Paul Scherrer Institute (PSI), Swiss Federal Laboratories for Materials Testing and Research (Empa) and the Agroscope Reckenholz-Tänikon Research Station (ART). They are considered to be the world leaders of consistent and transparent life cycle inventory data and use of the Ecoinvent database is recognised worldwide (Frischknecht *et al*., 2007).

Such an extensive materials impact potentials database is not available locally despite the fact that the Cement and Concrete Institute has published emission factors for building materials related to concrete production (Perrie, 2010). Therefore the Ecoinvent database is selected for use.

Version 2.2 (2010) of the Ecoinvent data was used for obtaining Life Cycle Impact Assessment (LCIA) factors of various materials. Several LCIA methods exist for which information are available on the Ecoinvent database. In aid of calculating the environmental impact, factors were obtained from the EDIP 1997/2003 method. This method was selected as similar impact units were observed for the proposed method. More specifically impact potential factors for the carbon footprint [kg CO_{2e}], acidification potential [kg SO_{2e}] and bulk waste [kg] were utilised. The Eco-Indicator 99 method works on a point system, creating difficulty to extract impact potential factors from the database.

As explained in Section 3.2, the EDIP method consists of three steps namely environmental impact assessment, normalisation with respect to a common reference and finally weighting of the impacts in terms of relative importance. This correlates to the proposed quantification method. Only the first step is implemented in the Ecoinvent database, normalisation and weighting should be done by the user separately.

Normalisation is done by dividing the environmental impact with a common reference in order to obtain dimensionless units for all impacts which are then comparable. A widely used reference is the average yearly environmental load in the region considered divided by die number of inhabitants. Region may refer to a country, continent, global or even a smaller local area (Goedkoop *et al*., 2008).

The weighting factors in the EDIP method are based on the political reduction targets for each environmental impact category (Stranddorf *et al*., 2005). The year 1994 has been selected as the reference year, purely as data was easily available for that year, simplifying the compilation thereof. The method stipulates a 10 year difference between the reference and target year, hence 2004 is the target year. Calculating these weighting factors simply imply dividing the actual impact value for the year 1994 with the target value of the year 2004.

Dimensionless weighting factors are linked to the above mentioned normalisation references with regard to the geographical area considered. Weighting factors for Denmark, Europe (EU-15) and the world are obtainable (Stranddorf *et al*., 2005). Normalisation and weighting factors used in this study can be seen in Table 5.

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

Environmental Impact	**Normalisation reference**		**Weighting factor**	**Reference year**	**Reference region**
	Unit	**Value**			
Carbon Footprint	kg CO_{2e}/per/yr	8.7E+03	1.12	1994	Global
Acidification Potential	kg SO_{2e}/per/yr	59	1.27	1990	Europe
Bulk Waste	kg/per/yr	1350	1.1	1991	Denmark

Where global factors are not available, it is advised to use European values for impact potentials located outside of Europe. As for bulk waste, the Danish weighting factor is provided due to a lack of availability for other regions (Stranddorf *et al*., 2005). The EDIP method is of Danish origin and it is possible that Denmark was the only country with waste reduction targets in 2004.

Aggregating the factors presented for the EDIP method into a single environmental impact index is allowed, although resources (kg) may not be included as a different weighting method is used (Goedkoop *et al*., 2008). Weighting factors are not based on political targets, instead on the proven reserves per person. A different method is selected in order to obtain the environmental impact for Resource Depletion separately, namely the Cumulative Exergy Demand method. Ten different impact categories are identified for this method, including seven energy categories and three material resources categories each represented with a MJ-eq value. Table 6 shows the ten categories along with a description of each.

Table 6: Categories of Cumulative Exergy Demand method (Hischier *et al.*, 2010)

Category	**Description**
Fossil	non-renewable energy resources, fossil
Nuclear	non-renewable energy resources, nuclear
Wind	renewable energy resources, kinetic (in wind), converted
Solar	renewable energy resources, solar, converted
Water	renewable energy resources, potential (in barrage water), converted
Primary Forest	non-renewable energy resources, primary forest
Biomass	renewable energy resources, biomass
Water resources	resources renewable material resources, water
Metals	non-renewable material resources, metals
Minerals	non-renewable material resources, minerals

South Africa mainly depends on fossil resources for energy production as shown in Figure 12. Derived from Figure 12, South Africa supplies 90.2 % of energy with fossil fuel resources. For this reason only four impact categories of the Cumulative Exergy Demand method were selected for use. They are highlighted in Table 6 above: fossil, water resources, metals and minerals.

Normalisation is not included in this method and in order to obtain an aggregated total, each impact category is multiplied with a weighting factor of 1.0 (Goedkoop *et al.*, 2008).

4.1.4 Spanish model for quantification of construction waste

The Spanish model was selected in order to estimate the construction waste generated as it is a simple to use method and based on the Bill of Quantities which forms the base of calculations in the following chapters. Local waste proportion factors are not yet available but can easily be replaced in the future when such studies have been done. Therefore Spanish values were used for the purpose of this study.

Referring to the article by Solis-Guzman *et al.* (2009), a summary of the equations and steps used to estimate the volume of construction waste from items on the Bill of Quantities are provided:

1. Calculate the material quantity per m^2 of the building.

2. Determine the apparent constructed volume VAC_i for each item *i* on the Bill with its quantity Q_i and respective unit. CC_i is a conversion factor.

$$VAC_i\ [m^3/m^2] = Q_i\ [unit/m^2] \text{ x } CC_i\ [m^3/unit] \tag{8}$$

3. Calculate the apparent wreckage waste volume $\mathrm{VAR_i}$ by multiplying with a dimensionless factor $\mathrm{CR_i}$.

$$VAR_i\ [m^3/m^2] = VAC_i\ [m^3/m^2] \text{ x } CR_i \tag{9}$$

4. Calculate the apparent packaging waste volume $\mathrm{VAE_i}$ by multiplying with a dimensionless factor $\mathrm{CE_i}$.

$$VAE_i\ [m^3/m^2] = VAC_i\ [m^3/m^2] \text{ x } CE_i \tag{10}$$

5. Add $\mathrm{VAR_i}$ and $\mathrm{VAE_i}$ and multiply with the building area to obtain the volume of waste for item *i*. Sum over all the items to determine the total waste volume [m^3].

6. To convert into total mass [kg] of waste generated, multiply the waste volume of each item with its respective density and sum over all.

4.2 Methodology

The quantification process can easily be implemented in a spreadsheet using the Bill of Quantities as the template. This simplifies mathematical operations and the tool can thus be presented in a user-friendly format. Information required for quantifying the environmental and economical impact may be obtained from the Bill of Quantities of the project. Material quantities are used as input values for calculating the environmental impact, whereas rates and prices are used to determine the cost. For each design type, a separate calculation sheet is used. This is typically an extension of the Bill of Quantities implementing the environmental and economical impact or cost calculations. The following two chapters will explain the specific calculations and assumptions in depth for both the conventional and Light Steel Frame Building design types.

Chapter 5

QUANTIFYING THE EI AND COST OF A CONVENTIONAL DESIGN HOUSING UNIT

This chapter explains the implementation of the proposed quantification method, consequently calculating the environmental impact and cost. The design type of focus in this chapter is the conventional brick and mortar design as a type of low-cost housing unit. A project at Watergang, Kaymandi, Stellenbosch, was used as an example where required.

5.1 Structural system

Section 2.5.1 provided a broad description on the conventional design and materials typically used. Furthermore, Figure 17 provided the system boundary selected for quantification purposes; however, it also showed the structural breakdown of the system. The substructure comprises of the foundation and slab whereas the top structure includes construction of the walls, roof system and various finishes. For the purpose of further calculations, the structure was further broken down into building elements to ease comparison of different design types later on. A list of the building elements follow with a short description of each thereafter:

- Foundations
- Floor slab
- External walls
- Internal walls
- Ceiling and insulation
- Roofing
- Roof covering

The foundation was designed as strip-footings and includes reinforced concrete bases with concrete hollow masonry units (blockwork) as the foundation walls. A simple reinforced concrete floor slab is then cast upon compacted fill material which acts as slab support with the slab bearing on the external foundation walls. A damp proof course is inserted between the foundation and external walls to prevent moisture from entering underneath the top structure. External walls consist of the construction of concrete hollow masonry courses with the external face plastered. Internal walls are similar but not plastered. Roofing entails a Howe timber truss system with purlins and galvanised sheeting as roof covering.

A detailed plan of a single 40 m^2 house and foundation details used for populating the Bill of Quantities can be seen in Appendix B.

5.2 Conventional design

A Bill of Quantities was obtained from the civil and structural engineering consultants on the Watergang Kayamandi Housing Project. This was used a template when quantifying the environmental impact of a low-cost house designed according to conventional principles.

For some building elements, a further breakdown of materials required was necessary in order to calculate the environmental impact more accurately. These include for example concrete foundations to be categorised as concrete and reinforcing steel along with foundation and external walls to be decomposed into blockwork, mortar, galvanised brickforce and certain layers filled with concrete. Table 7 shows the breakdown of building elements; seen as the indented text.

Table 7: Extract of expanded Bill of Quantities

Materials				
Item	Unit	Quantity	Rate [R/unit]	Cost [R]
Foundations				
Excavation	m^3	8.94	50.34	450.04
10 MPa concrete foundation (600x200mm)	m^3	3.00	791.92	2375.76
Reinforcing (4 x Y12)	kg	103.00		
190 mm blockwork including	m^2	14.90	103.04	1535.30
brickforce (75x2.8mm),	m	125.00		
galvanised	m^2	2.45		
filled with concrete	m^3	0.97		

Limited detail was given on the truss layout and quantities of materials needed as a sub-contractor would typically design and supply the materials for a quoted rate. It was therefore required to design the truss according to the NHBRC Home Building Manual (NHBRC, 1999) in order to obtain material quantities needed for further environmental impact calculations. A Howe type truss can be designed for different types of roof coverings, roof pitches and maximum spans according to detail plans. With known input details regarding the timber truss with roof sheeting, the truss layout was determined from Table 1, Section 4 of Part 2 (NHBRC, 1999) providing particulars such as the number of bays required, grade of timber, centre-to-centre truss spacing and the timber profile sizes needed.

5.3 Assumptions

Various assumptions were made for the implementation of the quantification model to fully function for this specific design type. A list follows:

- Project and construction time is estimated at one year. The normalisation step requires impact potentials to have a unit per year, resulting in dimensionless normalised values which can then be compared.
- Mortar and plaster sand:cement ratio taken as 4:1 (Addis, 1998). Impact potentials for mortar are not available on the Ecoinvent database; a ratio between the available factors for sand and cement were opted for.
- Transport of all materials from plant to site and transport of construction waste to landfill total a distance of 100 km. The implication of this selection is investigated with a sensitivity analysis in Chapter 9. A model can be proposed to quantify the total distances more accurately, but the process tends to become complex.
- 3.5 – 7.5 t truck used for transport. Small scale contractors are used for low-cost housing projects; therefore the size of the truck seems a fair estimation.
- Labour costs and cost of transporting materials to site are included in the rates given in the Bill of Quantities. This is typically how a Bill of Quantities is compiled in industry.
- All waste generated goes to landfill. If a proportion of waste is to be recycled or re-used, it will affect EI_4 (Waste Diversion) and EI_5 (Production Avoidance). The cumulative exergy from avoided production has to be subtracted from the exergy due to resource extraction and initial production. Recycling or other initiatives is not considered in this study, hence the effect of EI_5 is not taken into account.

Quantifying the environmental impact requires impact factors to be multiplied with the amount of input material. Factors obtained were taken as materials carefully selected from the Ecoinvent database to be closely related to the item on the Bill of Quantities. Table 8 shows the materials selected from the database and provides a description for each. Note that this table also includes possible alternative materials to the original design, stated previously, for subsequent optimisation purposes.

Table 8: Materials selected from the Ecoinvent database for conventional design type

Item on Bill	Ecoinvent Name	Unit	Description
Concrete	Concrete, normal, at plant	m^3	Includes the whole manufacturing processes to produce ready-mixed concrete, internal processes (transport, etc.) and infrastructure. Density: 2380 kg/m^3. Ingredients: Cement 300 kg, Water 190 kg, Aggregates 1890 kg.
Reinforcing	Reinforcing steel, at plant	kg	Mix of differently produced steels and hot rolling.
	Section bar rolling, steel	kg	The module describes the rolling process of section bar. It includes 50 % of the wire drawing process. Does not include the material being rolled.
Blockwork	Concrete block, normal at plant	kg	Includes the raw material normal concrete which is poured into a mould, air-dried and packed. Some transports and infrastructure are also included.
Lightweight concrete block	Lightweight concrete block, expanded clay, at plant	kg	Includes the raw materials, their transport to the finishing plant, the air-drying, the packing, the infrastructure and the disposal of wastewater and some solid household (e.g. packing material) waste.
Brickforce	Steel, low-alloyed at plant	kg	Mix of differently produced steels and hot rolling.
	Wire drawing, steel	kg	Includes the process steps: pre-treatment of the wire rod, dry or wet drawing, in some cases heat treatment and finishing. Does not include coating and the material being rolled.
	Zinc coating, coils (galvanising)	m^2	Includes the process steps surface cleaning, heat treatment, immersion in a bath of molten zinc and finishing treatment. Also includes zinc input and transportation to coiling plant.

Damp proof membrane/course	Polyethylene, granulate, at plant	kg	Aggregated data for all processes from raw material extraction until delivery at plant.
	Extrusion, plastic film	kg	This process contains the auxiliaries and energy demand for the mentioned conversion process of plastics.
Plaster	Silica sand, at plant	kg	Includes the raw material sand, a certain additional amount of conveyor belt and the energy for drying the sand. No requirements for administration are included.
	Portland calcareous cement, at plant (CEM II A-L 32.5)	kg	Includes the manufacturing processes mixing and grinding, internal processes (transport, etc.) and infrastructure. No administration and no packing are included. Composition: gypsum 5 %, additional milling substances 16 %, clinker 79 %.
Ceiling	Gypsum plaster board, at plant	kg	Production of board (incl. drying)
Thermal insulation	Glass wool mat	kg	Included processes: melting, fibre forming & collecting, hardening & curing and internal processes (workshop, etc.). Additionally transportation of raw materials and energy carrier for furnace, packing and infrastructure are included.
	Rock wool, at plant	kg	Included processes: melting, fibre forming and collecting, hardening and curing furnace, and internal processes (workshop, etc.). Transport of raw materials and energy carrier for furnace are also included.
Roofing	Sawn timber, softwood, planed, air dried at plant	m^3	Includes planing process. Planing mill is assumed to be located on the sawmill site. No transports are considered. Dust emissions are neglected for a lack of data.
Sheeting	Steel, low-alloyed at plant	kg	Mix of differently produced steels and hot rolling.

	Cold rolling	kg	Includes the process steps continuous pickling line, cold rolling, annealing, tempering, inspecting and finishing, packing coils or sheets, roll maintenance.
	Zinc coating, coils (galvanising)	m^2	Includes the process steps surface cleaning, heat treatment, immersion in a bath of molten zinc and finishing treatment. Also includes zinc input and transportation to coiling plant.
Roof Tiles	Roof tile, at plant	kg	Includes first grinding process, wet process, storage, forming and cutting, drying, firing, loading, packing and storage.
Transport	Transport, lorry 3.5-7.5 t, EURO3	tkm	Operation of vehicle; production, maintenance and disposal of vehicles; construction and maintenance and disposal of road.

Furthermore, when estimating the construction waste, assumptions were made to the proportions of remains and packaging material as proposed in Solis-Guzman *et al*., 2009. The article provides one with waste factors applicable to new construction projects as well as the demolition of buildings. These factors are classified according to a system used in building project budgets in Andalusia, Spain. Such proportionate values are not yet available locally therefore Spanish values are used for the purpose of this study – they are however believed to be similar. Table 9 gives the waste factors as a proportion of the volume of each item, aiding the estimation of construction waste for the conventional design using the Bill of Quantities.

Table 9: Waste factors for the conventional design (Solis-Guzman *et al*., 2009)

Item	**Unit**	**Proportion wreckage waste material CR_i**	**Proportion packaging waste material CE_i**
Concrete	m^3	0.03	0.00
Steel reinforcing	kg	0.05	0.00
External and internal walls	m^2	0.056	0.10
Plaster	m^2	0.03	0.00
Roof	m^2	0.061	0.03
Ceiling	m^2	0.05	0.20

Important to note that no construction waste was estimated for the following items: damp proof membranes, brickforce, bagged walls, transport and roofing. The trusses used as the roofing system are supplied by a sub-contractor to the construction site as an assembled product. It is therefore assumed that no construction waste is generated by this building element. Construction waste produced by the other excluded items is assumed to be negligible. The waste produced due to manufacturing of the products is calculated with the Waste from Production factor obtained from the Ecoinvent database. The distinction is explained by an example later on.

5.4 Environmental impact computation

Impact categories or indicators identified for determination of the environmental impact include Emissions, Resource Depletion and Waste Generation as mentioned in Section 3.3. The following section systematically explains how to determine the environmental impact potentials related to each indicator for the conventional brick and mortar design type.

5.4.1 Calculation sheet

The calculation sheet implements all the factors mentioned previously along with simple mathematical operations. Steps followed will be clearly explained with an example item on the Bill of Quantities, namely blockwork and mortar used for the construction of external walls. Appendix C shows the entire Bill of Quantities implementing these factors and calculations for each material item. References of certain values are provided if required.

For some items the units on the Bill and in the Ecoinvent database differ; therefore, a conversion is necessary before the amount of material can be multiplied with each environmental impact factor separately. For example the area of blockwork is required as the mass of materials:

$$\begin{aligned} \textit{Mass of blockwork} &= \textit{Area } [m^2] \text{ x } \textit{mass per area } [kg/m^2] \\ &= 75.0 \text{ x } 160.0 \\ &= 12\ 000 \text{ kg} \end{aligned} \tag{11}$$

The conversion factor of 160 kg/m^2 was obtained from the CMA Concrete Masonry Manual (Jane, 2005).

Environmental impacts as stated in the proposed quantification model include the Carbon Footprint, Acidification Potential, Resource Depletion and Waste Generation in respective units. Each of these is calculated using factors from the Ecoinvent database as follows:

$$\begin{aligned} \textit{Carbon Footprint} &= \textit{Mass [kg]} \text{ x } \textit{factor [kg } CO_{2e}\textit{/kg]} \\ &= 12\ 000 \text{ x } 0.12122 \\ &= 1454.64 \text{ kg } CO_{2e} \end{aligned} \tag{12}$$

$$\begin{aligned} \textit{Acidification Potential} &= \textit{Mass [kg]} \text{ x } \textit{factor [kg } SO_{2e}\textit{/kg]} \\ &= 12\ 000 \text{ x } 0.00027702 \\ &= 3.324 \text{ kg } SO_{2e} \end{aligned} \tag{13}$$

$$\begin{aligned} \textit{Resource Depletion} &= \textit{Mass [kg]} \text{ x } \textit{factor [MJ-eq/kg]} \\ &= 12\ 000 \text{ x } 0.817615 \\ &= 9811\ 32 \text{ MJ-eq} \end{aligned} \tag{14}$$

$$\textit{Waste Generation} = \textit{Waste from Production [kg]} + \textit{Construction Waste [kg]} \tag{15}$$

Where

$$\begin{aligned} \textit{Waste from Production} &= \textit{Mass [kg]} \text{ x } \textit{factor [kg/kg]} \\ &= 12\ 000 \text{ x } 0.01498 \\ &= 179.76 \text{ kg} \end{aligned} \tag{16}$$

Construction Waste = 1801.8 kg, calculated according to the steps explained in Section 4.1.4. Appendix C presents a layout of the waste estimation calculations.

Therefore

$$\begin{aligned} \textit{Waste Generation} &= 179.76 + 1801.8 \\ &= 1981.56 \text{ kg} \end{aligned} \tag{17}$$

Note that the impacts from transport are calculated as the product of the total mass (t) of the 40 m^2 house plus the mass of construction waste generated, a 100 km distance and the respective environmental impact factors for the truck used.

The Carbon Footprint for the functional unit, that is the 40 m^2 house, is the sum of all the individual kg CO_{2e} values for each material item. The total Acidification Potential, Resource Depletion and Waste Generation is determined in a similar fashion.

5.4.2 Graphical results

The following section provides graphical representations of the various impact categories. Each building element is shown separately. Conclusions follow each diagram with a concluding summary at the end of the chapter.

Figure 20 shows the Carbon Footprint in kg CO_{2e} of each building element for the functional unit.

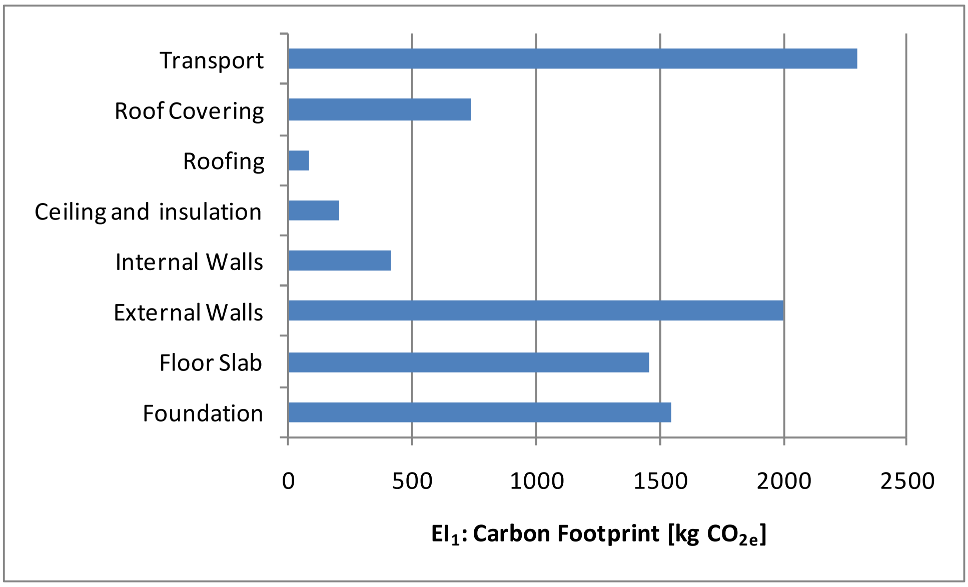

Figure 20: Carbon Footprint of each building element for the conventional design

Transport, external walls and the foundation, closely followed by the floor slab, have the largest Carbon Footprint in descending order of all building elements. The main component affecting the considered outcome is concrete along with other cementitious materials. The reason why transport contributes greatly may be prescribed to the mass of concrete materials which have to be transported. Furthermore, of all the materials required for construction of the conventional designed low-cost house, concrete has the largest environmental impact factor when it comes to the carbon footprint. The factor of 264.1 kg CO_{2e}/m^3 concrete is obtainable from the Ecoinvent database. This value is similar to values produced by the model using local emission factors for concrete mixes and processes quantified by the Cement and Concrete Institute (Perrie, 2010).

The next diagram, Figure 21, shows the Acidification Potential in kg SO_{2e}.

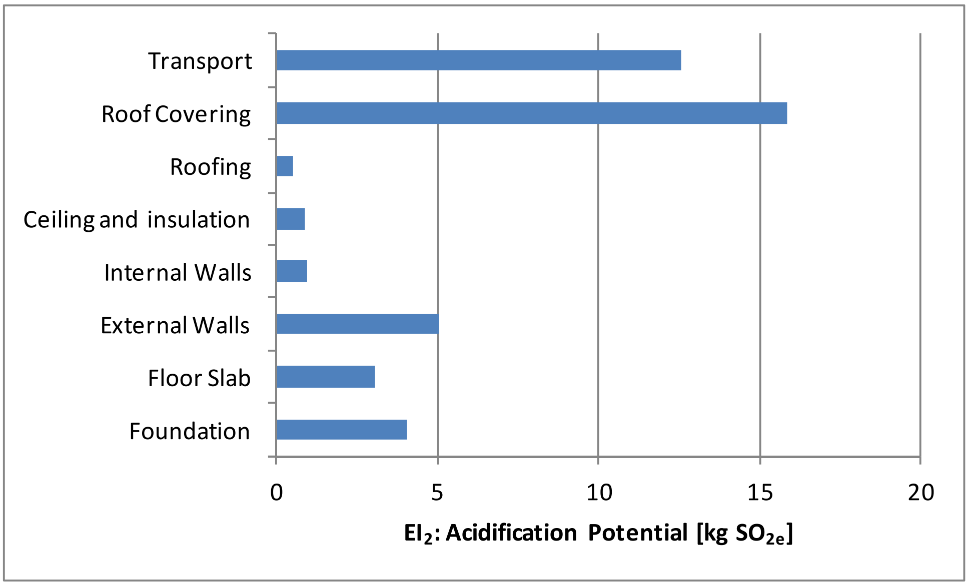

Figure 21: Acidification Potential of each building element for the conventional design

Clearly, roof covering and transport has the largest impact concerning Acidification Potential. Appendix C shows the calculation sheet for the conventional design type; note the large acidification potential arising from galvanising the sheeting used for roof covering. Even though the factor obtained from the database is not the largest considering all materials, the significant area which has to be galvanised brings about the result.

Figure 22 shows the impact of Resource Depletion similarly to the diagrams above.

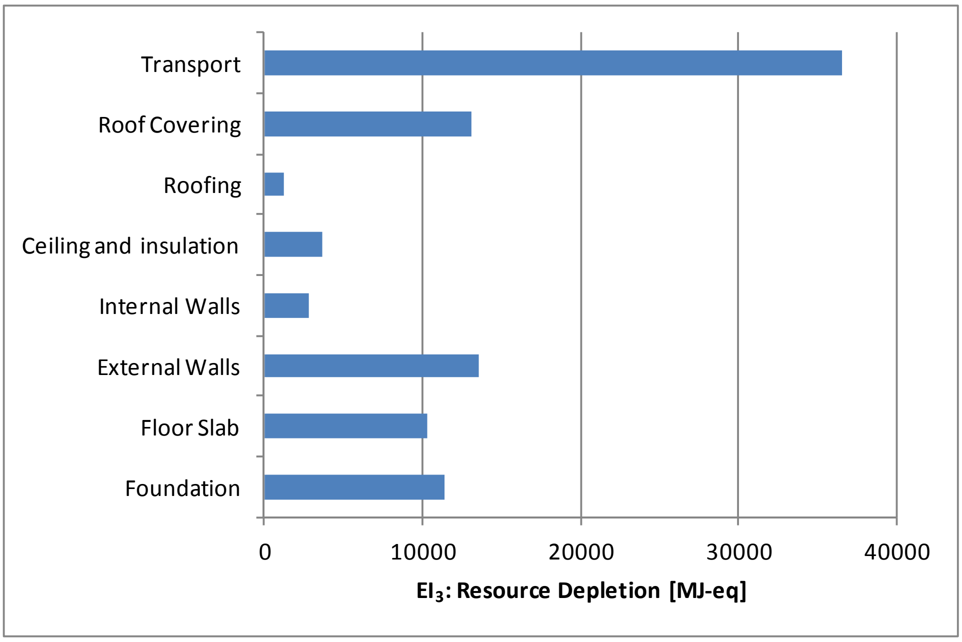

Figure 22: Resource Depletion of each building element for the conventional design

Transport evidently presents a major deviation from the other impacts as seen in Figure 22. This is possibly linked to the fact that large amounts of non-renewable fossil fuel resources are depleted for the truck to operate and transport the substantial mass of materials.

Lastly, the Waste Generation in kg for each building element is shown in Figure 23. Note that this is the sum of Waste from Production calculated with Ecoinvent database factors and Construction Waste amounts estimated with the model by Soliz-Guzman *et al*. (2009).

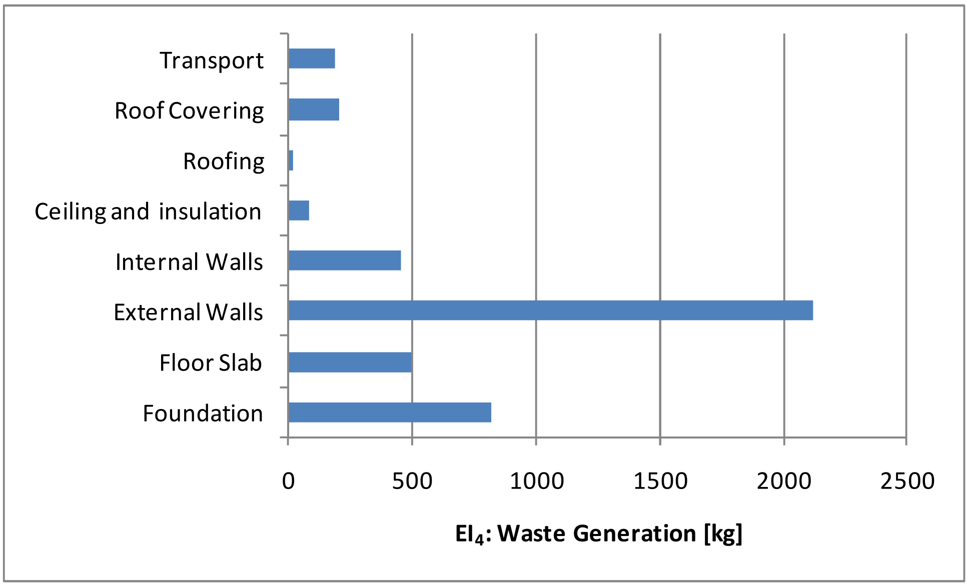

Figure 23: Waste Generation of each building element for the conventional design

The building element, external walls, clearly presents a major deviation from the other impacts shown. The construction waste calculation sheet shown in Appendix C indicates that the concrete blockwork used for external walls generate the largest amount of construction waste. This relates to the high volume proportions selected for the calculation of waste prediction.

5.5 Cost

The cost of the substructure and top structure for this design type totals R 51 478. Figure 24 shows the cost of each building element as a percentage of the total.

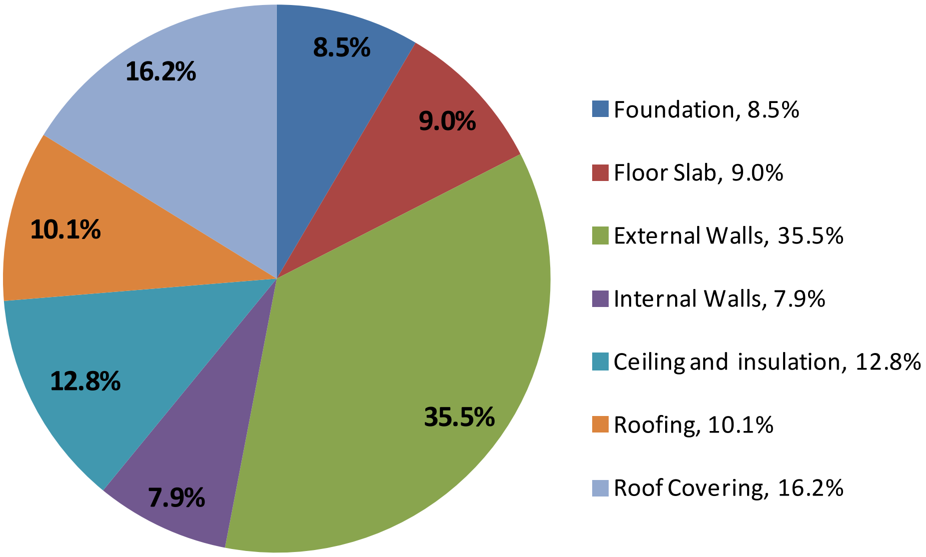

Figure 24: Conventional design price breakdown shown as percentages of the total

As seen in Figure 24, external walls are the greatest contributor concerning cost. This is purely because of the large area covered. Still, cheaper construction methods may exist. Second to external walls in terms of cost is the roof covering.

5.6 Concluding summary and remarks

Concluding this chapter is a summary of the results for the conventional design type and some remarks. A total of each environmental impact for the conventional design housing unit is provided in Table 10.

Table 10: Summarised results for conventional design

No.	Environmental Impact	Total	Unit
EI_1	Carbon Footprint	8736	kg CO_{2e}
EI_2	Acidification Potential	43	kg SO_{2e}
EI_3	Resource Depletion	92434	MJ-eq
EI_4	Waste Generation	4375	kg

It was seen that transport distinctively has a large effect on the three impacts: Carbon Footprint, Acidification Potential and Resource Depletion. Note that an assumption regarding the distance multiplied with the mass and respective factors was made for calculation purposes. The effect and significance of this assumption will be explored by means of a sensitivity analysis performed in Chapter 9.

Alternative materials for external walls and roof covering should be investigated as both affect the environmental impact and cost significantly. Optimisation of the design is possible; additionally this will be investigated in Chapter 8.

Chapter 6

QUANTIFYING THE EI AND COST OF A LSFB AS AN ALTERNATIVE

Various options can be considered for the construction of low-cost housing. This chapter will focus on the impact of a Light Steel Frame Building as an alternative to the conventional brick and mortar design. The design is relevant to site conditions at Watergang, Kayamandi, Stellenbosch. A detail explanation is provided as to how the quantification method is implemented for this design type.

6.1 Structural system

Section 2.5.2 provided a broad description on Light Steel Frame Buildings and materials typically used. Furthermore, Figure 18 provided the system boundary selected for quantification purposes; however, it also showed the structural breakdown of the system. The substructure comprises of the foundation and slab whereas the top structure includes construction of the steel structure, roof system, cladding, insulation and various finishes. For the purpose of further calculations, the structure was further divided into building elements similarly done for the conventional design. A material description of each building element is given next.

The foundation materials include concrete, steel reinforcing and concrete hollow masonry units. A similar floor slab as for the conventional design is constructed. External walls comprise of various layers but perform the same function as the plastered masonry walls for the conventional design, especially concerning weatherproofing, insulation and acoustics. These layers are erected in conjunction with the light steel frame wall panels and include fibre cement board external cladding, a vapour permeably membrane, orientated strand board used as a thermal break, glass wool bulk insulation and gypsum plasterboard as internal lining. Regarding internal walls, gypsum plasterboard is erected on both sides of the steel wall frame with glass wool insulation as infill. Construction of the ceiling is similar to the conventional design. The roofing system comprises of light steel frame trusses with similar profiles used for purlins and galvanised sheeting as roof covering.

6.2 LSFB design

Design of the light steel frame structure was done by a professional in the field (During, 2011). A similar layout and dimensions were used as for the conventional design of a 40 m^2 housing unit provided in Appendix B. The dead load applied in the design provided for two types of roof covering, namely sheeting and clay roof tiles. Appendix D contains the detailed drawings of the LSFB design. Drawings provided include the layout, side view of two wall panels and also truss specifications. Material usage reports are also included. Thereafter, the Bill of Quantities was compiled according to material and other specifications in SANS 517:2009.

Special attention was given to the foundation details. A strip-footing design was applicable to the conditions. The Light Steel Frame Building code (SANS, 2009) specifies that foundations should be designed to resist the horizontal loads and uplift forces due to wind or other loading conditions causing such forces. The following checks must be carried out: uplift resistance, horizontal stability and overturning both of the structure as a whole and of the individual parts. Furthermore, the code states that uplift forces shall be resisted by the weight equal to that of the foundation wall, the foundation itself and any fill above the foundation plus a proportion of the floor slab if applicable.

6.3 Assumptions

Assumptions were made for the implementation of the quantification model to fully function for the LSFB design alternative. These include:

- Project and construction time estimated at one year, similar to the conventional design.
- 10 % of mass added to steel profiles for fasteners as typically done in industry.
- Transport of all materials from plant to site as well as transport of construction waste to landfill total a distance of 100 km, similar to the conventional design.
- 3.5 – 7.5 t truck used for transport, similar to the conventional design.
- Assume the cost of transporting materials to site is included in the rates given in the Bill of Quantities, also the labour costs of LSFB erection is included in manufacturing costs.
- All waste generated goes to landfill due to similar reasons as assumed for the conventional design.

Quantifying the environmental impact requires impact factors to be multiplied with the amount of input material. Factors obtained were taken from the Ecoinvent database for materials carefully selected to be closely associated to the item on the Bill of Quantities. Table 11 shows the materials selected from the database and provides a description for each.

Table 11: Materials selected from the Ecoinvent database for LSFB as an alternative

Item on Bill	Ecoinvent Name	Unit	Description
Concrete	Concrete, normal, at plant	m^3	Includes the whole manufacturing processes to produce ready-mixed concrete, internal processes (transport, etc.) and infrastructure. Density: 2380 kg/m^3. Ingredients: Cement 300 kg, Water 190 kg, Aggregates 1890 kg.
Reinforcing	Reinforcing steel, at plant Section bar rolling, steel	kg kg	Mix of differently produced steels and hot rolling. The module describes the rolling process of section bar. It includes 50 % of the wire drawing process.
Brickwork (clay)	Brick, at plant	kg	Includes first grinding process, wet process, storage, forming and cutting, drying, firing, loading, packing and storage.
Brickforce	Steel, low-alloyed at plant Wire drawing, steel Zinc coating, coils (galvanising)	kg kg m^2	Mix of differently produced steels and hot rolling. Includes the process steps: pre-treatment of the wire rod, dry or wet drawing, in some cases heat treatment and finishing. Does not include coating and the material being rolled. Includes the process steps surface cleaning, heat treatment, immersion in a bath of molten zinc and finishing treatment. Also includes

			zinc input and transportation to coiling plant.
Damp proof membrane	Polyethylene, LDPE, granulate, at plant	kg	Aggregated data for all processes from raw material extraction until delivery at plant.
	Extrusion, plastic film	kg	This process contains the auxiliaries and energy demand for the mentioned conversion process of plastics.
Light steel profiles	Steel, low-alloyed at plant	kg	Mix of differently produced steels and hot rolling.
	Cold rolling	kg	Includes the process steps continuous pickling line, cold rolling, annealing, tempering, inspecting and finishing, packing coils or sheets, roll maintenance.
	Zinc coating, coils (galvanising)	m^2	Includes the process steps surface cleaning, heat treatment, immersion in a bath of molten zinc and finishing treatment. Also includes zinc input and transportation to coiling plant.
Cladding			
Fibre Cement Board	Fibre cement facing tile, at plant	kg	Includes the whole manufacturing process to produce fibre cement products, transports to plant and infrastructure.
Weatherboard	Sawn timber, softwood, planed, air dried at plant	m^3	Includes planing process. Planing mill is assumed to be located on the sawmill site. No transports are considered. Dust emissions are neglected for a lack of data.

Thermal break			
Orientated Strand Board (OSB)	Orientated strand board, at plant	m^3	Includes the inputs to the production processes and transports of those inputs. No process emission data are available.
Expanded Polystyrene (EPS)	Polystyrene foam slab, at plant	kg	Includes production and thermoforming of EPS.
Insulation			
Glass wool	Glass wool mat	kg	Included processes: melting, fibre forming and collecting, hardening and curing, and internal processes. Additionally transportation of raw materials and energy carrier for furnace, packing and infrastructure are included.
Rock wool	Rock wool, at plant	kg	Included processes: melting, fibre forming and collecting, hardening and curing furnace, and internal processes. Transport of raw materials and energy carrier for furnace are included. Not included are administration, packing and infrastructure.
Lining and ceiling			
Gypsum plasterboard	Gypsum plaster board, at plant	kg	Production of board (incl. drying)
Roof Covering			
Roof Tiles	Roof tile, at plant	kg	Includes first grinding process, wet process, storage, forming and cutting, drying, firing, loading, packing and storage.
Sheeting	Steel, low-alloyed at plant	kg	Mix of differently produced steels and hot rolling.

	Cold rolling	kg	Includes the process steps continuous pickling line, cold rolling, annealing, tempering, inspecting and finishing, packing coils or sheets, roll maintenance.
	Zinc coating, coils (galvanising)	m^2	Includes the process steps surface cleaning, heat treatment, immersion in a bath of molten zinc and finishing treatment. Also includes zinc input and transportation to coiling plant.
Transport	Transport, lorry 3.5-7.5 t, EURO3	tkm	Operation of vehicle; production, maintenance and disposal of vehicles; construction and maintenance and disposal of road.

Similar to Table 9, waste factors are given as a proportion of the volume of each item considered. See Table 12 for applicable factors used for the light steel frame design type.

Table 12: Waste factors for LSFB (Solis-Guzman *et al*., 2009)

Item	**Unit**	**Proportion wreckage waste material CR_i**	**Proportion packaging waste material CE_i**
Concrete	m^3	0.03	0.00
Steel reinforcing	kg	0.05	0.00
External and internal walls	m^2	0.056	0.10
Fibre cement facing tile	m^2	0.045	0.50
Thermal Insulation	m^2	0.01	0.00
Roof	m^2	0.061	0.03
Ceiling	m^2	0.05	0.20

Similar to the conventional design type, construction waste of brickforce, damp proof membranes and transport are not included. Since light steel frame profiles are pre-fabricated and the wall panels and trusses are assembled in the factory, it is safe to assume all waste contributing from this process is contained in the Waste from Production factor.

6.4 Environmental impact computation

The environmental impact of a Light Steel Frame Building is calculated for the same layout and site conditions as for the conventional brick and mortar design for comparison purposes.

6.4.1 Calculation sheet

Mathematical operations follow the same pattern as explained with the example in Section 5.4.1. The Bill of Quantities expanded to implement the environmental impact calculations as well as the volume of construction waste estimation for each item can be seen in Appendix E. References are provided where required.

6.4.2 Graphical results

The following section provides graphical representations of the various impact categories. Each building element is shown separately. Figure 25 shows the Carbon Footprint in kg CO_{2e} of each building element of the 40 m^2 LSFB house.

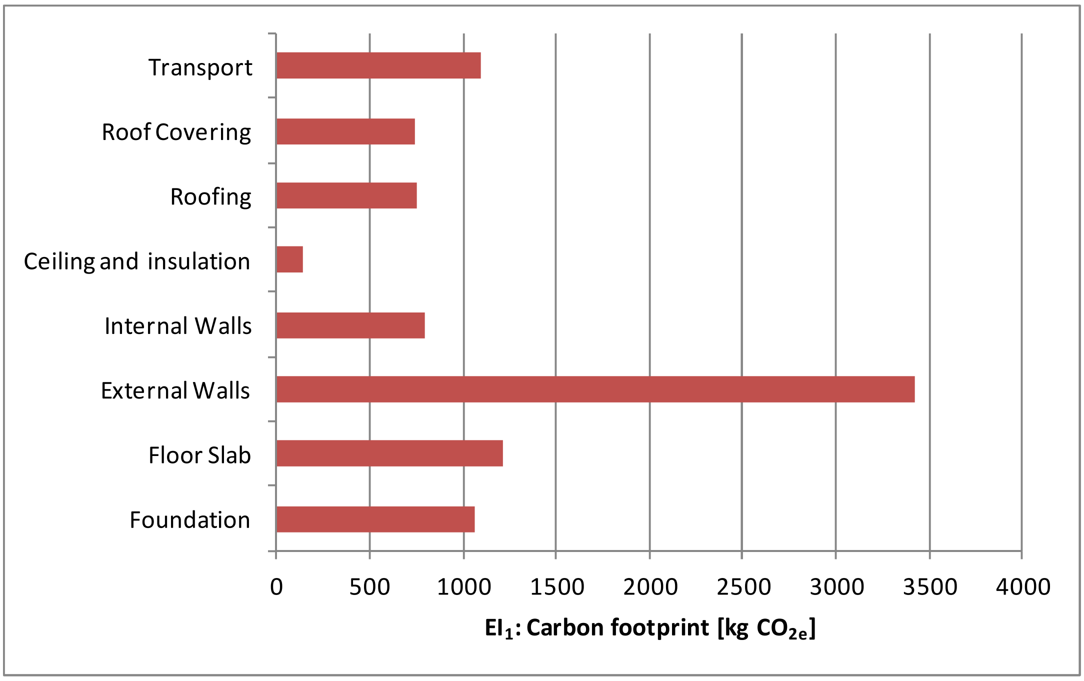

Figure 25: Carbon Footprint of each building element for the LSFB design

Similarly, Figure 26 shows the Acidification Potential.

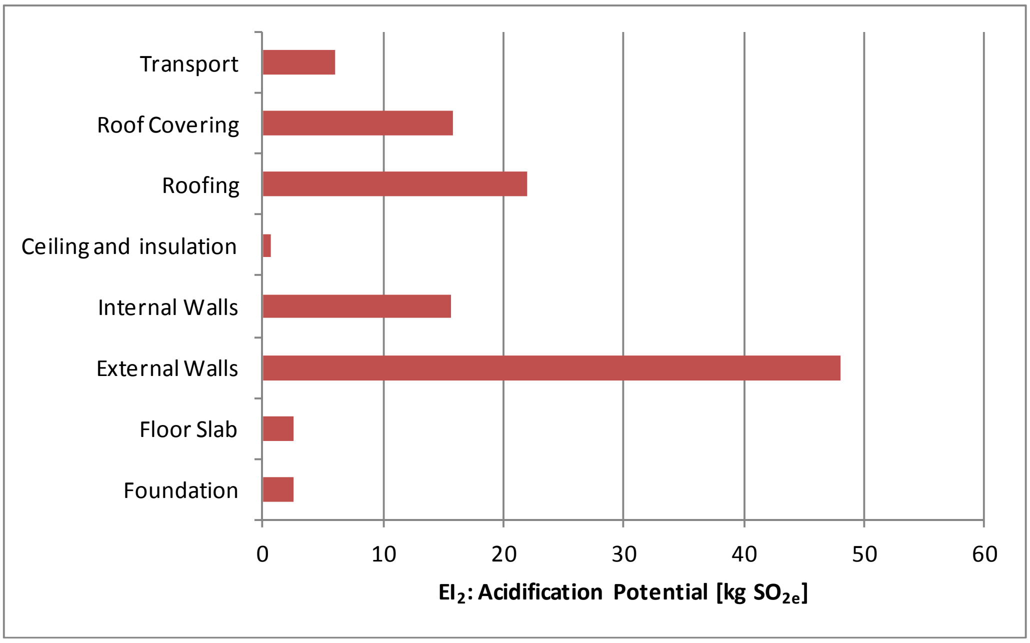

Figure 26: Acidification Potential of each building element for the LSFB design

In Figure 27, the impact of Resource Depletion can be seen for each building element in the Light Steel Frame Building.

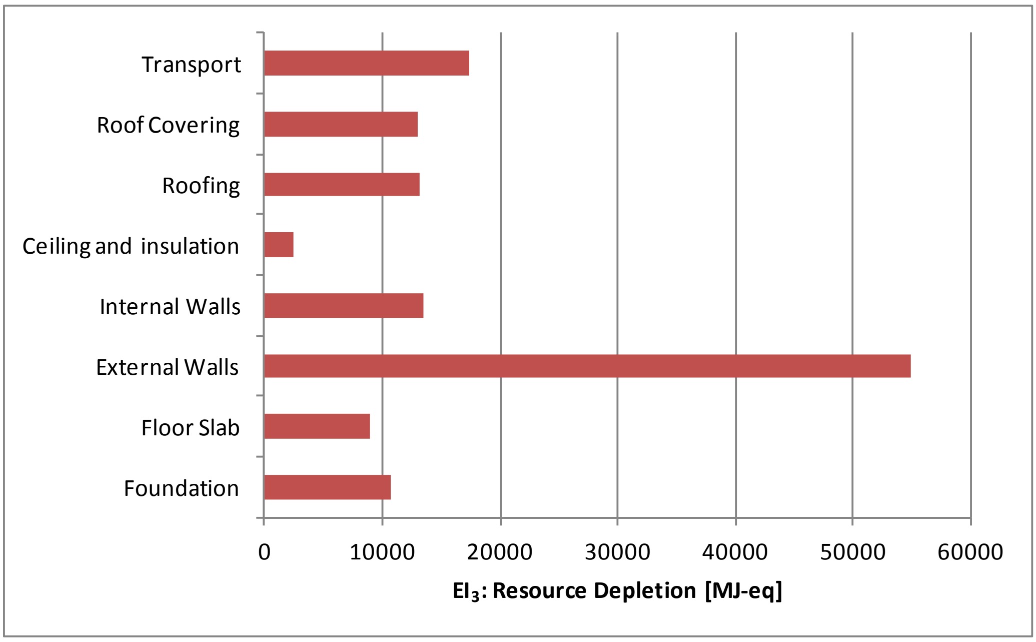

Figure 27: Resource Depletion of each building element for the LSFB design

Finally, the combined Waste from Production as well as predicted Construction Waste can be viewed in the graph in Figure 28.

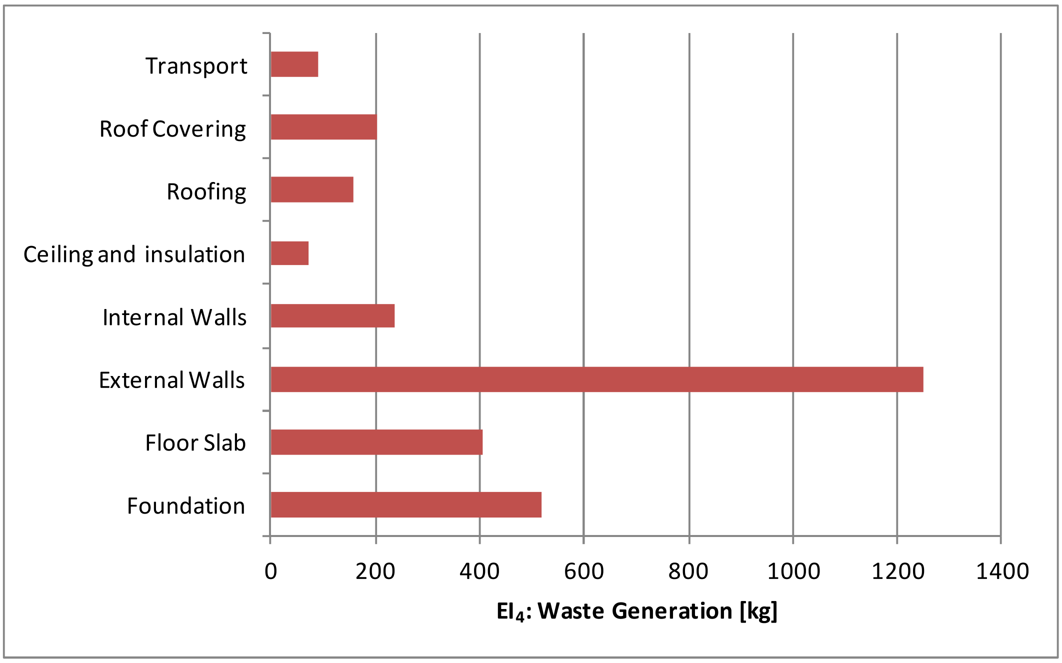

Figure 28: Waste Generation of each building element for the LSFB design

It is clear from Figures 25 through 28 that external walls present a major deviation from the other impacts in all cases. It is reasoned that this is because of the building element consisting of several layers of various materials along with the large area coverage, similar to the conventional design. These layers include the external cladding, damp proof membrane, thermal break, bulk insulation, internal lining as well as the light steel frame panel. Some of these materials have significant environmental impact potentials per unit which in turn sums to a substantial total when calculating the total environmental impact.

6.5 Cost

The total price of the LSFB substructure and top structure is calculated as R 68 217. Figure 29 shows the cost breakdown as percentages of the total for each building element.

Prices corresponding to elements similar in the Bill of Quantities for the conventional design type agree. Other rates were provided by Des Palm (2011) but 14% VAT had to be included manually. The cost of the external walls comprises almost half of the total price of the LSFB structure.

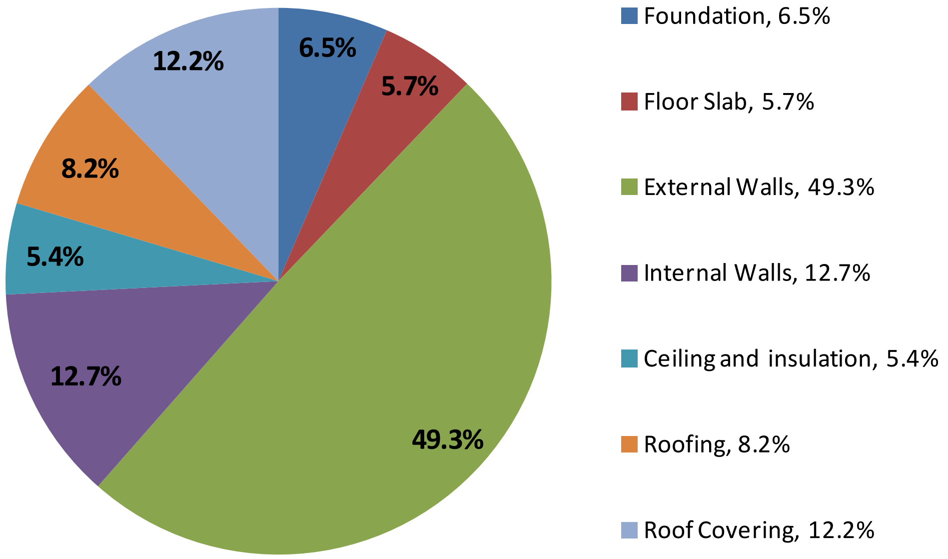

Figure 29: Proportionate price contributions for LSFB building elements

6.6 Concluding summary and remarks

In summary, a total of each environmental impact for the LSFB design housing unit is provided in Table 13. Compared to the summarised values for the conventional design type, only EI_4 provides a lower impact. At this point it seems that a LSFB unit does not provide better alternative results compared to the conventional design.

Table 13: Summarised results for LSFB design

No.	Environmental Impact	Total	Unit
EI_1	Carbon Footprint	9207	kg CO_{2e}
EI_2	Acidification Potential	113	kg SO_{2e}
EI_3	Resource Depletion	113943	MJ-eq
EI_4	Waste Generation	2933	kg

It is evident that alternative layouts of external walls be sought, as it is the dominating factor regarding both the environmental impact and cost. Alternative input materials may lead to a decrease in the Carbon Footprint, Acidification Potential, Resource Depletion, cost or a combination of these. Chapter 8 investigates the effect if material input parameters are substituted with alternatives in order to possibly optimise the given design. A detailed comparison is drawn between the two design types in the following chapter.

Chapter 7

COMPARISON OF MODEL IMPLEMENTATION FOR CHOSEN DESIGN TYPES

This chapter provides a broad comparison of the model implementation for both the conventional and LSFB design types. Firstly, the environmental impacts of respective building elements and the housing unit is compared whereafter the aggregated impact index is given. A cost comparison is also made.

7.1 Environmental impacts compared

The following section compares the environmental impact values for separate building elements, namely the foundation, floor slab, external walls, internal walls, ceiling and insulation, roofing and roof covering. The effect of transport is also included. Furthermore, the EI totals for each housing unit per design type are provided along with the normalised and weighted values to produce the EII.

7.1.1 Building elements

The EI for each building element is compared with regards to the Carbon Footprint, Acidification Potential, Resource Depletion and Waste Generation.

Figure 30 shows the Carbon Footprint comparison. The Carbon Footprint of transport for the conventional design is approximately twice the magnitude compared to the LSFB alternative. This is clearly due to the large difference in mass of the two structures. The conventional brick and mortar unit weighs 47.43 t whereas the LSFB has a mass of 22.44 t, almost half the mass of the conventional design. The difference in EI_1 for external walls is substantial. The various layers required for the LSFB, especially the fibre cement board external cladding, contributes largely to the Carbon Footprint. Also, the Carbon Footprint of the foundation for the conventional design generates slightly more CO_{2e} emissions since a heavier foundation is required for the conventional design. The Carbon Footprint for the other building elements is of similar order.

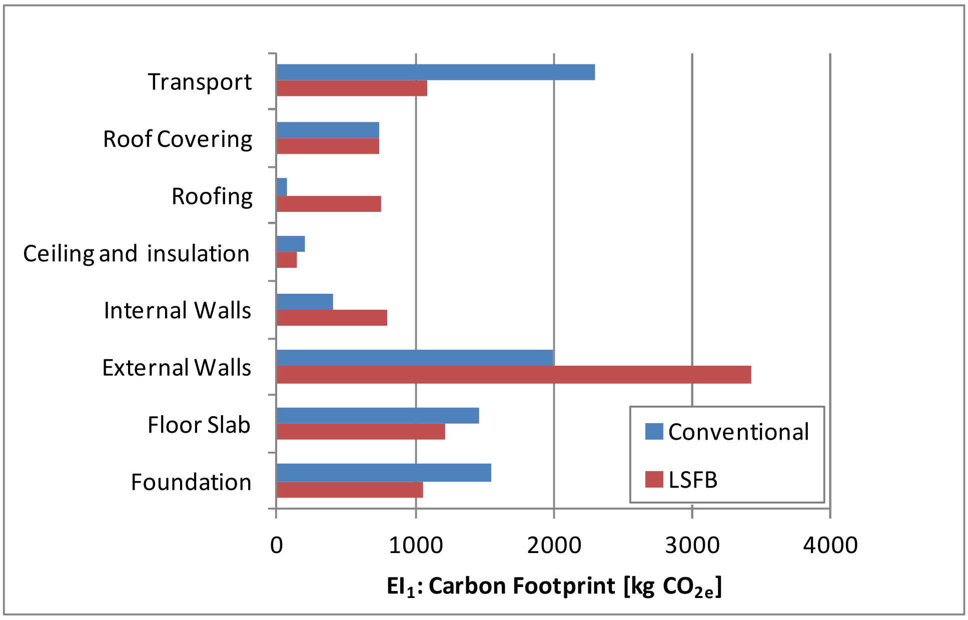

Figure 30: Comparison of Carbon Footprint for each building element

Similarly, the comparison of Acidification Potential for each building element for both design types can be seen in Figure 31. From this diagram it is evident that the manufacturing and construction of a LSFB unit produces the most kg SO_{2e}. Galvanisation of these light steel profiles leads to such a significant EI_2 for several building elements considered. Likewise, galvanising of roof sheeting results in a large Acidification Potential for both design types in this case.

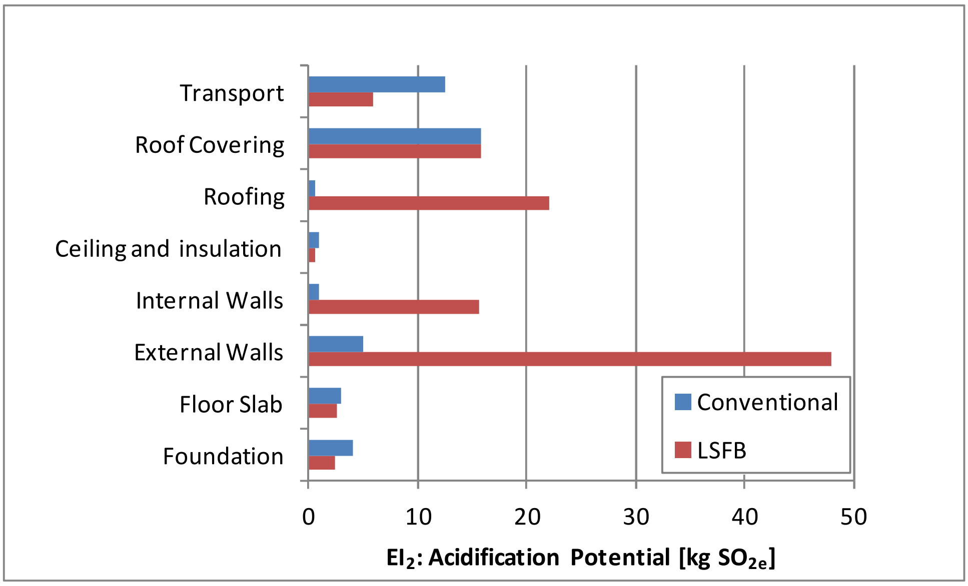

Figure 31: Comparison of Acidification Potential for each building element

Figure 32 graphically represents the comparison of Resource Depletion. EI_3 is of similar order for nearly all of the building elements except for transport, roofing and internal and external walls. Recall that the impact of transport is related to the mass of the unit; again the conventional design has a greater unit mass and will hence impact Resource Depletion to a greater extent. Concerning external walls, nearly the same quantity of exergy is required for the production of light steel profiles and galvanisation thereof when compared to the total for all material items needed to construct external walls with concrete masonry. Moreover, LSFB wall panels involve a variety of other material layers which in turn increase the effect on Resource Depletion for this particular building element.

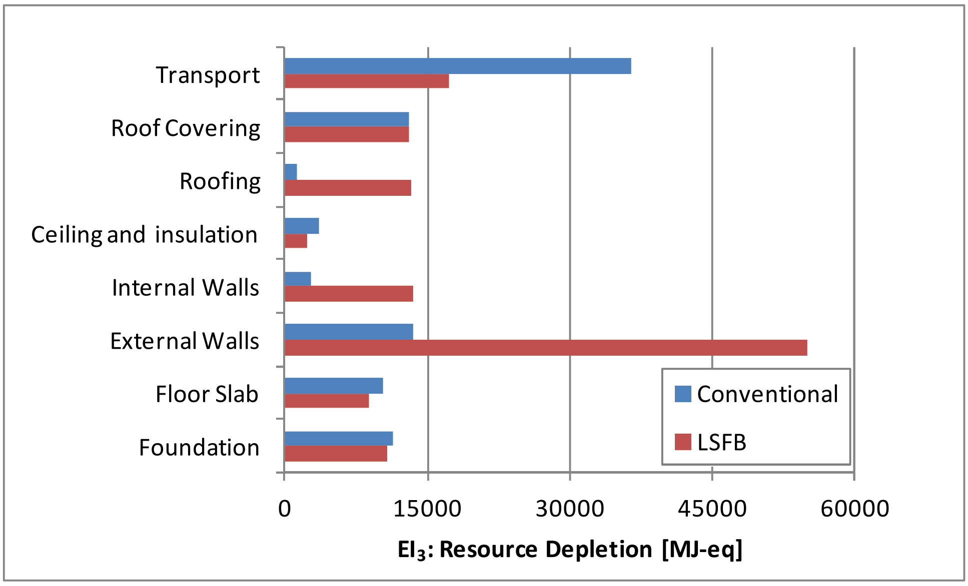

Figure 32: Comparison of Resource Depletion for each building element

Lastly, Figure 33 shows the Waste Generation for each building element. The values found for the conventional design are similar to that of the Watergang Kayamandi Housing Project. It is clear that a pre-fabricated building system, in this case a LSFB, generates less construction waste even though the Waste from Production is included in the totals portrayed in the diagram. The mass of waste generated by concrete blocks for the conventional design, as calculated with Spanish waste factors, is substantial. The factor typically considers the proportion of defective and leftover materials along with wastage and packaging thereof. Therefore, external walls, internal walls and foundation for the conventional design generate more waste than the LSFB unit as large quantities of concrete blocks are used during construction.

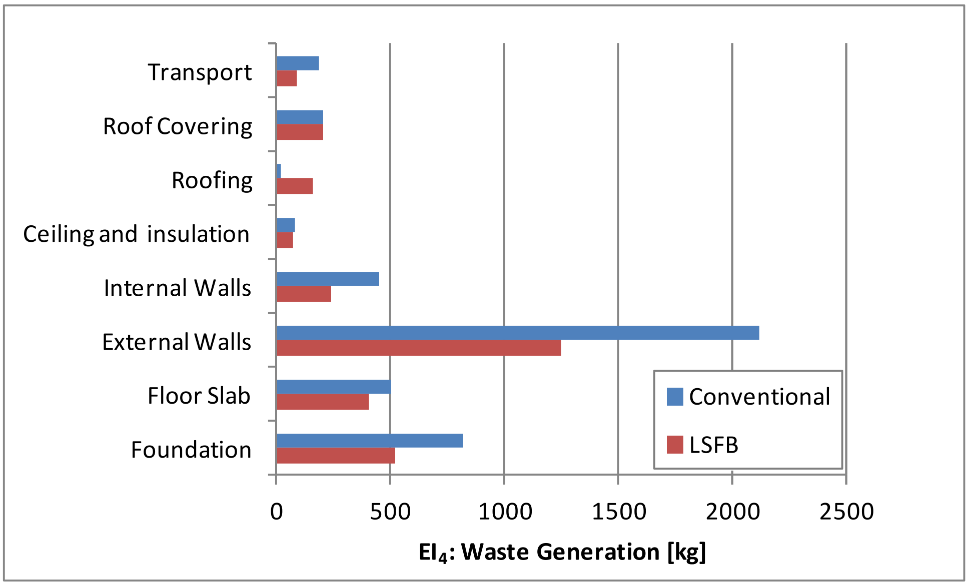

Figure 33: Comparison of Waste Generation for each building element

7.1.2 Environmental impact totals of housing unit

The environmental impact values given in Table 14 are the total impacts determined as the sum over all the material items and building elements for each indicator. Normalisation and weighting is done according to the values in Table 5 given previously.

Table 14: Environmental impact, normalised and weighted values for both design types

	Carbon Footprint [kg CO_{2e}]		**Acidification Potential [kg SO_{2e}]**		**Waste Generation [kg]**	
	CD	*LSFB*	*CD*	*LSFB*	*CD*	*LSFB*
Environmental Impact	8735.68	9207.18	42.90	113.14	4373.07	2933.10
Normalised	1.00	1.06	0.73	1.92	3.24	2.17
Weighted	1.12	1.19	0.92	2.44	3.56	2.39

CD - Conventional Design
LSFB - Light Steel Frame Building

Moreover, the weighted impact values are represented graphically in Figure 34. These show the relative importance of each impact relative to the other for both design types. The effect of each indicator can easily be derived from the diagram. Note, only the Carbon Footprint, Acidification Potential and Waste Generation is shown while Resource Depletion is considered separately as explained previously.

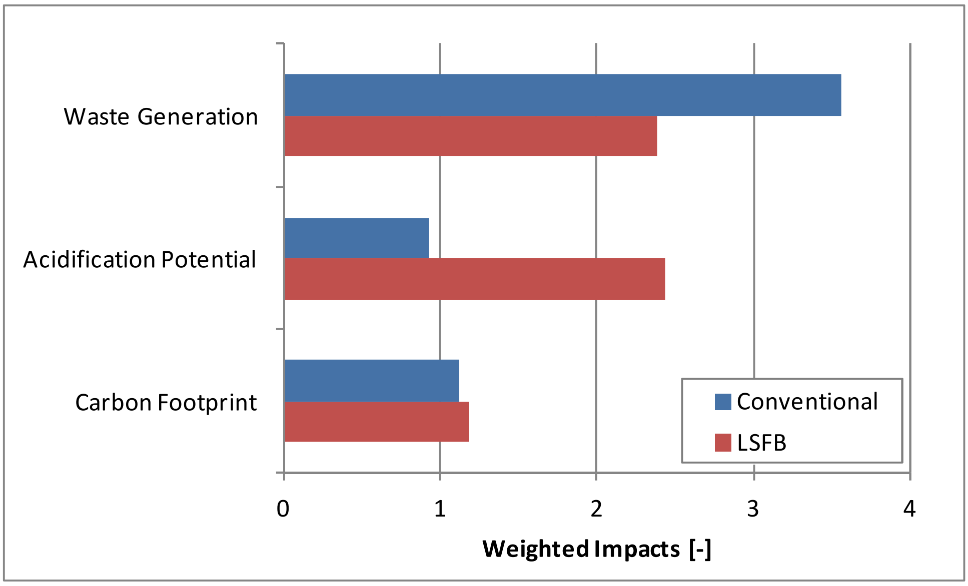

Figure 34: Weighted environmental impacts for each indicator and design type

Clearly, as seen in Figure 34, Waste Generation is the indicator resulting in the largest environmental impact, followed by Acidification Potential and Carbon Footprint respectively. Recall that the weighting factor used to determine the relative importance of Waste Generation is of Danish origin. This factor might not be applicable to local conditions thus care should be taken in the interpretation of this EI and the contribution thereof. A comparison on all three levels is listed next:

- The conventional design brings about the largest Waste Generation. The impact is almost 1.5 times more than for the LSFB design. No generation of construction waste was assumed for the pre-fabricated LSFB elements; however, the production waste is included.
- LSFB results in the greatest Acidification Potential. The impact is considerably more than that of the conventional design; approximately 2.7 times larger. This is mostly due to the galvanisation of the light steel profiles and roof sheeting used.
- The Carbon Footprint for both design types is similar. It is therefore important that a Carbon Footprint not be used as the only criterion in objective decision making.

In Figure 35 follows the impact values from Resource Depletion. The impact of Resource Depletion resulting from selecting LSFB as an alternative is significantly more than for the conventional design type. For the conventional design the total came to 92 432 MJ-eq whereas for LSFB a total of 133 943 MJ-eq was calculated. In reference with Figure 31, the Resource Depletion brought about by the external walls compared to other building elements for the LSFB option, considerably influences the total impact. This is possibly the reason for the conventional design proving to be the better alternative in this regard.

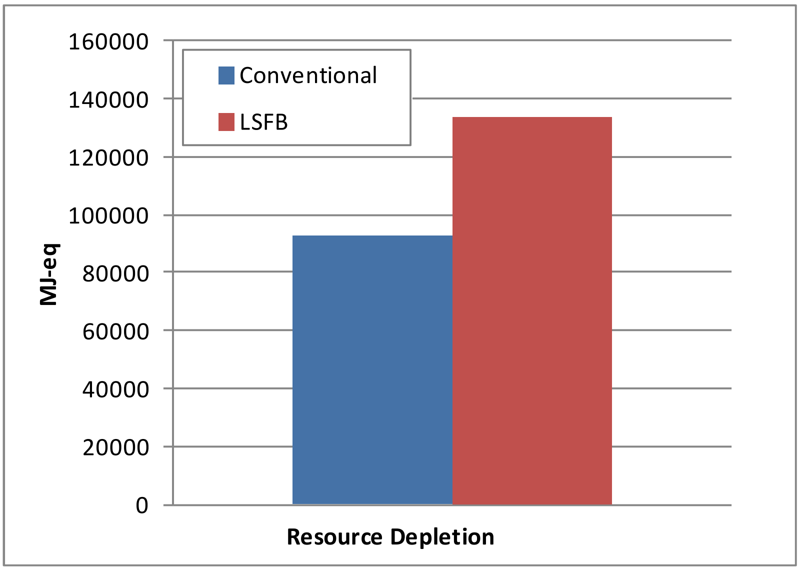

Figure 35: Environmental impact from Resource Depletion

7.1.3 Environmental Impact Index

The Environmental Impact Index (EII) is the sum of the weighted impact potentials for Carbon Footprint, Acidification Potential and Waste Generation. EII values are 5.61 for the conventional design and 6.00 for the LSFB respectively, shown graphically in Figure 36.

These two indices are alike even though the conventional design proves to be a better option if the EII is considered as selection criteria. The EII is optimised with the proposed environmental impact quantification method in Chapter 8 by substituting various material input parameters. Depending on the input materials, the outcome may differ since the given result is of similar order.

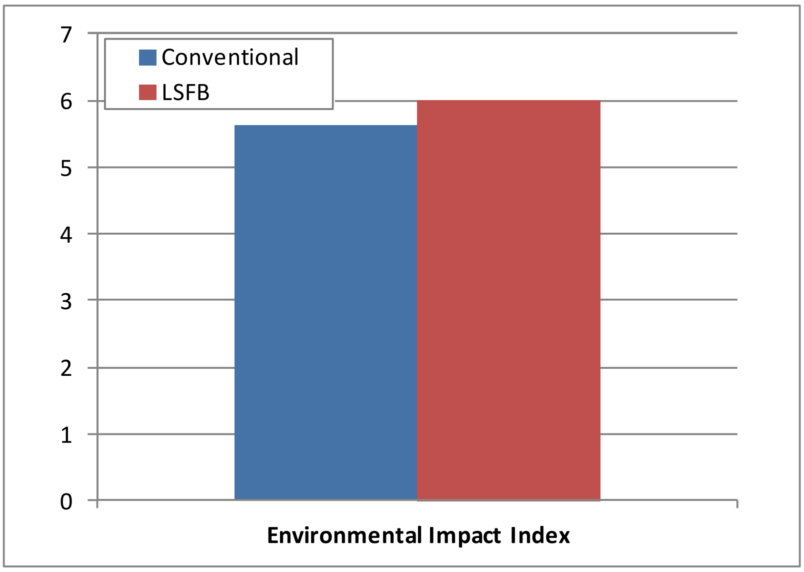

Figure 36: Environmental Impact Index for both design types

7.2 Cost comparison

A representation of the cost of each building element for both design types is given in Figure 37. The cost of nearly all building elements is of similar order except for the internal and external walls. Here the LFSB walling is almost double in price. It is clear that the cost of all materials required, performing a certain function in the layered wall element, add up to a substantial amount.

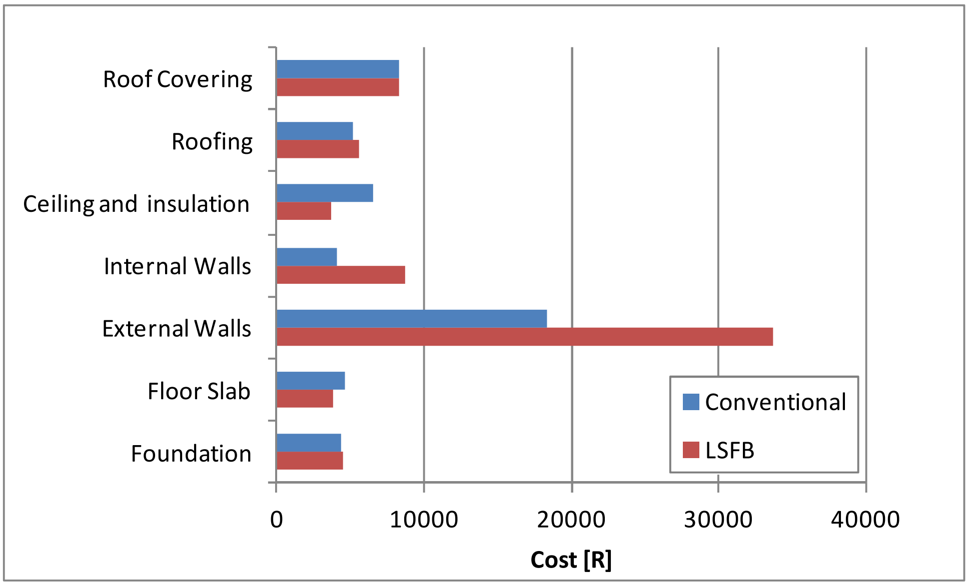

Figure 37: Cost comparison per building element

The total cost of each housing unit is given in Table 15.

Table 15: Total cost of each housing unit

Design Type	Total Cost [R]
Conventional	51 478
LSFB	68 217

The cost per housing unit is significantly more for the LSFB alternative. Keep in mind that only the Pre-Use Phase is considered during the model implementation. A study of the full life cycle cost will provide a more holistic view on the cost per unit over its lifetime. The LSFB unit might prove to be more cost efficient in the long run.

7.3 Concluding summary and discussion

The environmental impacts were compared for both design types with regard to building elements, the housing unit and finally the aggregated EII was provided. A cost comparison was also done. Apart from Waste Generation, the conventional design type turns out to be a better option regarding the Acidification Potential, Carbon Footprint (by a small margin), Resource Depletion, EII and total cost considering the input materials.

Building elements which considerably influence the EI of the conventional design include external walls and to a lesser extent the foundation. Transport impacts all EI's greatly. Considering the LSFB, similar trends are observed although roof covering also proves to have a significant impact.

To possibly decrease the environmental impact of building elements mentioned, alternative input materials should be considered. Optimisation of the respective designs is investigated in the following chapter. If the environmental impact and cost of building elements can be reduced by using alternative materials and designs, the total EI and consequently EII will surely decrease.

Chapter 8

THE PROPOSED MODEL AS AN OPTIMISATION TOOL

This chapter investigates the effect on the environmental impact and cost if different materials are selected as input for the respective design types. Graphical representations provided previously shows certain building elements result in large impacts. The following sections attempt to decrease the impact of building elements contributing significantly by substituting materials and in turn possibly producing an optimised design. The EI's, EII and cost is compared for both optimised design types generated.

8.1 EI optimisation with material input in building elements – conventional design

Remarks concluding Chapter 5 mentioned transport and external walls affecting the environmental impact of the conventional design considerably. Therefore, attempting to reduce the environmental impact of the external walls, lightweight hollow concrete masonry units were opted for. This in turn reduces the overall mass of the house also reducing the impact of transport. Different structural roof systems were considered as the Acidification Potential that arose from sheeting used as roof covering were reason for concern. Alternatives included a timber rafter roof system with sheeting as well as a timber truss system with roof tiles as covering. A different foundation design was selected for the purpose of investigation.

The following option combinations were decided upon, this is represented by the diagrams to follow:

- **Option 1**: design as in Chapter 5.
- **Option 2**: slab-on-ground foundation type, lightweight hollow concrete masonry units, timber rafters with sheeting, stone wool as insulation used in the ceiling.
- **Option 3**: timber trusses with clay roof tiles as roof covering superimposed on Option 2, possibly further optimising the original design as in Option 1. This implies that the following building elements will have the same impact as in Option 2: ceiling and insulation, internal walls, external walls, the floor slab and foundation.

Note that the slab-on-ground foundation was designed according to principles stipulated in the NHBRC Building Manual (NHBRC, 1999). Also, the timber truss in Option 3 had to be redesigned due to the different type of roof covering used, namely clay roof tiles. This was done according to the NHBRC Building Manual in a similar fashion as explained in Section 5.2. For this choice of roof covering compared to metal sheeting used in Option 1, the centre-to-centre truss spacing reduced in order to support the load of the clay roof tiles.

8.1.1 Carbon Footprint

From Figure 38 it is clear that Option 2 is not an improvement to the design and material selection as in Option 1. Although the lightweight hollow masonry units contributes less to the overall mass of the structure, the Carbon Footprint resulting from manufacturing such units is higher than for the conventional masonry units used. Furthermore, the alternative slab-on-ground foundation design does not prove to be a better choice considering the impact of strip-footings as applied in Option 1. The increased mass of the slab-on-ground foundation compared to strip-footings result in the effect of transport being alike. Only the roofing system used in Option 2 provides an alternative with a reduced impact. The type of roof covering used does not affect the Carbon Footprint much. The increased mass due to roof tiles selected for Option 3 explains the increase in the impact of transport.

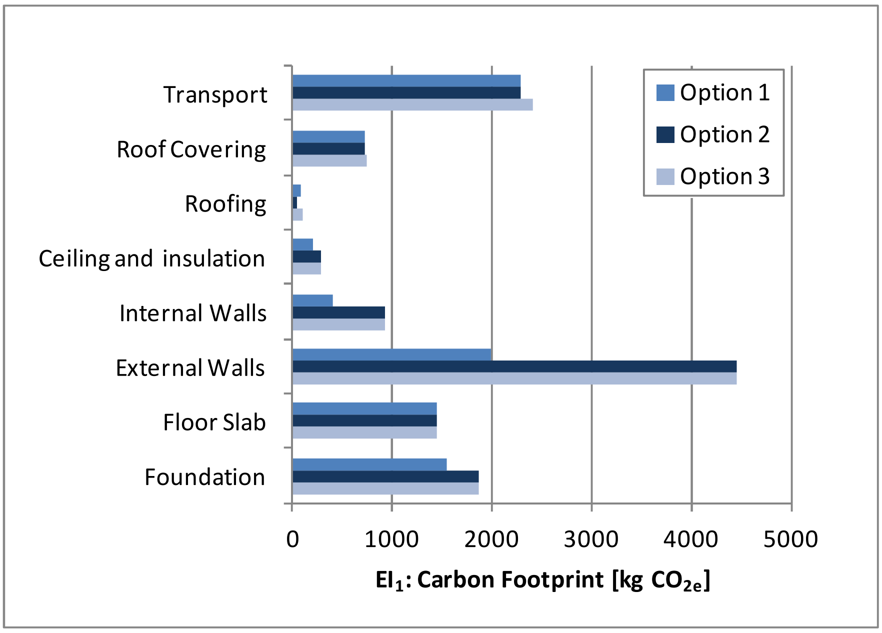

Figure 38: Carbon Footprint for alternative construction materials – conventional design

8.1.2 Acidification Potential

The effect on Acidification Potential if lightweight hollow concrete masonry units are used is substantial. The impact of external walls for Option 2 and 3 greatly differs from that of Option 1 as seen in Figure 39. Also, the Acidification Potential arising from galvanised sheeting as used in Options 1 and 2 is significantly higher than for the alternative in Option 3, clay roof tiles. If the principal criterion for material selection is the Acidification Potential impact thereof, then roof sheeting and lightweight hollow concrete masonry units would definitely be ruled out.

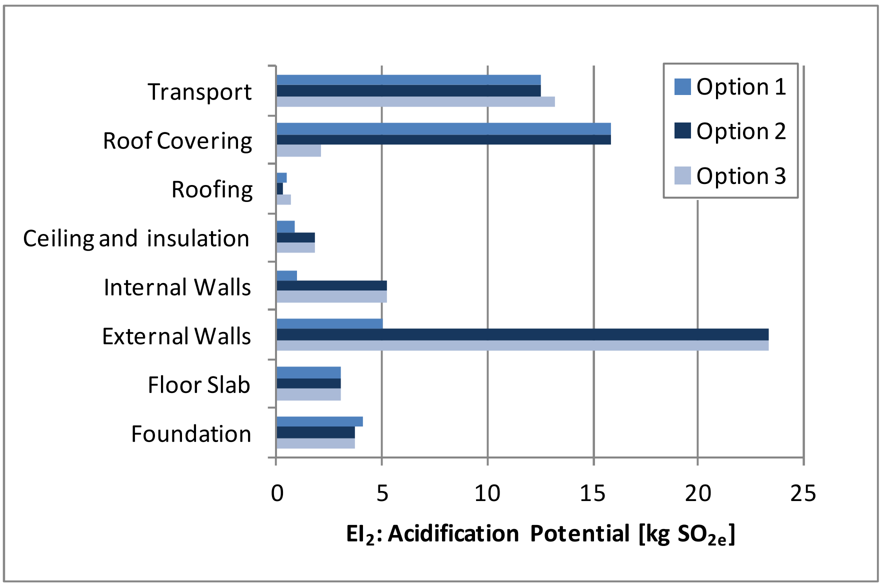

Figure 39: Acidification Potential for alternative construction materials – conventional design

8.1.3 Resource Depletion

Once again, the lightweight hollow concrete masonry units display a major deviation from the other impacts for applicable building elements; in this case with regards to the impact on Resource Depletion as shown in Figure 40.

As seen on the diagram, the impact of transport is similar for Options 1 and 2, this is purely coincidental. It is believed that the reduction in mass from utilising lightweight concrete masonry units is evened out by the heavier slab-on-ground foundation investigated. Option 3 results in a higher impact due to transport since the roof tiles contribute considerably to the overall mass of the structure.

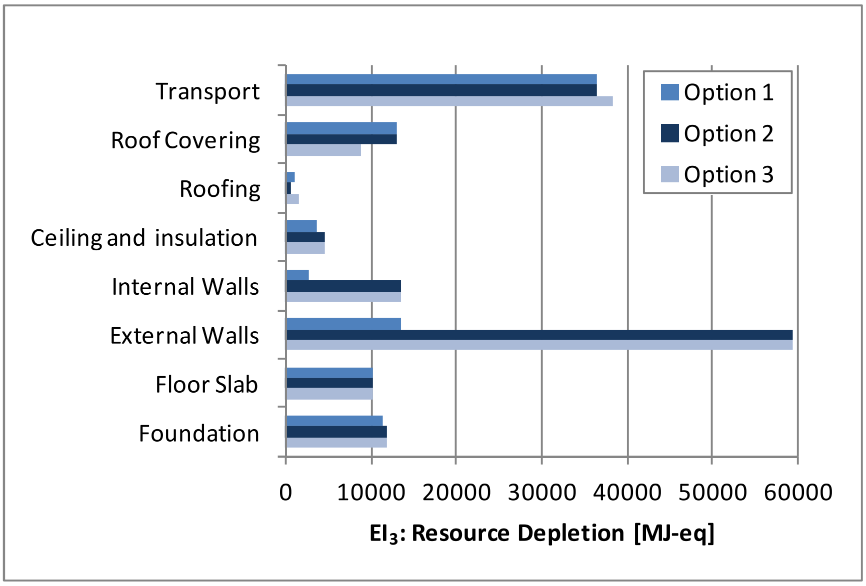

Figure 40: Resource Depletion for alternative construction materials – conventional design

8.1.4 Waste Generation

Figure 41 shows the Waste Generation for each building element respectively, taking into account the alternative construction materials used as input to the quantification process. Interestingly, the lightweight hollow concrete masonry units turn out to be an improvement to Option 1. This can be prescribed to the higher Waste from Production factor for conventional masonry units. Besides, when quantifying the mass of construction waste owing to concrete masonry units, the higher density for conventional masonry units results in more waste. This is purely because of the mathematical nature of the waste quantification model used.

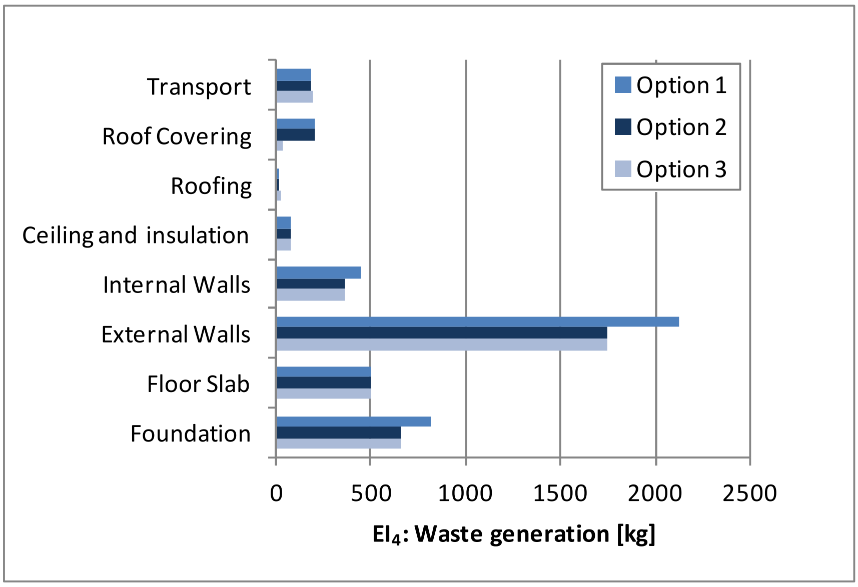

Figure 41: Waste Generation for alternative construction materials – conventional design

8.1.5 Cost

Lastly, a cost comparison is made. Note that the price of the two types of concrete masonry units used was assumed to be the same even though this is not necessarily realistic. From Figure 42 it can be seen that the chosen type of roofing system produces a significant variation in price. The timber rafter system is the cheapest, followed by the trusses used in conjunction with sheeting and lastly the increased number of trusses required for roof tiles used as covering.

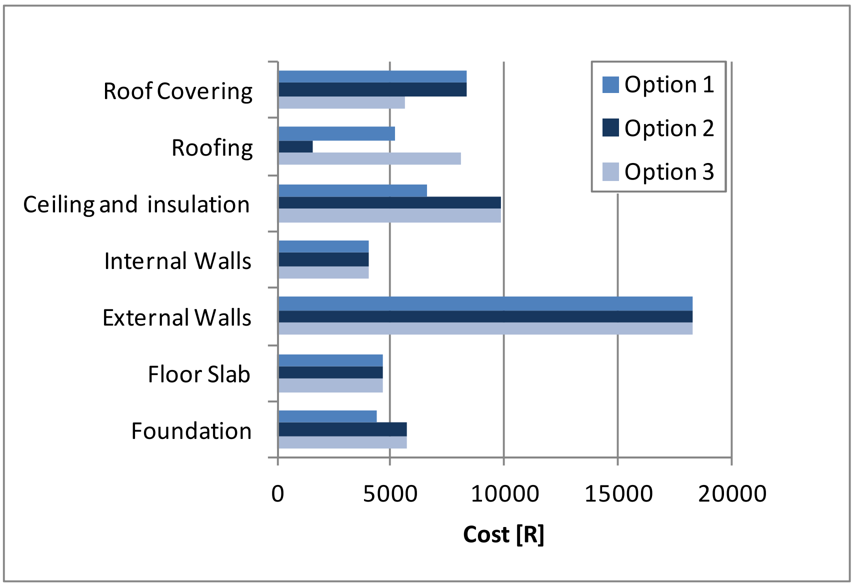

Figure 42: Cost comparison for different materials used – conventional design

Also, the figure shows that roof tiles solely are a cheaper roof covering material than sheeting. Recall that the design of the truss or rafter system is dependent on the type of roof covering. Careful consideration should be made as the cost of both the roof covering and roofing system must be added before the optimum can be selected.

8.1.6 Summary of conventional design options

Table 16 shows the environmental impact totals for the design options considered for the conventional design type. In general, Option 1 proves to be the better alternative regarding all environmental impacts except for Waste Generation, also in terms of cost.

Table 16: Environmental impact totals for conventional design options

	Unit	Option 1	Option 2	Option 3
Carbon Footprint	**[kg CO_{2e}]**	8 736	12 078	12 271
Acidification Potential	**[kg SO_{2e}]**	43	66	53
Resource Depletion	**[MJ-eq]**	92 434	149 925	148 482
Waste Generation	**[kg]**	4 375	3 741	3 595
Cost	**[R]**	51 478	52 458	56 255

8.2 EI optimisation with material input in building elements – LSFB

Remarks concluding Chapter 6 stated that alternative material combinations for external walls should be explored as the economical and environmental impacts are substantial concerning the LSFB design. The following sections show the comparison between two design options selected for investigation:

- **Option 1:** design as in Chapter 6.
- **Option 2:** slab-on-ground foundation, weatherboard as external cladding, expanded poly-styrene as the thermal break, stone/rock wool used for bulk insulation and roof tiles as an alternative to sheeting as roof covering.

Section 8.2.6 describes the various external wall layer combinations in more detail. Thereafter the outcome or implication of using these alternative materials is discussed.

8.2.1 Carbon Footprint

Substituting orientated strand board (OSB) with expanded polystyrene (EPS) as a thermal break and replacing the fibre cement board cladding with weatherboard, results in a significant reduction in the Carbon Footprint of the external walls as seen in Figure 43. This can be ascribed to the substantial reduction in mass of the external walls by replacing the mentioned materials. Little change in the Carbon Footprint occurs for the other building elements.

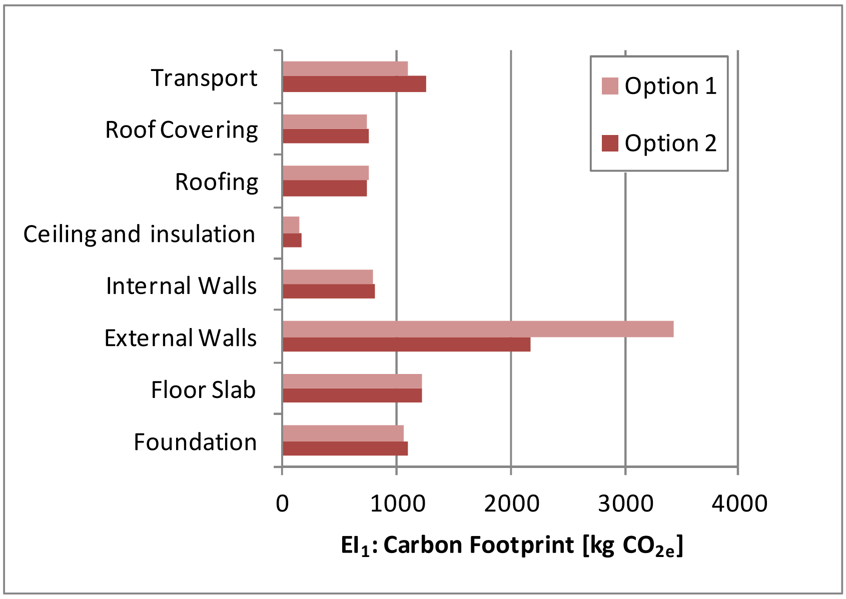

Figure 43: Carbon Footprint for alternative construction materials – LSFB design

8.2.2 Acidification Potential

Galvanisation of the steel profiles or roof sheeting is the biggest contributor to Acidification Potential. It can clearly be seen in Figure 44 that Option 2 results in a reduced Acidification Potential when it comes to roof covering. This is mainly because of galvanised roof sheeting being replaced by clay roof tiles.

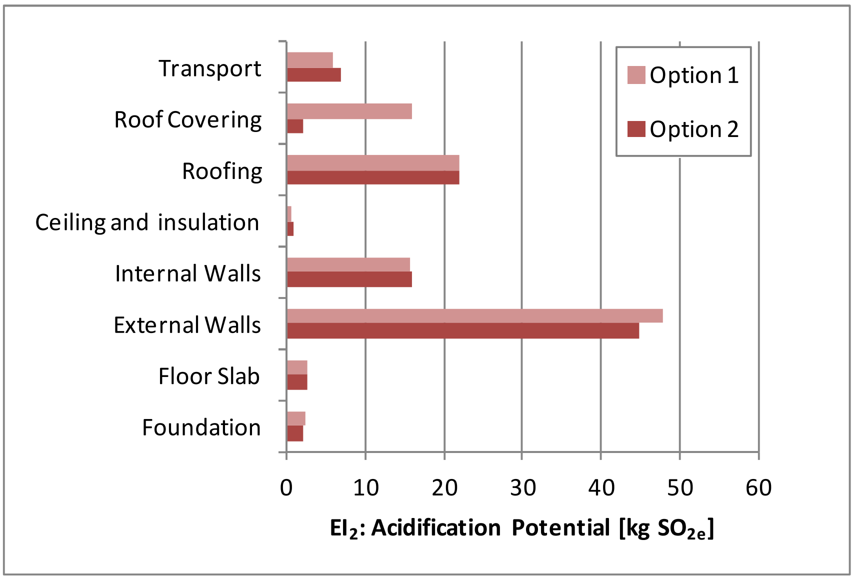

Figure 44: Acidification Potential for alternative materials – LSFB design

The Acidification Potential for other building elements shown alters slightly for the two options given. The visible reduction in Acidification Potential regarding the external walls for Option 2 is related to the combination of materials substituted.

8.2.3 Resource Depletion

Option 1 consequently provides a reduced impact in terms of Resource Depletion regarding transport of materials as seen in Figure 45. Increased mass due to roof tiles is the possible explanation for this result. Recall from Section 6.2 that the design of the LSFB unit was done according to a specified dead load in order to provide for both types of roof covering, namely sheeting and clay roof tiles. This results in the same value for roofing for both options.

Option 2 is the better alternative considering the following building elements: roof covering, external walls and foundations. For roof covering, more exergy is required to produce steel sheeting and galvanisation thereof compared to clay roof tiles. Concerning external walls, a reduction of approximately 16500 MJ-eq occurs when replacing OSB with EPS and substituting fibre cement board cladding with weatherboard planks. Lastly, the slab-on-ground foundation for Option 2 proves to be a better alternative than strip-footings when considering Resource Depletion. Note that clay bricks were used for the foundation walls in Option 1. This was selected because in the case where the client would like brick veneer as external cladding, the external layer of the foundation walls can be extended upwards to serve as the brick veneer. The use of concrete masonry units for foundation walls would possibly result in less exergy extraction.

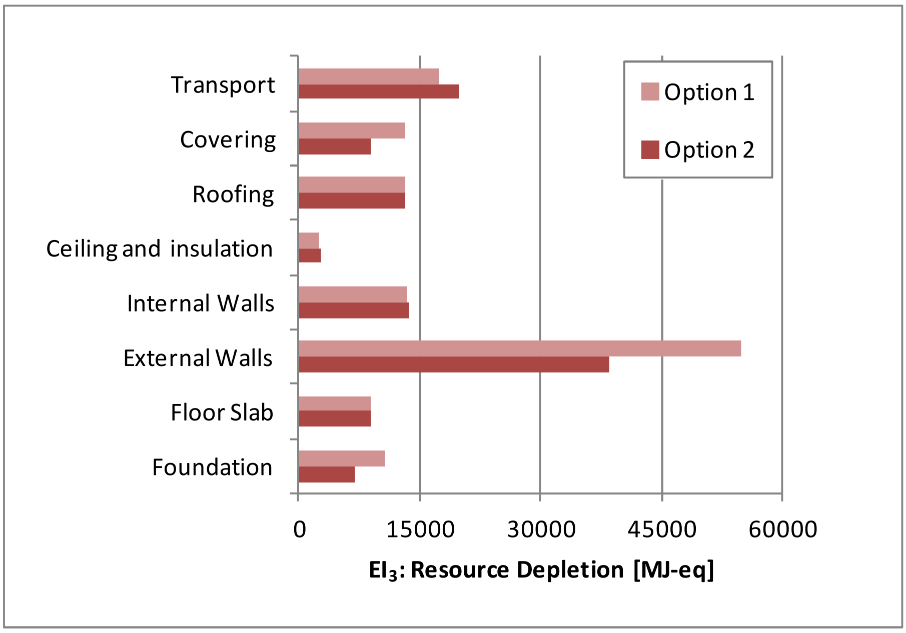

Figure 45: Resource Depletion for alternative construction materials – LSFB design

8.2.4 Waste Generation

Figure 46 shows the Waste Generation for the two options stated as the sum of the Waste from Production and Construction Waste.

Roof covering related to Option 1 has a significantly larger impact than Option 2. The Waste from Production factor for sheeting is almost a hundred times larger than the factor for clay roof tiles. Consequently, more waste is generated.

Furthermore, the combination of materials for the external walls in Option 1 leads to 50 % more waste generated than for Option 2. This is mainly because of the use of fibre cement board as external cladding along with OSB as a thermal break. Calculating the mass of construction waste requires the volume of waste for each building element to be multiplied with the respective material density factor. The density for fibre cement board and OSB is considerably more than weatherboard planks or EPS used in Option 2. Therefore Option 1 contributes to a greater extent to the mass of construction waste generated.

Finally, strip-footing foundations produce more waste than slab-on-ground foundations. Mostly since the waste proportion factors for the brickwork in foundation walls result in more waste generated than for slab-on-ground foundations.

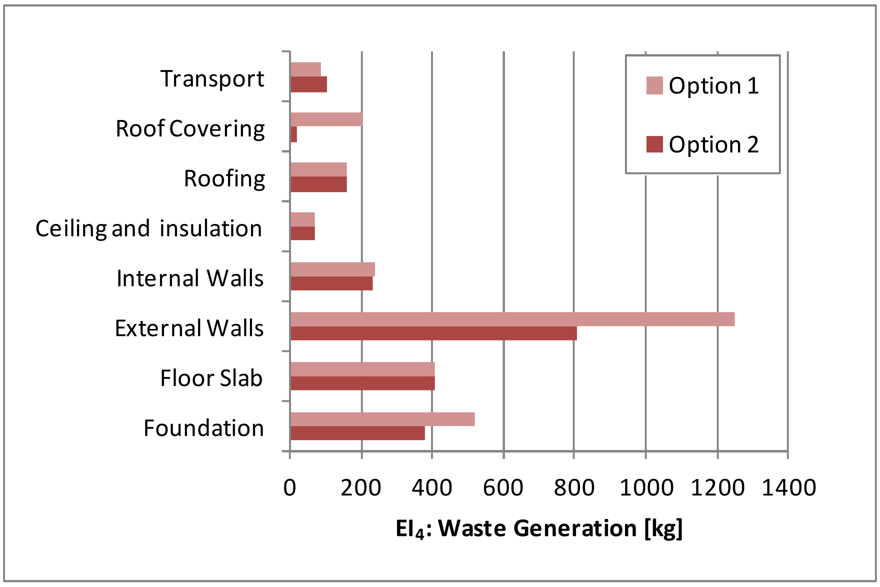

Figure 46: Waste Generation for alternative construction materials – LSFB design

8.2.5 Cost

As the economical impact is not the main focus, various materials are assumed to have the same cost due to the lack of available information locally. Figure 47 shows the cost comparison for the various building elements.

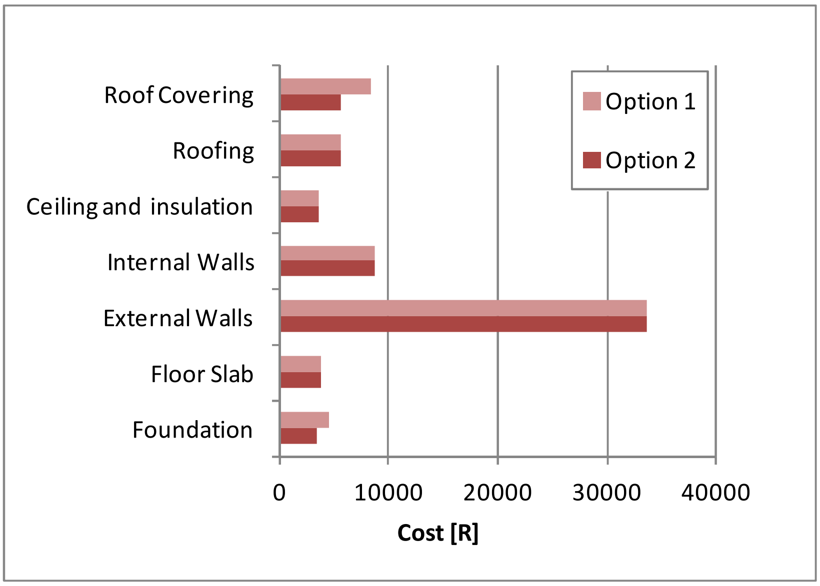

Figure 47: Cost comparison for alternative materials – LSFB design

It is clear that substituting roof sheeting with clay roof tiles is a cheaper alternative. Furthermore, the slab-on-ground foundation as in Option 2 provides a less costly alternative if designed correctly.

8.2.6 Combination of layers for external walls

According to SANS 517:2009, various combinations of material layers for external walls can be used. In the previous options, only two combinations have been considered. This part investigates the effect of six other possible combinations as seen in Table 17.

Table 17: Material layer combinations for external walls

Option	External cladding	Thermal Break	Bulk Insulation
1	Fibre cement board	Orientated strand board	Glass wool
2	Weatherboard planks	Expanded Polystyrene	Rock/Stone wool
3	Weatherboard planks	Orientated strand board	Glass wool
4	Weatherboard planks	Orientated strand board	Rock/Stone wool
5	Weatherboard planks	Expanded Polystyrene	Glass wool
6	Fibre cement board	Orientated strand board	Rock/Stone wool
7	Fibre cement board	Expanded Polystyrene	Glass wool
8	Fibre cement board	Expanded Polystyrene	Rock/Stone wool

The respective environmental impacts were calculated for the mentioned combinations and the outcomes can be seen in Table 18.

Table 18: Environmental impacts for given combinations

Option	EI_1 [kg CO_{2e}]	EI_2 [kg SO_{2e}]	EI_3 [MJ-eq]	EI_4 [kg waste]
1	3425.8	48.0	54902.2	1249.9
2	2172.4	44.9	38497.6	805.0
3	2454.4	45.9	46169.8	859.8
4	2504.4	46.6	46539.2	853.8
5	2122.4	44.3	38128.2	811.2
6	3475.9	48.6	55271.5	1239.7
7	3039.9	46.4	46860.6	1197.1
8	3143.9	47.0	47229.9	1191.1

The shaded cells show the minimum for each environmental impact respectively. Considering the impacts individually and not normalising or weighing the values into an aggregated total, it is clear that Option 5 provides the minimum with regards to external walls.

8.2.7 Summary of LSFB design options

Table 19 shows the environmental impact totals for the design options considered for the LSFB type. Option 2 proves to be the better alternative regarding all environmental impacts and cost.

Table 19: Environmental impact totals for LSFB design options

	Unit	Option 1	Option 2
Carbon Footprint	**[kg CO_{2e}]**	9 207	8 203
Acidification Potential	**[kg SO_{2e}]**	113	97
Resource Depletion	**[MJ-eq]**	113 943	112 634
Waste Generation	**[kg]**	2 933	2 176
Cost	**[R]**	68 217	64 521

8.3 Environmental impacts and cost of optimised housing unit designs

The combination of materials rendering a reduced environmental impact and cost for the several building elements were used as input to obtain an optimised design of a low-cost house for both the conventional and LSFB design types. Material combinations resulting in minimum impacts per building element were selected according to the following criteria: if more than one of the EI_i's are reduced and the cost is a minimum. The selected building materials can be seen in Table 20. These are consequently used as input for the optimised design of each housing unit and comparisons between the two design types are drawn.

Table 20: Material input for optimised designs

Building element	**Conventional Design**	**LSFB design**
Foundations	Strip-footings	Slab-on-ground
Floor slab	100 mm 25 MPa concrete slab with steel mesh reinforcement	100 mm 25 MPa concrete slab with steel mesh reinforcement
External walls	140 mm concrete masonry units, plastered externally	Weatherboard cladding, EPS thermal break, glass wool insulation and gypsum plasterboard as internal lining
Internal walls	90 mm concrete masonry units, bagged	Gypsum plasterboard as lining with glass wool insulation
Ceiling and insulation	Gypsum board and glass wool mat	Gypsum board and glass wool mat
Roofing	Timber rafter system	Light steel frame trusses
Roof covering	Zincalume galvanised sheeting	Clay roof tiles

Even though clay roof tiles in combination with light steel frame trusses provide a minimum environmental impact for the LSFB design, clay roof tiles were not selected for the conventional design. This is due to the fact that the timber truss roofing system which would be required to support the clay roof tiles, increase the environmental impact significantly. Therefore the timber rafter system which may only be constructed in conjunction with galvanised sheeting according to design principals in the NHBRC Home Building Manual (NHBRC, 1999) was opted for.

A similar calculation procedure as explained in Chapters 5 and 6 is adopted in order to determine the impact of the optimised housing units. The succeeding information shows the comparison of results.

Figure 48 gives the separate normalised and weighted environmental impacts for both design types. The LSFB unit clearly generates less waste whereas the conventionally designed housing unit has less than half the impact on Acidification Potential. Since a large percentage of the LSFB unit is assembled in a factory under supervised conditions, it explains the reduced amount of waste generated when compared to the conventional brick and mortar design. Again, the galvanising of light steel frame profiles and sheeting has a profound impact on Acidification Potential. The Carbon Footprint for both design types is similar.

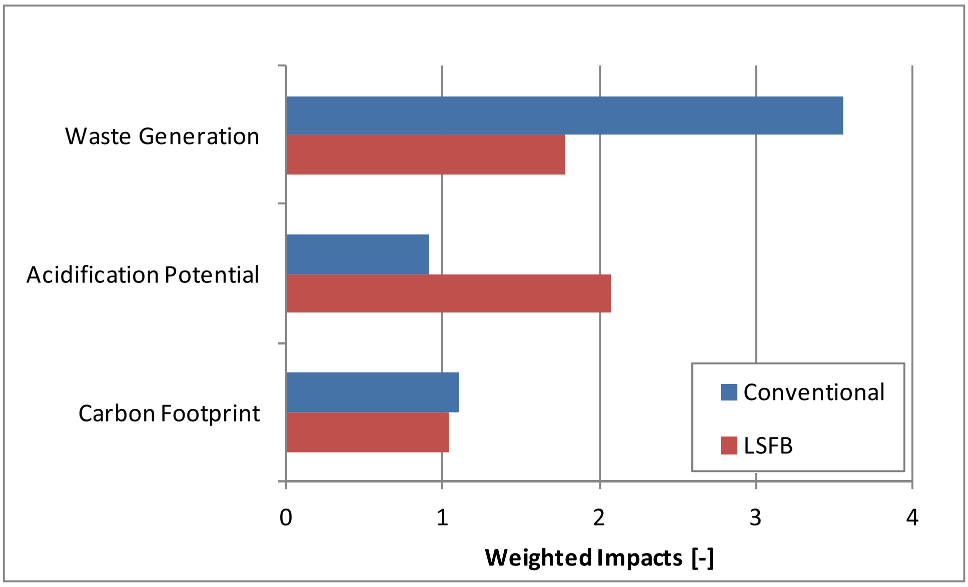

Figure 48: Normalised and weighted environmental impacts

For the original input data, Resource Depletion for the conventional design totalled 92 434 MJ-eq. It can be seen in Figure 49 that this value has been reduced slightly by the optimisation process. Alternatively for the LSFB design, the original 133 528 MJ-eq has been reduced to 111 502 MJ-eq by substituting certain input materials. This is a substantial reduction of almost 17 %. Still the LSFB unit has a worse effect on Resource Depletion.

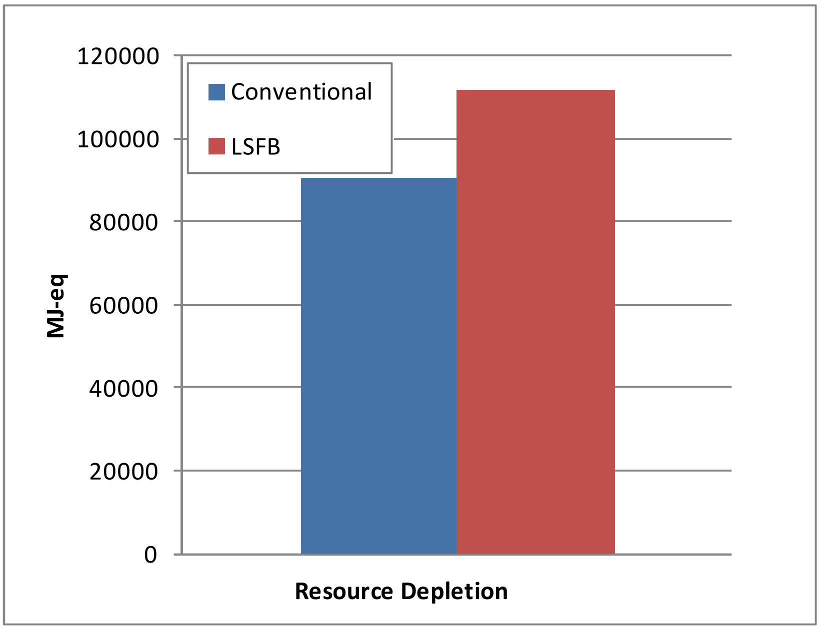

Figure 49: The effect on Resource Depletion for the optimised designs

Likewise, the Environmental Impact Index (EII) is reduced for both design types. Section 7.1.3 states the EII's for the original input data; 5.61 for the conventional design and 6.00 for the LSFB alternative. In Figure 50, the output for the optimised housing units is given in terms of an EII. The conventional design has undergone a marginal reduction from 5.61 to 5.57, but the EII for the LSFB unit as decreased from 6.00 to 4.89. Note that the LSFB design type is favoured slightly in the optimal case.

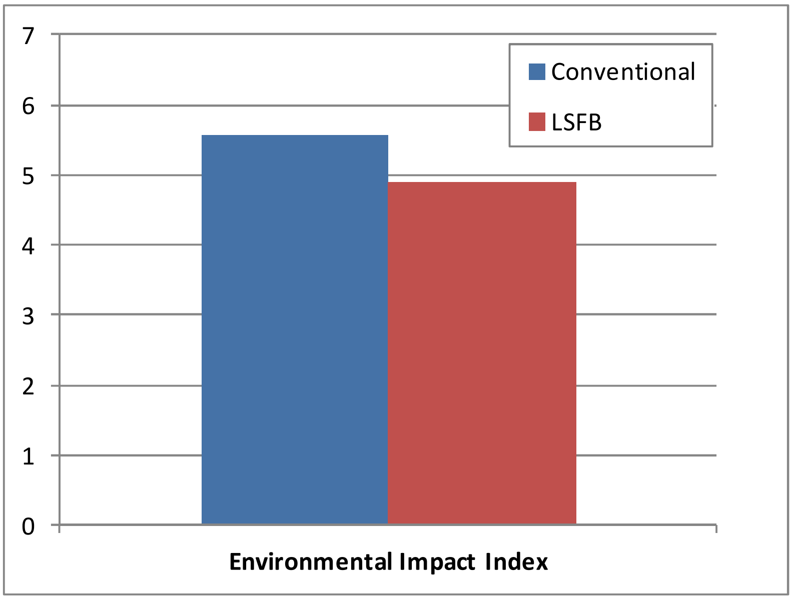

Figure 50: Aggregated impact index for the optimised designs

Furthermore, changes in the mass and cost of the housing units have occurred. The mass of the conventional brick and mortar designed housing unit has decreased from 47.34 t to 44.85t; this will have a significant effect on the impact transport has on the environment. The mass of the LSFB unit has increased from 22.44 t to 25.63 t mostly due to roof tiles used in stead of sheeting.

Regardless of the increase in mass, the optimised LSFB unit is less costly than the original design. The original LSFB unit is priced at R 68 216 whereas the optimised unit costs R 62 863. Keep in mind that various materials were assumed to have the same cost, thus this outcome may not prove to be reliable. However, the rates of the conventional design are trustworthy and a reduction in unit price of R 2 651 amounts to an optimised unit cost of R 48 826. Note that this does not include the cost of services.

8.4 Concluding summary and remarks

This chapter showed that by substituting materials used for certain building elements, a reduction in the environmental impacts considered is possible. This is an important step during the design process as the aim should be to have a minimum impact on the environment while reducing costs at the same time. The purpose of the optimisation process is to show that simple adjustments made can result in significant reductions which in turn provide an optimised design alternative.

Note that a minimum for transport is not mentioned as this is dependant on the total mass of the house considered and not building elements separately. The final cost of the unit also depends on all the materials required. This will be looked into in the following chapter.

Even though definite conclusions cannot be drawn to which design type proves to be the best option, optimising the design demonstrates to be a worthy and suitable process to pursue. Selecting the best housing unit type depends on the criteria established for this decision making process. A choice can be made based on the cost, EII, effect on Resource Depletion or a combination of these. The purpose of this study is not to prove which design type succeeds over the other, it purely shows that mathematical impact calculation and optimisation tools may prove valuable during the decision making process.

Chapter 9

SENSITIVITY ANALYSIS

Based on the optimised designs, a sensitivity analysis is performed on some variables which were assumed to have specific values while calculating the respective environmental impacts. The purpose of this exercise is to establish whether the assumptions made have a significant effect on the outcome or whether it is negligible. Variables considered include the distance covered by transporting materials and waste, the percentage of construction waste generated (this is related to the factors selected to determine the volume of construction waste) and weighting factors used for calculating the EII.

9.1 Transport

The effect of the distance travelled while delivering materials and transporting waste to landfill is measured against the EII and Resource Depletion separately. A total distance of 100 km was assumed for the original calculations. The sensitivity analysis considers a variation in distance between 0 – 200 km.

The unit for the transport entry in the Ecoinvent database is tonne-kilometres (tkm). Recall that a 3.5 - 7.5 t truck is used for transporting materials. Firstly the mass of each housing unit is multiplied with the distance in km. Thereafter the value is multiplied by the various environmental impact factors. These include the Carbon Footprint, Acidification Potential and Waste Generation factors of the truck used for transport. The results regarding transport are normalised, weighted, aggregated and added to the EII calculated with all required input materials for a 0 km distance travelled. The impact exclusive of transport, that is for 0 km travelled, is alike for both design types although the LSFB unit is slightly favoured. The graphical representation can be seen in Figure 51.

Although the increase in the EII for the conventional design is larger as the distance increases, the graphs have a positive gradient for both design types. An additional 27 % is added to the EII for the conventional design over 200 km while an increase of approximately 17 % is observed for the LSFB alternative. Even though these two graphs illustrated in Figure 50 will never intersect, different input data may result in the opposite outcome. Consequently the LSFB unit might prove a better solution in terms of the EII after a certain distance for example or vice versa.

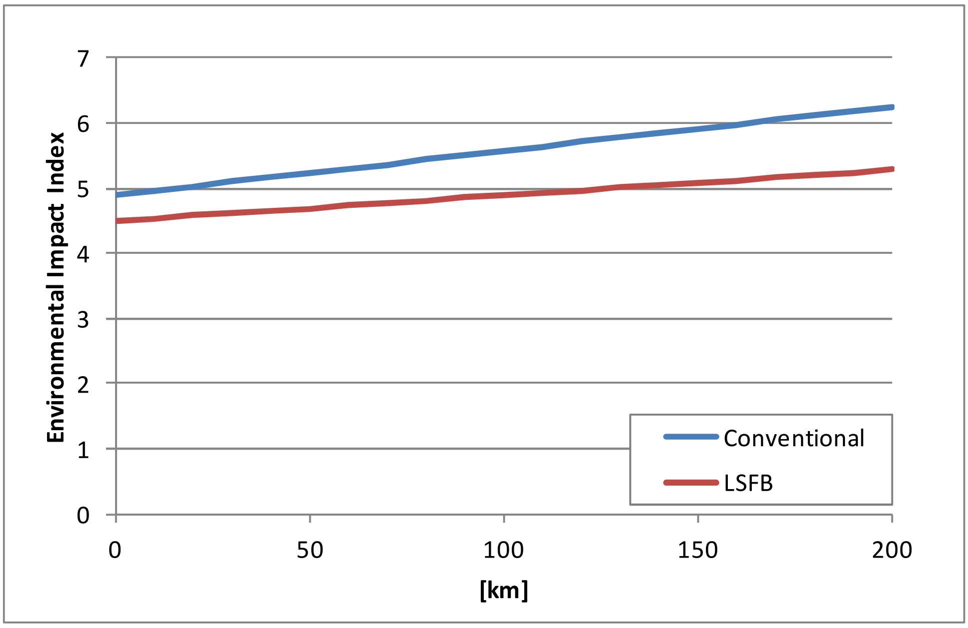

Figure 51: The effect of distances travelled on the EII

A similar calculation was done regarding the effect of transporting distances on Resource Depletion. The same steps were followed as explained previously, except no normalising or weighting of the impacts were performed. Figure 52 shows the graphical output.

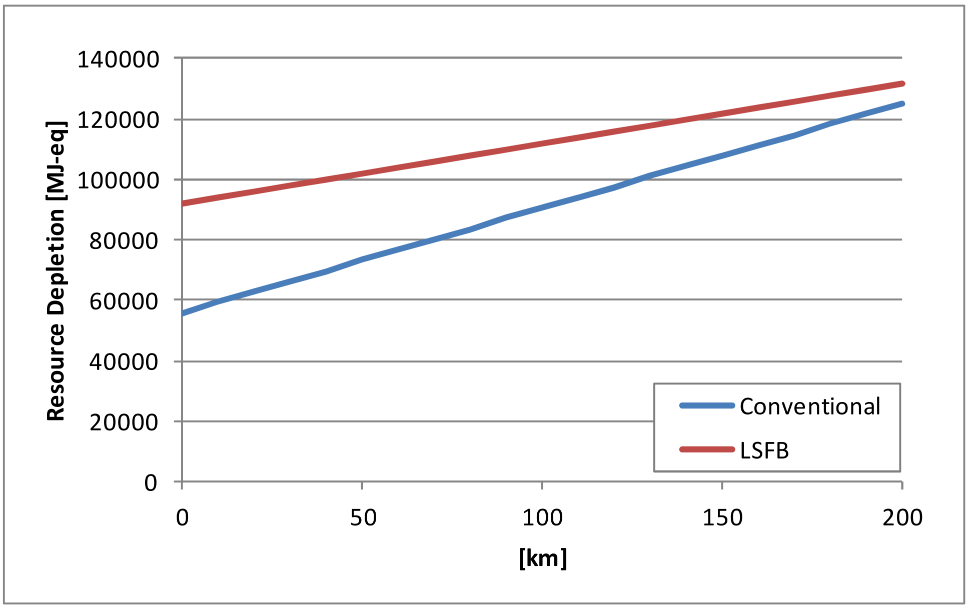

Figure 52: The effect of distances travelled on Resource Depletion

For a 0 km distance travelled, the LSFB design impacts Resource Depletion approximately 1.65 times more than the conventional design option. The picture soon changes as the slope of the graph depicting the effect of the conventional design is much steeper. The impact on Resource Depletion increases with a substantial 125 % over 200 km whereas for the LSFB alternative it grows with 43 %.

The mass of the conventionally designed unit is 1.75 times more than that of the LSFB house. Evidently this is the reason for the steep gradient observed for the conventional design type.

The two graph lines are bound to intersect if slightly more than a total of 200 km distance is covered. If a selection is based on the impact on Resource Depletion, careful consideration is advised as one option may favour the other for certain conditions only.

It can be concluded that these results and desired outcomes are sensitive towards the transporting distances covered. Even though the EII is sensitive towards the distances travelled, it is not sensitive when the EII is used for comparison of different design types.

9.2 Construction waste

A further study was undertaken to measure the effect the amount of construction waste has on the EII. Firstly, the aggregated results, or EII, were determined exclusive of construction waste to be used as baseline. Note that construction waste affects EI_4 as well as the impact transportation has since the transport of waste to landfill is included in the calculations. Construction waste is varied as a percentage of the total mass (excluding construction waste) of the housing unit. A range between 4 and 10 % was considered. For each percentage, the total EII was determined for both design types. This is done by adding the normalised and weighted impact of construction waste along with transport to the already computed EII values used as the baseline. Figure 53 shows this graphically.

For construction waste percentages under 8 %, the conventional design type shows to result in a lower EII while the reverse results in the LSFB alternative. The gradient of the LSFB curve is less steep than the conventional design, pertaining to the fact that a large part of the light steel frame housing unit is pre-fabricated; generating less waste under controlled conditions. The diagram shows that the EII is quite sensitive to the percentage of construction waste generated. The EII for the conventional design increases by half of its original magnitude as the percentage construction waste is varied from 4 - 10 % while a similar increase is noticed for the LSFB type, but only by an amount of 25 % in this case.

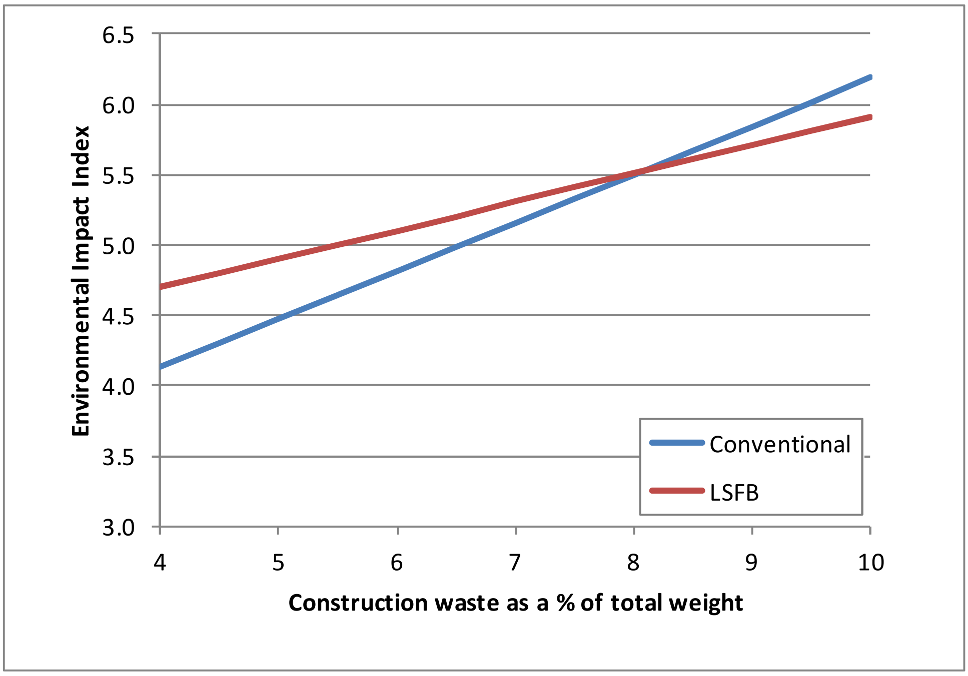

Figure 53: Change in EII as the % construction waste is varied

It is important to realise what the amount of construction waste, as a percentage of the total mass of the unit, for the optimised designs are. These values can be seen in Table 21.

Table 21: Construction waste as a % of total unit mass

Design Type	**Percentage construction waste**
Conventional	8 %
LSFB	5 %

If the percentage of construction waste for the conventional design type can further be reduced by incentives such as re-use, recycling, monitoring and so forth, this option will have the smaller impact on the EII since the LSFB curve produces higher EII values for the range of construction waste below 8 %.

Only the effect on the aggregated impact index was considered in this section as Resource Depletion will be affected minimally if all waste goes to landfill. However, if recycling or other incentives occur, the ‘saving’ in virgin exergy should be subtracted from the existing total value. This is added as a remark since it does not fall under the scope of this study.

9.3 Weighting factors

Finally, the change in the Environmental Impact Index is investigated for a variation in the weighting factors used to calculate the aggregated total. The EII consists of the sum of three normalised and weighted impacts namely the Carbon Footprint, Acidification Potential and Waste Generation. For each of these, the respective weighting factors were varied between 0.9 and 1.4 for a single impact while the others were kept constant. See Figure 54.

Recollecting previous information from Table 5, the weighting factors chosen for calculating the environmental impacts are given in Table 22.

Table 22: Weighting factors

Environmental impact	Weighting factor
Carbon Footprint	1.12
Acidification Potential	1.27
Waste Generation	1.10

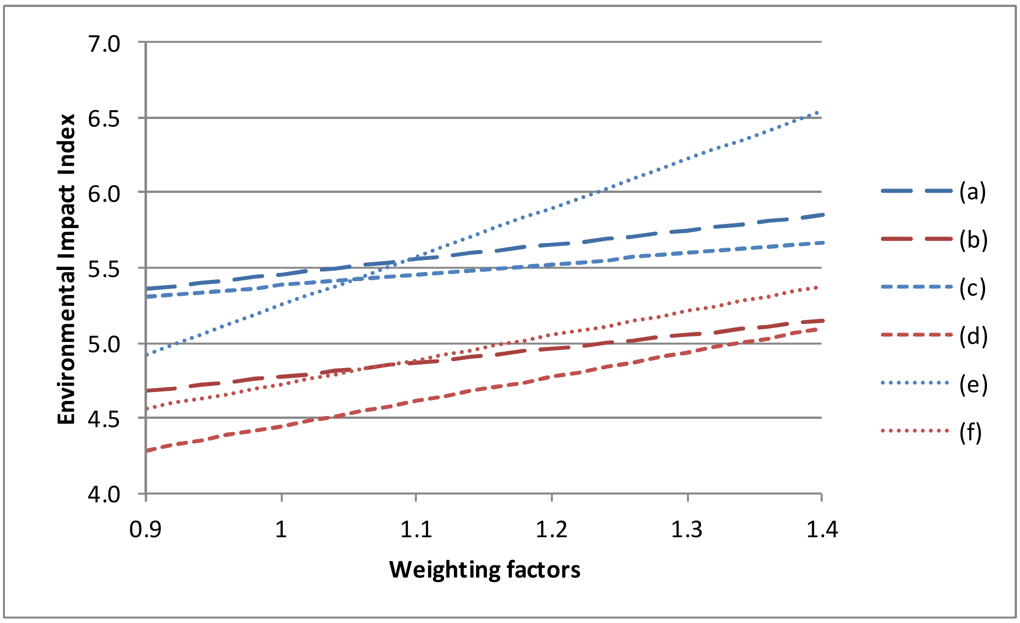

Figure 54: Change in EII as weighting factors are varied

(a) Conventional design: Carbon Footprint weighting factor varied

(b) LSFB: Carbon Footprint weighting factor varied

(c) Conventional design: Acidification Potential weighting factor varied

(d) LSFB: Acidification Potential weighting factor varied

(e) Conventional design: Waste Generation weighting factor varied

(f) LSFB: Waste Generation weighting factor varied

The change in the EII as the Carbon Footprint weighting factor is varied is quite significant. Although the curves for the two design types are parallel, in other words the same effect on the EII for both design types are observed as the weighting factor is altered, the slope of the lines is approximately one.

Regarding Acidification Potential, the value chosen as weighting factor does not significantly influence the impact when considering the conventional design. However, for the LSFB design a slope of approximately 1.6 is noticed on the respective curve.

Lastly, looking at the effect on the EII as a range of weighting factors for Waste Generation is analysed, it is clear that this is a sensitive value concerning the conventional design type. The curve plotted has a slope of about 3.6; still the LSFB alternative also represents a significant gradient of 1.6.

In summary, weighting factors used for calculating aggregated totals should be selected carefully as the outcome is sensitive towards it and will affect the end result. However, regarding comparison of design types in terms of the EII, the outcome is not sensitive towards the selected range of weighting factors. Even though the factor for EI_1 is global and can be assumed to be a realistic value for South African conditions, the other weighting factors for EI_2 and EI_4 are for Europe and Denmark respectively. It can be argued that these values may not correspond to local conditions for a developing country like South Africa. Future studies should consider determining these weighting factors for local conditions and more recent data, not 1994/2004.

9.4 Summary and observations

To conclude this chapter, a sensitivity analysis on three variable assumptions, namely transport distances, percentage of waste generated and weighting factors was performed. The EII is sensitive towards the distance travelled; however, in terms of design type comparison the EII is not sensitive towards it. Similarly, the EII is sensitive towards weighing factors chosen, but for comparison purposes the EII is not sensitive towards the range of weighting factors selected. Then again, the EII shows sensitivity towards construction waste as a percentage of the total mass of the unit but this also influences the final result. Such a study is advised in order to determine which assumptions significantly impact the outcome, in this case the percentage of construction waste generated.

Chapter 10

CONCLUSIONS AND RECOMMENDATIONS

Globally and in South Africa, it is seen that the construction industry significantly impacts the environment, economy and society whereas the objective should be to reduce this negative impact. Aiming to reduce this impact locally, the low-cost housing sector is selected as a platform to implement sustainability motivators within the residential sector. The low-cost housing sector presents potential when it comes to sustainability improvements as each of the three spheres of sustainability, namely economic, environmental and social, plays a crucial role in this sector. Various studies have been done on the economical and social fields, but little information exists on the impact low-cost houses have on the environment.

A need for a local scientifically based quantification method in order to determine the environmental impact of the built environment, more specifically low-cost housing, has been identified. Existing global methods are complex, implemented with difficult to understand databases and expensive to operate. Several studies related to the economical en social impacts of the local Housing Sector have been done previously. A simple and easy-to-use analysis-orientated environmental impact quantification method is proposed in this study incorporating selected indicators namely Emissions, Resource Depletion and Waste Generation. It is recommended that the model be expanded to include other conclusive indicators if future research proves necessary for South African conditions, obtaining more accurate results.

The proposed model has the capability of calculating and optimising the environmental impact of a building unit. Furthermore, the method has been implemented and demonstrates that the model operates in its supposed manner, is simple and also user-friendly. It was shown that this mathematical tool proves useful during the decision making process. This model can be used during the conception phase as a tool guiding the decision around which low-cost housing design type would prove more environmentally friendly. Note that clear criteria on how to select the best option should be established beforehand and must be related to the specific project needs. The simple calculations along with easy to understand graphical output makes this a valuable tool to use.

Various assumptions as listed in Chapters 4 through 6 have been made for this model implementation to fully function. These may be altered if more accurate data arise in future. The calculation of the Environmental Impact Index tend to obscure the influence of the individual impacts, still it is useful for comparison purposes. It is recommended that the possible integration of Resource Depletion into the EII be investigated in future. This may provide a more realistic aggregated index. With regards to determining the EII, global and European normalisation references and weighting factors were used. If possible, these values should be determined for a local context and replaced in the model workings. Also, proportions used to estimate the volume of waste expected as determined from the Bill of Quantities, were of Spanish origin. It is important that these ratios be substituted by locally determined values to obtain an end result for the specific region considered, namely South Africa.

Provision should be made for alternative building technologies to be able to get a foothold in the local low-cost housing construction sector. It has been shown that LSFB units are worth investigating as an alternative to the conventional brick and mortar design but should be confirmed with a more accurate LCA. It is recommended that this study be expanded in future to include the whole building life cycle. This will provide one with the bigger picture right from the start and aid in objective decision making before construction commences. This extensive scope may show that an initial increase in the economical impact, else known as the cost of the unit, may prove to have a reduced environmental impact in the long run.

It is important to include transport in these life cycle assessment calculations as it would be unrealistic to exclude it from the system boundary. A more accurate method of determining the total distance travelled should be investigated in future studies. In general, local resources and material suppliers should be used for construction materials as this will decrease the distances that have to be travelled.

As construction waste has a significant effect on the environmental impact, the focus should turn to effective waste management strategies and the implementation thereof. If recycling initiatives are implemented, this will in turn reduce the amount of construction waste ending up in landfill also affecting the impact transport has. Other incentives such as increasing dumping costs, sorting waste on site followed by recycling or re-use strategies will result in less waste being transported to a landfill site.

No legislation exists with regards to the environmental impact of low-cost housing units. Even though an Environmental Impact Assessment of the project is done beforehand, no guidelines with regard to energy efficient or sustainable building materials or methods are available. It is proposed that the NHBRC Home Builders Manual of 1999 be revised to include sustainable initiatives. Alternative building technologies may be included here along with a tool to assist in the decision making process, typically as what is presented in this study.

If the need arises for comprehensive quantification which includes all three spheres of the sustainability model, ways of quantifying the social impacts of this sector can be integrated with the proposed model calculating the environmental and economical impacts producing an aggregated sustainability index.

Lastly, to improve the automation and appearance of the proposed analysis-orientated quantification model, it is suggested that it be developed into a software application which can then be easily distributed and used in design offices.

The proposed analysis-orientated method along with these recommendations will aid the improvement of the environmental dimension of sustainability for the built environment in South Africa.

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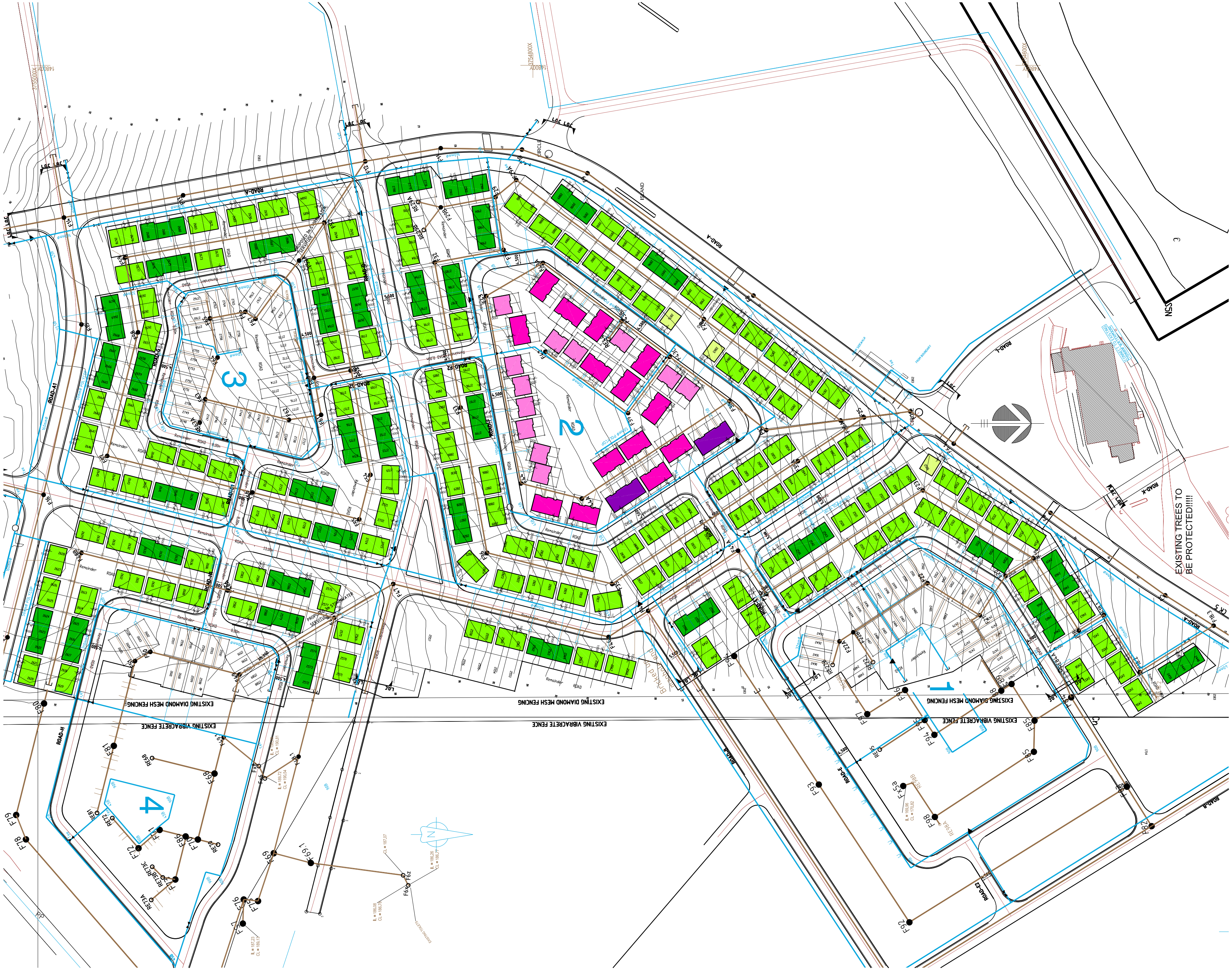
APPENDIX A



General notes:
1. Contractor and Sub-Contractors to check all levels and dimensions on site before any work is commenced and any discrepancies to be reported to the Architect immediately.

2. Figured dimensions to be taken in preference to scaled measurements and large scale details supercede small scale drawings.

3. All work to be done in accordance National building regulations SABS 0400 and all requirements of Municipal and Local Authorities concerned, to be adhered to.

4. Natural light and ventilation area of all openings in accordance SABS 0400 Part O natural light area : min.10% of floor area and natural ventilation : min.5% of floor area.

5. All glass areas bigger than 1sqm and at a height of less than 300mm from finished floor level to be 6mm safety glass.

6. All cavities below floor level to be filled with concrete and dpc's to be stepped.

NOTE:
REFER TO UNIT TYPE LAYOUTS FOR DETAILED SETTING OUT OF UNITS

6 OF THE UNIT TYPE 1 INDICATED ON PLAN WILL BE ALLOCATED TO HABITAT FOR HUMANITY

SITE POSITIONS TO BE PEGGED BY LAND SURVEYOR

REVISION		
REV1	26SEP2007	PLATFORM LAYOUT FOR DOUBLE STOREY -CLUSTER 2

- 🟩 TYPE 1 - 1 UNIT CLUSTER
- 🟩 TYPE 1 - 2 UNIT CLUSTER
- 🟩 TYPE 1 - 3 UNIT CLUSTER
- 🟨 TYPE 2 - 2 UNIT CLUSTER
- 🟧 TYPE 2 - 3 UNIT CLUSTER
- 🟥 TYPE 2 - 4 UNIT CLUSTER
- 🟪 TYPE 3 - 2 UNIT CLUSTER
- 🟪 TYPE 3 - 3 UNIT CLUSTER
- 🟪 TYPE 3 - 4 UNIT CLUSTER

DENNIS MOSS PARTNERSHIP
ARCHITECTS URBAN & REGIONAL PLANNERS LANDSCAPE ARCHITECTS
17 MARKET STREET - P.O. BOX 371 - STELLENBOSCH 7599 - SOUTH AFRICA
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EMail: info@dmp.co.za - Website: www.dmp.co.za
dmp

CLIENT:
STELLENBOSCH MUNICIPALITY

PROJECT TITLE:
KAYAMANDI WATERGANG
PHASE 1 A

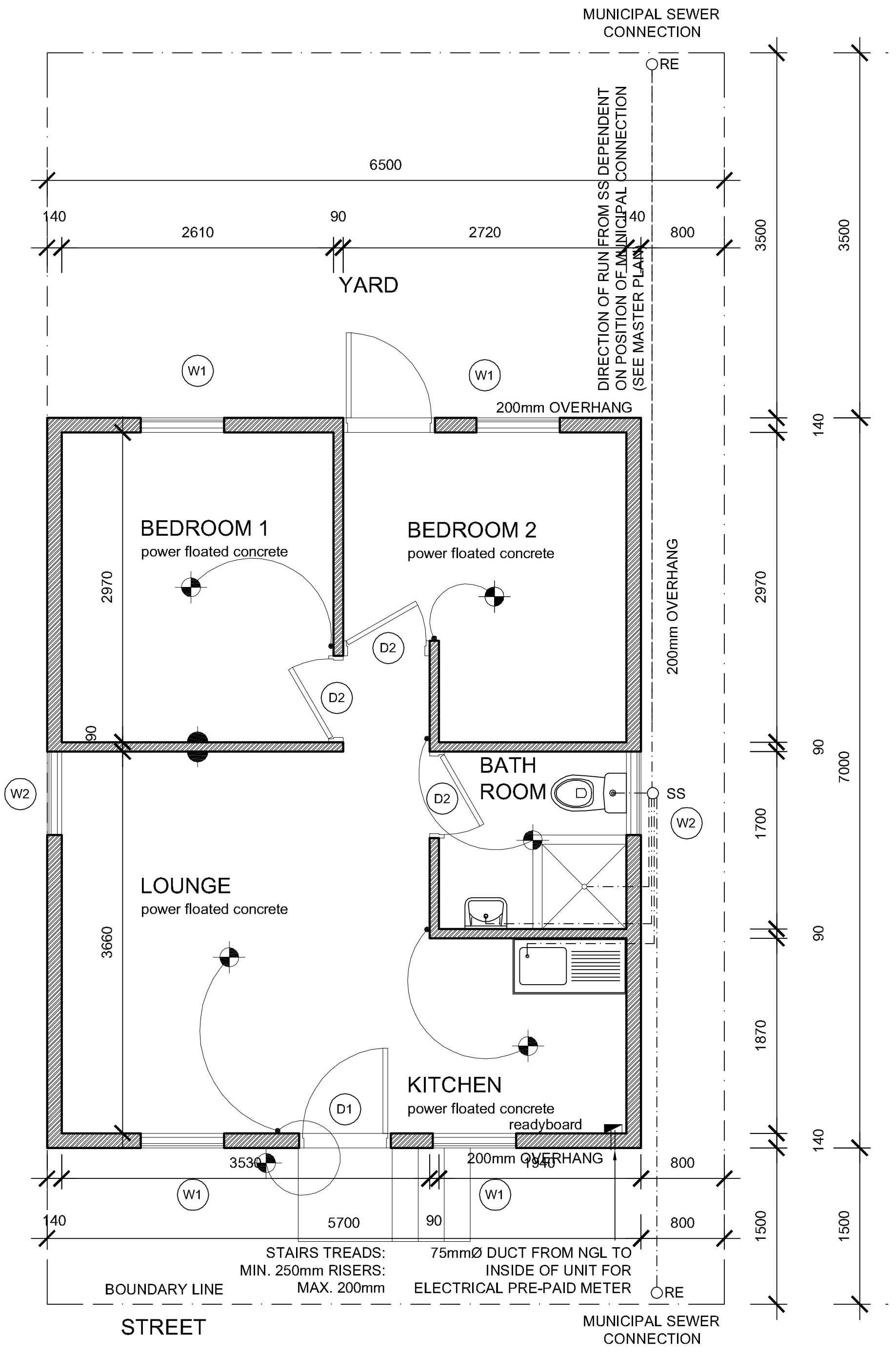
DRAWING TITLE:
PLATFORM LAYOUT
522 SITES

PROJECT No:	Z 2873	SCALE:	1:500
DRAWING No:	109	DATE:	18 SEP 2007
REV:	1	DRAWN: DA	CHECKED: JL

FOR CONSTRUCTION

APPENDIX B

NOTE:
- REFER TO MASTERPLAN FOR FOR SITE PLAN FOR PLACEMENT AND SPECIFICATION
- ELECTRICAL INSTALLATION NOT PART OF TENDER
- ALL STRUCTURAL WORK AS PER STRUCTURAL ENGINEER



DENNIS MOSS PARTNERSHIP
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TEL: +27 (0) 21 887 0124 FAX: +27 (0)21 886 5393
EMail: info@dmp.co.za - Website: www.dmp.co.za
dmp

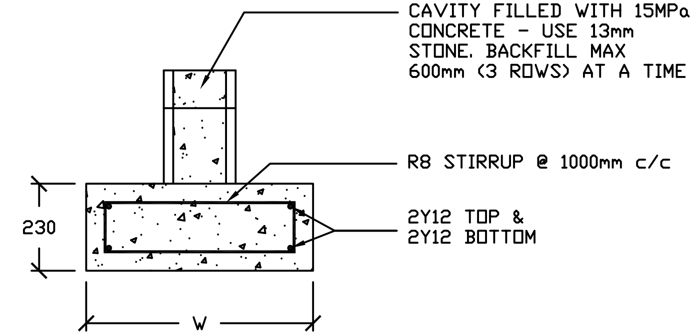
CLIENT:
STELLENBOSCH MUNICIPALITY

PROJECT TITLE:
KAYAMANDI WATERGANG
PHASE 1A
STELLENBOSCH

DRAWING TITLE:
UNIT TYPE 1
SINGLE UNIT
SUBSIDY UNIT - 40m²
SITE - 78m²

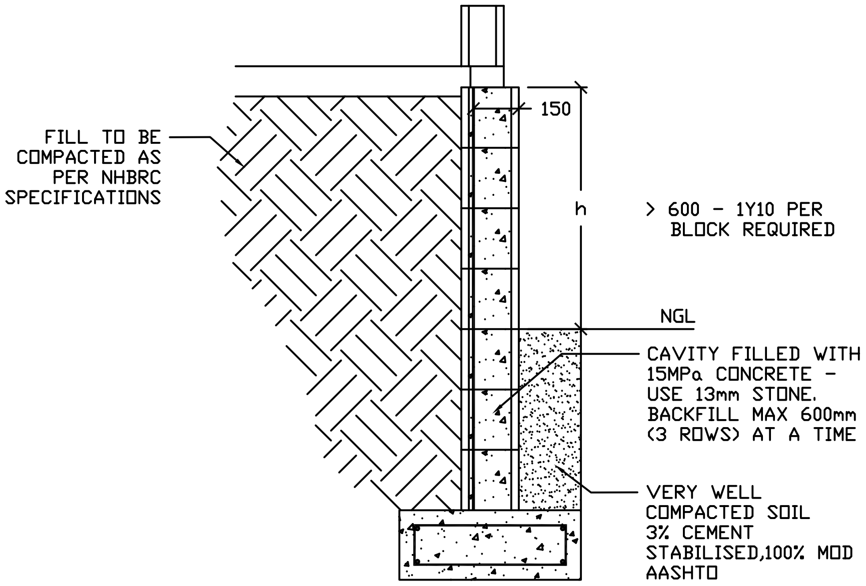
PROJECT No.: Z2873
SCALE: 1:50
DRAWING No.: 103
DATE: 18 SEP 2007
REV.: 00
DRAWN: DA
CHECKED: JL

FOR CONSTRUCTION



W = 600 (SINGLE STOREY)
W = 700 (DOUBLE STOREY)
W = 800 (DIVIDING WALL)

DETAIL A 1:20



DETAIL A 1:25

FOR CONSTRUCTION

WEC-Consult (Pty) Ltd
CONSULTING ENGINEERS & PROJECT MANAGERS

CLIENT:
STELLENBOSCH MUNICIPALITY

PROJECT TITLE:
KAYAMANDI WATERGANG
PHASE 1A
STELLENBOSCH

DRAWING TITLE:
STRIP FOUNDATION AND
RETAINING WALL DETAIL

PROJECT No: S734	SCALE: AS SHOWN
DRAWING No: S734-01	DATE: 25.10.2007
REV. 01	DRAWN: NVDM CHECKED: JNL
SIGN	DATE

APPENDIX C

Conventional Design: Environmental Impacts

														Waste generation EI_4			
Materials					Conversion			Carbon Footprint EI_1		Acidification Potential EI_2		Resource Depletion EI_3		Waste from Production		Construction Waste	
Item	Unit	Quantity	Rate [R/unit]	Cost [R]	Ecoinvent unit	Conversion factor	New Amount	factors [kg CO_{2e}]	per item	[kg $SO_{2e/}$unit]	per item	[MJ-eq/unit]	per item	[kg/unit]	per item	m^3 per item	kg per item
Foundations																	
Excavation	m^3	8.94	50.34	450.04					0.00		0.00		0.00		0.00	0.00	0.00
10 MPa concrete foundation (600x200mm)	m^3	3.00	791.92	2375.76	m^3			264.1000	792.30	0.5066	1.52	1512.3900	4537.17	23.7230	71.17	0.09	216.00
Reinforcing (4 x Y12)	kg	103.00						1.6841	173.47	0.0057	0.59	26.8955	2770.24	0.2769	28.52	0.00	5.15
190 mm blockwork including	m^2	14.90	103.04	1535.30	kg	160.00 [1]	2384.00	0.1212	288.99	0.0003	0.66	0.8176	1949.19	0.0150	35.71	0.33	357.96
brickforce (75x2.8mm),	m	125.00			kg	0.11 [2]	13.62	2.1555	29.35	0.0078	0.11	36.1469	492.28	0.7218	9.83	0.00	0.00
galvanised	m^2	2.45						4.4401	10.86	0.28458	0.70	76.75068	187.75	0.27793	0.68	0.00	0.00
filled with concrete	m^3	0.97			m^3			264.1000	255.14	0.5066	0.49	1512.3900	1461.09	23.7230	22.92	0.03	69.56
Floor Slab																	
Damp proof membrane 250 micron	m^2	41.00	5.93	243.13	kg	0.23 [3]	9.43	2.6085	24.60	0.0098	0.09	81.1856	765.58	0.0586	0.55	0.00	0.00
25 MPa concrete (power floated)	m^3	4.92	850.00	4182.00				264.1000	1299.37	0.5066	2.49	1512.3900	7440.96	23.7230	116.72	0.15	354.24
steel mesh ref 193	m^2	41.00	5.22	214.02	kg	1.93 [4]	79.13	1.6841	133.27	0.0057	0.45	26.8955	2128.24	0.2769	21.91	0.00	3.96
External walls 140 mm																	
Two top courses of brickwork to be filled with 10 Mpa concrete	m^3	0.65			m^3			264.1000	171.67	0.5066	0.33	1512.3900	983.05	23.7230	15.42	0.02	46.80
Blockwork, mortar &	m^2	75.00	205.01	15375.75	kg	160.00 [5]	12000.00	0.1212	1454.64	0.0003	3.32	0.8176	9811.38	0.0150	179.76	1.64	1801.80
brickforce as NHBRC standard	m	125.00			kg	0.11 [6]	13.62	2.1555	29.35	0.0078	0.11	36.1469	492.28	0.7218	9.83	0.00	0.00
galvanised	m^2	2.45						4.4401	10.86	0.28458	0.70	76.75068	187.75	0.27793	0.68	0.00	0.00
Plaster externally (12mm thick)	m^2	75.00	32.51	2438.25	kg	27.60 [7]	2070.00	0.1605	332.26	0.0003	0.59	0.9594	1986.06	0.0023	4.73	0.03	62.10
Bagged internally	m^2	75.00	6.13	459.75			0.00		0.00		0.00		0.00		0.00	0.00	0.00
DPC (110mm width) - 375micron	m	29.00	0.70	20.30	kg	0.03 [8]	0.88	2.6085	2.30	0.0098	0.01	81.1856	71.48	0.0586	0.05	0.00	0.00
Internal Walls 90 mm																	
Blockwork, mortar	m^2	26.00	132.00	3432.00	kg	130.00 [9]	3380.00	0.1212	409.72	0.0003	0.94	0.8176	2763.54	0.0150	50.63	0.37	401.54
Bagged	m^2	52.00	12.24	636.48			0.00		0.00		0.00		0.00		0.00	0.00	0.00
Ceiling and Thermal Insulation																	
6.4 mm gypsum plaster board and	m^2	40.00	164.29	6571.60	kg	5.70 [10]	228.00	0.3540	80.72	0.0012	0.27	5.3486	1219.49	0.0131	2.99	0.06	56.96
50 mm glass wool laid to manufacturers specifications, finished with coverstrips (incl cornices)	m^2	40.00			kg	2.00	80.00	1.4934	119.47	0.0074925	0.60	30.110873	2408.87	0.24145	19.32	0.00	0.00
Roofing																	
Howe type truss to be designed by supplier for 7 m span	Sum	1.00	4553.14	4553.14	m^3		0.63	88.8730	55.99	0.5546	0.35	1337.8280	842.83	18.4910	11.65	0.00	0.00
114x38 wall plate including beam filling	m	12.00	20.27	243.24	m^3		0.05	88.8730	4.62	0.5546	0.03	1337.8280	69.55	18.4910	0.96	0.00	0.00
50x76 mm purlins on edge at maximum 1.2 m spacing	sum	1.00	404.38	404.38	m^3		0.22	88.8730	19.25	0.5546	0.12	1337.8280	289.77	18.4910	4.01	0.00	0.00
Roof Covering																	
0.54 mm Fielders corrugated Colorbond G550 AZ150 anti-corrosive	m^2	46.00	168.39	7745.94	kg	5.03 [11]	231.38	2.1191	490.32	0.0082	1.91	38.0209	8797.28	0.6900	159.66	0.00	21.45
"Zincalume" based steel sheeting	m^2	46.00						4.4401	204.24	0.28458	13.09	76.7507	3530.53	0.2779	12.78	0.00	0.00
Ridge cappings 450 mm girth	m	6.00	99.50	597.00	kg	2.26	13.58	2.1191	28.78	0.0082	0.11	38.0209	516.36	0.6900	9.37	0.00	0.00
galvanised	m^2	2.70						4.4401	11.99	0.28458	0.77	76.7507	207.23	0.2779	0.75	0.00	0.00
Transport (100km)	tkm	4734.00			tkm			0.48632	2302.24	0.0026554	12.57	7.715323	36524.37	0.039471	186.86		
Total impact				R 51,478.08					8735.77		42.90		92434.31		977.47		3397.52
																Total EI_4 [kg] =	4374.98

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] www.sigscp.co.uk

[9] CMA Masonry Manual 2007 Table 7.3

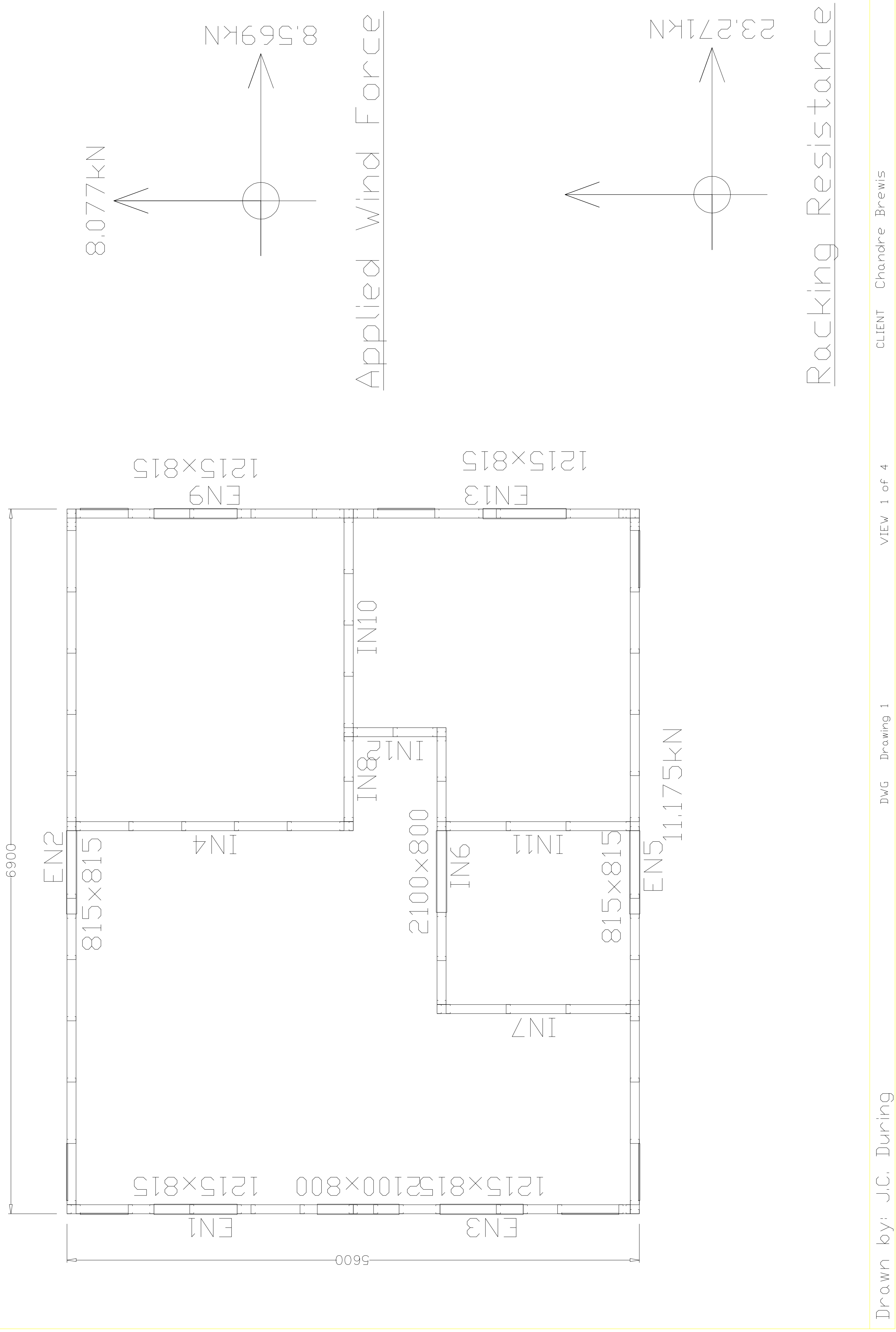
[10] www.gyproc.co.za

[11] www.clotansteel.co.za

Conventional Design: Estimation of Construction Waste

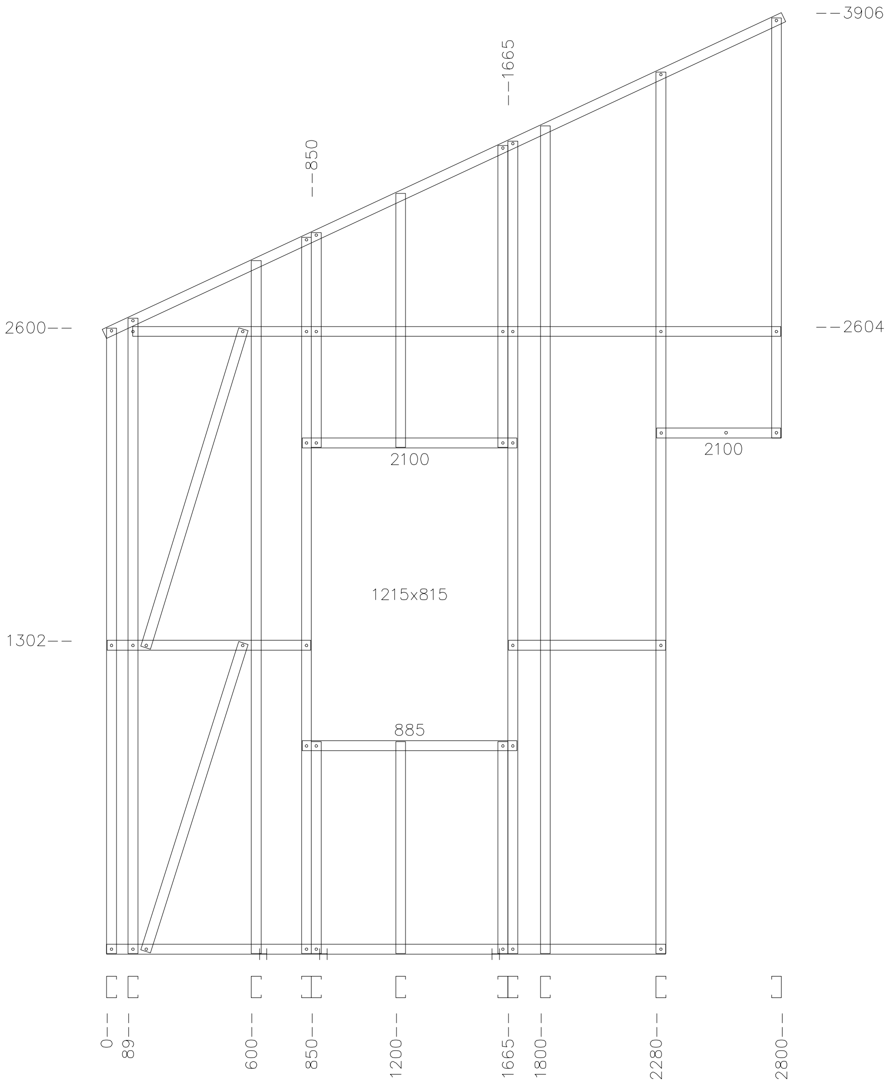
Material	Unit on Bill	Quantity	Quantity/m^2	CC$_i$	VAC$_i$	CR$_i$	VAR$_i$	CE$_i$	VAE$_i$	m^3 waste	m^3 waste	Density	kg waste
	unit		unit/m^2	m^3/unit	m^3/m^2	-	m^3/m^2	-	m^3/m^2	per m^2	per house	kg/m^3	per house
Foundations													
Excavation	m^3	8.94	0.22										0.00
10 MPa concrete foundation (600x200mm)	m^3	3.00	0.08	1.0000	0.0750	0.0300	0.0023	0.0000	0.0000	0.00	0.09	2400.00	216.00
Reinforcing (4 x Y12)	kg	103.00	2.58	0.0001	0.0003	0.0500	0.0000	0.0000	0.0000	0.00	0.00	7800.00	5.15
190 mm blockwork including	m^2	14.90	0.37	0.1400	0.0522	0.0560	0.0029	0.1000	0.0052	0.01	0.33	1100.00	357.96
brickforce (75x2.8mm),	m	125.00	3.13		0.0000		0.0000		0.0000	0.00	0.00		0.00
galvanised	m^2	2.45	0.06		0.0000		0.0000		0.0000	0.00	0.00		0.00
filled with concrete	m^3	0.97	0.02	1.0000	0.0242	0.0300	0.0007	0.0000	0.0000	0.00	0.03	2400.00	69.56
Floor Slab													
Damp proof membrane 250 micron	m^2	41.00											0.00
25 MPa concrete (power floated)	m^3	4.92	0.12	1.0000	0.1230	0.0300	0.0037	0.0000	0.0000	0.00	0.15	2400.00	354.24
steel mesh ref 193	kg	79.13	1.98	0.0001	0.0003	0.0500	0.0000	0.0000	0.0000	0.00	0.00	7800.00	3.96
External walls 140 mm													
Two top courses of brickwork to be filled with 10 Mpa concrete	m^3	0.65	0.02	1.0000	0.0163	0.0300	0.0005	0.0000	0.0000	0.00	0.02	2400.00	46.80
Blockwork, mortar &	m^2	75.00	1.88	0.1400	0.2625	0.0560	0.0147	0.1000	0.0263	0.04	1.64	1100.00	1801.80
brickforce as NHBRC standard	m	125.00	3.13		0.0000		0.0000		0.0000	0.00	0.00		0.00
galvanised	m^2	2.45	0.06		0.0000		0.0000		0.0000	0.00	0.00		0.00
Plaster externally (12mm thick)	m^2	75.00	1.88	0.0120	0.0225	0.0300	0.0007	0.0000	0.0000	0.00	0.03	2300.00	62.10
Bagged internally	m^2	75.00											0.00
DPC (110mm width) - 375micron	m	29.00											0.00
Internal Walls 90 mm													
Blockwork, mortar	m^2	26.00	0.65	0.0900	0.0585	0.0560	0.0033	0.1000	0.0059	0.01	0.37	1100.00	401.54
Bagged	m^2	52.00	1.30		0.0000		0.0000		0.0000	0.00	0.00		0.00
Ceiling and Thermal Insulation													
6.4 mm gypsum plaster board and	m^2	40.00	1.00	0.0064	0.0064	0.0500	0.0003	0.2000	0.0013	0.00	0.06	890.00	56.96
50 mm glass wool laid to manufacturers specifications, finished with coverstrips (incl cornices)	m^2	40.00	1.00		0.0000		0.0000		0.0000	0.00	0.00		0.00
Roofing													
Howe type truss to be designed by supplier for 7 m span	Sum	1.00	0.03		0.0000		0.0000		0.0000	0.00	0.00		0.00
114x38 wall plate including beam filling	m	12.00	0.30		0.0000		0.0000		0.0000	0.00	0.00		0.00
50x76 mm purlins on edge at 1.2 m spacing	sum	1.00	0.03		0.0000		0.0000		0.0000	0.00	0.00		0.00
Roof Covering													
0.54 mm Fielders corrugated Colorbond G550 AZ150 anti-corrosive	m^2	46.00	1.15	0.0005	0.0006	0.0610	0.0000	0.0300	0.0000	0.00	0.0023	9490.00	21.45
"Zincalume" based steel sheeting	m^2	46.00	1.15		0		0		0	0.00	0.00		0.00
Ridge cappings 450 mm girth	m	6.00	0.15		0		0		0	0.00	0.00		0.00
galvanised	m^2	2.70	0.0675		0		0		0	0.00	0.00		0.00
Transport (100km)	tkm												
										m^3	**2.71**	kg	**3397.52**

APPENDIX D


8.569kN
8.077kN
Applied Wind Force
23.271kN
Racking Resistance
CLIENT Chandre Brewis
1215x815
EN9
1215x815
EN13
IN10
IN12
IN8
IN4
EN2
815x815
2100x800
IN6
IN11
815x815
EN5
11.175kN
IN7
6900
1215x815
2100x800
1215x815
EN1
EN3
5600
VIEW 1 of 4
DWG Drawing 1
Drawn by: J.C. During

Panel Cutting List		
S8975 Plate	1	2319
S8975 Plate	1	2688
S8975 Plate	1	3109
S8975 Plate	1	515
S8975 Plate	1	651
S8975 Plate	1	844
S8975 Plate	2	891
S8975 Stud	1	1053
S8975 Stud	1	1251
S8975 Stud	1	1342
S8975 Stud	1	1382
S8975 Stud	1	1742
S8975 Stud	1	2594
S8975 Stud	1	2635
S8975 Stud	1	2874
S8975 Stud	1	2971
S8975 Stud	1	3370
S8975 Stud	1	3433
S8975 Stud	1	3657
S8975 Stud	3	879
S8975 Stud	1	890
#10–16x16 Wafer Screw		84

Panel Weight 48kg



<<< Joins EN2

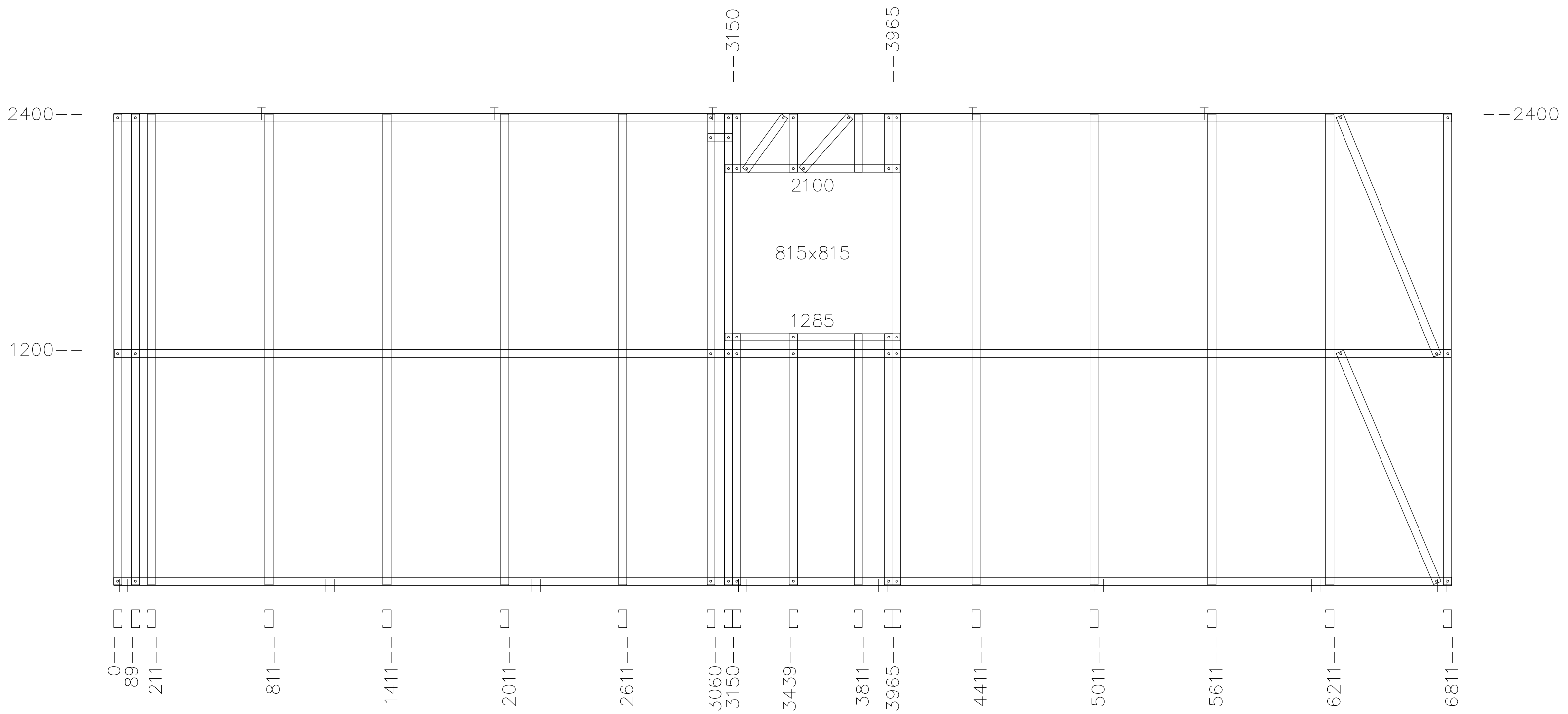
Wall EN1

Joins EN3 >>>

Chandré Brewis View 1 of 13 Dwg Drawing2 Client Client Name

Panel Cutting List		
S8975 Plate	1	125
S8975 Plate	1	6805
S8975 Plate	2	6811
S8975 Plate	2	891
S8975 Stud	1	1277
S8975 Stud	4	1279
S8975 Stud	1	1316
S8975 Stud	15	2394
S8975 Stud	4	294
S8975 Stud	1	339
S8975 Stud	1	364
#10–16x16 Wafer Screw		94

Panel Weight 74kg



<<< Joins EN9

Wall EN2

Joins EN1 >>>

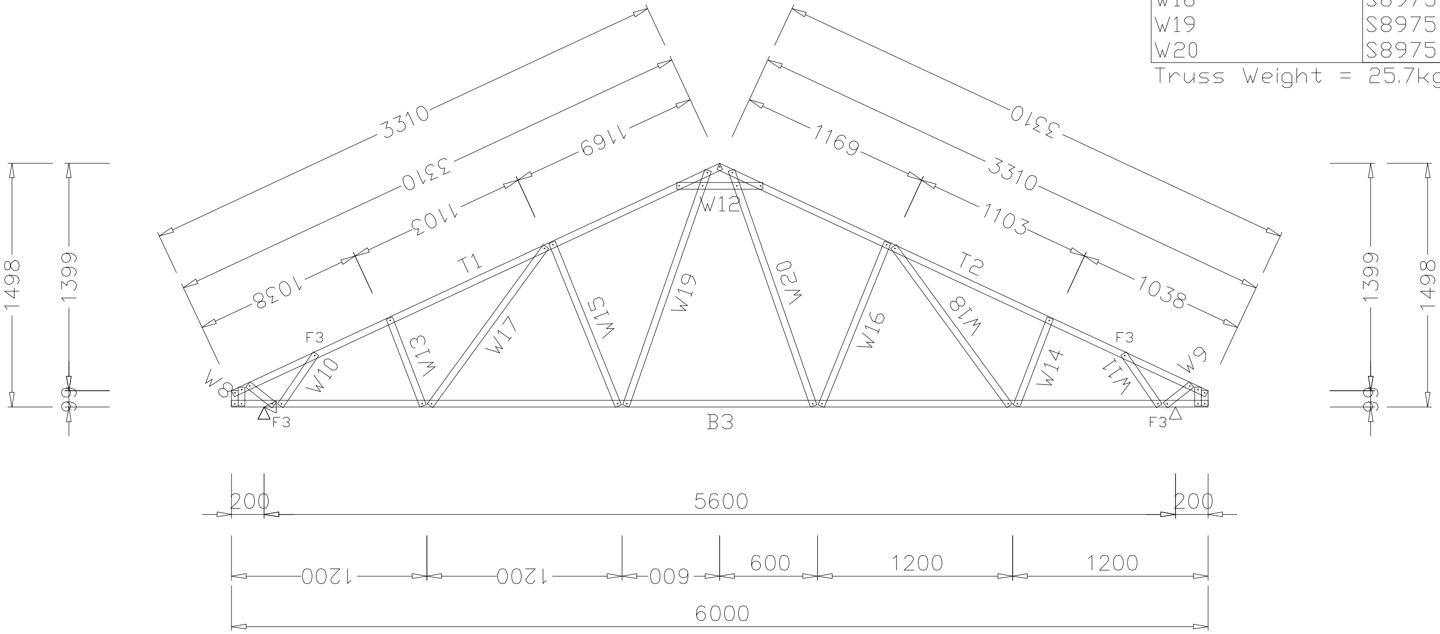
Chandré Brewis   View 2 of 13   Dwg Drawing2   Client Client Name

Truss Parts Summary	
#10-16x16 Tek	390

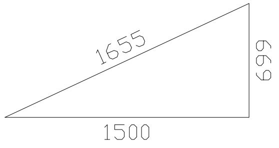
Minimum Fasteners per Connection = 2
Unless Otherwise Marked

Truss Materials Summary			
T1	S8975	5	3310
T2	S8975	5	3310
B3	S8975	5	6000
W4	S8975	5	97
W5	S8975	5	97
W6	S8975	5	116
W7	S8975	5	116
W8	S8975	5	206
W9	S8975	5	206
W10	S8975	5	390
W11	S8975	5	390
W12	S8975	5	530
W13	S8975	5	578
W14	S8975	5	578
W15	S8975	5	1085
W16	S8975	5	1085
W17	S8975	5	1210
W18	S8975	5	1210
W19	S8975	5	1534
W20	S8975	5	1534

Truss Weight = 25.7kg



Mark As N1 Qty = 5
W35-SHEET-1120-25.000°
Analysis Status = Passed 85%
FS=6000 AP=3000 AH=1498



'AS/NZS 4600:2005-D' 'SHEET' 0.250 0.200 0.650 0.00 0.200 600 20 20 0.9 1.0 0.000 0.2 1 0 0 1 1 0.3 1.0

Drawn by: J.C. During | DWG Drawing 4 | VIEW 4 of 4 | CLIENT Chandre Brewis

ProCAD SFSI Framing Module Panel Usage Report

Job Details

Company	Chandré Brewis		
Project	Client Name		
Job Ref.	???		
Designer	JC During		
Drawing No.	wall panels.dwg	Report Date	29-03-2011

Report By Panels

ID	Section	Quantity	Length	Total	Weight (kg)	Cost
EN1	S8975 Stud	1	1053	1053	1.147	
EN1	S8975 Stud	1	1251	1251	1.363	
EN1	S8975 Stud	1	1342	1342	1.461	
EN1	S8975 Stud	1	1382	1382	1.505	
EN1	S8975 Stud	1	1742	1742	1.897	
EN1	S8975 Plate	1	2319	2319	2.525	
EN1	S8975 Stud	1	2594	2594	2.825	
EN1	S8975 Stud	1	2635	2635	2.870	
EN1	S8975 Plate	1	2688	2688	2.928	
EN1	S8975 Stud	1	2874	2874	3.129	
EN1	S8975 Stud	1	2971	2971	3.235	
EN1	S8975 Plate	1	3109	3109	3.385	
EN1	S8975 Stud	1	3370	3370	3.670	
EN1	S8975 Stud	1	3433	3433	3.739	
EN1	S8975 Stud	1	3657	3657	3.982	
EN1	S8975 Plate	1	515	515	0.561	
EN1	S8975 Plate	1	651	651	0.709	
EN1	S8975 Plate	1	844	844	0.919	
EN1	S8975 Stud	3	879	2637	2.872	
EN1	S8975 Stud	1	890	890	0.969	
EN1	S8975 Plate	2	891	1782	1.941	
				43739	47.632	
EN2	S8975 Plate	1	125	125	0.136	
EN2	S8975 Stud	1	1277	1277	1.391	
EN2	S8975 Stud	4	1279	5116	5.571	
EN2	S8975 Stud	1	1316	1316	1.433	
EN2	S8975 Stud	15	2394	35910	39.106	
EN2	S8975 Stud	4	294	1176	1.281	
EN2	S8975 Stud	1	339	339	0.369	
EN2	S8975 Stud	1	364	364	0.397	
EN2	S8975 Plate	1	6805	6805	7.411	
EN2	S8975 Plate	2	6811	13622	14.834	
EN2	S8975 Plate	2	891	1782	1.941	
				67831	73.868	
EN3	S8975 Plate	1	1040	1040	1.133	
EN3	S8975 Stud	1	1086	1086	1.182	
EN3	S8975 Stud	1	1342	1342	1.462	
EN3	S8975 Stud	1	1359	1359	1.479	
EN3	S8975 Stud	1	1398	1398	1.522	
EN3	S8975 Stud	1	1626	1626	1.771	
EN3	S8975 Stud	1	1742	1742	1.897	

Report By Panels

ID	Section	Quantity	Length	Total	Weight (kg)	Cost
EN3	S8975 Plate	1	2261	2261	2.462	
EN3	S8975 Stud	1	2594	2594	2.825	
EN3	S8975 Stud	1	2626	2626	2.860	
EN3	S8975 Plate	1	2635	2635	2.870	
EN3	S8975 Stud	1	2906	2906	3.165	
EN3	S8975 Plate	1	3010	3010	3.278	
EN3	S8975 Stud	1	3062	3062	3.335	
EN3	S8975 Stud	1	3461	3461	3.769	
EN3	S8975 Stud	1	3629	3629	3.952	
EN3	S8975 Plate	1	394	394	0.429	
EN3	S8975 Plate	1	485	485	0.528	
EN3	S8975 Stud	3	879	2637	2.872	
EN3	S8975 Plate	2	891	1782	1.941	
EN3	S8975 Stud	1	981	981	1.069	
				42056	45.799	
EN5	S8975 Plate	1	125	125	0.136	
EN5	S8975 Stud	2	1277	2554	2.781	
EN5	S8975 Stud	4	1279	5116	5.571	
EN5	S8975 Stud	2	1316	2632	2.866	
EN5	S8975 Plate	1	195	195	0.212	
EN5	S8975 Stud	16	2394	38304	41.713	
EN5	S8975 Stud	4	294	1176	1.281	
EN5	S8975 Stud	1	339	339	0.369	
EN5	S8975 Stud	1	364	364	0.397	
EN5	S8975 Plate	1	6805	6805	7.411	
EN5	S8975 Plate	2	6811	13622	14.834	
EN5	S8975 Plate	2	891	1782	1.941	
				73014	79.512	
EN9	S8975 Stud	1	1012	1012	1.102	
EN9	S8975 Plate	1	1129	1129	1.229	
EN9	S8975 Stud	1	1209	1209	1.317	
EN9	S8975 Stud	1	1329	1329	1.447	
EN9	S8975 Stud	1	1603	1603	1.746	
EN9	S8975 Plate	1	2194	2194	2.389	
EN9	S8975 Stud	1	2594	2594	2.825	
EN9	S8975 Plate	1	2711	2711	2.952	
EN9	S8975 Stud	1	2832	2832	3.084	
EN9	S8975 Stud	1	2929	2929	3.190	
EN9	S8975 Plate	1	3010	3010	3.278	
EN9	S8975 Stud	1	3328	3328	3.625	
EN9	S8975 Stud	1	3391	3391	3.693	
EN9	S8975 Stud	1	3671	3671	3.998	
EN9	S8975 Stud	1	3797	3797	4.135	
EN9	S8975 Stud	1	3839	3839	4.180	
EN9	S8975 Plate	1	755	755	0.822	
EN9	S8975 Stud	1	849	849	0.924	
EN9	S8975 Stud	3	879	2637	2.872	
EN9	S8975 Plate	2	891	1782	1.941	
				46601	50.749	
IN4	S8975 Stud	7	2394	16758	18.249	
IN4	S8975 Plate	1	2705	2705	2.946	
IN4	S8975 Plate	2	2711	5422	5.905	
				24885	27.100	

ProCAD SFSI Framing Module Panel Usage Report Cont.

Report By Panels

ID	Section	Quantity	Length	Total	Weight (kg)	Cost
IN6	S8975 Plate	1	1003	1003	1.092	
IN6	S8975 Plate	1	125	125	0.136	
IN6	S8975 Stud	8	2394	19152	20.857	
IN6	S8975 Plate	2	2710	5420	5.902	
IN6	S8975 Stud	3	294	882	0.960	
IN6	S8975 Plate	1	876	876	0.954	
IN6	S8975 Plate	1	895	895	0.975	
				28353	30.876	
IN7	S8975 Plate	1	1885	1885	2.052	
IN7	S8975 Plate	1	1891	1891	2.059	
IN7	S8975 Plate	1	1891	1891	2.059	
IN7	S8975 Stud	5	2394	11970	13.035	
				17636	19.206	
IN8	S8975 Stud	3	294	882	0.960	
IN8	S8975 Plate	1	831	831	0.904	
IN8	S8975 Plate	1	831	831	0.905	
				2544	2.770	
EN13	S8975 Stud	1	1082	1082	1.179	
EN13	S8975 Stud	1	1128	1128	1.228	
EN13	S8975 Stud	1	1188	1188	1.294	
EN13	S8975 Plate	1	1264	1264	1.376	
EN13	S8975 Stud	1	1372	1372	1.494	
EN13	S8975 Stud	1	1411	1411	1.536	
EN13	S8975 Stud	1	2594	2594	2.825	
EN13	S8975 Plate	1	2635	2635	2.870	
EN13	S8975 Stud	1	2635	2635	2.870	
EN13	S8975 Stud	1	2668	2668	2.905	
EN13	S8975 Plate	1	2800	2800	3.049	
EN13	S8975 Stud	1	2908	2908	3.167	
EN13	S8975 Plate	1	3109	3109	3.385	
EN13	S8975 Stud	1	3307	3307	3.602	
EN13	S8975 Stud	1	3507	3507	3.820	
EN13	S8975 Stud	1	3787	3787	4.124	
EN13	S8975 Stud	1	3881	3881	4.226	
EN13	S8975 Plate	1	709	709	0.772	
EN13	S8975 Stud	1	827	827	0.901	
EN13	S8975 Stud	4	879	3516	3.829	
EN13	S8975 Plate	2	891	1782	1.941	
EN13	S8975 Stud	1	968	968	1.054	
				49078	53.445	
IN10	S8975 Plate	1	2135	2135	2.325	
IN10	S8975 Plate	2	2141	4282	4.663	
IN10	S8975 Stud	6	2394	14364	15.642	
				20781	22.631	
IN11	S8975 Plate	1	1796	1796	1.955	
IN11	S8975 Plate	1	1802	1802	1.962	
IN11	S8975 Plate	1	1802	1802	1.962	
IN11	S8975 Stud	4	2394	9576	10.428	
				14975	16.308	
IN12	S8975 Stud	3	294	882	0.960	
IN12	S8975 Plate	1	821	821	0.894	
IN12	S8975 Plate	1	821	821	0.894	
				2524	2.748	

```
Truss Material Report

Company Name        Chandré Brewis
Client Name         Client Name
Job Number          ???
Dwg Number          truss diagram.dwg
Current Date        29-03-2011


Materials Summary

Material                              Length    Weight

S8975                                 117917    128.53
                                                128.53

Parts Summary

#10-16x16 Tek                            390
```

APPENDIX E

LSFB: Environmental Impacts

														Waste generation EI_4			
Materials					Conversion			Carbon Footprint EI_1		Acidification Potential EI_2		Resource Depletion EI_3		Waste from Production		Construction Waste	
Item	Unit	Quantity	Rate [R/unit]	Cost [R]	EcoInvent unit	conversion factor	new amount	[kg CO_{2e}/unit]	per item	[kg SO_{2e}/unit]	per item	[MJ-eq/unit]	per item	[kg/unit]	per item	m^3 per item	kg per item
Foundations																	
Excavation	m^3	4.06	50.34	204.58												0.0000	0.00
Concrete (400x150mm) - 25 MPa	m^3	1.54	850.00	1310.70	m^3			264.1000	407.24	0.5066	0.78	1512.3900	2332.11	23.7230	36.58	0.0463	111.02
Reinforcing (2-Y10)	kg	31.35			kg			1.6841	52.80	0.0057	0.18	26.8955	843.17	0.2769	8.68	0.0002	1.57
Brickwork (clay) - double layer cavity wall	m^2	12.70	230.00	2921.00	kg	171.00 [1]	2171.70	0.2388	518.52	0.0006	1.35	3.1435	6826.83	0.0063	13.77	0.1783	338.79
Mortar	m^3	0.19			kg	2100.00 [2]	399.00	0.1605	64.04	0.0003	0.11	0.9594	382.82	0.0023	0.91	0.0001	0.14
Brickforce	m	76.20			kg	0.11 [3]	8.30	2.1555	17.89	0.0078	0.07	36.1469	300.09	0.7218	5.99	0.0000	0.00
Floor Slab																	
Concrete (100mm - 25MPa)	m^3	4.00	850.00	3400.00	m^3			264.1000	1056.40	0.5066	2.03	1512.3900	6049.56	23.7230	94.89	0.1200	288.00
Reinforcing - Mesh ref 193	m^2	41.00	5.22	214.02	kg	1.93 [4]	79.13	1.6841	133.27	0.0057	0.45	26.8955	2128.24	0.2769	21.91	0.0003	2.05
Damp proof membrane	m^2	41.00	5.93	243.13	kg	0.23 [5]	9.43	2.6085	24.60	0.0098	0.09	81.1856	765.58	0.0586	0.55	0.0000	0.00
Anchor Bolts																	
External Walls																	
Light steel profiles	m	357.00	29.64	10581.48	kg		386.10	2.1191	818.20	0.0082	3.18	38.0209	14679.99	0.6900	266.42	0.0000	0.00
galvanised	m^2	134.95			m^2			4.4401	599.17	0.2846	38.40	76.7507	10357.20	0.2779	37.51		
Fasteners: #10-16x16 wafer screws	No.	530.00															
Cladding - 9mm fibre cement board	m^2	75.00	131.10	9832.50	kg	12.60 [6]	945.00	1.0915	1031.47	0.0026	2.47	10.1962	9635.39	0.1881	177.72	0.3679	515.03
Vapour permeable membrane	m^2	75.00	6.76	507.02	kg	0.23 [7]	17.25	2.6085	45.00	0.0098	0.17	81.1856	1400.45	0.0586	1.01	0.0000	0.00
Thermal Break - OSB	m^2	75.00	45.60	3420.00	m^3	0.02	1.43	312.7200	445.63	1.3923	1.98	7659.4071	10914.66	30.3060	43.19	0.0143	11.40
Bulk Insulation - 25mm glass wool	m^2	75.00	57.00	4275.00	kg	1.00 [8]	75.00	1.4934	112.01	0.0075	0.56	30.1109	2258.32	0.2415	18.11	0.0188	0.75
Gypsum plasterboard lining - 15mm	m^2	75.00	67.15	5035.95	kg	14.10 [9]	1057.50	0.3540	374.39	0.0012	1.26	5.3486	5656.18	0.0131	13.86	0.1755	164.97
Internal Walls																	
Light Steel profiles	m	125.00	29.64	3705.00	kg		133.80	2.1191	283.54	0.0082	1.10	38.0209	5087.31	0.6900	92.33	0.0000	0.00
galvanised	m^2	47.25						4.4401	209.79	0.2846	13.45	76.7507	3626.47	0.2779	13.13		
Fasteners: #10-16x16 wafer screws	No.	224.00		0.00													
Gypsum plasterboard lining - 15mm	m^2	52.00	67.15	3491.59	kg	14.10	733.20	0.3540	259.57	0.0012	0.87	5.3486	3921.62	0.0131	9.61	0.1217	114.38
Bulk Insulation - 25mm glass wool	m^2	26.00	57.00	1482.00	kg	1.00 [10]	26.00	1.4934	38.83	0.0075	0.19	30.1109	782.88	0.2415	6.28	0.0065	0.26
Ceiling and Insulation																	
Gypsum Plasterboard - 6.4mm	m^2	40.00	34.94	1397.64	kg	5.70 [11]	228.00	0.3540	80.72	0.0012	0.27	5.3486	1219.49	0.0131	2.99	0.0640	56.96
Bulk Insulation - Glass wool mat 25mm	m^2	40.00	57.00	2280.00	kg	1.00 [12]	40.00	1.4934	59.74	0.0075	0.30	30.1109	1204.43	0.2415	9.66	0.0100	0.40
Roofing																	
Light Steel profiles	m	131.00	29.64	3882.84	kg		141.38	2.1191	299.61	0.0082	1.17	38.0209	5375.51	0.6900	97.56	0.0000	0.00
galvanised	m^2	49.52						4.4401	219.86	0.2846	14.09	76.7507	3800.54	0.2779	13.76		
Fasterners: #10-16x16 TEK	No.	390.00															
Purlins	m	57.00	29.64	1689.48	kg	1.07	61.10	2.1191	129.49	0.0082	0.50	38.0209	2323.23	0.6900	42.16	0.0000	0.00
galvanised	m^2	22.06						4.4401	97.94	0.2846	6.28	76.7507	1693.04	0.2779	6.13		
Covering																	
Sheeting	m^2	46.00	168.39	7745.94	kg	5.03 [13]	231.38	2.1191	490.32	0.0082	1.91	38.0209	8797.28	0.6900	159.66	0.0023	21.45
galvanised	m^2	46.00						4.4401	204.24	0.2846	13.09	76.7507	3530.53	0.2779	12.78		
Ridge cappings 450 mm girth	m	6.00	99.50	597.00	kg	2.26	13.58	2.1191	28.78	0.0082	0.11	38.0209	516.36	0.6900	9.37	0.0000	0.00
galvanised	m^2	2.70						4.4401	11.99	0.2846	0.77	76.7507	207.23	0.2779	0.75		
Transport (100km)	tkm	2245.72			tkm			0.4863	1092.14	0.0027	5.96	7.7153	17326.44	0.0395	88.64		
Total impact				R 68,216.87					9207.18		113.14		133942.94		1305.93		1627.17
																Total EI_4 [kg] =	2933.10

References

1 SANS 10160-2 Table A.2

2 CMA Concrete Masonry Manual

3 lorraine@impiwire.co.za

4 www.steeldalemesh.com

5 www.sigscp.co.uk

6 www.ufcc.co.za

7 www.sigscp.co.uk

8 SANS 10160-2 Table A.6

9 www.gyproc.co.za

10 SANS 10160-2 Table A.6

11 www.gyproc.co.za

12 SANS 10160-2 Table A.6

13 www.clotansteel.co.za

LSFB: Estimation of Construction Waste

Material	Unit on Bill	Quantity	Quantity/m^2	CC_i	VAC_i	CR_i	VAR_i	CE_i	VAE_i	m^3 waste	m^3 waste	density	kg waste
			unit/m^2	m^3/unit	m^3/m^2	-	m^3/m^2	-	m^3/m^2	per m^2	per house	kg/m^3	per house
Foundations													
Excavation	m^3	4.064	0.10										
Concrete (400x150mm) - 25 Mpa	m^3	1.542	0.04	1.0000	0.0386	0.0300	0.0012	0.0000	0.0000	0.00116	0.0463	2400	111.0240
Reinforcing (2-Y10)	kg	31.35	0.78	0.0001	0.0001	0.0500	0.0000	0.0000	0.0000	0.00001	0.0002	7800	1.5675
Brickwork (clay)	m^2	12.7	0.32	0.0900	0.0286	0.0560	0.0016	0.1000	0.0029	0.00446	0.1783	1900	338.7852
Mortar	m^3	0.19	0.00	0.0120	0.0001	0.0300	0.0000	0.0000	0.0000	0.00000	0.00007	2100	0.1436
Brickforce	m	76.2											
Floor Slab													
Concrete (100mm - 25MPa)	m^3	4	0.10	1.0000	0.1000	0.0300	0.0030	0.0000	0.0000	0.00300	0.1200	2400	288.0000
Reinforcing - Mesh ref 193	m^2	41	1.03	0.0001	0.0001	0.0500	0.0000	0.0000	0.0000	0.00001	0.0003	7800	2.0500
Damp proof membrane	m^2	41											
Anchor Bolts													
External Walls													
Light steel profiles	kg	386.1033	9.65										
Fasteners: #10-16x16 wafer screws	No.	530											
Cladding - 9mm fibre cement board	m^2	75	1.88	0.0090	0.0169	0.0450	0.0008	0.5000	0.0084	0.00920	0.3679	1400	515.0250
Vapour permeable membrane	m^2	75											
Thermal Break - OSB	m^2	75	1.88	0.0190	0.0356	0.0100	0.0004	0.0000	0.0000	0.00036	0.0143	800	11.4000
Bulk Insulation - 25mm glass wool	m^2	75	1.88	0.0250	0.0469	0.0100	0.0005	0.0000	0.0000	0.00047	0.0188	40	0.7500
Gypsum plasterboard lining - 15mm	m^2	75	1.88	0.0150	0.0281	0.0560	0.0016	0.1000	0.0028	0.00439	0.1755	940	164.9700
Internal Walls													
Light Steel profiles	kg	133.8029	3.35										
Fasteners: #10-16x16 wafer screws	No.	224											
Gypsum plasterboard lining - 15mm	m^2	52	1.30	0.0150	0.0195	0.0560	0.0011	0.1000	0.0020	0.00304	0.1217	940	114.3792
Bulk Insulation - 25mm glass wool	m^2	26	0.65	0.0250	0.0163	0.0100	0.0002	0.0000	0.0000	0.00016	0.0065	40	0.2600
Ceiling and Insulation													
Gypsum Plasterboard - 6.4mm	m^2	40	1.00	0.0064	0.0064	0.0500	0.0003	0.2000	0.0013	0.00160	0.0640	890	56.9600
Bulk Insulation - Glass wool mat 25mm	m^2	40	1.00	0.0250	0.0250	0.0100	0.0003	0.0000	0.0000	0.00025	0.0100	40	0.4000
Roofing													
Light Steel profiles	kg	141.383	3.53										
Fasterners: #10-16x16 TEK	No.	390											
Covering													
Purlins	m	57	1.43										
Sheeting	m^2	46	1.15	0.0005	0.000621	0.0610	3.79E-05	0.0300	1.86E-05	0.00006	0.0023	9490	21.4516
Ridge cappings 450 mm girth	m	6.00											
galvanised	m^2	2.70											
Transport (100km)	tkm												
										m^3	**1.1259**	kg	**1627.1661**