GREEN ROOF RETROFITTING:

A STUDY INTO THE STRUCTURAL IMPLICATIONS ASSOCIATED WITH GREEN ROOF RETROFITS

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Upon reaching this milestone, I would like to express my sincerest and heartfelt gratitude to all of those individuals who have sacrificed time and parted with golden knowledge for the betterment of this study. Without those individuals, this study would not have been possible and it is for this reason that this study is dedicated to the following individuals:

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ABSTRACT

The realities of climate change have fast become apparent. It is for this reason that vast quantities of research explored potential mitigation methods to alleviate the strain placed on the environment and the planet by climate change. Structural engineers and the greater engineering community utilise green building practices in an effort to reduce carbon emissions and hence, lower the carbon footprint of a structure. One such practice has been the introduction of green roofs. This study looks at the potential of retrofitting structures with green roofs. It investigates various construction materials and their influence on the potential of retrofitting structures with green roofs. In addition, this thesis investigates the influence of considerations given during structural design such as a structure's span and the utilisation of different section sizes, in an attempt to provide a general assessment into the practicality of a green roof retrofit. This study has shown that there is a significant potential in retrofitting existing structures with green roofs. In addition, the results of the study have shown that concrete structures are more likely to have a higher potential to be retrofitted. The potential to be retrofitted with a green roof depends on the carrying capacity that in turn depends on a range of factors. However, the primary factor in the magnitude of the carrying capacity is essentially the choice of element decided upon by the structural designer. This study has proved that green roofs have the potential to reduce the temperature of the substructure to a greater degree when compared to other roof types. It has further proved that green roofs possess the potential to significantly reduce storm water run-off in comparison to other roof types. However, this study has highlighted that there is significant basis for further investigation into structural implications associated with green roofs and other relevant areas.

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LIST OF ABBREVIATIONS

GHG-Green house gases

UV- ultraviolet

GRPP-Green roof pilot project

m-Metres

mm- Millimetres

kN/m- KiloNetwons per meter

kN.m- KiloNetwon meter

CO_2.eq./m^2-Carbon dioxide equivalent per square meter

R-Rands

AMSL-Above mean sea level

CBD- Central Business District

BTU- British Thermal Unit

kWh-Kilowatt-Hour

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CHAPTER 1: INTRODUCTION

1.1 Introduction

This chapter serves as an introduction to the research being carried out. It highlights the aims and objectives that are sought to be investigated and achieved. In addition, it highlights the desired outcomes that are intended to be completed at the end of the study. This chapter also serves to indicate the order in which the research is to be structured.

1.2 Research motivation

According to NASA (2016), global temperature patterns show a steady increase in the Earth's temperature, attributed to numerous factors. The most dominant of which, being the increase in carbon emissions. It has therefore, become increasingly more important to reduce carbon emissions and hence, carbon footprints-a concept coined as going 'green'.

South Africa is a country that has vast natural beauty and an array of rich fauna and flora. However, the present and emerging threats that come with climate change pose a real threat to the future of these natural phenomena and to the country's people. (Griffin, 2012)

In terms of the total greenhouse gas (GHG) emissions in South Africa, the City of Durban accounts for 5.2% of this total and in terms of global GHG emissions, accounts for less than 0.1%. However, the city is not excluded from the impacts of climate change. Already the city has recorded changes in the availability of water, damage to infrastructure, threats to biodiversity and ecosystem stability, impacts on agriculture, food security and health, higher energy consumption and negative economic impacts. Of all the socio-economic denominations, it is suggested that the poor will be most affected (Morgan & O'Donoghue, 2014).

Today, there is a strong emphasis in the engineering field to adopt 'greener' practices in design. One of these practices involves the development of a green roof-a term often used to describe vegetated roofs, roof terraces and roof gardens (living roofs and walls). According to Scholz-Barth and Weiler (2009), the term 'green roof' has grown from a simplistic description to one that has become significantly important in both, ecological and social bases. The authors further suggest that the term has become synonymous with alleviating conditions such as pollution, the urban heat island effect, stormwater run-off and providing efficiency in urban land utilization.

This study is, therefore, vital to develop and understand the concept of green roofs particularly with respect to retrofitting. Green roofs, in actuality, is not something to be looked at in isolation but should be seen as a method of alleviating, on a small scale, the negative effects associated with development in urban areas and on a larger scale, carbon emissions and essentially contributions to climate change. Furthermore, developing and understanding the structural implications that form the foundations of green roof design is pivotal. It should be noted that a simplified technique could be utilized to assess if a structure can carry a green roof i.e. without performing any relevant calculations initially, with regard to a structure's carrying capacity, structures that contained ballasted roofs i.e. those who's surface is covered by stone, have the structural integrity to carry a green roof provided that the green roof is designed to the exact weight per square meter to that of the stone. This would essentially form a substitution of material from ballasted roof to green roof. However, this study not only seeks to meet the aims identified in Chapter 1.4 but seeks to identify those factors that influence a structures ability to carry an additional load and hence, its retrofitting potential. This is done in an attempt to attain a greater understanding of the principles behind retrofitting and reserve capacities formulating grounds upon which ordinary structures may be investigated for retrofitting.

1.3 Research question

How do structural considerations such as material choice, section sizes, span, etc., influence the ability to retrofit a structure with a green roof?

1.4 Aims

The primary aim of this study is to identify the structural considerations and their influence on the potential of retrofitting a structure with a green roof. In addition, in an attempt to present a solution to the plight or part thereof, of the underprivileged, this study aims to identify the feasibility of retrofitting low-cost housing with green roofs.

1.5 Objectives

The objectives of this study will be to investigate:

- Various alternatives to provide an improved measure of sustainability that can be implemented in existing structures.
- Advantages and disadvantages to the use of green roofs.

- Hydrological characteristics of a roof green roofs i.e. drainage and run-off characteristics.
- Green roof practices that are being implemented in different regions of the world.
- Green roof practices that are currently being implemented in South Africa.
- Designs and limitations of green roofs on the structure.
- Quantify potential savings of carbon emissions.
- Structural assessments of various types of structures together with various construction materials.
- The effects of temperature between various roof types through experimentation of different roof models.
- The effects of run-off between various roof types through experimentation of different roof models.
- Influences on the carrying-capacity of a structure.

1.6 Anticipated measurable results

Anticipated Results:

- Measure of the amount of carbon emissions to be saved through the implementation of a typical green roof.
- Measures required in ensuring existing structures are suitable for the implementation of green roofs.
- Determination of possible alternatives.

Outcomes:

An understanding of the relationship between the implementation of ‘greener’ building practices, specifically green roofs, and the associated carbon emissions is expected. In addition, an understanding of the relationship between structural design choices and their ability to sustain a greater load.

Discussion:

After considering the results of the study a discussion into the feasibility of the use of green roofs in new or retrofitting of existing buildings, as a means to reduce carbon emissions and electricity and essentially create a more sustainable building, is anticipated. In addition, structural considerations that influence or hinder the potential of a structure to be retrofitted with a green roof, will be discussed.

1.7 Scope of study

Due to the lack of existing building designs attributed to the legal frameworks surrounding them, this thesis focuses on the design of typical structures found in three main sectors of construction i.e. residential, industrial and commercial. The design of the structures considers locations where similar structures currently exist.

1.8 Structure of thesis

The thesis is to be structured into a division of ten chapters as follows:

- Chapter 1: *Introduction*

Chapter one serves as an introduction to the research being carried out. It highlights the need for the study in relation to current circumstances and proposes the aims and objectives that are sought to be achieved during the study to produce a conclusive argument.

- Chapter 2: *Literature review*

Chapter two highlights the various sources of literature utilised in the study to achieve an understanding of the theory in relation to the nature of the study at hand. It involves a critical review of the existing literature and forms the basis for the identification of gaps in current research and the groundwork for a comparison of existing literature and the results obtained from this study.

- Chapter 3: *Methodology*

Chapter three serves as an explanatory chapter and forms an explanation of the various methods implored throughout the study in an attempt to achieve the aims and objectives set out, as well as to further produce a conclusive argument in relation to the research being carried out.

- Chapter 4: *Literature review of typical structures utilised in this study*

Chapter four is a representation of the theory behind the various structural types designed in an attempt to produce experimental results that would align itself to the determination of the aims and objectives of the study.

- Chapter 5: *Structural Analysis*

Chapter five presents a structural analysis that combines the use of quantitative and qualitative assessments utilised to determine the factors that contribute and influence a structure's retrofitting potential.

- Chapter 6: *Temperature Analysis*

Chapter six serves as a representation of the assessments carried on both, a quantitative and qualitative basis to determine the temperature reduction capabilities of green roofs in comparison to a conventional roof system.

- Chapter 7: *Stormwater Runoff Analysis*

Chapter seven presents the assessment of the potential of green roofs to reduce the stormwater runoff from structures carried out utilising quantitative and qualitative methods.

- Chapter 8: *Retrofitting Potential*

Chapter eight is a presentation of an assessment into the potential of retrofitting existing structures with green roofs based on factors identified during the study.

- Chapter 9: *Life-cycle assessment and cost benefit analysis*

Chapter nine presents the analysis and findings of green roof life-cycles and the associated cost-benefit analysis.

- Chapter 10: *Conclusion and Recommendations*

Chapter nine serves to present the concluding arguments of the study and further presents recommendations for future studies through gaps highlighted in research and findings obtained from the study.

CHAPTER 2: LITERATURE REVIEW

2.1 Introduction

This chapter serves as an introduction to the major issue of concern and highlights the importance for this study in the present day. As such, it defines the issue of climate change and the associated effects experienced. Concepts such as carbon emissions, carbon footprints and green roofs are discussed and notable gaps in research are presented. Furthermore, this chapter serves to highlight existing structural knowledge and capabilities and implications surrounding green roofs and the potential to retrofit structures.

2.2 Climate change defined

Mankind has become accustomed to the climatic conditions that vary based on daily or seasonal time frames. However, there is growing evidence to suggest that in addition to these naturally occurring climatic variations, the measure of the average climatic conditions over a predetermined amount of time are changing over and above the expected rate. Climate change refers to an increase in the atmospheric temperature of the Earth and directly results in changes experienced in both, global and local weather patterns and sea levels (Greenstone, et al., 2010). This increase is attributed to an increase in carbon emissions and effectively an increase in one's carbon footprint. Climate change has resulted in an increase in temperature, rise in sea levels, unexpected weather conditions and phenomena and changes in rainfall patterns throughout the global. As such, this results in various negative consequences ranging from prevalent drought conditions, increased health concerns, destruction of ecosystems and biodiversity and a decrease in fertile land, in the least (News24, 2010).

Throughout the history of the Earth, its climate has changed a number of times. In the past 650,000 years alone, the Earth has gone through seven glacial advances and retreats. The most recent of which, had seen a glacial event end approximately 7000 years ago, signalling the dawn of the climate era as we know it and most importantly marking the beginning of human civilization (NASA, 2008).

In the past, most of these events were attributed to changes in the amount of incoming solar energy as a result of minor variations in the Earth's orbit. However, the current changes, the current warming trend being of particular concern, have most likely been induced by human activity. Furthermore, this rate is described as one that is unparalleled in the past 1,300 years (NASA, 2008)

2.2.1 Rising sea levels

Globally, in the last century, sea levels have risen approximately 17 centimetres. However, this rate has almost doubled in value in the last ten years alone, in comparison to the rate of the last century (NASA, 2008).

Primarily, rising sea levels can be attributed to two factors i.e. the addition of water through melting ice and the expansion of sea water through increasing temperatures. *Figure 2.2.1* illustrates satellite observations of the changes in sea level since the year 1993. As of February 2016, the sea height variation was recorded at 74.75 millimetres, at a rate of change of 3.4 millimetres per year (see *Figure 2.2.1)*. For the twenty-three-year period in which the sea level change has been observed sea levels have changed approximately 75 millimetres. This rising trend will only be accelerated with the increased melting of the polar ice caps.

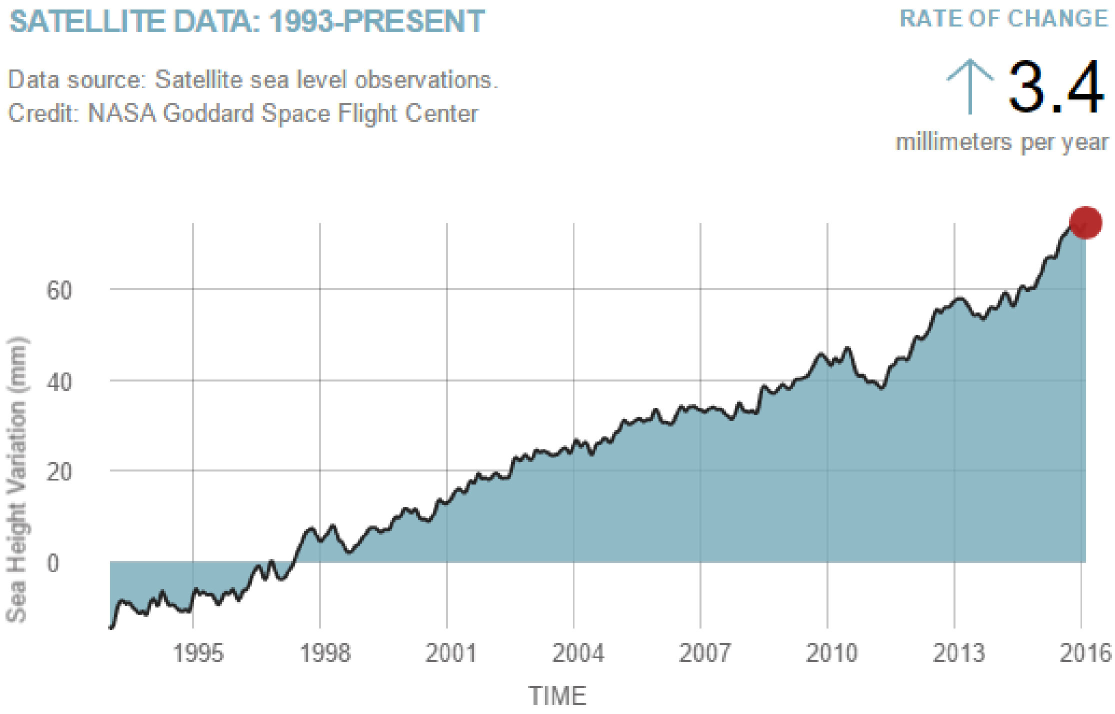


Figure 2.2.1: Sea level variation by satellite (after NASA, 2008)

Figure 2.2.2 illustrates the observed change in the sea level as recorded through the use of coastal tide gauges from the year 1870 to the year 2000. For the 130-year period in which the sea level change has been observed, the levels have changed approximately 200 millimetres.

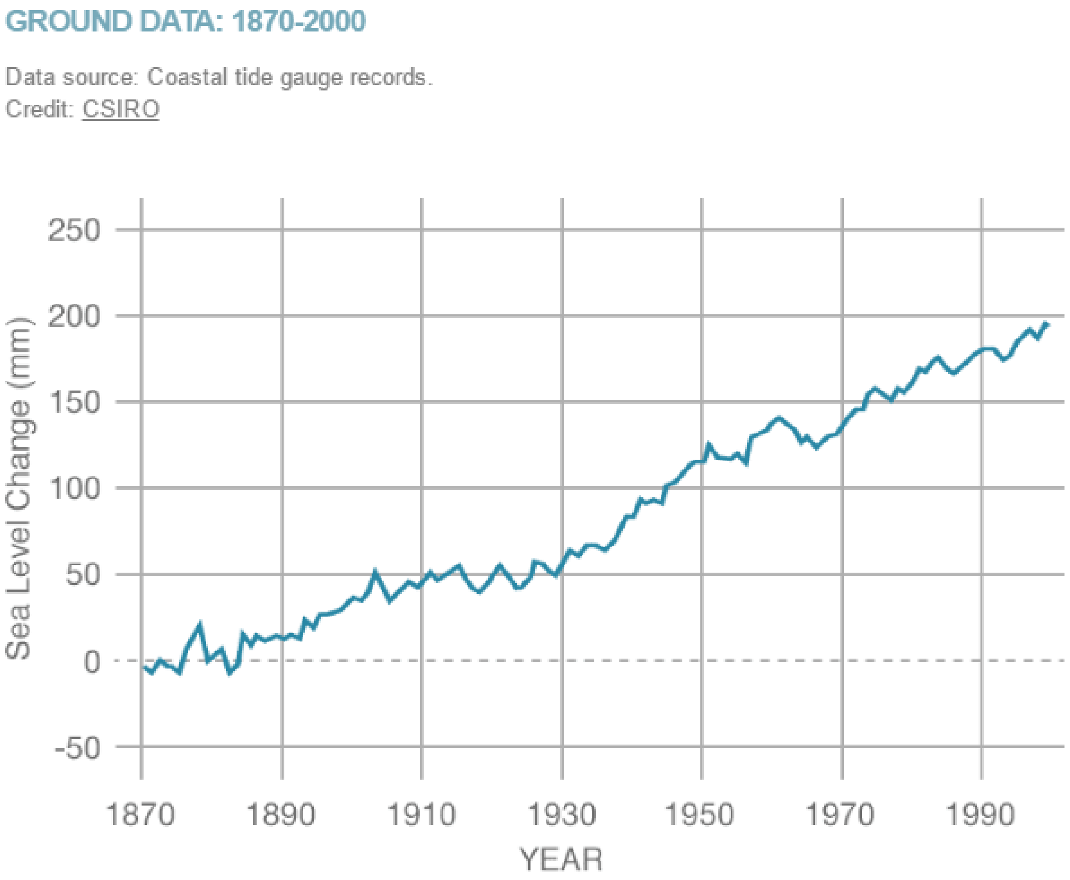


Figure 2.2.2: sea level variation by coastal tide gauges (after NASA, 2008)

Both graphs show that over the years there was fluctuations in the recorded sea levels. However, the trend is clearly illustrated. Sea levels are on the rise and this could impact on the lives of people along the coast and have further negative consequences.

2.2.2 Global temperatures

A 134-year global surface temperature data record shows that the temperature of the Earth has increased since the year 1880, with the majority of this increase in temperature occurring since the 1970s. Temperature records further show that the since the year 1981, the Earth has seen 20 of its warmest years. Whereas, excluding the year 1998, the ten warmest years have occurred since the year 2000. As per January 2015, the latest measurement was recorded at 0.87°C, making the year the warmest on record (see *Figure 2.2.3*)

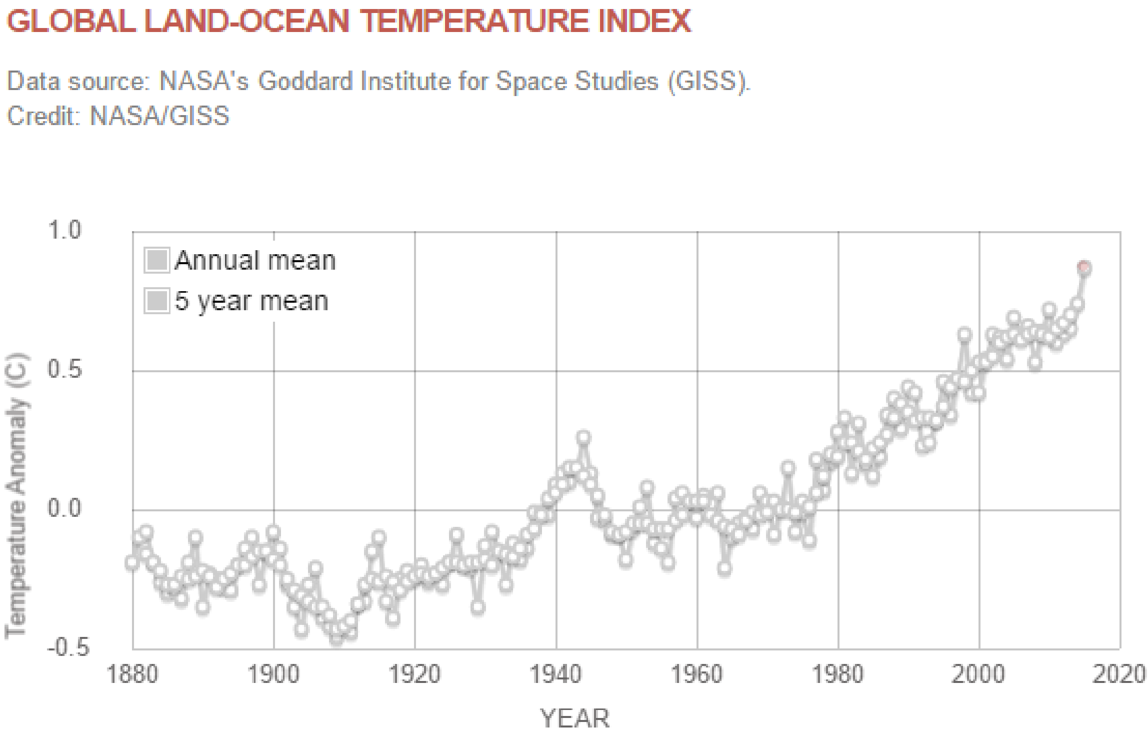
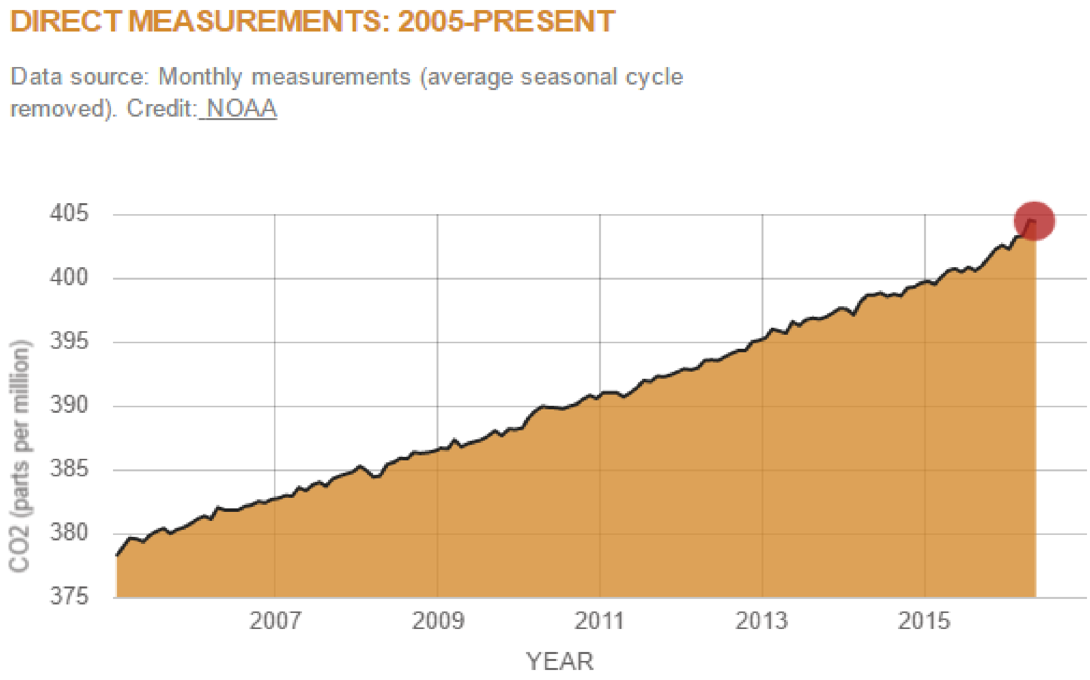


Figure 2.2.3: Global temperature change (after NASA, 2008)

2.2.3 Carbon dioxide

Carbon dioxide (CO_2) is a GHG that is often released through activities that are regarded as being essential for economic and social development. The gas is further released through naturally occurring activities such as respiration and volcanic eruptions. *Figure 2.2.4* illustrates the most recent recorded atmospheric carbon dioxide levels. As of May 2016, the latest measurement was recorded at 404.36 parts per million (ppm). It is evident that the graph depicts an increasing trend in the level of CO_2 in the atmosphere. In the eleven-year period in which the atmospheric CO_2 levels were documented i.e. 2005-Present, the levels have risen approximately 25 parts per million.

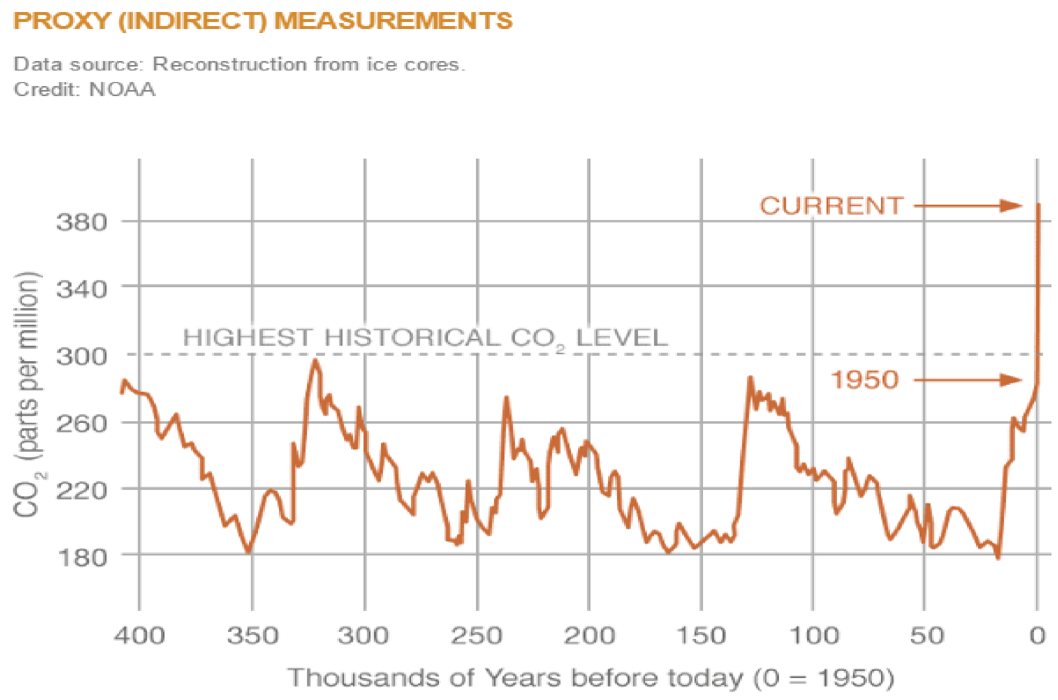


DIRECT MEASUREMENTS: 2005-PRESENT

Data source: Monthly measurements (average seasonal cycle removed). Credit: NOAA

Figure 2.2.4: Carbon Dioxide changes from 2005-2016 (after NASA, 2008)

Through the utilisation of ice cores, CO_2 levels for the last three glacial cycles were reconstructed and illsutrated in *Figure 2.2.5*. The graphs shows that CO_2 have fluctated as per every 100 years. However, current trends show that the CO_2 levels have displayed an incremental increase, placing current levels over 400 parts per million. This increase can be attributed to changes occurring around the year 1950.



PROXY (INDIRECT) MEASUREMENTS

Data source: Reconstruction from ice cores.
Credit: NOAA

Figure 2.2.5: Carbon dioxide records from ice cores (after NASA, 2008)

Both graphs show the mid-tropospheric carbon dioxide distribution and concentration globally. The increase in carbon is suggested to have resulted in the occurrences of the other two phenomena. In an effort to combat the rising levels of CO_2, it is imperative to first understand these carbon emissions and the carbon footprint, together with contributions to the phenomena at an individual level.

When looked at collectively, these occurrences reinforce the idea that a more concerted effort is needed to combat the various issues of climate change. Based on the trends of the relative graphs it can be assumed that the situation shall become progressively worse in subsequent years. The consequences of which, will possibly have a major impact on the global population both, socially and economically, as well as the state of the environment. This further reinforces the motivation for increased greener building practices and concepts such as green roofs as a potential mitigation strategy.

2.2.4 Climate change in South Africa

Scientists in the fields of health and the climate have determined the health impacts as a result of climate change and how they affect different regions of the world. Their results, as illustrated in *Figure 2.2.6*, ironically depicts regions of the World that are said to contribute the least to global warming, as being amongst those that are most susceptible to disease and death, as a result of increased temperature. From the figure, it is evident that South Africa is amongst the most severely affected with a mortality rate estimated at between 70-120 people per every million (University of Minnesota, 2015).

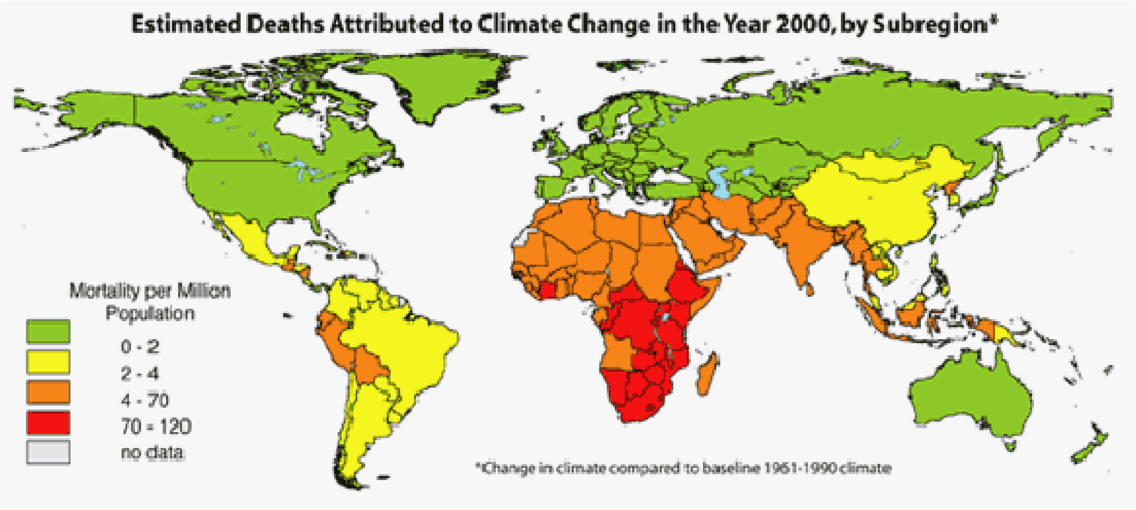


Figure 2.2.6: Estimated deaths attributed to climate change (Source: University of Minnesota, 2015)

According to Morgan & O'Donoghue (2014), in a global context, the continent of Africa is the smallest contributor to the concentrations of GHGs in the Earth's atmosphere. However, it is a continent that experiences significantly worse consequences and possesses the smallest capabilities to deal with the changes brought about by climate change. The country of South Africa on the other hand, has be deemed a significant contributor to the levels of GHG emissions, as a result of an energy intensive economy powered by fossil-fuels. With its sensitive socio-economic and environmental aspects and water-stressed state, the country is said to be amongst the most vulnerable to the impacts of climate change on the continent. The authors go on to state that it is predicted that by mid-century temperatures along the coast of South Africa will rise by 1-2°C and inland temperatures will rise between 2-3°C. In addition, by the year 2100, temperatures are projected to rise by 3-4°C along the coastal areas and between 6-7°C inland. This change in temperature will impact on the health of individuals, agriculture, natural resources and that of the environment (Morgan & O'Donoghue, 2014).

2.2.5 Climate change in the City of Durban

The City of Durban, forms part of the global community and as a result, contributes to the global quantity of greenhouse gas emissions. The eThekwini Municipality compiled an inventory of the total amount of GHG emissions recorded in the city for the year 2012. There findings showed that a total of 29,360,395 tCO_2e had been emitted in the entire city alone. This quantity is a representation of a 47% increase in emissions over a period of 10 years. A total of 19,937,000 tCO_2e, had been recorded in the year 2002. When reporting on GHG, international standards require a division of the total emissions into three scopes. These scopes are defined as follows (Morgan & O'Donoghue, 2014):

- Scope 1-refers to direct emissions which are a result of the combustion of raw materials for the primary purpose of generating energy and the combustion of fuel sources for purposes of transport
- Scope 2- refers to indirect emissions that come as a result of the processes of electricity and steam production for the purpose of sale.
- Scope 3-refers to emissions that account for the collective indirect emissions bar scope 2 emissions.

The eThekwini Municipality has further divided the city's total GHG emissions into two sub-divisions i.e. one to account for emissions from local government and the second to account for emissions from the greater community.

Figures 2.2.7-2.2.8 represent the distribution of the City of Durban's total GHG emissions by scope and by sector respectively. Whereas, *Tables 2.2.1-2.2.2* represent a detailed breakdown of the total GHG emissions per scope for the two sub-divisions.

Table 2.2.1: Local Government Emissions by Scope for the city of Durban (after Morgan & O'Donoghue, 2014)

Local Government Emissions by Scope			
Emissions Scope	GHG Sources	Emissions (tCO_2e)	Emissions (%)
Scope 1	Combustion of Stationary and Mobile Fuel, Treatment of Waste water, Disposal of Solid Waste	391 810	26
Scope 2	Electricity Consumption, Transmission and Distribution	1 101 398	72
Scope 3	Employee Air Travel, Operation of Transit Vehicles, Consumption of electricity through Eskom owner streetlights	33 222	2
	Total	**1 526 430**	**100**

Table 2.2.2: Community Emissions by Scope for the city of Durban (after Morgan & O'Donoghue, 2014)

Community Emissions by Scope			
Emissions Scope	GHG Sources	Emissions (tCO_2e)	Emissions (%)
Scope 1	Combustion of Stationary and Mobile Fuel, Disposal of Solid Waste, Enteric Fermentation, Pre-harvest sugar cane burning	11 580 783	40
Scope 2	Electricity Consumption	12 573 397	44
Scope 3	Air and Marine Transport	4 679 785	16
	Total	**28 833 965**	**100**

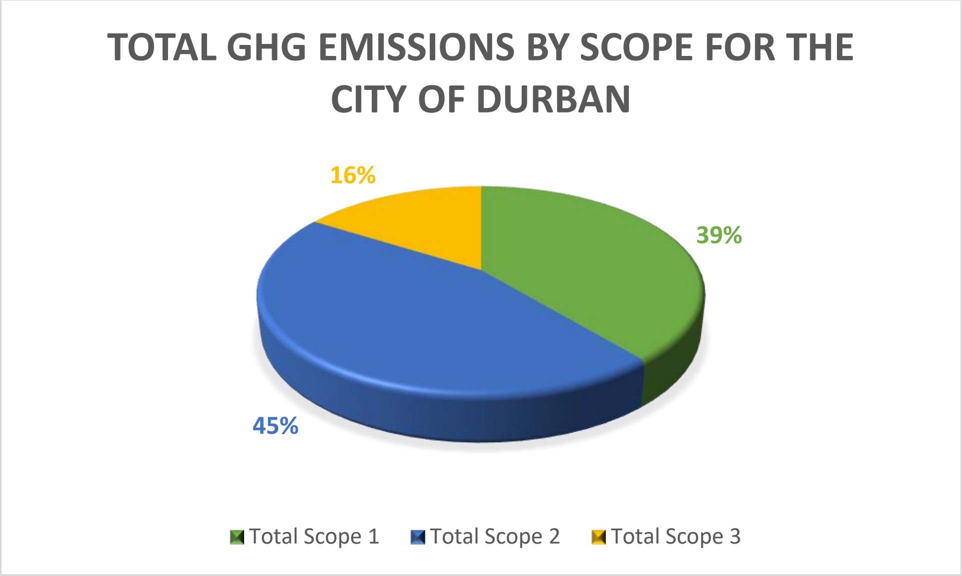


Figure 2.2.7: Durban's total GHG emissions by scope (after Morgan & O'Donoghue, 2014)

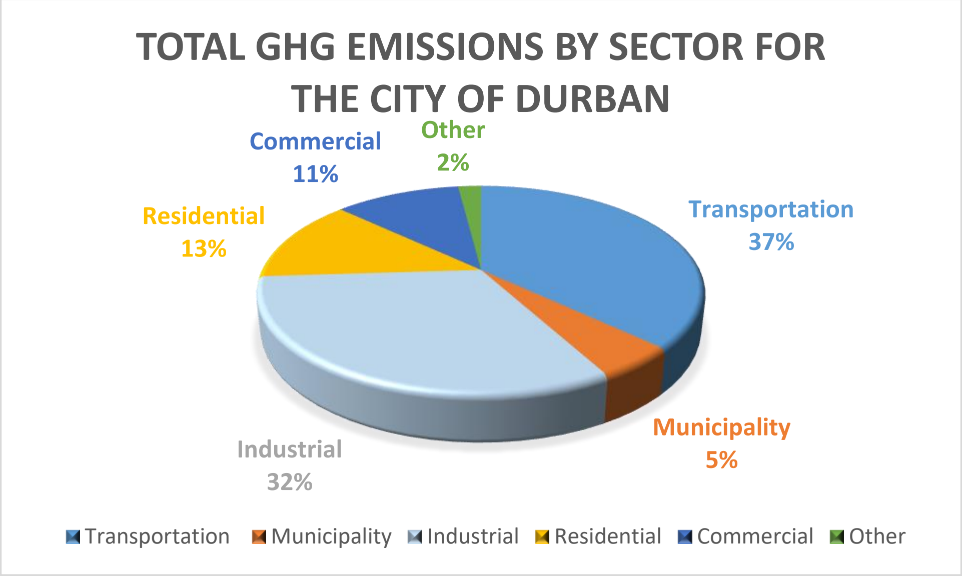


Figure 2.2.8: Durban's total GHG emissions by sector (after Morgan & O'Donoghue, 2014)

In accordance with a report created by Golder Associates Africa (2010), who have established projections in terms of climate change for the City of Durban, there are various changes that can be expected. For instance, the city can expect an increase in the average annual temperature in the region of 1.5-2.5°C by the year 2065, with a further increase between 3-5°C by the year 2100. The Northern regions of the Municipality are expected to experience an increase in the long duration, defined as one day and longer, rainfall events by 20%. Whereas, the Western regions are expected to experience an increase in the short duration rainfall events. As a result, these regions run the risk of a potential increase in localised flooding of up to 30%. In addition, the city is expected to experience an increase in rainfall variability of between 30-100%, year on year. An increase in the frequency of heat waves together with rainfall patterns that have a higher erosion capability is also projected. The report further projects that future sea levels are expected to rise at a much higher rate in comparison to the current rise of 2.7 (+/- 0.05) mm/year (Morgan & O'Donoghue, 2014).

The Authors' findings highlight the GHG emissions associated with the various daily activities. Based on these research findings, it is evident that mitigation strategies need to be imposed within the various sectors, with a focus on the largest contributors in order to potentially reduce the effects of climate change experienced locally.

Figure 2.2.9, shows the flooding of the city of Durban's beach promenade which caused destruction to property along the promenade, in the year 2007. This has been attributed to high spring tides. Climate change will only serve to accelerate the frequency and magnitude of these occurrences.

Figure 2.2.9: Flooding of the Durban promenade (Source: eThekwini Online, 2007)

2.3 Carbon footprint

Greenstone, et al. (2010), suggests that a carbon footprint is a system of measurement and is used to measure an individual's impact on the environment and more specifically, their addition to the impact of climate change, through simply performing day-to-day activities. Essentially, it is a representation of the amount of GHG caused by those activities through the combustion of fossil fuels and is measured in units of Kilograms of Carbon Dioxide (CO_2) equivalent.

Greenstone, et al. (2010), states that of the total global GHG emissions the building sector is responsible for over a third of that total. This high portion comes as result of the fact that buildings require a large amount of energy to ensure efficient operation. However, Greenstone, et al. (2010), goes on to state that the building sector is also a sector that has huge potential to effectively reduce the massive contribution it makes to the global GHG emissions. In 2004, the building sector in the United States of America, which comprises of both the commercial and residential sectors, accounted for 39% of the total CO_2 emissions and was accredited for consumption of 70% of the total electricity load.

Researchers, Albadry, et al., (2017), corroborate this idea and adds that the building sector alone contributes approximately 40% of the world’s total energy consumption, after the industry and transport sectors, and approximately a third of the global greenhouse gas emissions. This contribution varies from city to city. In Egypt, it was reported to contribute 51% of the total energy consumption. The researchers go on to state that over the next 20 years the expected energy utilisation is expected to grow by approximately 34% globally, at an average rate of 1.5% per annum. According to the International Energy Agency for the consumption of energy trends, primary energy consumption and carbon emissions have grown by approximately 49% and 43% over the last two decades respectively (Albadry, et al., 2017).

2.4 Structural techniques and strategies to reduce carbon emissions

Presently, there are various techniques and strategies that can be utilised to reduce carbon emissions from a structure. However, in line with the theme of green roofs the following chapter presents strategies or techniques in terms of alternate roof structures or alternative physical green engineering methods that can be utilised.

2.4.1 Brown roofs

“Brown” roofs are more commonly known as being a biodiverse form of green roofs. These roofs are designed with the specific purpose of creating a biologically diverse habitat for an array of fauna and flora that previously had been sustained through abandoned or disused land. Brown roofs are installed utilising a similar procedure to that of green roofs however, brown roofs utilise growing media that is primarily composed of recycled building material, soil and waste material from a site. Thereafter, brown roofs are left to the processes of nature to be colonised by fauna and flora (US Government, National Park Service, 2010).

2.4.2 Cool roofs

"Cool roofs" are roofs that are made of material that have a high degree of reflectance (see *Figure 2.4.1*). Cool roofs are seen as an alternative to green roof systems and can be utilised on buildings that are historic or those that are too steeply pitched to sustain a green roof. Cool roofs are assessed based on their measure of solar reflectance-the amount of solar energy reflected by a roof and thermal emittance-the roofs ability to radiate and dissipate absorbed heat (US Government, National Park Service, 2010).

Figure 2.4.1: Illustration of a "cool" roof (Source: US Government, National Park Service, 2010)

2.4.3 Blue roofs

"Blue roofs" are the name given to rooftops that may contain a body of water and is essentially utilised as a form of recreational area. Blue roofs can take the form of pool areas, eco-showers and water sculptures, to name a few. Run-off from these types of roofs can be used as irrigation for green roof systems or as a cooling mechanism for a structure's roof assembly. Much like any other roof application, assessments need to be done to assess the impact of construction of blue roofs on individual structures (US Government, National Park Service, 2010).

2.4.4 Living walls

A living wall is often referred to as vertical garden or biowall. It is a system of planting vegetation vertically. The living walls technique forms an active heat barrier that may essentially reduce the required cooling requirements of the building (Gunnell, 2009).

From a structural viewpoint, potential mitigation of the effects of climate change is centred around adopting green building practices. Essentially, green building practices aim to provide structures that reduce the impacts imposed on the environment. This is done through the utilisation of materials and methods that are both, suitable for use and do not result in environmental harm during the processes of manufacture or utilisation (Gunnell, 2009). One particular technique that has gained popularity is the use of green roofs.

2.5 Green roofs

Greenstone, et al. (2010), defines a green roof as the roof of a structure having being wholly or partially covered with vegetation intentionally. Assimakopoulos, et al. (2008), defines a green roof as an engineered roof system that allows for the development and growth of rooftop vegetation whilst, simultaneously protecting the integrity of the underlying roof structure.

Green roofs are not a modern concept. The earliest form of the concept dates as far back as 600 BC. The hanging gardens of Babylon were the earliest documented form of green roofs and is also accredited as being one of the seven wonders of the ancient world (Oberndorfer, 2007). To the present day, Nordic people continue a century’s old tradition of adding turf or vegetation to their roofs (Connop, et al., 2013).

2.6 Green roof projects in south Africa

In South Africa, there have been various green roof projects that were undertaken indicating the potential to sustain green roofing and highlighting a growing industry. This chapter highlights two such projects conducted in the country.

2.6.1 Durban

In response to climate change, the eThekwini Municipality had initiated the eThekwini Municipal Climate Change Programme (MCCP) and the Greening Durban Programme in the year 2010. The initiative aimed to reduce the carbon footprint of various buildings and essentially facilitate positive climate change. One of the major actions taken was the conversion of one of the buildings within the City Engineers Complex into one with a green roof (see *Figure 2.6.1*). This formed part of the city’s Green Roof Pilot Project (GRPP).

Figure 2.6.1: Green roof at eThekwini City Engineers Complex (Source: Green roof Designs,2011)

2.6.2 Cape town

The City of Cape Town Municipality’s *Management of Urban Stormwater Impacts Policy of 2009*, makes specific mention of Water Sensitive Urban Design (WSUD). The WSUD has the potential for introducing green roofs into the policy as it acknowledges green roof design as a measure that encourages and promotes amenity, biodiversity and aesthetics. In addition, there is talk of the possibility of incentives being introduced to promote this category of design. To highlight the potential around this type of design, the city has gone on to publish a handbook called *“Cape Town Smart Building Handbook of 2012”*. The book features a green roof pilot project (see *Figure 2.6.2*) carried out on one of the city owned buildings (Cape Town Government, 2012).

Figure 2.6.2: Green roof in the city of Cape Town (Source: Cape Town Government,2012)

These cases are a fraction of the green roof projects in South Africa. This highlights the fact that there is significant potential and room for growth in the development and introduction of green roof systems in the country.

2.7 Types of green roofs

Green roofs are primarily classified as either direct or modular and can be further classified as being extensive or intensive. A direct green roof is defined as a green roof that is built in layers and is fitted directly onto the roof of a structure (see *Figure 2.7.1* and *Figure 2.7.2*). A modular green roof is defined as a green roof that is built from a system of modules or containers in which vegetation is planted (Greenstone, et al., 2010).

2.7.1 Direct green roofs

2.7.1.1 Extensive green roofs

Extensive green roofs are defined as those that contain a soil or growing medium depth of less than 20 cm, resulting in a composition that is fairly shallow (Greenstone, et al., 2010). Scholz-Barth & Weiler (2009), corroborate this definition and go on to state that extensive green roofs are primarily utilised for an array of environmental benefits that range from storm water management to thermal insulation. The researchers further suggest that these types of green roofs are rarely irrigated and have the expectation of a minimal maintenance requirement.

2.7.1.2 Intensive green roofs

In contrast to an extensive green roof, an intensive green roof is defined as a direct green roof with a soil depth that is at a minimum of 20 cm and reaches a maximum depth of 1 m.

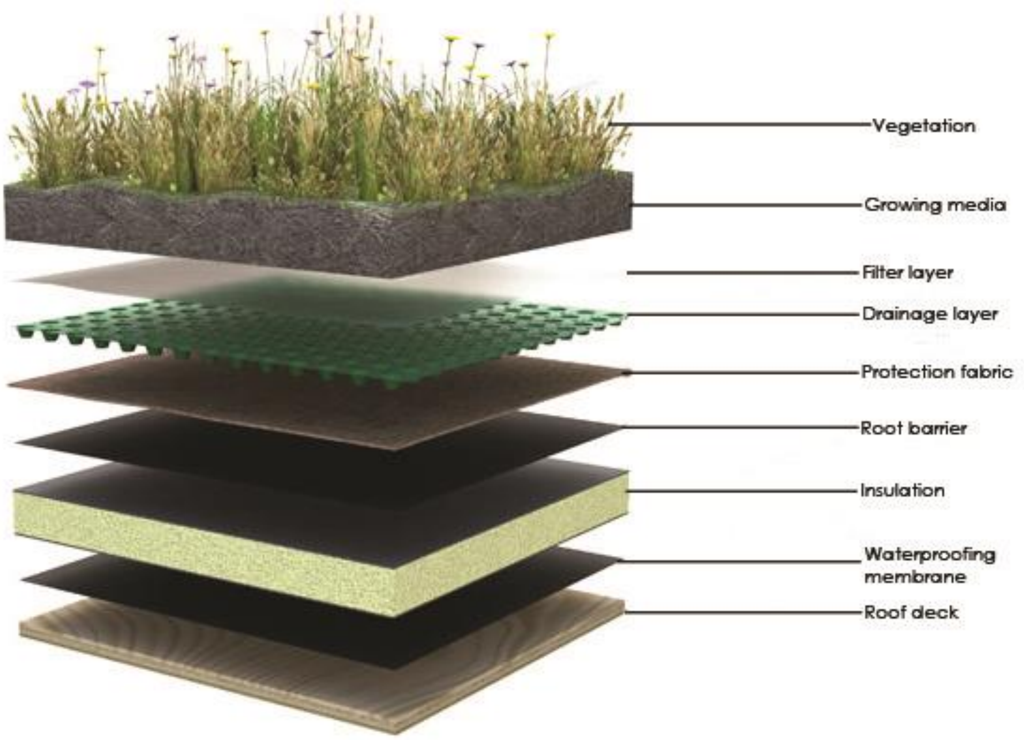


Figure 2.7.1: Typical composition of a direct green roof (Source: Green Roofs Direct, 2005)

Figure 2.7.2: Direct green roof in Toronto, Canada and Chicago, USA (Source: Green Roofs Direct, 2005)

2.7.2 Modular green roofs

Modular green roofs are a form of green roof that is constructed utilising individual portable containers. Each module is constructed as an individual vegetation support system that is later combined to form an expansive green roof.

In summary, Bianchini and Hewage (2012), conclude that through the use of a single type of green roof system environmental benefits can be maximized. However, each type does provide some form of environmental benefit. Costs associated with installation, construction and maintenance are dependent on the type of green roof system used. In addition, in comparison to the other two green roof types, extensive green roofs have proved to be lighter in weight and yields a lower maintenance cost. This supports the findings of Scholz-Barth & Weiler (2009).

2.8 Disadvantages of green roofs

The use of any technique or strategy, dependent on its nature, may possess various disadvantages. Green roofs can be disadvantageous in many aspects. The following chapter highlights the various forms of green roofs and their associated disadvantages.

2.8.1 Direct

2.8.1.1 Intensive

Intensive green roof systems are often regarded as being disadvantageous for use as a green roof based on the properties it possesses. Intensive green roof systems add a greater dead load upon the roof due to its added weight. These green roof systems also require irrigation and as a result it is more energy, water and material intensive. In comparison to extensive green roof systems, intensive green roofs require higher capital costs and produce higher maintenance costs during operation. As a whole, intensive green roof systems are more complex systems when compared to the other green roof systems available (Reed & Wilkinson, 2009). As a result, more expertise is required in design and installation. These findings support that of researchers Kuhn and peck (2008), who state that intensive green roof systems are those that are often regarded as accessible and characterised by properties of deeper soil layers and hence, greater weight, are those that require higher capital costs and maintenance requirements but at the same time allow for a significant increase in the diversity of plant life that can be utilised in a green roof system.

2.8.1.2 Extensive

When compared to intensive green roof systems, extensive green roof systems offer smaller storm water retention capacities and are less energy efficient. Due to the nature of the system, plant choice is limited. Furthermore, this system provides little to no access for the purposes of recreation, amongst other uses (Reed & Wilkinson, 2009). Thus, this type of system often becomes unattractive to many. Kuhn and peck (2008), regard extensive green roofs as being those that are often inaccessible and are characterised by having shallower soil depths and as such, lower weight. However, as a result, these systems allow for a smaller plant diversity. The authors go on to state that these green roof systems boast lower capital costs and minimal maintenance requirements.

2.8.2 Modular

As previously discussed modules or containers are used in a modular green roof. These are advantageous due to the fact that they are eco-friendly and are generally made from recyclable material. Modules offer resistance to UV light and are made in a variety of sizes thus, increasing the options of suitable plant life that can be utilised in a green roof. Each module boasts built-in systems of drainage and water storage, allowing for reduction in the rate of rainfall run-off and storage of water intended for plant use respectively. In addition, due to the reservoir under the modules, each one is raised approximately 30 mm off the roof surface allowing for the unhindered movement of air that aids in the cooling and insulation of the roof. Modules are easily transportable, allows for flexibility in the design of a green roof and improved access for maintenance. Due to the nature of the modules, they could be utilised as ponds, improving the biodiversity of the green roof through the introduction of aquatic plants and the attraction of creatures that thrive in water (Greenstone, et al., 2010).

In an attempt to clearly define a comparison between direct and modular green roof systems, the systems were assessed based on factors such as weight, installation, cost, maintenance, alterations and plant life (see *Table 2.8.1*)

Table 2. 8.1: Comparison of direct and modular green roofs based on various factors (after Greenstone, et al., 2010)

Factor	Direct roof gardens	Modular roof gardens
Weight	Heavier than modular green roofs and may require additional structural support.	Can be installed on any roof provided that it is of sound condition and has the necessary structural capacity. Can also be utilised on corrugated roofs and those with a maximum pitch of 15^{o}.
Installation	Requires the installation of various layers prior to reaching the planting stage.	Offers a degree of ease and flexibility as modules can be pre-planted. This also offers faster construction of the green roof.
Cost	May be cheaper when compared to the cost of the number of modules that would be required to complete the green roof system.	Modules can be quite costly and one may require many modules. As such, costs begin to escalate.
Repair and maintenance	If a problem arises, layers will have to be physically removed and checked to resolve the issue. This can negatively impact on the health of plants.	Due to planting in modules, sectionalisation is present and this allows for ease of maintenance.
Additions to design	In order to add new plant life, consideration must be made toward the time that it will take for plants to grow and the associated difficulty.	Modules provide green roofs in sections and can therefore, be changed or modified with relative ease.
Plant life	Plants have sufficient room growth.	Modules may restrict root growth.

2.9 Advantages of green roofs

The following chapter presents the advantages of utilising green roofs and highlights that collectively, the advantages of green roofs far outweigh that of the associated disadvantages.

2.9.1 Air quality

Green roofs are reportedly linked with the promotion of better air quality based on the nature of the system i.e. being composed of flora. Plants, depending on the type, can substantially reduce the amount of carbon dioxide in the atmosphere. This statement is supported by Reed and Wilkinson (2009), who further add that green roofs acts as a means of pollution abatement by trapping and filtering nitrous oxides and other volatile compounds through the system. As such, green roofs play a considerable role in improving the quality of air.

2.9.2 Biodiversity and habitat creation

Green roofs promote biodiversity as these essentially form habitats for an array of wildlife. In Europe, as part of a project of increasing wildlife corridors found in urban areas, two types of green roof habitats were implemented. The first, known as a “Stepping stone habitat” is defined as a habitat that serves as a link between isolated habitats. However, this type of link is one that exists by air only and as such, involves migratory birds, insects and seeds. The second habitat is known as an “island”. This habitat is one that remains isolated and as such, is home to specific variations of plants that possess properties of seed dispersal not spread by means of air nor over short distances (Kuhn & Peck, 2008).

2.9.3 Fire resistance

According to researchers Kuhn and Peck (2008), there is significant research to suggest that green roof systems have the potential to control the spread of fires from structure to structure via rooftops. This is particularly evident in cases where growing mediums in a green roof system are completely saturated. However, it is to be noted that vegetation on a green roof system itself can present a potential fire risk if they are dry. As a result, it is suggested that, in regular intervals, “fire breaks” should be incorporated into the design of a green roof system.

2.9.4 Energy conservation

Due to the nature of a green roof system, green roofs provide thermal reduction and insulation to the structures upon which they are placed. During the winter season, green roofs keep in warmth within a structure. In opposition, during the summer season green roofs provide cooler temperatures through the processes of photosynthesis and evapo-transpiration. Through the process of photosynthesis plants absorb radiant energy from the sun and through evapo-transpiration, water collected from plants is vapourised and causes the faster water molecules to rise, effectively cooling the surrounding environment. These therefore, reduce temperatures thus, reducing the need for excessive air conditioning (Kuhn & Peck, 2008).

Reed and Wilkinson (2009), state that with respect to energy conservation, percentages of between 15%-30% can be recorded in structures that utilise green roofs. The variation in the amount of energy that is conserved is attributed to the variations in climate, green roof medium depth and construction and performance. The researchers go on to state that through energy conservation a structure uses less energy and thus, accordingly, greenhouse gas emissions are reduced.

A study conducted by Canadian researchers Liu and Baskaran (2003), to evaluate the thermal performance of green roofs, show that the use of green roofs can effectively reduce the need for cooling of a structure's internal spaces and hence, a structure's energy demands (see *Figure 2.9.2*). Their study showed that a conventional roof, defined as that of a bitumous, concrete, asphalt or gravel roof top, retained temperatures as high as 70°C in the summer period (see *Table 2.9.1*). As a result, a high energy input to cool the structure below is required from the heat expended of the sun. In contrast, a green roof reduces the amount of heat flowing into the structure below, lowering the energy requirement for cooling by as much as 95% per square metre. In addition, the study found that a green roof reduced the heat lost from the structure during the winter season in the region of 26% (see *Table 2.9.2*).

Reed and Wilkinson (2009), in contradiction, state that the potential that green roofs possess in lowering the temperature of a roof's surface is between 10°C -15.5 °C. The researchers do however, corroborate the idea that the smaller the heat gain within the structure, the less cooling potential required and further state that, in areas where darker vegetation is used, lower temperatures will be recorded.

The researchers utilised an experimental roof area of approximately 72 m^2 that was later divided equally and each half was modified into a green roof and a bituminous roof (defined as 'Reference' in *Figure 2.9.1*) respectively. The surface of the respective roofs was coated with a light grey membrane. This choice was made on the grounds of neutrality and essentially trying to avoid being excessively bright or excessively dark, that would have otherwise impacted on the results of the study. With reference to *Figure 2.9.1*, over the course of the study the daily average energy demand for the experimental green roof had reduced from approximately 6-7.5 kWh/day to approximately 1-1.5 kWh/day. Whereas, the Reference roof did not display substantial changes.

Table 2.9.1: Average daily temperatures experienced during the 660-day study (after Liu and Baskaran, 2003)

Temperature greater than:	**Reference roof**		**Green Roof**		**Ambient Temperature**	
	No. of days	% of days	No. of days	% of days	No. of days	% of days
30˚C	342	52	18	3	63	10
40˚C	291	44	0	0	0	0
50˚C	219	33	0	0	0	0
60˚C	89	13	0	0	0	0
70˚C	2	0.3	0	0	0	0

Table 2. 9.2:Heat flow per unit area through the surfaces of the roofs during the 660-day study period (after Liu and Baskaran, 2003)

	Reference roof	**Green Roof**	**Reduction**
Heat gain	19.3 kWh/m^2	0.9 kWh/m^2	95%
Heat loss	44.1 kWh/m^2	32.8 kWh/m^2	26%
Total heat flow	63.4 kWh/m^2	33.7 kWh/m^2	47%

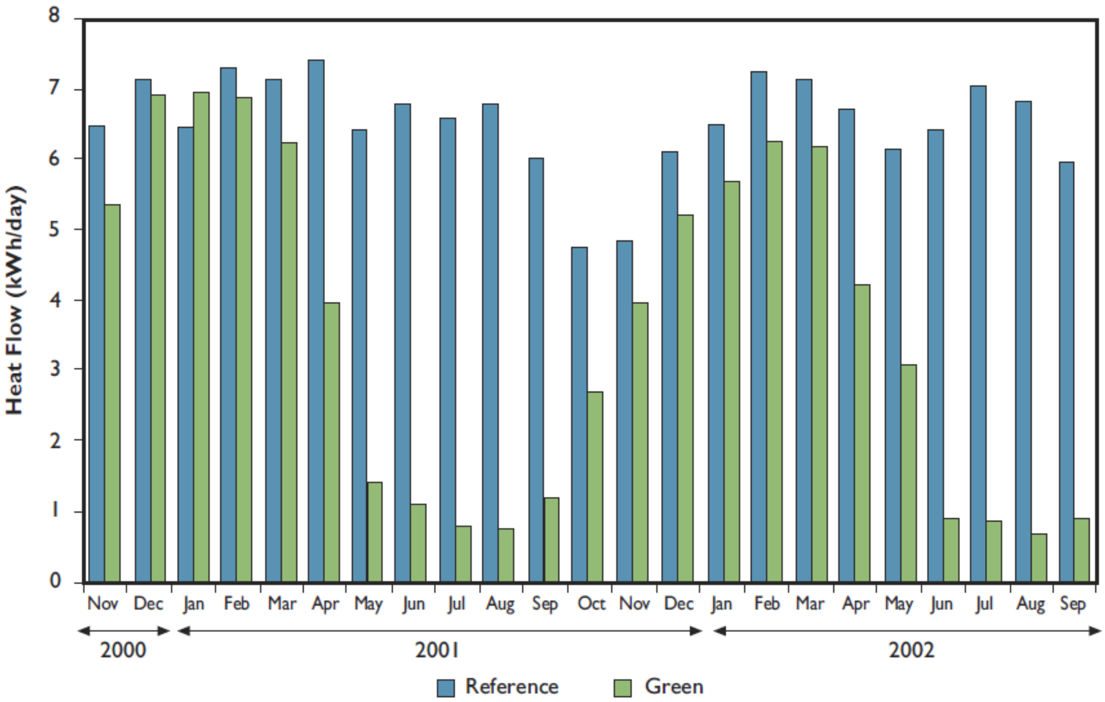


Figure 2.9.1: Comparison of the average heat flow through two roof types (after Liu and Baskaran, 2003)

Further studies conducted by Belarbi, et al. (2012), conclude that green roofs form an effective solution to the issue of thermal discomfort and the associated increase in cooling demands in buildings. The researchers had investigated air temperatures in three different countries (see *Table 2.9.3*). They had found that the total energy demand was smaller in a green roof in comparision to a conventional roof. Their findings support that of the Candian researchers.

Table 2. 9.3: Temperatures and demands from the respective roof types in three different cities (after Belarbi, et al. 2012)

City	**Mean indoor air temperature (˚C)**		**Maximum indoor air temperature (˚C)**		**Heating demand (kWh/m^2)**		**Cooling demand (kWh/m^2)**		**Total energy demand (kWh/m^2)**	
	1	2	1	2	1	2	1	2	1	2
Athens	33.9	31.3	35.4	32.7	*14.1*	*15.2*	*26.4*	*12.5*	40.5	*27.7*
La Rochelle	28.4	26.4	30.1	28	*36*	*36.1*	*2.5*	*0.1*	*38.5*	*36.2*
Stockholm	25.6	24.2	27.2	25.8	*131*	*120.3*	*0*	*0*	*131*	*120.3*
1-Conventional roof 2-Green roof										

These experiments have reached a general consensus that green roofs form a means of conserving energy in comparison to that of other roof types.

2.9.5 Green spaces and health

Due to the nature of urban areas, predominately central business districts, green roofs have become almost a sanctuary to individuals in these areas. It offers a place of tranquillity that aids in the improvement of physical and mental health. Research has shown that some individuals experience a reduction in stress when exposed to areas of natural greenery (Greenstone, et al., 2010).

2.9.6 Reducing building temperatures and the urban heat island effect

Research suggests that green roofs play a pivotal role in reducing the urban heat island effect. Bianchini and Hewage (2012), state that the urban heat island effect is an explanation as to why temperatures are higher in urban areas as compared to rural areas. Whereas Greenstone, et al. (2010), defines the urban heat island effect as the product of material and surfaces such as concrete, brick, stone and tar, found in and around a city, that absorbs and retains radiant heat from the sun and later releases it into the surrounding area. It is estimated that on average the temperature in an urban area is between 5˚to 15˚ degrees higher than that of a rural area. This comes as a result of the change in land cover from wide open spaces to tall buildings with the contributors noted above. *Figure 2.9.2* shows a graphical representation, that is not to scale, of the concept of the urban heat island effect. According to Gunnel (2009), if 8% of buildings within a city utilises green roofing, the resulting effect on the ambient temperature will be a reduction of 2˚C.

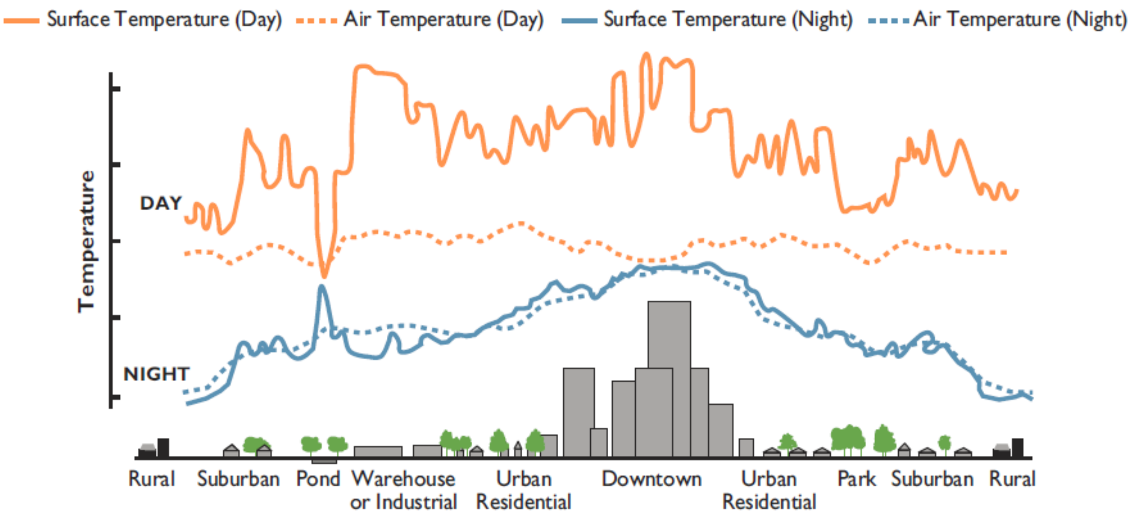


Figure 2.9.2: The urban heat island effect (Source: Greenstone, et al., 2010)

In addition, a study in New York city, that experiences a 2.5 °C annual average temperature between the urban and rural areas, concluded that the use of green roof systems lowered the city's surface urban air temperature, on average, by 0.4°C and 0.7°C at the highest temperatures respectively (Pearce & Semaan, 2016).

A study conducted during the eThekwini Municipality's Green Roof Pilot Project proved that through the utilisation of a green roof, effects imposed by air temperatures in a building can be reduced (see *Figure 2.9.3*). The study involved recording daily temperatures above a green roof and another on a conventional roof for a period of eight months. The results showed that the average temperatures on the green and on the conventional roof were that of 22˚C and 41˚C respectively. The average temperature difference between the two roof types was determined to be approximately 18˚C (Greenstone, et al., 2010).

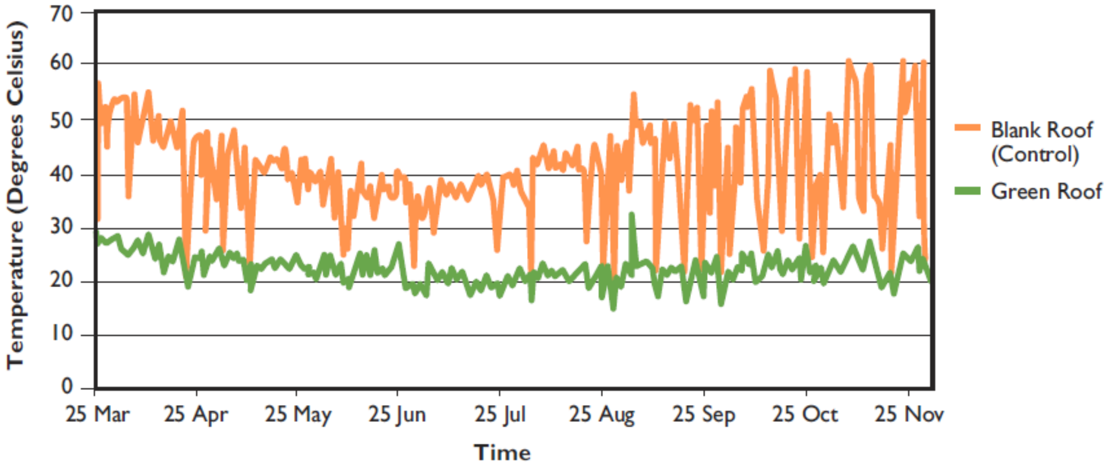


Figure 2.9.3: Temperatures recorded on the two roofs (Source: Greenstone, et al., 2010)

A study carried out in the City of Hong Kong, in an attempt to evaluate both the design and performance of a green roof system, involved an assessment of the thermal performance of a conventional roof versus that of a green roof. The study proved that green roofs have a much lower temperature during the day as opposed to that of a conventional roof (see *Figures 2.9.4-2.9.5*) (Hui, 2006).

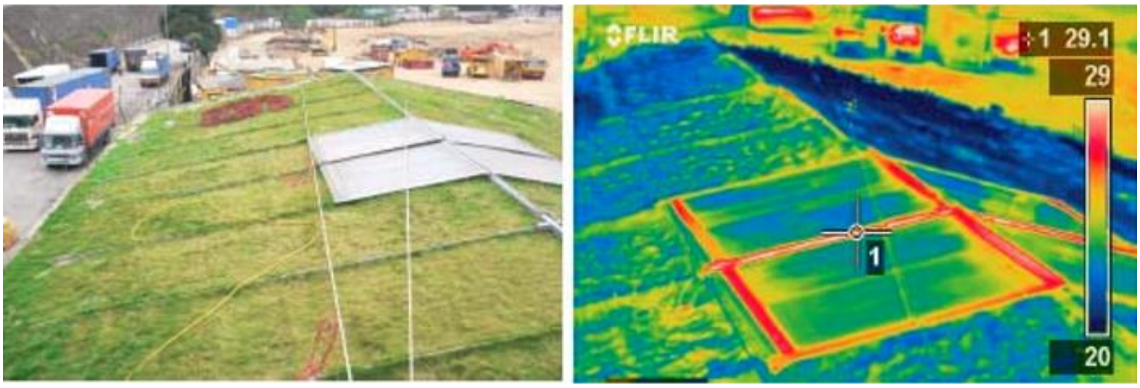


Figure 2.9.4: Thermograph of green roof system (Source: Hui, 2006)

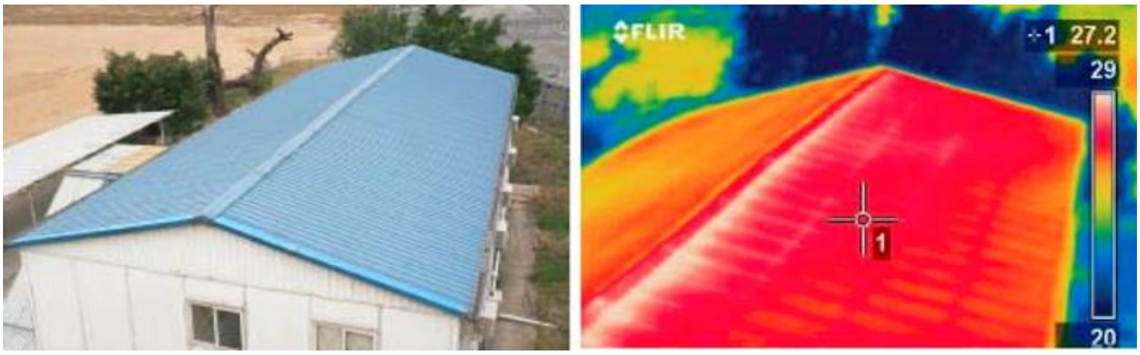


Figure 2.9.5: Thermograph of conventional roof (Source: Hui, 2006)

As a measure of consistency, temperatures for the study was measured in the non- air-conditioned attic in both buildings. Temperatures on the green roof were found to reach a maximum of 30˚C whereas, temperatures on the conventional roof fluctuated between 40˚C and a maximum recorded temperature of 60˚C (Hui, 2006).

Both studies support the idea that green roofs have the potential to reduce temperatures within buildings through a reduction in roof surface temperature. As a result, through the use of green roof systems, buildings possess the potential to become less energy intensive, as well as, the potential to further reduce their carbon footprint and contribution to GHG emissions.

2.9.7 Extension of roof life

Over time, the impact of ultraviolet (UV) light, high temperatures and exposure to the elements can negatively impact on the structural integrity and design life of a structure (Greenstone, et al., 2010). A life cycle assessment of alternate roof types conducted by European researchers (see *Table 2.9.4*) was investigated during the GRPP and it was found that the utilisation of green roofs can potentially double the design life of the supporting roof structure. This is due to the benefit of non-direct exposure to the factors that contribute to the deterioration of rooftops that green roofs offer.

Table 2. 9.4: Life cycle assessment of various roofs (after Greenstone, et al., 2010-based on data from 2003)

Roof type	Cost of construction (R/m^2)	Repair intervals (Years)	Renovation intervals (Years)	Renovation cost during design life(R/m^2)	Disposal cost (R/m^2)	Total (R/m^2)
Bitumen	320	10	15	1920	160	2560
Gravel	400	15	15-20	2000	200	2360
Green roof	680	-	Occasional	320	160	1480

It is evident that although green roofs carry a significantly higher initial cost, the costs of renovations result in the other two roof types becoming significantly higher. According to researchers Reed and Wilkinson (2009), green roofs are designed to a minimum design life of 50 years. This significantly improves the design life of conventional roof types, that are suggested to require replacement every 20 years (Greenstone, et al., 2010).

Costs associated with green roofs will vary per region and specification. With reference to *Table 2.9.4*, the total cost of the respective roofs makes the green roof the most economical. The total cost of the green roof amounts to R1480/m^2. This makes the green roof approximately 42% cheaper than the bitumen covered roof type and approximately

37% cheaper than the gravel roof type. However, this evaluates roof types at the assumed designed phase. For roofs that shall be retrofitted with green roofs the cost of the installation may potentially be offset in the long-term through a reduction in maintenance costs.

2.10 Green roofs and their ability to reduce storm water run-off

Through certain economic and social factors, a city begins to expand and as it does, so too does the quantity and magnitude of buildings and hence, rooftops. In addition, land usage for development of roads and other services expands. As a result, larger quantities of impermeable surfaces are created, which in turn leads to a greater run-off rate and this then impacts on the quality of water, state of the urban environment and is potentially the source of various other problems. It is expected that climate change will only serve to further intensify the amount and rate of run-off (Berndtsson, 2010).

Storm water is most substantial in urban or built-up areas where most surfaces are impermeable resulting in increased run-off from the surface. In times of extended rainfall or intense weather conditions, this can place a large strain on the existing storm water management network and could have negative consequences. Carter and Jackson (2007), state that storm water run-off attributed to urban land zones and other impervious surfaces are among the most detrimental to water receiving bodies. The authors further state that green roof systems are fast becoming one of the most sought-after storm water management practices in the United States of America.

Studies conducted during the eThekwini Municipality's GRPP (Greenstone, et al., 2010), proved that green roofs have the potential to reduce the amount and velocity of storm water run-off from a structure. Their system consisted of a basic system to measure the amount of rain collected in various collection chambers and a more complex system to measure the velocity of the storm water run-off (see *Figure 2.10.1*).

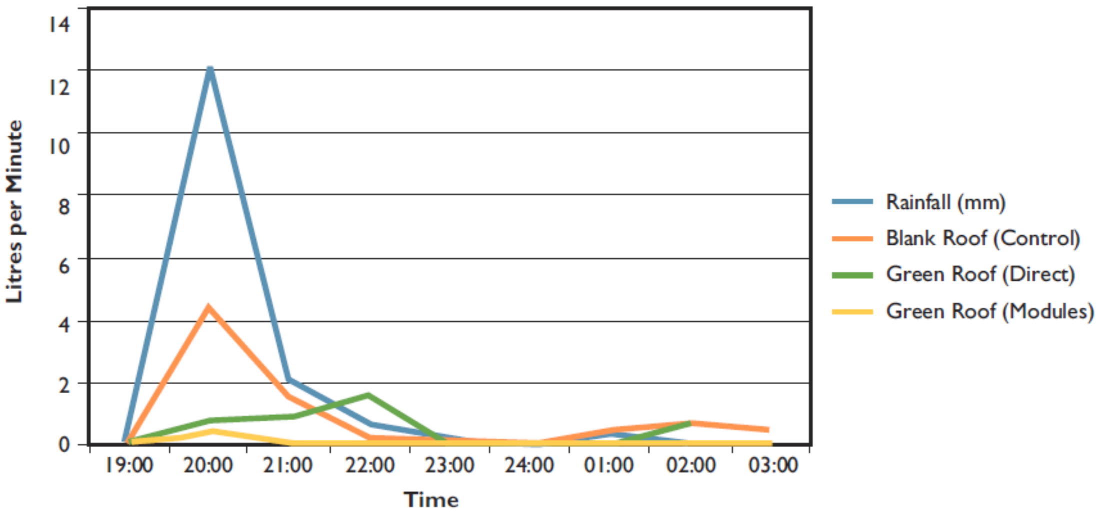


Figure 2.1.1: Comparison of rainfall run-off from a conventional roof and that of a green roof (Source: Greenstone, et al., 2010)

It is evident that from *Figure 2.10* green roofs have the potential to significantly reduce the peak rainfall run-off from a rooftop. This effectively reduces the amount of storm water discharging into the storm water management network over the short term and potentially reducing the risk of flooding. Hermy et al. (2006), corroborates this idea and further states that research conducted in Sweden, found that a storm water management network was improved when the Swedish researchers had disconnected impervious land cover zones from the network and introduced an open rainfall management system that comprised of ponds and green roof systems.

The GRPP study utilised eight plot areas of approximately 50 m^2 each. A maximum flow rate of twelve litres per minute was measured in terms of rainfall during the eight-hour long observation period. At this flow rate a run-off of approximately one litre per minute was measured from the direct green roof. However, this value had steadily increased to approximately two litres per minute as the study progressed. This can be attributed to the green roof absorbing water to the point of saturation and thereafter releasing excess water. Run-off from the modular green roof was measured at a flow rate of approximately half a litre per minute. In comparison, the conventional roof was observed as being the roof with the highest run-off measured at more than four litres per minute.

Greenstone, et al. (2010), state that studies conducted in Germany, who have implemented tariffs for storm water accumulation on impermeable surfaces, show that a green roof with soil 10cm in depth, can effectively reduce a structure's storm water run-off by as much as 50% annually. Reed and Wilkinson (2009), agree to this statement when the authors state that when utilising green roofs, the reduction in a structure's storm water volume is in the region of between 50%-85%.

This ability that green roofs possess can positively impact on the cost of future developments. The eThekwini Municipality by-laws require that all storm water run-off be attenuated on site in an attempt to ensure that post-development does not exceed pre-development storm water run-off levels. This reduction in storm water run-off can essentially lower costs of structures, as construction of attenuation tanks will not be required. *Table 2.10.1* highlights components and their corresponding factors that influence or contribute to the rate of storm water run-off.

Table 2. 10.1: Factors that influence the water retention and run-off characteristics of a green roof (after Greenstone, et. al.,2010)

Component	Factors
Green roof system	• Number of layers • Material type • Soil depth • Soil type • Vegetation type and cover • Geometry of roof structure i.e. pitch and length • Roof positioning i.e. Sun facing or shadowed • Age of roof structure
Weather	• Extent of dry period • Extent of wet period i.e. intensity and duration of rain • Season • Climatic conditions i.e. Wind conditions, air temperature, humidity

2.11 The types and characteristics of growth media available

The type and characteristics of growth media utilised in a green roof plays a pivot role in the success of the green roof. According to Greenstone, et al. (2010), the ideal medium in which to grow plants would be those that are lightweight, have good drainage characteristics and have the ability to retain adequate water without becoming waterlogged. Greenstone, et al. (2010), further states that international research shows that the use of lightweight material such as expanded clay, vermiculite, perlite or even volcanic rock, is most suitable for plant growth. In an attempt to reduce costs of a green roof project one can experiment with and produce a growing medium. As part of the research into the practicality of roof gardens in Durban, the eThekwini Municipality had investigated the attributes of various growth mediums to determine their respective properties and essentially determine the most suitable one (see *Figure 2.11.1*).

Figure 2.11.1: Mediums tested-vermiculite, potting mix, Berea red sand, compost, and perlite (Source: Greenstone, et al., 2010)

The mediums were sourced locally and ranged from organic to inorganic variants (see *Table 2.11.1*). In order to determine the loading capacity of the respective mediums, the mediums were weighed when dry and in a state of saturation and their values recorded.

Table 2. 11.1: Various growing mediums tested (after Greenstone, et al., 2010)

Medium	Dry weight per litre (g)	Saturated weight per litre (g)
Perlite	174	461
Vermiculate	178	596
Potting mix	337	749
Compost	264	760
Ash	786	878
LECA	784	930
Brick crushed	1200	1400
Berea red sand	1500	1800

Their findings and due to the high loading capacity determined, had resulted in the need for a specialised growing medium to be developed. As such, they had tested a combination of various mediums, these included:

- Combination 1: A combination which consisted of 60% compost, 20% vermiculite and further 20% perlite.
- Combination 2: A combination that contained 50% Berea red sand, 20% compost, 15% vermiculite and a further 15% perlite.

However, as a further test, the sole use of potting mix was utilised in a single area. Their findings showed that combination 1 and 2 resulted in positive, noticeable plant growth, whereas the potting mix had not yielded substantial growth. Of the two combinations, combination 2 was significantly heavier due to the weight of the Berea red sand and as a result had necessitated the use of a shallower soil depth. Seeing that plants tend to grow better in deeper soil, soil depth becomes a critical factor in the health of plants.

This highlights the fact that it is critical to determine the loading capacity of the proposed green roof site to avoid structural failure and implement an appropriate green roof system that will ensure successful plant growth. In addition, utilising combinations of growing mediums may result in a medium that is practical, cheaper and of greater benefit as opposed to using a singular medium.

2.12 Plant selection

One of the most important factors in green roof construction is plant selection. Plants will affect the ability of a roof to absorb carbon dioxide, other air pollutants, rainfall and attenuate storm water run-off. Conditions at the height of a roof top differs from that of the ground. As such, plants will be exposed to high temperatures, run the risk of having little to no water, may become highly saturated in periods of extended rainfall and some may fall in the shadows of taller buildings. Greenstone, et al. (2010), suggest that ideally, plants should have resistance to temperature, wind, drought and flooding. In addition, should be smaller in size, low growing and be able to grow from seed or vegetative methods, in the event of parent plants dying out. Selected plants should have the ability to fill up spaces to ensure that a green roof gives the perception of being complete. In an attempt to promote locally occurring biodiversity, plants should be indigenous and endemic. Greenstone, et al. (2010), further states that plants grown within 50km from the site of the proposed green roof i.e. those that are better suited to prevailing local conditions, have a higher chance of survival, will reduce the carbon footprint of the plants utilised and further promotes the genetic composition of locally occurring plant life.

2.13 Planting a green roof according to a theme

More often than none, green roofs are planted for a specific purpose or with the intention of that purpose being a by-product of the initial goal. As such, green roofs can be planted for a specific theme i.e. selecting plants types based on their properties for the purpose of producing a desired effect. A green roof system can contain one or more themes and the most common of these themes are as follows (Greenstone, et al., 2010).

2.13.1 Promoting insect life and attracting avian life

The aim of the theme of promoting insect life and attracting avian life is to increase the number of insect and bird life that can be seen or found within the green roof system. This is done by means of utilising plant life that creates refuge, is a source of food and can act as a nursery for insects and other organisms (Greenstone, et al., 2010).

2.13.2 Aesthetics

The main aim of the aesthetic theme is to create a green roof system that is appealing to the visual sense. This theme utilises plant life that varies in size, texture and colours (Greenstone, et al., 2010).

2.13.3 Water consciousness

The water consciousness theme aims to reduce the number of times a green roof system needs to be watered by introducing plant life that is tolerant to low water or borderline drought conditions. This theme is beneficial to roof tops that do not offer easy accessibility (Greenstone, et al., 2010).

2.13.4 Carbon sequestration

The aim of the carbon sequestration theme is to maximise the trapping or sequestration of carbon dioxide in the atmosphere, essentially reducing the contributions to GHGs and thus, further reduction to the contribution of climate change (Greenstone, et al., 2010).

2.13.5 Food security

The aim of the food security theme is to maximise the usage of the roof top and green roof system by utilising the green roof system as a medium to grow fruit and vegetables (Greenstone, et al., 2010).

2.14 Designing a roof garden

Much like any other project, arrogance or a lack of understanding can result in failure. When planning to develop a roof garden, one needs to consider three fundamental factors i.e. location, structure and vegetation. To further ensure that there is an understanding of the purpose of the green roof, consideration to what is required and what is to be expected must be given (Scholz-Barth & Weiler, 2009).

2.14.1 Location factors

- Climate-at a local and regional scale
- Volume of rainfall that is experienced within the area of the proposed site
- Exposure to natural elements such as sunlight, wind, snow, etc.

2.14.2 Structural factors

- Carrying capacity of the roof
- Roof pitch
- Shading from sunlight and rain through proximity to another structure
- Hot or cold air emissions from air conditioning units and/or other components
- Height and proximity of parapet walls
- Access to perform installation and maintenance safely
- Wind speeds

- Rainfall
- Existing drainage

2.14.3 Vegetation factors

- Substrate depth required by plants of choice
- Tolerance to drought
- Tolerance to shade
- Habitat or environmental concerns

2.15 Structural considerations

Supporting a green roof over a structure requires an effective structural support system. An effective structural support system is much easier to implement in structures that are yet to be designed. This is based on the fact that the design of a green roof can be taken into consideration in the preliminary design of the structure whereas, in existing structures an analysis of practicality must be performed prior to the construction of a green roof. Structurally, one must take into consideration the effects of dead loads, live loads and depending on the type of plants being planted on a green roof, wind loads upon the structure. Furthermore, all designs must meet the regulations proposed by local building codes and any relevant design codes. When considering a green roof system, the following are common load systems that one can expect (Scholz-Barth & Weiler, 2009):

2.15.1 Load effects

One of the main factors that forms an integral part of the determination of two of the most important considerations for green roofs, feasibility and cost, is additional loading (Kuhn & Peck, 2008). For structures in the design stage, additional loading imposed due to the implementation of a green roof can be taken into account with relative ease. However, for an existing structure, the additional loading has to fall within the, governing, carrying capacity of the roof.

2.15.1.1 Dead loads

In terms of dead loads, one must consider the self-weight of the elements being used in the green roof. In a direct green roof system, the self-weight of the elements ranging from the waterproofing layers to the plants being planted in the system have to be taken into account. Furthermore, depending on whether the direct green roof system is classified as extensive or intensive, the weight of the soil layer will differ due to the depth stipulated by each layer. In contrast, in a modular green roof system the self-weight of the modules, together with the plants and any materials utilised as protection for the roof, need to be taken into consideration (Scholz-Barth & Weiler, 2009). Gartner (2008), states that in order to account for future additions of growth mediums to the green roof system the specific depth should be increased by 15%. In addition, the researcher provides questions that aim to assist in the determination of Dead loads. These are:

1. What type of green roof system is to be designed i.e. direct or modular?
2. Is the green roof to be sloped?
3. What will be the depth of the green roof system?
4. What plant life is to be utilised in the green roof?
5. Will the green roof consist of trees or other taller plant life?
6. Will there be decorative pieces i.e. water features, boulders, etc.?
7. Will there be water storage or retention systems upon the roof?

2.15.1.2 Live loads

Live loads will vary depending on the accessibility of the roof upon which the green roof is to be situated. As such, in cases where a green roof is designed to be accessible to provide access to groups of people, the live load will be at a maximum. In cases where a green roof has been designed for access but only to provide maintenance, the live load will be at a minimum (Scholz-Barth & Weiler, 2009). According to Gartner (2008), live loads will depend and vary as per local codes and occupancy type. The researchers recommend that extensive green roof systems be designed for a minimum of approximately 60 Kg/m^2 and intensive green roof systems to a minimum of approximately 100 Kg/m^2 when considering live load reductions. In order to assist in determining Live Load, the following questions should be asked (Gartner, 2008):

1. Will the green roof be utilised by people or will it only be accessible during maintenance?
2. Will the green roof be accessible to vehicular traffic?

2.15.1.3 Wind loads

From a structural point of view, wind loading can be considered as negligible when acting on grass or low-lying plant life. However, it must be taken into account when green roofs contain trees and other taller plant life. With that said, Scholz-Barth and Weiler (2009), state that, to a structural engineer wind loading will not be the most critical case of consideration on a green roof.

2.15.1.4 Seismic Loads

With regard to seismic loads, Gartner, 2008, state that when considering seismic loading, the entire saturated dead load of a green roof system is to be considered as part of the seismic mass.

2.15.2 Effects of structural elements

Different structural elements influence the success or failure of a green roof project in different ways. The following chapter identifies various elements and their associated effects on green roofs.

2.15.2.1 Roof type

In accordance with traditional building definitions, a roof can be considered as either being flat or sloped. The benefits of each vary. For instance, a flat roof will retain much more rain or snow, as compared to a sloped roof which will create a greater run-off. The choice of roof slope is often one of personal choice, practicality and purpose of the structure. Sloped roofs may have more of an aesthetic appeal for some, whereas flat roofs prove to be more practical in long spanning systems. Both roof types are subjected to high temperatures at direct exposure. However, this proves more severe on flat roofs due to direct exposure to sunlight at all times. With that said, according to Scholz-Barth and Weiler (2009), constructing and maintaining a green roof system is generally easier on a flat roof or a roof that has a slight slope. This comes as a result of a green roof system not being subjected to the gravity and shear forces that one would expect to act on a green roof system constructed on a sloped roof. However, Greenstone, et al. (2010), adds that flat roofs also carry a disadvantage i.e. if a roof is too flat it allows for water to accumulate which can lead to root rot and further damage to the plant life. Greenstone, et al. (2010), does not deny that green roof systems can be constructed on sloped roofs but goes on to state that on a sloped roof the pitch becomes critical. In cases where the pitch is in excess of 10°, the substrate material is subjected to the forces of gravity and causes the material to slump or slip off completely. The researchers go on to state that ideally a green roof system should lie on a roof that has a pitch of between 3°-10°, if a sloped roof is to be utilised.

2.15.2.2 Decking or structural slab

When a green roof system is designed and installed upon a structure, the structure's roof is considered to be the floor that will serve as the primary support structure for the system.

As such, this surface upon which the green roof will be constructed, spanning the length of the beams or joists, is the deck of the green roof system. The deck of a green roof system can be comprised of a variety of different material and structural systems, ranging from plywood to metal or concrete. Scholz-Barth & Weiler (2009), suggest that of these materials, reinforced concrete is the most suitable for use in green roof systems due to the large load-bearing capacity it can withstand. Based on the fact that a structural concrete deck may be cast in place with reinforcement or poured over a metal deck and made to fill it, once a suitable choice is made upon the deck or slab surface, this choice will then lead to the choice of a suitable waterproofing system. However, each choice will impact on the suitability of a green roof system. Materials such as tile, slate or metal roofs make installation of a green roof system and the functionality of waterproofing difficult. Of particular concern is the use of metal whose properties cause the expansion and contraction of the material as per fluctuation in temperature. These movements of the material cause the membranes within the green roof system to undergo stress. In addition, because metal is a good conductor of heat, when it is heated by radiant energy from the sun, the heat is transferred into the green roof system and directly into the vegetation and growing mediums. However, the temperature fluctuation effect can be negated through the use of thermal insulation.

Ensuring that retention of water within a green roof system is at an optimal level, is key to the survival of a green roof. Plants cannot utilise water if it is drained faster than they can absorb it and as a result runs the risk of dying out. On the contrary, if a green roof system gains too much water, the growing mediums can be faced with anaerobic conditions that will result in the soil becoming toxic to the vegetation.

Scholz-Barth & Weiler (2009), state that in order for both the roof deck and green roof system to drain any excess water, the gradient of the roof deck should be that of 1%. For concrete decks that are cast in-situ, a gradient of 2% should be applied to take into account the sag of the concrete over time.

2.15.2.3 Waterproofing

The main purpose of the waterproofing layer is to ensure that water (be it from rain, snow, or condensation) in the green roof system is kept out of the structure below. As previously discussed the choice of waterproofing should be coordinated with the other components within the green roof system to ensure the survival and long-term performance of the green roof. If the waterproofing layer fails, consequently it could result in the collapse of the green roof system.

In accordance with the findings of Gartner (2008), the following questions are to be raised in order to assist in determining drainage and water proofing:

1. What type of drainage plan will be in place or required?
2. What type of water proofing is to be provided?
3. Will there be any leak detection systems in place?
4. What type of drainage plan will be in place or required?
5. What type of water proofing is to be provided?
6. Will there be any leak detection systems in place?

2.15.3 Serviceability considerations

2.15.3.1 Deflection

Deflection criteria for green roof systems are generally calculated in the same way that one would perform on a normal roof structure. However, with green roof systems there are other criteria that must be taken into account when determining the most accurate deflection criteria. For instance, if membranes utilised for waterproofing will be susceptible to damage from deflection and/or ponding (Gartner, 2008).

2.15.4 Structural misconceptions

According to Gartner (2008), when working with green roofs most structural engineers live with three common misconceptions or misunderstandings that lead to over-conservative assumptions. Modern green roof systems aim to implement sustainable practices and often utilise a combination of engineered soils with lightweight insulation and drainage layers. As such, the first misconception made by some structural engineers is to utilise full saturated weight of soil for the entire depth of the green roof system. As a result, it becomes an over-conservative assumption due to the fact that a green roof system does not comprise entirely of soil. The second of these misconceptions, is the assumption that a green roof system is a soil load, as these generally cover lateral earth pressures, as opposed to a dead load.

2.15.6 Load combinations

When analysing envelopes, a structure should be assessed under two conditions. Firstly, the structure with its conventional roof and secondly, the structure with the green roof system. The envelope analysis strategy allows for the determination of maximum and minimum moment and shear conditions.

According to Gartner (2008), the following structural checks are relevant to green roof systems and should be taken into account, when applicable:

1. Verification of irregularities in seismic mass for conditions of conventional roof and fully saturated roof conditions.
2. Structural elements supporting green roofs i.e. gravity beams, seismic drags/collectors and any other connections, must be evaluated for conditions of high bending in combination with axial loads.
3. Careful evaluation is needed for punching shear in concrete slabs.
4. Careful evaluation of plastic hinges that are expected in lateral systems.
5. Consideration to the sequencing of construction of the shear wall and bracing, in an attempt to prevent dead loading

2.16. Assessment of existing structures

A structural assessment can be defined as a process to determine the reliability of an existing structure to carry current or future loading. Typically, a structural assessment is carried out utilising limit state principles with characteristic values and partial safety factors. A structural assessment is typically performed when there is a change in resistance of the structural material. Changes in the material resistance arise in circumstances where there is evidence of corrosion, fatigue or other time-dependent processes or with a change in loading patterns. In addition, occurrences that result in structural damage such as those caused by accidental actions can further result in reduced material resistance. However, structural assessments can also be carried out in an attempt to analyse the current structural reliability of a structure or when there is a desired change in the design working life of a structure. Assessments vary in levels of sophistication and a graded assessment is recommended i.e. beginning with the conservative levels and thereafter moving on to the more refined upper levels. *Figure 2.16.1* is a graphical representation of the various assessment levels together with what each level encompasses (Hille, et al., 2006). Currently, there are codes that explicitly address the issue of structural assessment. One such code is the *"ISO 13822 – Bases for design of structures — Assessment of existing structures"*. The ISO 13822 code provides the general requirements and procedures that are to be utilised for the assessment of existing structures utilising the principle of structural reliability and considering specific problems on existing structures. In addition, the ISO 13822 code explains why current standards with regard to structural design are not sufficient for a reliability assessment of existing structures and for the design of the applicable repairs and upgrading (Holicky, 2010). Furthermore, Holicky (2010), states that present design codes do not provide procedures for the assessment of the current state and resistance of materials of existing structures. The ISO 13822 code further states that structures that are designed and constructed utilising earlier codes or those that have been designed and constructed utilising "good construction practice" with no codes applied may be considered safe to resist actions and may be considered serviceable for future use.

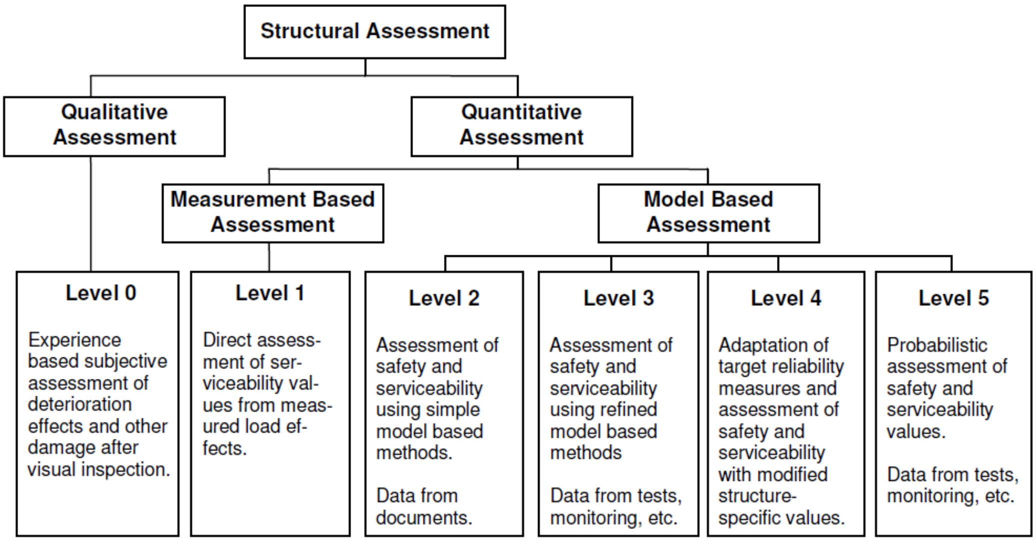


Figure 2.16.1: Various structural assessment levels (after Hille, et.al., 2006)

To conduct an assessment of an existing structure two main objectives are established i.e. the minimisation of costs and the assurance of structural safety.

2.16.1 Structural safety and serviceability:

The main aim of the structural safety and serviceability assessment is to ensure that the structure or parts thereof do not fail under loading. This form of assessment is carried out for ultimate limit states and are inclusive of (Hille, et al., 2006):

- Equilibrium loss of a structure or parts thereof
- The achievement of a structures resistance capacity
- The transformation of a structure or part thereof into a mechanism
- The instability of a structure of part thereof

A limitation of structural use may arise through a reduction of serviceability. It is based on this fact that serviceability assessments may prove to be necessary. Serviceability limit states are inclusive of (Hille, et al., 2006):

- A reduction in the working life of a structure through localised damaged
- Deformations that affect the efficient use of a structure
- Discomfort caused to people through excessive vibrations

2.16.2 Cost minimization:

Systems to manage single structures were developed in an attempt to minimise the overall cost through the optimisation of inspections, maintenance and repairs. The primary task of such processes is to assess the structural conditions in order to determine its current state and evaluate the future performance of a structure (Hille, et al., 2006).

2.16.3 Methods of structural analysis

2.16.3.1 Simple analysis methods

Simple structural analysis involves using basic conservative methods to calculate load effects through simple structural models. Typical simple analysis methods are inclusive of space frame analysis under a simple load distribution and linear elastic material behaviour, resulting in lower bound equilibrium solutions (Hille, et al., 2006).

2.16.3.2 Complex analysis methods

Complex analysis methods are utilised in instances where simple analysis methods fail. Complex methods are refined and include methods such as finite element analysis and non-linear methods such as yield line analysis, in an attempt to result in higher capacities. Complex methods model material behaviour such as shrinkage and creep of reinforced concrete structures and take into account interactions between components such as bondage and tension stiffening in reinforced concrete structure. This is done in an attempt to uncover hidden reserve capacities and reduce conservatism. In addition, to conduct a complete probability safety verification, stochastic finite elements can be utilised to model a structure. Stochastic finite elements take into account the spatial correlation of the applicable random variables (Hille, et al., 2006).

2.16.3.3 Adaptive models

Adaptive modelling automatically updates structural parameters utilising measured data such as changes in displacements, strains or damage values (e.g. crack width) to make new information about the structural behaviour during assessment available (e.g. long-term monitoring) (Hille, et al., 2006).

2.16.4 Reliability verification

Although structural analysis is utilised to obtain information with regard to the structural state, reliability verification is done to assess the actual evaluation of the safety and serviceability margin of an existing structure. Essentially, reliability verification describes the distance between the actual real state and the limit state of the structure. Approaches to reliability verification is graphically illustrated in *Figure 2.16.4.1* (Hille, et al., 2006).

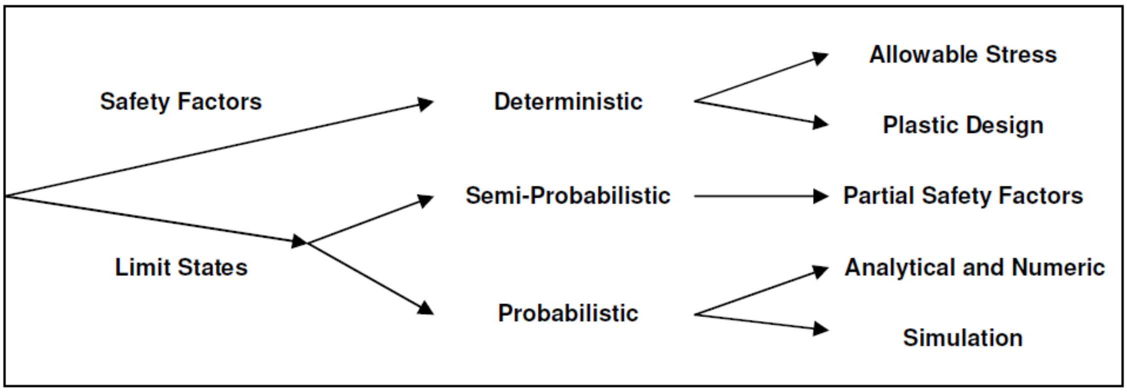


Figure 2.16.2: Reliability verification approaches (after Hille, et. al., 2006)

2.16.4.1 Deterministic verification with global safety factors:

The deterministic verification method is commonly referred to as the traditional way of defining safety. The method is based completely on experience and the safety measures are empirical. The most common deterministic safety measure is the global factor of safety. The global factor of safety is defined as the ratio between the resistance and the load effect. A typical method of deterministic verification is the concept of permissible stress. Another concept is that of the ‘load factor’. The load factor concept represents the ratio of the ultimate strength of a member to the working load. Deterministic methods of verification that contain only one global factor of safety contain considerable amounts of uncertainty and is therefore recommended to be utilised exceptionally within the assessment of existing structures (Hille, et al., 2006).

2.16.4.2 Partial safety factors:

The semi-probabilistic approach is based on the principle of limit state. The primary concern of the approach is to ensure that failure does not arise within a component of the existing structure of the structure itself, commonly described as Ultimate Limit State

(ULS). In addition, it is important to analyse the structural effects of applied loading that may arise in a serviceability failure, described as the Serviceability Limit State (SLS). As a result, partial safety factors are established as a safety measure to guard against variations in the design parameters that may arise on the resistance or load side (Hille, et al., 2006).

2.17. Layers on a typical green roof system

A green roof acts as a system composed from various layers. The following chapter highlights the typical layers in a green roof and its associated purposes.

2.17.1 Root barrier layer

The root barrier layer is the furthermost layer found in a green roof system and is the layer above a structure's roof. The purpose of this layer is to provide additional waterproofing to a structure's roof and to further protect it from possible root penetration from the above assembly. A root barrier layer is important due to the fact that as plant roots grow and strengthen, they push further into the soil in an attempt to seek out further water and nutrients. Given enough time, without the proper protection, a structure's roof can become susceptible to penetration, impacting on its structural integrity. Furthermore, asphalt-based materials utilised in green roofs require root barrier layers because roots can easily break down these organic based materials and utilise them as a source of food. In contrast, synthetic materials the likes of thermosetting EPDM and thermoplastic PVC offer resistance to root penetration and can further act as a waterproofing layer (Scholz-Barth & Weiler, 2009). Root barriers can be found in two forms i.e. a physical or chemical barrier. A physical root barrier generally comprises of a thin layer of low-density polyethylene or polyethylene material. Chemical barriers, involve the use of chemicals that inhibit root penetration such as those containing copper (Bianchini & Hewage, 2012).

In order to evaluate the suitability of root barrier layers an assessment based on the following performance characteristics should be considered:

- Density (Kg/m^3)
- Tensile strength (N/mm^2)
- Elongation to failure (%)

2.17.2 Drainage layers

The characteristics of green roofs make them capable of being water retaining structures. As such, Bianchini and Hewage (2012), suggest that it is of utmost importance to provide empty spaces between layers to allow free movement of excess water from the green roof system. The provision of empty spaces reduces the risk of potential leakage onto a structure’s roof. Taking into account the density of water, any extra water on a structure’s roof adds significant weight that could possibly impact on the structural integrity of a structure; it is therefore essential to ensure a proper drainage system is in place in order to remain within the carrying capacity of a structure’s roof. Having an effective drainage system further protects the root barrier from taking on excess water. Excess water encourages root growth and could potentially damage the root barrier layer and the roof structure. Drainage layers vary based on the green roof system, prevailing weather conditions and the assembly of a structure’s roof. Research conducted by Bianchini and Hewage (2012), state that materials such as polyethylene and polypropylene, that are both light and thin, are favoured for use in extensive green roof systems; whereas polymer based materials are preferred in other green roof systems due to the ease of transportation and installation, high strength, durability and low cost of production that they offer. In practice, the polymer material is generally bonded to either one or both sides of a geotextile material in order to prevent the migration of particles from the growing media which can essentially block drainage paths. Bianchini and Hewage (2012), further suggest that depending on the type of green roof system utilised, the thickness of the drainage material can vary from 1 cm to 1.5 cm. Intensive green roofs are designed such that they are able to carry higher loads as compared to that of an extensive green roof system. As such, the drainage material on an intensive green roof system can be thicker and heavier. The drainage layer itself is typically around 4 cm in thickness, as it comprises of the drainage material and natural filtration and drainage i.e. through the use of small pebbles or stones.

Green roof systems tend to absorb an amount of water that is sufficient enough to supply all the vegetation and still keep the soil layer moist. However, any amount of water over and above this limit could result in, as mentioned earlier, the depletion of oxygen and creation of anaerobic conditions in the green roof system. As such, this excess water must be diverted to drainage outlets (through- or subsurface) for release.

2.17.2.1 Stone aggregates

Stone aggregates such as crushed stone, gravel and river rock can be utilised for use in a drainage layer. To ensure consistent and reliable drainage, these materials need to be washed, cleaned and made free of fine particles. The washing and cleaning of stone aggregates are also carried out to prevent the fine material from entering and clogging the adjacent geotextile material. Furthermore, stone aggregate selected for use should stem from a parent material that is of sound strength and has good long-term properties. (Scholz-Barth & Weiler, 2009)

2.17.2.2 Lightweight aggregates

Lightweight aggregates the likes of balled or expanded clay, expanded shale or slate, along with other ceramic based products, are favoured for use in industry as an alternative to stone aggregates. This comes as a result of the attribute of being lightweight that the aggregates possess. Furthermore, the consistency in size that these aggregates offer, allow them to be graded and selected for specific purposes i.e. from that of a desired rate of compaction, to a flow rate through the selected aggregate. However, lightweight aggregates prove to be much more expensive when compared to stone aggregates. On a positive note, the excess cost can be offset against the cost of implementing a similar stone aggregate drainage system, as this would involve increased costs for strengthening a structure to carry the stone aggregate.

2.17.2.3 Synthetic and composite drainage products

In cases where load and depth factors become restricting, thin profiled products such drainage mats or panels are favoured as compared to several millimetres of aggregate. These drainage products further offer ease of installation, properties of being lightweight and the ability to perform functions such as water retention and aeration.

For green roof systems that have a shallow growing medium layer (extensive), drainage mats or panels may be adequate in providing drainage, provided that they fall within the minimum weight criterion that is needed to prevent uplift due to wind action (Scholz-Barth & Weiler, 2009). In addition, if drainage mats or panels are to be utilised they must be checked to ensure that they provide adequate retention capacity for a given system.

For green roof systems that are intensive by definition, drainage mats or panels should not be considered as being sufficient in providing adequate drainage but instead, should be seen as a component to supplement a drainage system. Depending on the composition of a green roof system, one can utilise drainage aggregates together with the drainage mats or panels, in order to achieve the desired drainage rate (Scholz-Barth & Weiler, 2009).

2.17.2.4 Drainage mats

Drainage mats can be utilised in both vertical and horizontal drainage applications. When used horizontally and in a thin profile, it proves to be most effective. Most drainage mats are manufactured with an attachment of some form of geotextile or filtration fabric. As such, the specification of each type varies and should be selected for use based on the green roof's system requirements.

2.17.2.5 Drainage panels

Much like drainage mats, drainage panels can be used in either vertical or horizontal applications. However, the intended application of the panels will determine the fabrication method of choice i.e. reservoirs being depressed or raised. Drainage panels retain water in reservoirs called "cups" and disperse excess volumes of water through openings in the "cones". When the reservoirs are depressed they serve to retain water until they can no longer do so causing the excess water to escape through the openings. Conversely, when the reservoirs are raised essentially, they can no longer function as reservoirs and the water begins to disperse through the openings.

2.17.2.6 Drains

Drains form an essential part of any green roof system. The main function of drains is to direct any excess water from the surface and that of the subsurface into the main stormwater system (Scholz-Barth & Weiler, 2009).

In order to evaluate the suitability of drainage an assessment based on the following performance characteristics should be considered:

- Water storage capacity (L/m^2)
- Filling volume (L/m^2)
- Flow rate (L/s/m^2)
- Weight (both dry and saturated) (Kg/m^2)
- Compressive strength (kN/m^2)

2.17.3 Aeration mats and panels

Aeration mats and panels are provided as a relief mechanism to the build-up of hydrostatic pressure within a green roof system and to further increase airflow in the soil. Commonly utilised types of aeration mats and panels are those of non-compressive panels, fibres or cones (Scholz-Barth & Weiler, 2009).

2.17.4 Moisture retention mats

Moisture retention mats are utilised to aid in the retention of both, moisture and nutrients. These mats serve as a slow release mechanism to the roots and vegetation of a green roof system. Generally, moisture retention mats vary as per manufacturer but are commonly composed of fibres of polypropylene that are stitched through a sheet of polyethylene. Moisture retention mats are additional layers and are not utilised all the time but when they are utilised these mats typically form an added layer below that of the drainage layer in a green roof system. Furthermore, in order for a retention mat to be suitable for use an assessment must be made based on the growing medium depth and type, together with the availability of irrigation and the drainage systems.

2.17.5 Filter layer

A filter layer is needed in a green roof system to prevent particles from the upper layers infiltrating into and blocking the drainage layer. Furthermore, the filter layer helps maintain the health and integrity of both the growing media and vegetation on a green roof system. In order to produce lightweight and thin filter layers, material such as polymeric fibres or polyolefins are utilised. Furthermore, to provide ease of installation, a filter layer is bonded to the drainage layer that will form part of a green roof system. Bianchini and Hewage (2012), state that due to the bondage of the two layers and essentially the filter layer becoming part of the drainage layer, little to no technical information exists on the specifications of thickness and weight of filter layers.

2.17.5.1 Filter fabrics

Filter fabrics are a geotextile material generally made from polypropylene fibres and exists in both woven and non-woven forms. These fabrics are commonly utilised as a source of soil stability and to promote drainage, whilst acting as a separator of the various layers within a green roof system. However, the main intended function of a filter fabric is to prevent the migration of fines from the growing medium into the drainage layer.

Filter fabrics boast properties of good puncture strength, permeability and tear resistance (Scholz-Barth & Weiler, 2009).

In order to evaluate the suitability of filter layers an assessment based on the following performance characteristics should be considered:

- Weight (kg/m^2)
- Tensile strength (kN/m^2)
- Flow rate under a hydraulic head of 10 cm ($L/s/m^2$)
- Effective pore size (m^2)
- Penetration force (N)

2.17.6 Water retention layer

A water retention layer, as the name suggests, is a layer that is provided with the aim of controlling and retaining runoff water in order to keep the growing media moist and supply the vegetation with water. The retention capacity of a green roof is dependent on factors such as, the type of green roof system, vegetation utilised, a structure's roof assembly, prevailing weather conditions and soil saturation limits. When dealing with extensive green roof systems it is important to note that these systems require a smaller water retaining capacity as opposed to intensive green roof systems. This comes as a result of the differences in depths of the growing media and vegetation layers. Intensive green roof systems can be found to have larger vegetation that require a larger quantity of nutrients for survival. When compared to other layers in a green roof system the water retention layer is a layer typically made from mineral wool or polymeric fibres and is installed above the filter layer. The factors mentioned above effect the thickness of the water retention layer and as such, effects the retention performance and saturated weight of the green roof system. The depth of a water retention layer can vary from 1 cm to 6.5 cm (Bianchini & Hewage, 2012).

In order to evaluate the suitability of water retention layers an assessment based on the following performance characteristics should be considered:

- Water storage capacity (L/m^2)
- Layer thickness (mm)
- Dry weight (kg/m^2)
- Tensile strength (kN/m^2)

- Durability

2.17.7 Growing media layer

The growing media layer forms the source of nutrients and water to sustain the vegetation within a green roof system. The characteristics of the layer provide spaces for root growth which strengthen and anchor the vegetation, making them capable of withstanding high wind forces and other severe weather conditions. The age and content of a growing medium is highly important, as it directly influences the performance of the green roof system.

According to Bianchini and Hewage (2012), limitations imposed to the carrying capacity of a structure’s roof have led manufacturers to resort to the development of green roof specific mediums. Typically, growing mediums are designed such that they provide a balance between performance and weight and therefore, contain a large amount of porous material with a smaller amount of organic content. The relationship shared between the vegetation type and the resultant growing medium layer thickness is directly proportional. Vegetation that are smaller is size, such as moss, require shallower depths in comparison to that of a shrub which would require a much larger depth for sufficient root anchorage. As such, a general growing medium layer can vary in thickness from 20 cm to 120 cm (Bianchini & Hewage, 2012).

2.18 Types of waterproofing

Waterproofing is arguably one of the most important layers in a green roof as it prevents water from damaging the roof of a structure. Waterproofing differs in complexity and functionality. The following chapter represents various types of waterproofing and their associated uses.

2.18.1 Built-up roofing

Built-up roofing is a type of waterproofing that involves the assembly of alternating layers of felts and molten bitumen to form a water proofing system. The felts, being made from fibrous material, provide reinforcement and integrity for the waterproofing system. The bitumen serves as a binder to hold the waterproofing membrane together and further acts as the primary resistance to water within the green roof system (Scholz-Barth & Weiler, 2009).

2.18.2 Single-ply

Single-ply waterproofing membranes are classified as such due to the fact that only one layer within the membrane provides the water proofing. The use of single-ply waterproofing membranes dates back to the 1970’s and involves the utilization of elastomeric or thermoplastic sheets that would be applied to a structure’s roof through a range of different methods (Scholz-Barth & Weiler, 2009).

2.18.3 Fluid-applied membranes

Fluid-applied waterproofing membranes is used in cases such as those with complex or unusual geometry. Compounds that are water-repellent such as asphalt emulsions, silicones and neoprene are applied to these structures through the use of specialised sprayers and/or rollers (Scholz-Barth & Weiler, 2009).

2.19 Polymers

Green roof systems enforce weight limitations on a structure’s roof. For this reason, the characteristics of being light weight and highly durable are essential to have in the type of material being used in a green roof system. For this reason, Bianchini and Hewage (2012), state that polymer materials such as polypropylene and polyethylene are suitable. The aim of providing light weight material is to ensure that installation onto existing structures is done with relative ease and to further avoid creating excessive costs.

The furthermost layers in a green roof system are subjected to high stresses as a result of the large loads from above. Therefore, material throughout the green roof system should possess resistance to high tensile stress and punctures, that polymer materials provide. Industry recognises polymers as a material that has many application and as many benefits such as: versatility, lightweight, highly durable, resistance to corrosion, insulation, cheap, and adaptability. In addition, polymers have become more environmentally friendly based on the recycling and reusing capabilities, making the material more attractive.

CHAPTER 3: METHODOLOGY

3.1 Introduction

Chapter 3 is a representation of the methodology utilised in order to conduct the various aspects of this thesis. This chapters serves as an explanatory chapter and elaborates on how various literature sources have been examined to present a literature review that is both, applicable to the topic at hand and further highlights areas that require additional research. This chapter further serves as a representation of the steps taken in order to conduct case studies that are deemed to be feasible and attempts to meet the aims and objectives set out initially.

3.2 Approaches to conducting research

Research can be conducted in various ways and often depends on the aim that the researcher is trying to achieve. For purposes of this thesis, three methods were assessed based on their potential contribution to the study.

3.2.1 Qualitative

Adopting a qualitative approach requires an assessment of various literature sources pertinent to the study at hand. This approach was utilised as part of a critical assessment of the research when formulating the literature review. In addition, a qualitative approach was utilised when undertaking the theoretical analysis for the respective components of the study i.e. the temperature, stormwater and structural analysis.

3.2.2 Quantitative

In a quantitative approach, mathematical and scientific principals are used as tools to investigate relationships and theories underpinned in literature. For purposes of this study, a quantitative approach was adopted to quantify raw data in an attempt to obtain a desired output.

3.2.3 Mixed approach

A mixed research approach essentially combines both the quantitative and qualitative research approaches in order to provide a more holistic approach to conducting research.

3.2.4 Selected approach

This thesis utilises a mixed research approach. This choice follows on from an evaluation of the respective approaches and the decision to try and achieve a comprehensive study.

3.3 Planning of the thesis

In order to attain direction and ensure that every applicable aspect of the study would be covered, a research proposal was developed. The proposal incorporated aspects such as the aims, objectives as well as the purpose of the study. These aspects form the baseline for the study and around which the research had been structured.

3.4 Literature review

The literature review represents a critical review of the various sources of literature utilised. Literature was sourced through various avenues ranging from electronic journal articles to hardcopy books. The research for the literature review focused around determining the potential of retrofitting existing structures with green roofs, assessing factors that influence the retrofitting potential and the associated implications. It further identifies the major issue of concern i.e. climate change and recognises green roofs as a suitable mitigation method. It assesses the effects of climate change at a national scale in South Africa and at a local scale in the City of Durban. The literature review also focuses on green roofs that have been implemented in South Africa as a means of supporting the argument for the utilisation of green roofs.

3.5 Structural Analysis

The structural analysis formed a critical aspect of the study and would therefore need to be assessed with a degree of thoroughness. Two methods were utilised as a means of complimenting the findings of each study as well as provide insight into aspects not evident in the other study.

3.5.1 Theoretical assessment

A theoretical assessment investigating various green roof studies in existence was carried out with the aim of identifying the possible structural considerations taken to ensure that the structures, whether taken into account during the design phase or being retrofitted, had the necessary requirements to sustain an additional load in the form of a green roof. In addition, the assessment of the publicised literature studies would aid in determining the most common type of structure or structural material identified as a potential green roof retrofit option, the reasons behind the choice of green roof system and the possible role that the age of a structure plays in the retrofitting capabilities.

3.5.2 Structural Designs

In order to obtain a greater understanding of the potential for retrofitting structures with green roofs, structural building plans were needed in order to calculate the structure's carrying capacity and to further assess, where applicable, the allowable additional loading capacity for a possible green roof design. Furthermore, structural checks would need to be carried out on the structure post-green roof installation to determine the implications of the additional load on each element within the building. However, based on various legal and confidentially agreements these plans could not be obtained. It was then decided to carry out the design of various building types with the associated respective based on typical structures and typical loading characteristics. The preliminary design of the structures was carried without the incorporation of an additional load allowance for future development. This was done in order to assess the properties of the various materials and structures to determine if the existing structure would be able to accommodate a green roof. In order to assess the effect that various structures and materials could potentially have on the ability to retrofit a green roof onto a structure, three different building materials i.e. steel, concrete and timber were investigated together with three different building uses i.e. industrial, commercial and residential.

The Flow chart depicted in *Figure 3.5.1* illustrates the basic process undertaken in order to conduct the design of the various structures. Further detailed processes are highlighted in the respective building categories that follow.

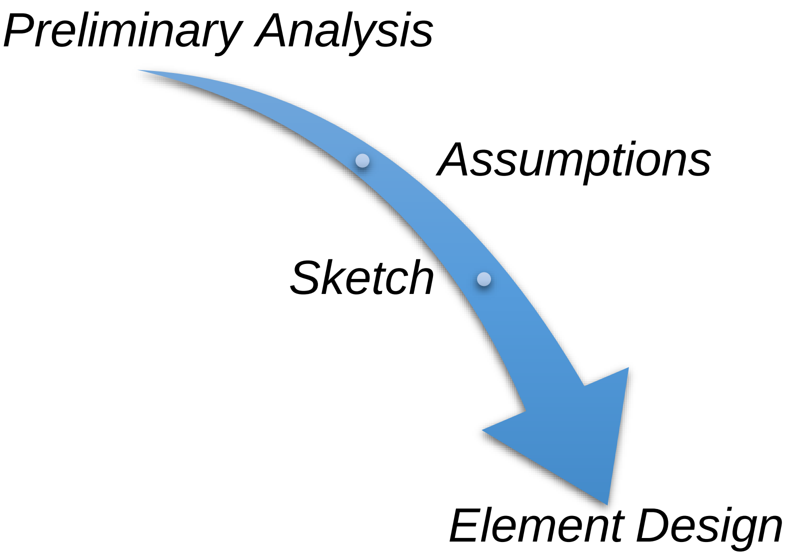


Figure 3.5.1: Flow chart utilised for the design process

Preliminary Analysis. The preliminary analysis involves the identification of the potential location for the respective structures, assessing the structure in terms of feasibility and its intended use and thereafter, determining the building dimensions and further requirements.

Assumptions. The assumptions involve determining the necessary assumptions that need to be made prior to carrying out the design of the structure in terms of section sizes, loading and other respective categories. Subsequently, this lead to various iterations and the determination of the optimal elements for the respective load.

Sketch. A sketch was done in order to provide a visual aid prior to conducting the design of the structure. The sketch would aid in the determination of the behaviour of the structure under the influence of the applied loading.

Element design. The design of the various elements in the respective structures would be carried out at the final stage of the process. This comes as a result of the outcomes of the preceding stages.

3.5.2.1 Industrial building

Preliminary Analysis

- Practically, the industrial building should be similar to those found in other industrial parks.
- It was decided that the primary construction material would be steel.
- The structure would be duo-pitched, supported by internal steel frames.
- The structure would be covered with cladding and roof sheeting.

Assumptions

- The building would be 40 m long by 20 m wide
- The height to the eaves would be 5 m
- The roof would be duo pitched at a pitch of 14°
- Located within the River Horse Valley industrial park
- Frames would be spaced 5 m centre to centre
- An allowance of 1 kN/m would be provided for connections within the dead load
- Klip-Loc 406 roof sheeting to be utilised
- Purlins were initially assumed as 100 x 50 x 20 x 2.5 Channel Sections
- Purlins were assumed to be 1.4 m centre to centre spacing
- Beams were initially assumed as 203 x133 x 30 I-Beams
- Columns were initially assumed as 203 x 203x 60 H-columns

Element Design

- The first stage of the design process involved the determination of the wind loading acting on the structure.
- Following on from the wind loading, the design of the purlins and sag bars were carried out.
- Thereafter, the total loading acting on the structure, taking into account dead, live and wind loads, had been determined and a frame analysis carried out.
- The frame analysis produced the maximum bending moments, shear and axial forces to which the structural elements were design to sustain.
- The final stages of the design involved the design of the remaining structural elements such as the beams, columns, etc.

Figure 3.5.2: Procedure for the industrial building design

The information presented in *Figure 3.5.2* forms a summary of the design of the industrial building. The information provided in the subsequent paragraphs highlights how various aspects of the design was conducted. Due to the variety that exists in terms of size of industrial buildings, a building size of 40 m in length and 20 m in width was assumed.

The primary choice of construction material was chosen to be structural steel based on typical structures.

It was assumed that the structural steel frames would be spaced at a distance of 5 m center to center. The structure was assumed to be duo-pitched and the pitch of the roof was assumed to be 15°. The height to the eaves rafter was assumed to be 5m and as a result considering the pitch of the roof and the distance to the pinnacle of the structure, the total height of the structure was calculated to be 7.5 m.

Once the structure had been dimensioned, wind loading was carried out in accordance with the SANS 10160-3 code of practice. In order to determine the peak-wind pressure the air density for the respective building was needed. Due to the fact that this was a hypothetical situation it was assumed that the building would be situated in the same industrial park as those buildings depicted in *Figure 3.2.1*. As a result, an altitude of 30 m above mean sea level was utilised for the determination of the peak wind pressure. In order to determine the critical wind direction, wind loading was calculated for wind at both the 0° and 90° directions. After carrying out the necessary calculations, the most onerous case of wind loading had been utilised for the design of the building. Cpe,10 factors, those specified as design of small elements, was utilised in determining the external pressure coefficients.

Following the wind loading calculation, it was assumed that the building will be clad in Klip-Loc 406 roof sheeting. Through further research it was decided to utilise aluminium roof sheeting that was specified as being 5 mm thick with a maximum allowable purlin spacing of 1.5 m. As such, a 1.4 m centre to centre spacing was assumed to be appropriate for the design. The sheeting would be carried by the purlins in the roof structure. The purlins were assumed to be 100x50x20x2.5 channel sections and the necessary calculations and checks were carried out to determine the adequacy of the section.

Following the purlin design, a frame analysis was carried out to determine the maximum bending moment, shear forces and reactions at the supports. The supports were assumed to be fixed as it offers greater stability. However, as a result, moments will be induced at the base of the support and the moment will be dissipated into the foundations essentially requiring a deeper section size. For the frame analysis, the beam and column sizes were assumed and the respective self-weights were included in the total dead load acting upon the frame. Together with the dead load, a live load was applied to the structure. The imposed live load was assumed to be applied for maintenance purposes only and hence, a load of 0.25 kN/m^2 was utilised in accordance with the SANS 10160-2 code of practice.

Following on from the determination of the various loading acting upon the structure, the frame analysis was conducted for three cases:

1. 1.2 x Dead Load + 1.6 x Live Load
2. 0.9 x Dead Load + 1.3 x Wind Load
3. 1.35 x Dead Load + 1.0 x Live Load

These load cases were assessed and the results of the most onerous case utilised for the element design within the structure.

Utilising the maximum moments and shear forces, the assumed section size for the support beams of the structure were checked in bending, shear and deflection. This was undertaken in order to determine if the section was adequate and was the most economical section that could be utilised for the structure.

Utilising the maximum moments and the maximum axial force, the assumed column section was checked in combined bending and compression.

In order to determine the carrying capacity and the applicable weight of a green roof that potentially could be installed, the structural elements were checked to the point where any further additional loading would cause failure to one of the elements of the structure. The difference in the loading applied to the structure and that which could be applied such that the structure is loaded to capacity, was found to be the design load for the green roof structure. The loading was converted to a square meter load to facilitate easier calculations.

3.5.2.2 Commercial Building

Preliminary Analysis

- Practically, the commercial building should be similar to those found in other office parks.
- It was decided that the primary construction material would be concrete.
- The building would be enclosed with glass.

Assumptions

- Two floors.
- Square in plan with a flat roof and rectangular in elevation.
- Total height of building equal to 10 m.
- Columns are spaced 5 m apart in either direction of the building.
- Wind loading would be resisted by the entire structure and therefore, no shear walls or lift shafts would be required. For this reason, columns would be analysed as unbraced in both directions. Lateral stability would be provided by the frame of the structure and therefore the structure would not be braced through the use of shear walls or lift shafts.
- Slabs were initially assumed to be 200 mm thick.
- Columns were initially assumed to be 350 mm x 300 mm.
- Beams were initially assumed to be 600 mm x 300 mm.
- A 50 mm screed layer would be applied to the slabs as a finish.

Element Design

- The first stage of the design process involved the determination of the wind loading acting on the structure.
- A frame analysis was conducted on the entire structure utilizing the wind loading only.
- A sub-frame analysis was conducted utilizing the ultimate loading i.e. the dead and live loads.
- Following on from the frame analysis, the design of the slabs was carried out.
- The support beams were then designed followed by the design of the columns.

Figure 3.5.3: Procedure for the commercial building design

The information presented in *Figure 3.5.3* forms a summary of the design of the commercial building. The information provided in the subsequent paragraphs highlights how various aspects of the design was carried out. The commercial building designed was assumed to have two floors and rectangular in plan. In terms of building dimensions, the building was assumed to be 20 m long, 20 m wide and 10 m in height. The roof of the structure was assumed to be flat. The structure, being a hypothetical design was assumed to be located in the same office park as those buildings illustrated in *Figure 3.3.1*. This assumption was made in order to determine the altitude above mean sea level of the site that was needed to determine the peak wind pressure. As a result, an altitude of 170 m above mean sea level was utilised for calculation purposes.

Wind loading was carried out in accordance with SANS 10160-3 code of practice and was calculated for wind at both the 0° and 90° directions in order to determine the most critical loading case. However, due to the geometry of the structure, the wind loading in either direction would produce the same results. After carrying out the necessary calculations, the results of the most onerous case of wind loading had been utilised for the design of the building. Cpe,10 factors, those identified for element design, was utilised to determine the external pressure coefficients.

As previously mentioned, the primary construction material was decided to be reinforced concrete, conforming to the typical commercial building. The structure consists primarily of three reinforced concrete elements i.e. beams, columns, and slabs. The design process had begun by assuming the section sizes for the various elements. The beams were assumed to be 600 mm x 300 mm rectangular beams. The columns were assumed to be rectangular in plan with dimensions of 350 mm x 300 mm. The floor slabs were assumed to be 200 mm thick.

Utilising this information, the self-weights of the respective elements were calculated which would form the composition of the total dead load acting on the structure. The structure utilised two different live load factors. An imposed load of 2.5 kN/m^2, obtained from the SANS 10160-2 code of practice, was utilised for the first-floor slab, applied for office areas. The roof of the structure was assumed to be inaccessible and would therefore only require an applied imposed live load of 0.25 kN/m^2 for maintenance purposes.

To determine the design moments and forces, two analyses were conducted. The first, a complete frame analysis utilised the design wind loading acting upon the structure, as it was assumed that the frame provides lateral stability to the structure. The second, a sub-frame analysis was used to assess the ultimate loading on the structure. The results of the analyses from the two separate cases were added together to achieve the ultimate design moments and forces.

The ultimate loading for the structure was assessed utilising the following load cases and the most onerous case utilised for the element design:

1. 1.2 x Dead Load + 1.6 x Live Load
2. 1.35 x Dead Load + 1.0 x Live Load

The sub-frame analysis for the ultimate loading case was done using three separate loading cases in order to determine a bending moment envelope that would yield the maximum design bending moments and the respective maximum design forces from each case.

Following the determination of the maximum design forces and moments, the slabs for the structure were designed. The slabs were designed as two-way spanning elements, supported by the concrete beams. The slabs were designed in accordance with the SANS 10100-1 code of practice.

Following the design of the slabs, the design of the beams was carried out. The beams were designed to carry the self-weight of the slabs and that of itself. Utilising the maximum moment derived from the bending moment envelope, the assumed beam section size was checked in bending, shear and deflection. For each case the aim was to carry out the applicable checks in accordance with the SANS 10100-1 code of practice to ensure that the section was adequate and if it were the most feasible section size utilised.

The final structural element of design was the columns. The columns were designed such that it would be able to support the superstructure composed of the beams and slabs. The assumed column section size was checked in two directions, in accordance with the SANS 10100-1 code of practice to ensure that the section was indeed adequate to carry the design moment and axial force.

Following the structural design, the carrying capacity of the structure was determined in order to establish the additional weight that the structure could carry. The carrying capacity of a structure was calculated by increasing the ultimate load to the first point of failure amongst the structural elements. The difference between the current loading patterns and the increased loading pattern was utilised as the design weight of the green roof structure. Subsequently, the effects of the additional loading, was checked throughout the structure in order to provide certainty that all structural elements were still capable of carrying the additional loading.

3.5.2.3 Low-cost housing

Preliminary Analysis

- Practically, the design of the low-cost house should be similar to those found in other low-cost housing developments.
- It was decided that the primary construction material for the roof structure would be timber.
- The structure would be duo-pitched, supported by internal timber trusses.
- The rest of the structure would be constructed with brickwork.

Assumptions

- The structure would be 7.3 m long and 7.1 m wide
- The structure would be located in the Waterloo region as illustrated in Figure 3.4.3
- Roof overhang would be 400 mm on either side
- Grade 5 SA Pine Timber
- Truss member sizes were 38 mm wide by 76 mm deep
- Cement roof tiles
- Roof battens would be 38 mm by 38 mm spaced at 345 mm centre to centre
- Roof trusses would be spaced at 900 mm centre to centre
- Timber material density was assumed to be 5 kN/m^3

Element Design

- The first stage of the design process involved the determination of the wind loading acting on the structure.
- Following on from the wind loading, the design of the roof battens was carried out.
- Thereafter, the total loading acting on the roof structure, taking into account dead, live and wind loads, had been determined and a truss analysis carried out.
- The truss analysis determined the member forces within the truss which then allowed for the determination of the allowable stresses and deflections of the members and the truss in its entirety.
- Thereafter, the carrying capacity of the structure was determined.

Figure 3.5.4: Flow chart depicting the low-cost housing design

The information presented in *Figure 3.5.4* forms a summary of the design of the low-cost house. The information provided in the subsequent paragraphs highlights how various aspects of the design was carried out. Research was conducted into the typical structure for a low-cost house. Various low-cost housing projects around South Africa were looked at to obtained a general consensus. In addition, the websites of various companies constructing low-cost housing were looked into. Once the typical structure was obtained, a sketch was done in order to aid in visual presentation. Assumptions were made with regard to the overhang of the roof structure as well as to the span of the internal roof trusses in accordance with the design specifications of the typical low-cost housing roof truss manufacturers.

In terms of dimensions of the structure, the structure was assumed to be 7.3 m long and 7.1 m wide following on from the typical low-cost housing plan as illustrated in *Figure 4.4.2.*

Wind loading for the structure was done in accordance with the SANS 10160-3 code of practice. The assumption of the building location provided the elevation of the structure above mean sea level. The elevation had been a key parameter in determining the peak wind pressure for the region. Following on from the peak wind pressure determination, the internal and external pressure coefficients were calculated. In order to account for the maximum wind load acting on a respective part of the structure, the external pressure coefficient corresponding to the largest area of the zone under consideration was utilised. This coefficient was then utilised to find the net pressure acting on the respective zone which was later multiplied by the peak wind pressure to determine the wind load acting on the structure.

It was assumed that the roof structure will contain Grade 5 SA Pine timber trusses at a span of 900 mm. The roof tiles and sheeting would be supported by Grade 5 SA Pine timber battens spaced at 345 mm centres. In terms of loading acting upon the structure it was assumed that the live loading would be based on an allowance for maintenance purposes hence, an imposed load of 0.25 kN/m^2 was utilised in accordance with the SANS 10160-2 code of practice. It was assumed that the roof tiles to be used would be those made from cement with a density of 23 Kg/m$^{3.}$

The roof structure was assumed to contain roof battens that would carry the weight of the roof tiles and roof trusses that would be designed to carry the weight of the resultant superstructure.

In order to determine the member forces acting in the truss the dead and live loads were determined and applied as a uniformly distributed load. The loading was factored in accordance with the SANS code of practice utilising the following load cases and the most onerous results utilised:

1. 1.2 x Dead Load + 1.6 x Live Load
2. 0.9 x Dead Load + 1.3 x Wind Load
3. 1.35 x Dead Load + 1.0 x Live Load

The uniformly distributed load was then converted into point loads acting at the joints and the analysis of the truss performed, utilising the method of joints to determine the member forces. To account for the moments that may arise in members of the truss structure, the individual members were designed to incorporate the loading from the truss analysis together with uniformly distributed load.

The carrying capacity of the structure was determined utilised the same method implored in the preceding designs. The ultimate load of the structure was increased to the initial point of failure from a structural element within the structure. The nett result of the increased loading that ultimate loading produced the design green roof load.

3.6 Temperature Analysis

To assess the ability of green roof systems to reduce the temperature within the structure it has been placed on, investigations were carried out on published studies in literature together from an experimental basis.

3.6.1 Theoretical assessment

A critical assessment of the various studies found in literature was performed with the aim of determining the temperature reduction performance of green roofs. The assessment would help identify the potential issues faced by researchers and provide an unbiased account of the temperature reduction performance of green roof systems. In addition, the theoretical assessment will be utilised to further strengthen the findings of the experimental assessment undertaken or vice versa to present a holistic assessment.

3.6.2 Experimental assessment

Due to the various implications associated with the construction of actual roof models it was deemed impractical and as a result, a simulation of how various roof types would affect the temperature experienced in a building's substructure was carried out. The purpose of the simulation had been to identify if, in accordance with literature, green roofs do possess the potential to significantly reduce substructure temperature in comparison with other roof types.

The experiment investigated the following roof types:

- Green roofs
- Concrete roofs
- Tiled roofs

The green and concrete roof types were created in containers, whilst the tiled roof had involved the use of a roof tile placed upon a container. For the concrete roof model, concrete was cast in the container and set aside to cure. The green roof model was built utilising potting soil and a variety of seedlings. The potting soil was cast into the container and the seedlings were planted in an assortment of positions to ensure that the model would be completely covered by the vegetation. A digital thermometer was utilised to record temperatures above and below the models. It was assumed that the digital thermometer would yield greater accuracy in the temperature readings. To measure the heat below the roof models, the models were elevated on a hollow cement brick and the digital thermometer placed on the inside of the brick. The models were placed such that they model would cover the brick and therefore, the heating and cooling effect of the substructure would be influenced by the model i.e. the model would take the direct radiant energy from the sunlight and further shade the brick and thermometer and in theory, should result in a noticeable temperature difference. To measure the temperature above the roof models, a thermometer was placed on the surface of the respective models to record the effects of the ambient air temperature and the potential influence of radiant heat from that of the respective roof material (see *Figures 3.6.1-3.6.3*).

The experiment was conducted outside to maximise the effects of temperature change as conducting the experiment indoors would be influenced by the rate of cooling and heating of the respective structure. However, placing the models outside would also introduce influences from air flow and further material absorption factors but it was decided to continue with this placement to simulate what would be assumed, as the natural environment of a roof structure. The roof models were placed alongside each other to reduce the margin of error that may appear as a result of change in location. Utilising the same containers allowed for models of the same size to be created. This would further reduce any potential error as heating and cooling would occur on the same surface area. The temperature of the various roof models was recorded in hourly intervals for changes in the ambient air temperature to be noticeable.

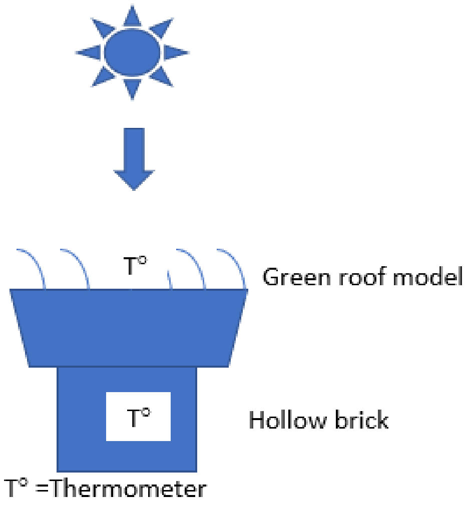


Figure 3.6.1: Illustration of green roof temperature simulation model

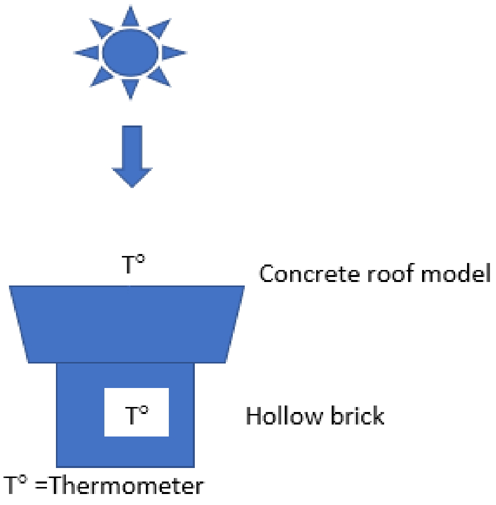


Figure 3.6.2: Illustration of concrete roof temperature simulation model

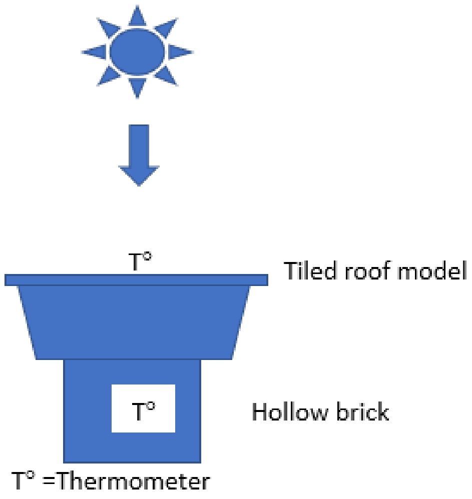


Figure 3.6.3: Illustration of green roof temperature simulation model

3.7 Stormwater Run-off Analysis

An assessment of the stormwater reduction capabilities of green roofs was carried out utilising studies found in literature and through experimentation to determine the extent to which green roof reduce stormwater runoff and in the process either proving or disproving the theory surrounding stormwater reduction from green roofs.

3.7.1 Theoretical assessment

An assessment of studies publicised in literature with regard to the potential reduction of storm water runoff from a structure through the utilisation of a green roof was assessed on the basis of providing a critical, unbiased evaluation of the subject. The existing studies will highlight common concerns and results between studies and will further add to the findings of the experimental assessment performed, essentially presenting an expansive assessment of the subject matter.

3.7.2 Experimental assessment

The various roof models were utilised to assess the run-off characteristics of each roof type. The aim of this simulation was to identify if green roofs do possess a lower storm water run-off rate in accordance with the theory underpinned in literature and if so, assess the difference in run-off rate amongst the roof types.

In order to simulate rainfall, a polystyrene container had been modified by punching holes through its base in an attempt to reduce the concentration of the water falling onto the roof models and create a more natural rainfall effect. In order to provide a measure of consistency and provide a more accurate comparison it was decided to utilise the same volume of water per simulation. As a result, it was assumed that a litre of water would be sufficient per trial. This assumption was first tested on the green roof model taking into account the fact that the growing medium will retain a volume of the water until complete saturation of the medium is attained. Once the benchmark had been tested and proved sufficient, it was applied throughout. The various roof models were placed on a large tray that would serve as a simulated catchment area and allow for the volume of run-off to be quantified (see *Figures 3.7.1-3.7.3*-graphical representations of the individual model setup). Utilising a measuring jug, the volume of water was passed through the modified polystyrene container and onto the roof models. The volume of water not absorbed by the materials and that which had passed onto the tray was then measured as the run-off volume. The experiment was then repeated three times per roof model in order to determine an average run-off volume for the various roof models. The trials were not conducted consecutively as this would influence the amount of run-off, particularly in the green roof due to saturation of the medium. As a result, the trials were conducted days apart from the preceding trials to ensure that the models would become dry and the green roof model become unsaturated.

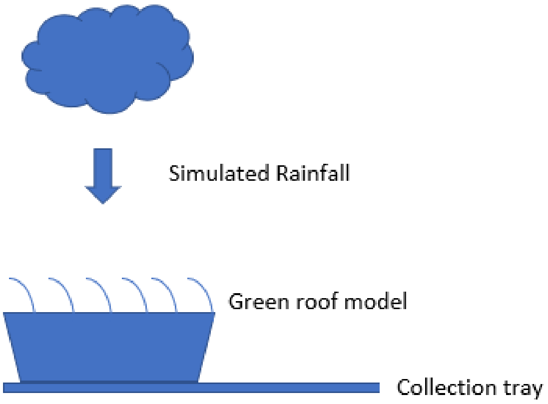


Figure 3.7.1: Illustration of green roof model stormwater runoff simulation

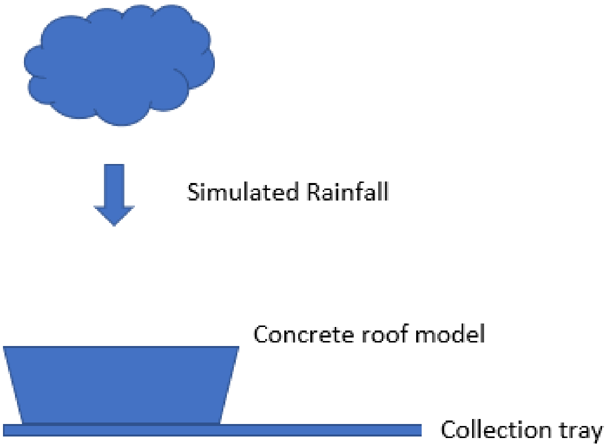


Figure 3.7.2: Illustration of concrete roof model stormwater runoff simulation

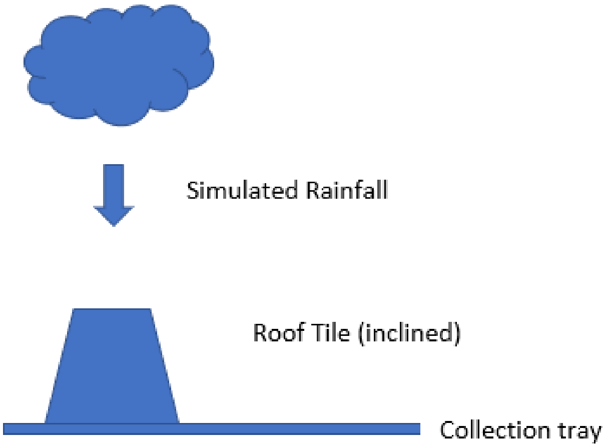


Figure 3.7.3: Illustration of tiled roof model stormwater runoff simulation

To test the run-off potential from a concrete roof, the model was cast with gaps between the container and the concrete to simulate drainage conduits i.e. gutters and downpipes that would typically transfer water from the rooftop to the drainage conduit at the base of the building. Theoretically, concrete will not allow water to pass through and if the model had been cast without any gaps it would result in pooling of water until the water had overflowed the container. This explains why water pools in some places on a roof after a rainfall event. However, not all water that falls upon the roof remains behind due to the camber on roof finishes for drainage. Subsequently, to determine the volume of run-off from a concrete roof, similar properties had to be incorporated into the concrete model.

To test the run-off potential from the tiled roof, the roof tile was angled to mimic that of a typical low-cost house. As such, based on gravity and the angle of the roof structure theoretically most of the water should run-off the structure. However, with build-up of particulate matter and the absorption from the tile material some water is expected to be retained by the tiled roof. It is based on these factors that each simulation had been tested on a dry tile.

The potential retention of storm water will be quantified in terms of the amount of carbon emissions that can be saved through a reduction in the utilisation of potable water that would have been used as hydration for the green roof. The difference between the average run-off volume of the green roof and that of the other roof models was utilised to determine the average volume of water retained that could be achieved if the green roof was utilised instead. The carbon emission savings are based on the emissions associated with the water treatment process from entry into the dam until entry into the distribution network. These highlight the emissions produced at each phase of the water treatment process which then allows for the total process to be added to determine the carbon emissions per kL for potable water. As such, the carbon emission factors for each process (see *Figure 3.7.4*) were added together and multiplied by the difference in average run-off from the roof models to determine the quantity of carbon emissions that are emitted and hence, the quantity that can be saved if a green roof is utilised upon the other roof type. This is further based on saturated volumes of the green roof that would be attained during a rainfall event and thereafter not require the use of potable water as a means to hydrate plant life and in addition, a reduced water volume going through the water treatment process.

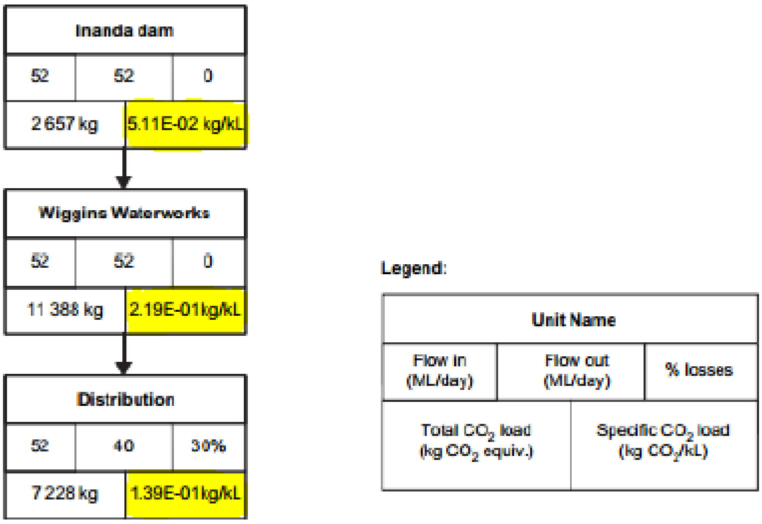


Figure 3.7.4: Carbon emission factors associated with the water treatment process (after Buckley, et al., 2009)

3.7.2.1 Rainfall data

In order to model the maximum potential carbon emission savings from a roof area in the City of Durban, rainfall data was required. The data was obtained from readings of a rain gauge set up at the City Engineers Complex (see *Figure 3.7.5*) which is located in the Central Business District of Durban. The readings of the rain gauge are uploaded to a website from which the data can be sorted into hourly, daily or monthly data. This experiment utilised average monthly rainfall data from the beginning of the year 2013 to the end of year 2015, in order to determine an average monthly rainfall data set.

Figure 3.7.5: Location of rain gauge station (Source: Google Earth, 2016)

In summary, the Chapter above represents detailed methodologies and experimental procedures utilised to obtain and quantify the data presented in Chapters 5 through 9. It aims to give the reader an understanding of the processes involved to promote understanding of the information presented further on in the thesis.

CHAPTER 4: LITERATURE REVIEW OF TYPICAL STRUCTURES UTILISED IN THIS STUDY

4.1 Introduction

This chapter presents the theoretical background to the types of structures utilised to perform an experimental structural analysis. Due to the fact that land use zones are primarily divided into three zones and therefore, allow for the classification of structures into residential, commercial or industrial properties, it was decided to conduct a case study on the various types of buildings and assess how each one would compare structurally in terms of retrofitting potential. The chapter comprises of hypothetical scenarios based on the typical structures together with representative loading conditions based on typical load types that can be expected. In terms of investigating residential properties the case study focuses on the potential of retrofitting low-cost housing with green roofs for the purpose of sustainable farming and further assesses how its utilisation will influence the quality of life of the affected individuals. This study was chosen to present a possible green engineering solution to the plight faced by those classified as being underprivileged in South Africa. The primary aim of each scenario was to assess the effects on a structure's carrying capacity and hence, the feasibility of a green roof installation, based on elements such as span, slab or material thickness, etc.

4.2 Industrial building

Industrial buildings are typically large spanning structures that are comprised of a series of structural steel frames covered by a cladding or sheeting type of material. Steel is often utilised as the material of choice due to the ease of construction, its material properties and the increased floor space that it offers. In order to determine the potential of retrofitting industrial buildings with green roofs, a typical building design similar to those evident in *Figure 4.2.1* was conducted. Typical loading that acts upon industrial structures are dead loads, live loads for maintenance purposes and given their size and height, wind loading. These structures are often long spanning and contain no internal columns or support structures.

Figure 4.2.1: Aerial view of a typical industrial park (Source: Google Earth, 2016)

4.3 Commercial buildings

Commercial buildings vary in size and shape. These buildings are often utilised as office spaces and incorporate those structures that do not form part of the residential and industrial sectors. Generally, commercial buildings utilise reinforced concrete as the primary construction material. These structures often vary from single floor structures to those that have multiple floors supported by an internal beam and column system. Typical loading types upon these structures include wind loading, dead loads, live loads and in certain cases, live loads applied to accessible rooftops. Typical commercial buildings are illustrated in the aerial view of an office park in *Figure 4.3.1*.

Figure 4.3.1: Aerial view of a typical commercial office park (Source: Google Earth, 2016)

4.4 Low-Cost Housing

Figure 4.4.1 shows results of previous census data collected with regard to poverty levels in South Africa at both, a National and Provincial level. According to Stats SA, of the total population of the province of KZN, 63% of people live in poverty (see *Figure 4.4.1*). In addition, although there has been a decrease since 2006, National poverty levels in 2009 were recorded at 56.8%. This highlights the fact that there is a need for measures that aim to empower the underprivileged and impoverished.

The national government states that as of the year 1994, 2.68 million state funded homes were built in South Africa as part of the reconstruction and development plan (RDP) (Moodley, 2014). Individuals whom qualify for low-cost housing are said to receive a total monthly income of less than R3500.

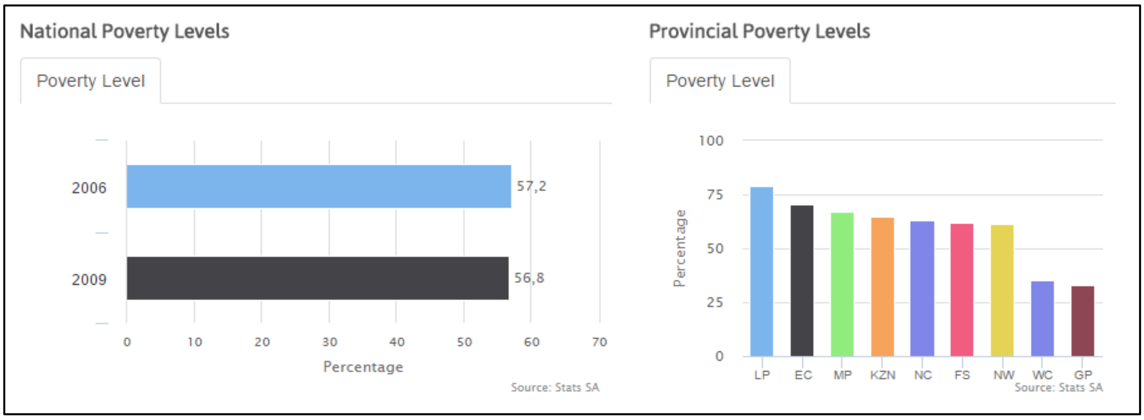


Figure 4.4.1: Poverty levels in South Africa (Source: Stats SA, 2000)

According to the National Housing Code of 2009, for government to provide housing that is up to standard it must provide a residence with a minimum floor space of 40 m^2 that can accommodate two bedrooms, a bathroom and a combined kitchen and living space (Settlements, 2009).

According to a case study conducted on the housing situation in South Africa by Gyproc Saint Gobain (2011), the typical plan for a low-cost house is as illustrated in *Figure 4.4.2*. However, low-cost housing can vary from single houses to blocks of flats.

The typical structure of a low-cost house comprises of brickwork walls and roof structures. The roof structure of a low-cost house is typically composed of timber trusses and battens, clay roof tiles and a water proof sealant. The majority of the force acting upon the roof structure is carried by the roof trusses and transferred through the wall structure and thereafter, dispersed into the foundations. The typical loading acting upon the structure involves dead loads, live loads and wind loads.

Generally, low-cost housing developments are situated on graded plots of land without any further development, resulting in the area around the house being compacted earth without significant vegetation cover. In addition, due to the large number of low-cost housing developments, these are often classified as being densely populated areas relative to the land occupied (see *Figure 4.4.3*).

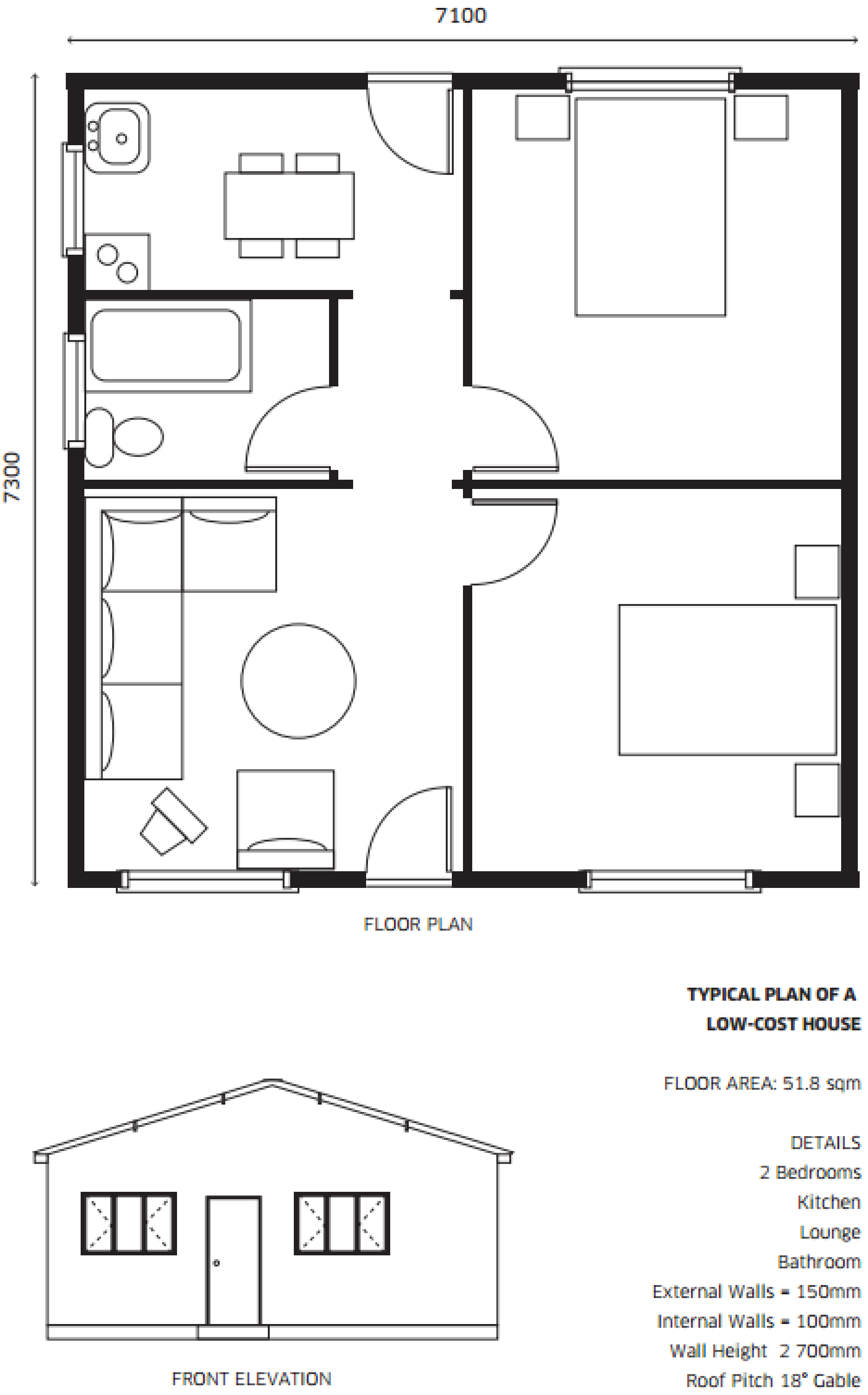


Figure 4.4.2: Typical plan of a low-cost house (after Gyproc Saint Gobain, 2011)

Figure 4.4.3: Aerial photograph of a typical low-cost housing development (Source: Google Earth, 2016)

CHAPTER 5: STRUCTURAL ANALYSIS

5.1 Introduction

This chapter of the research presents the findings of both a theoretical analysis, investigating various studies publicised in literature and an experimental analysis determining the underlining factors that effects the carrying capacity of various structures and hence, the retrofitting potential. The study was carried out with the aim of producing an evaluation in terms of the aims of the research. It highlights the key findings and discusses the potential implications in terms of the overall topic.

5.2 Theoretical analysis

A study of a variety of existing green roof structures presented in literature studies was carried out to determine the most common form of green roof structures. In addition, the study aims to identify the commonality between the type of green roof systems and the structures upon which they are constructed.

The case studies were investigated based on:

- The type of green roof system installed
- The type of structure upon which the green roof was installed

The study of existing green roof systems will provide insight into the potential structures that are most likely to carry an additional load in the form of a green roof and the green roof systems that are the most popular.

A range of existing structures that have green roof systems in place in the city of London were investigated on the previous mentioned parameters. A summary containing the main details of each green system is as follows:

5.2.1 London green roof studies

A range of green roof systems in and around the City of London were investigated on their structural properties and current green roof systems (City of London Corporation, 2011).

5.2.1.1 One Poultry

The green roof system located upon the structure situated at One Poultry is reported to be an approximate 450 m^2 intensive green roof design. The structure upon which the green roof was constructed is mixed use development type utilised as office and retail space.

The building was constructed in the year 1997 from reinforced concrete and has a total roof area of approximately 2500 m^2.

5.2.1.2 107 Cheapside

The building located at 107 Cheapside, is a mixed used development currently being utilised as office and retail space. The structure was constructed in the 1950s from reinforced concrete. Developers decided to construct two types of green roofs on the structure i.e. an extensive and intensive system on the 1187 m^2 roof area. The combined green roof system represented a 20% coverage of the total roof area with the construction of the 44.5 m^2 extensive and 188.81 m^2 intensive green roof systems.

5.2.1.3 10 Queen Street Place

The 10 Queen Street Place structure is currently utilised as a mixed used development type utilised as office, retail and an underground car park. The building was constructed from reinforced concrete in the year 1991 with a total roof area of approximately 4905 m^2. The green roof system was reported to cover approximately 50% of the total roof area. The intensive system comprised of 302 m^2 soft landscaping and 2170 m^2 hard landscaping.

5.2.1.4 150 Cheapside

The 150 Cheapside building is reported to be a mixed used development structure utilised as office and retail space. The building was constructed in 2009 with reinforced concrete and has a total roof area of approximately 1990 m^2. The extensive green roof system upon the structure represents a 79% roof coverage with 1025 m^2 of soft landscaping and 556 m^2 of hard landscaping.

The study carried out on the existing green roof retrofit projects in London provide evidence to support the fact that retrofitting can be conducted on existing structures. An emerging trend from the study suggests that reinforced concrete structures are typically the structural type onto which a green roof system is retrofitted with all four retrofits being carried out upon reinforced concrete structures. Another noticeable trend from the study shows that of the four retrofits, three of the green roofs were intensive systems and they sharing a common factor, all the supporting structures were constructed the 1900s. This suggests that structures that are much older have the heavier (Intensive) green roof systems fitted.

In addition to the London case studies, major green roof systems in the United States of America were investigated.

5.2.2 American green roof studies

Green roof systems within the United States of America were investigated to determine the structural properties of structures that current support green roof systems (Waterproof Magazine, 2010).

5.2.2.1 Chicago City Hall

The Chicago City Hall is a concrete structure with a intensive green roof system that is comprised of a range of lightweight soils that extend 102-458 mm in depth. The weight of the system is reported to, during heavy rainfall, weigh as much as 2.87 KN/m^2. It was also reported that the overdesigning for during the building's construction in the late 19th century has attributed to the structure having the necessary capacity to carry the large additional load.

5.2.2.2 Atlanta City Hall

The Atlanta City Hall was reported to have been constructed 50 years after the construction of the Chicago City Hall. The structure is a predominately reinforced concrete structure that now accommodates a 280 m^2 green roof system. During preliminary investigations engineers determined that the design of the building allowed the structure to carry an additional load of approximately 8.91 KN/m^2. This made the structure more than capable of carrying the total green roof system of approximately 2.68 KN/m^2.

5.2.2.3 Bronx J Building

The Bronx J building was constructed around the 1920s from reinforced concrete and given its age, was regarded as a historic building. This was the contributing factor to the preservation of the structure under its historic designation implying that the structure could not be demolished. However, the building had undergone a complete transformation when it was identified as one of the structures as part of a number within a redevelopment plan. The transformation included a green roof system in excess of 1000 m^2. The study suggests that due to the age of the structure, the structure's carrying capacity exceeded the minimum required load to sustain a green roof system.

5.2.2.4 Schwab Hospital

As part of the Schwab Hospital's plan to assist in the rehabilitation of patients, a designated area to carry out horticultural therapy was proposed. In order to achieve this, the executives at the hospital decided to implement a green roof system. The structure was constructed in 1998 from reinforced concrete and was designed to accommodate an additional floor as part of a proposed future development plan. As a result, the structure had the necessary structural capacity to carry the proposed additional loading imposed by the green roof structure.

5.2.2.5 A&P Lofts

In the case of the A&P lofts, the structure, without any structural upgrades, did not meet the required additional load carrying capacity to sustain a green roof. The structure was constructed in the year 1930 utilising red brick as the primary construction material. In order to sustain a green roof system, structural engineers utilised a steel support frame system that allowed the green roof to be raised and constructed approximately 150 mm off the existing roof structure.

5.2.2.6 Ballard library

The Ballard library forms a subsidiary of the City of Seattle's public libraries. The library was constructed in 2005 and comprises of a combination of a wooden framed roof structure supported by slender structural steel columns. The roof structure was designed to be inaccessible and is estimated to be 1900 m^2. The structure now accommodates a 20500 sq ft extensive green roof system at a 25% slope utilised for test and research purposes.

The studies of the American green roof systems provide further evidence of the potential of existing structures to be retrofitted with green roofs and in particular, the retrofitting potential of concrete structures. The cases provide evidence that the retrofitting potential and the ability of a structure to carry an additional load is largely dependent on the considerations taken during the design process in terms of structural members. This is evident when considering the Ballard library green roof system, the structure is a both a relatively new structure and makes use of structural steel and timber construction materials deviating from the common reinforced concrete structures.

5.2.3 Results and discussion of the theoretical analysis

In an attempt to present an objective analysis, green roof systems from different regions of the world were assessed to determine the type of structure that is most commonly retrofitted with a green roof and how the age of the structure has influenced the carrying capacity of the structure and hence, its ability to be retrofitted with a green roof.

The findings of the study show that the most common form of green roof retrofits take place upon concrete structures and in particular, structures that are much older (attributed to the potential construction utilising ‘good building practices’). However, the research further highlights that green roof retrofits are not limited to concrete structures but is entirely dependent on the structure’s carrying capacity which, in turn, is dependent on the structural elements of the associated structure. From the study of the literature it has also highlighted that in certain cases, concrete structures or any other structure for that matter, may not necessarily be able to sustain an additional load and in such cases, a structural upgrade would be required.

A greater understanding of the relationship between the elements of a structure and the structural carrying capacity and the basis of the findings may provide further insight into the potential of retrofitting existing structures with green roofs.

5.3 Experimental analysis

In an attempt to add to the findings of the prior theoretical analysis carried out, an experimental analysis was conducted to investigate the variation in structural carrying capacity and hence, the retrofitting capability in structures with dissimilar construction materials.

5.3.1 Industrial building

This chapter presents the results of the experimental analysis with regard to the industrial building type of structure.

5.3.1.1 Wind loading

The results of the wind loading calculation after taking into account the various assumptions in terms of locality, produced a peak wind pressure of 0.78 KPa. This pressure was then multiplied by the nett result of the difference between the external and internal pressure coefficients to determine the wind load acting upon the structure. A summary of the pressure coefficients together with the nett result between the internal and external pressure coefficients can be seen in *Figure 5.3.1*.

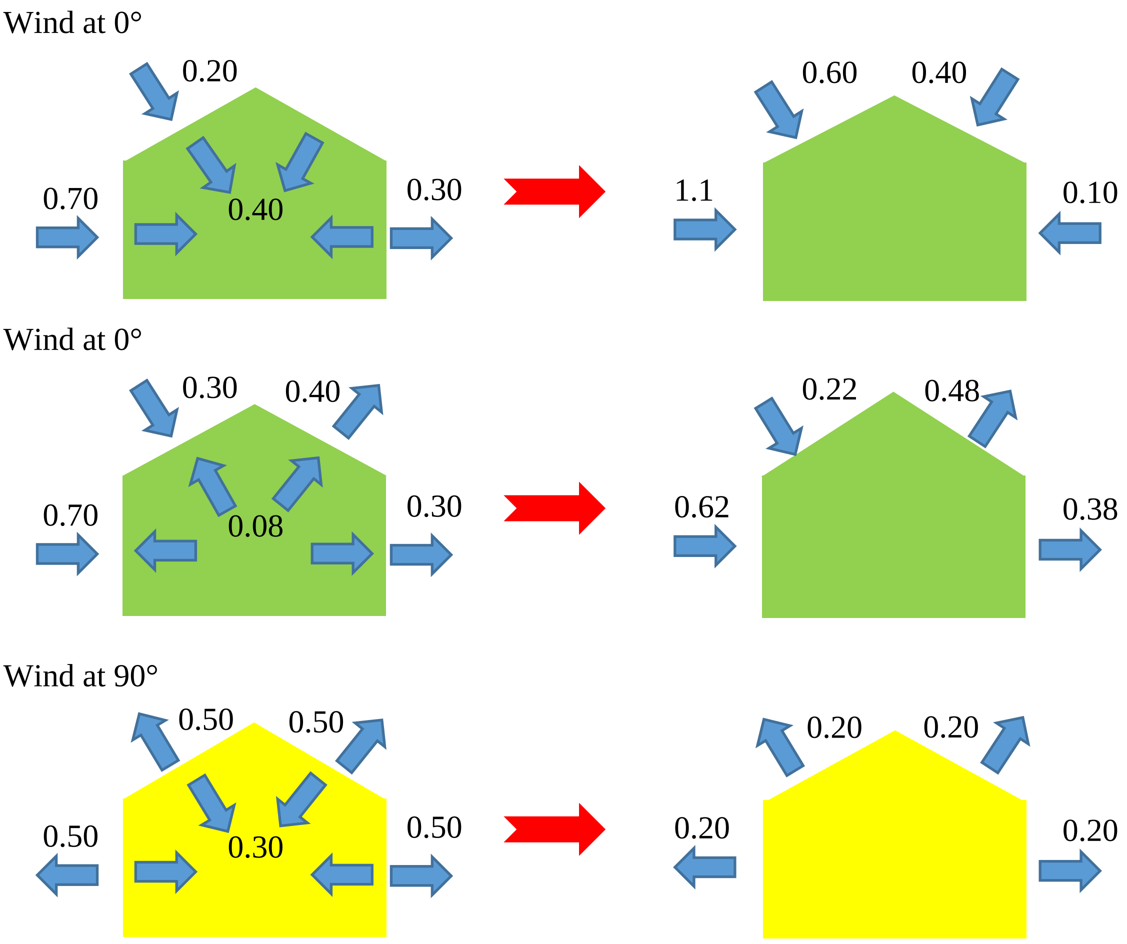


Figure 5.3.1: Pressure coefficients for wind loading on the designed industrial building

With reference to the Figure it is evident that the most onerous wind loading case is the first case of the wind acting at 0°.

5.3.1.2 Purlin

The purlins were designed utilising the highest wind load from the most critical case acting on the roof structure. A cold form channel section size of 100x50x20x2.5 was assumed and checked in terms of its adequacy. The total load acting on the structure was found to be 0.77 kN/m. This included a Dead Load of 0.05 kN/m, a Live Load of 0.25 kN/m and a Wind Load of 0.47 kN/m. Two loading cases were checked i.e. cases of upward loading and downward loading. The downward loading case utilised a load combination of 1.2 x Dead Load + 1.6 x Live Load, whilst the upward loading case utilised a load combination of 0.9 x Dead Load - 1.3 x Wind Load.

The ultimate moment in the downward loading case was found to be 2.12 kN.m whereas, the ultimate moment in the upward loading case was found to be 2.59 kN.m. Utilising this information the moment of resistance for the section was calculated and checked to determine its adequacy. The calculations produced a moment of resistance of 3.078 kN.m. Hence, the section proved to be adequate. The purlin design was carried out initially in an attempt to eliminate a further unknown when conducting the frame analysis.

5.3.1.3 Frame analysis

To determine the forces and max moment to which the elements of the portal frame would be designed to, a frame analysis was conducted on the two load cases mentioned previously. Section sizes for both the beams and columns were assumed and the adequacy of the assumed section sizes checked. The bending moment diagrams of the frame analysis for each case is shown graphically in *Figures 5.3.2* and *5.3.3*.

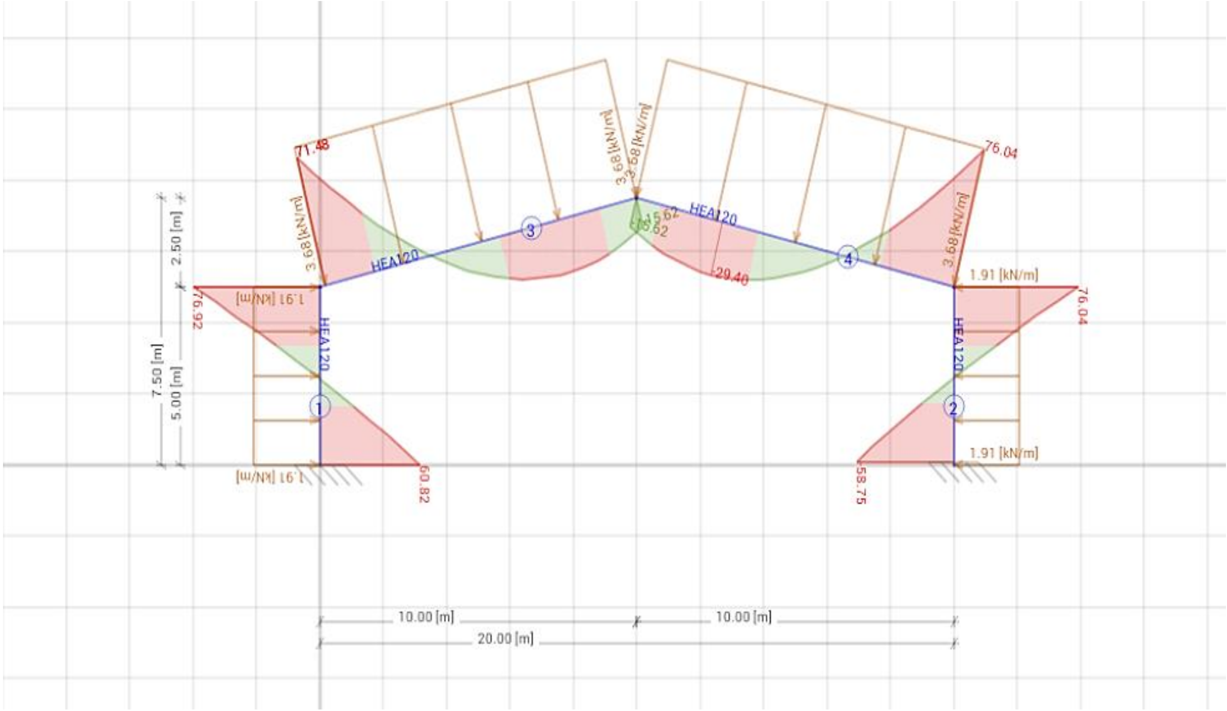


Figure 5.3.2: Bending moment diagram for 1.2Dead Load + 1.6Live Load case

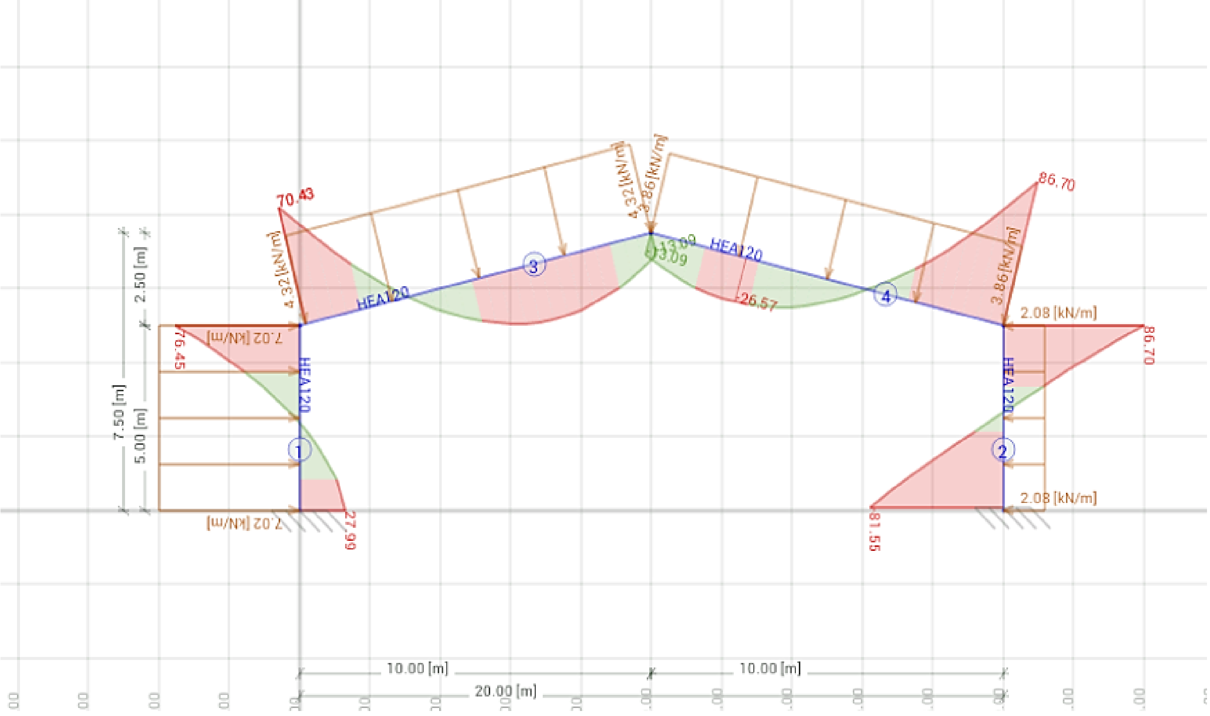


Figure 5.3.3: Bending moment diagram for 0.9Dead Load + 1.3Wind Load case

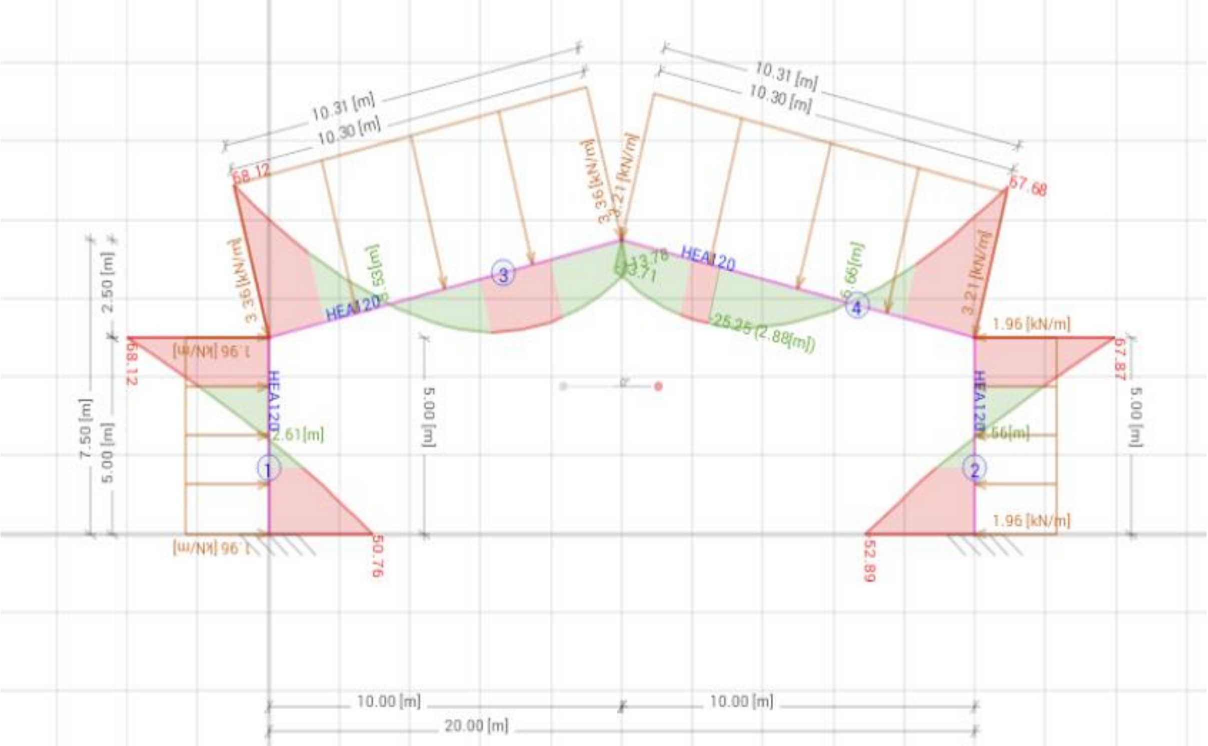


Figure 5.3.4: Bending moment diagram for 1.35Dead Load + 1.0Wind Load case

As illustrated in the Figures, it was found that the second load case produced a maximum design moment of 86.70 kN.m. Utilising this moment, the beams were designed with the intention to contain a capacity to resist this moment. Through calculations it was found that a section size of 203x133x30 was adequate in terms of bending. However, the section had failed in deflection. As a result, a deeper section size was chosen.

Through further calculations it was found that a 305x165x 46 I-section would be adequate in terms of bending and deflection. Given the loading conditions, the section had the capacity to resist a moment of 231,74 kN.m, 145.04 kN.m above the ultimate moment. However, the actual deflection of the section was calculated to be 32.47 mm with a recommended deflection of 34.33 mm. As a result, the section narrowly passes. Drawings of the structure together with the main elements of design can be found in *Appendix A*.

5.3.1.4 Post-green roof

Considering the fact that the green roof would be placed upon the roof sheeting and thereafter, performing a top down analysis of the effects of the additional loading upon the structure it was found that the purlins of the structure would fail under any further additional load. This came as a result of the element being solely designed to carry the weight of the sheeting and the element's self-weight.

However, with deflection of the beam member over the long span being the limiting criteria, it was then calculated that each frame would be able to support an additional dead load of 0.2 kN/m. In order for a green roof system to be deemed practical all interconnected, load-carrying elements of the structure are required to pass the necessary checks in accordance with the relevant standards under the additional load. In industrial buildings, due to the fact that the smallest load carrying element are the purlins these form the limiting factor in the potential green roof installation. Hence, if a green roof design is not included in the preliminary design of the structure or if the purlins have not been overdesigned for, a green roof retrofit may not be possible on industrial buildings without implementing costly structural upgrades.

5.3.1.5 Summary

The purpose of the industrial building design had been to determine the relationship and behaviour of the structural elements within the structure in an attempt to assess the ability of these types of structures to carry additional loading apart from the design loading. The primary reasoning behind this was to determine the potential for green roof retrofitting. In order to determine this potential, the design did not incorporate the dead load associated with a green roof. The design of the structure under the calculated loading resulted in the primary support elements for the portal frames being calculated to be 305x165x46 I-section Beams and 203x203x46 H-section columns. For the roof structure the primary support element was calculated to be 100x50x20x2.5 cold-formed channel purlins. The maximum design moment for the primary support elements was calculated to be 86.70 kN.m. The maximum design moment for the primary support element in the roof structure was calculated to be 2.59 kN.m. Following on from the design of the structural elements, the carrying capacity of the structure was determined. The carrying capacity was determined as the additional load that the structure can accommodate prior to the failure of a dependant structural element. The results of the calculations highlighted the fact that the primary support elements were able to carry an additional 2 kN/m. However, the structure was limited to the capacity of the purlin as these elements had failed prior to the primary support elements.

The design of the industrial building is limited in a sense that it utilises typical loading conditions and assumes that in order to provide the most cost effective, efficient and feasible design, structural elements will be optimised i.e. not be overdesigned for and the smallest, most adequate elements will be utilised. However, the design has highlighted the behaviour and influences of certain design considerations in industrial buildings.

Greater section sizes offer greater stiffness and hence, reduces the actual deflection of the member. For the ultimate moment of 87.6 kN.m an I-section size of 203x133x30 offers a moment of resistance of 111.27 kN.m. However, in terms of deflection the section fails. Utilising the above mentioned section the actual deflection was calculated to be 109.28 mm, whilst the recommended deflection was estimated at 34.33 mm. As a result, a deeper section had to be chosen. Deflection of members in industrial, long spanning structures proves to be the greatest factor in member selection. The hypothetical design scenario carried out, produced loading that could be carried by smaller members. However, a deeper section had to be chosen in order for the deflection to be adequate.

The findings achieved by carrying out the design shows that there is potential in the primary structural support members to sustain a greater load than which they have been designed to. However, this additional load that the structure can carry is further limited to the carrying capacity of the purlins, as the element is solely designed to carry the superstructure of the roof system i.e. the weight of the sheeting and the element’s self-weight. Increasing the loading to the limits of the primary support elements may result in failure of the purlins and the potential collapse of the roof structure. Green roof application may however, be applicable with a form of structural upgrade.

5.3.2 Commercial building

The results of the experimental analysis with regard to the commercial building structural type is presented in the chapter to follow.

5.3.2.1 Wind loading

Wind loading was done in accordance with the SANS 10160-3 Code of Practice. Following the assumption that the structure would be located within the Westway Office Park, the peak wind pressure acting within the area was calculated to be 0.65 KPa. The peak wind pressure was utilised to calculate the wind loading acting upon the structure by multiplying the pressure to the nett result of the external and internal pressure coefficients. *Figure 5.3.4*, presents a summary of the pressure coefficients together with the nett result between the internal and external pressure coefficients carried out during the wind analysis of the entire structure.

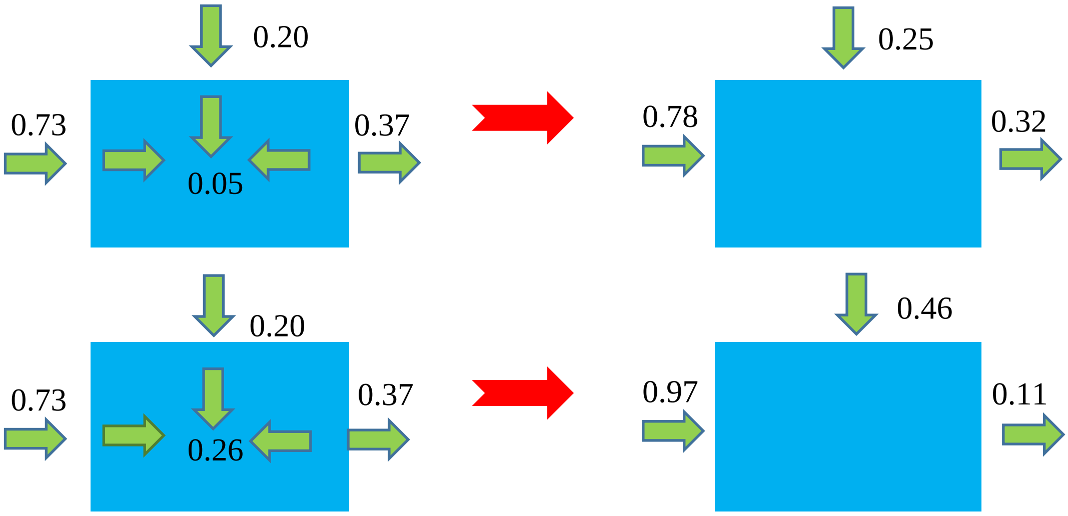


Figure 5.3.4: Pressure coefficients for wind loading on the designed commercial building

5.3.2.2 Frame analysis

A frame analysis was conducted in order to determine the maximum bending moments and respective forces. The structural elements were assumed to be cast in-situ and as a result, it was assumed that the structure would behave as a rigid frame. The structure was 20 m wide with columns 5 m apart. This produced a symmetrical structure. As a result, a single frame was analysed. The frame was 10 m wide with columns on either floor, spaced 5 m apart in either direction. The frame comprised of columns and beams. The beams were designed to support the slab elements and were therefore considered as being cast in-situ with the slabs. Subsequently, the beams would be supported by the columns.

Two frame analyses were performed. A complete frame analysis was done utilising only the design wind loading ignoring the dead and live loads. Thereafter, a frame analysis was done utilising a simplified sub-frame analysis of the beam and column action that incorporated the dead and live loads. The results obtained from both frame analyses were combined to obtain the ultimate design moments and forces.

This symmetrical analysis however, cannot accurately model the sway of the entire structure properly and as a result, a sway analysis for the entire structure was carried out. The analysis results have been graphically illustrated in *Figure 5.3.5.* The results show that the building will undergo a 95 mm deflection over the 20 m length of the building.

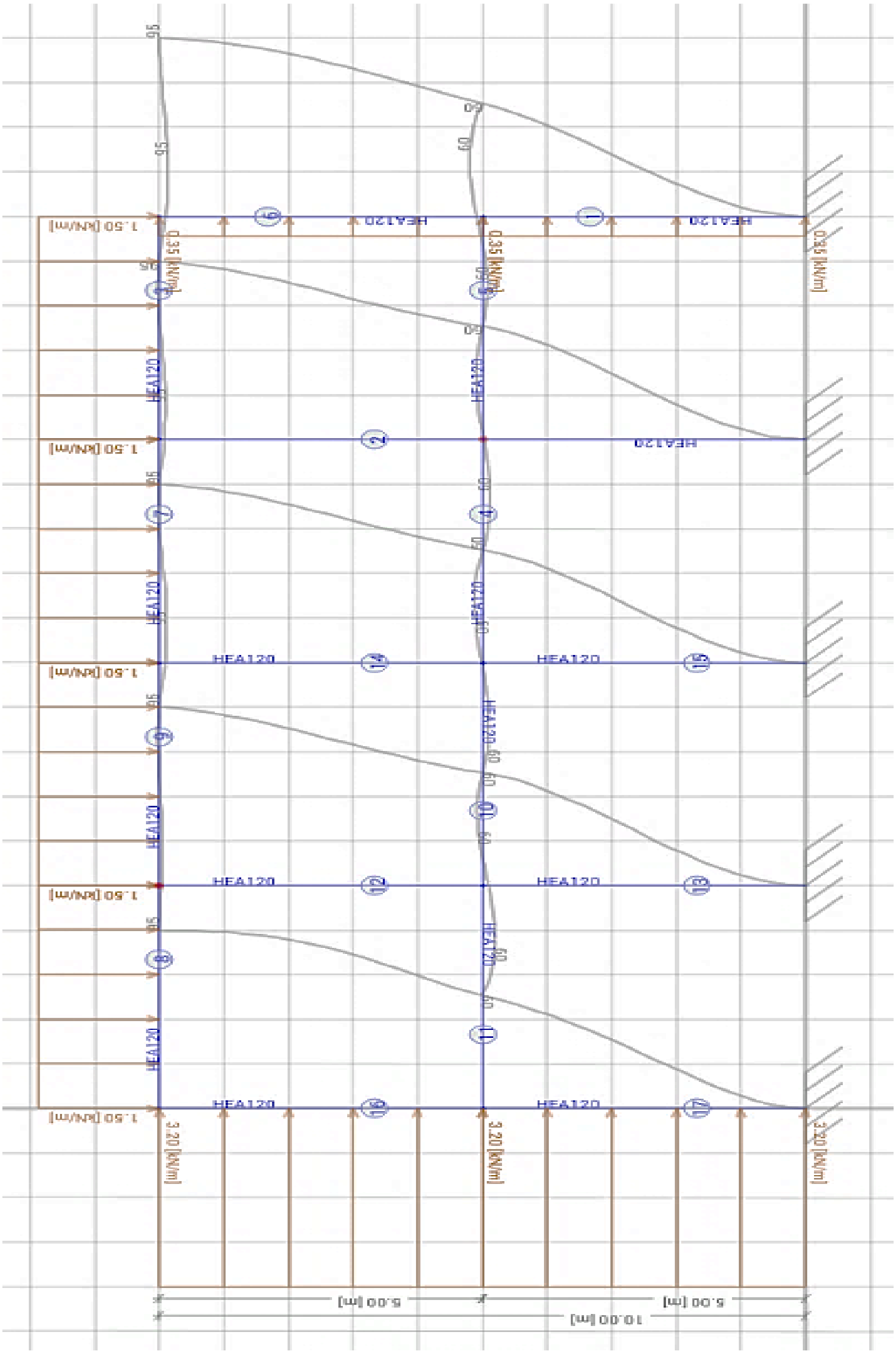


Figure 5.3.5: Sway of the structure

The results of the frame analysis from the design wind loading is illustrated in *Figure 5.3.6*. From the Figure it can be seen that the maximum moment was found to be 42.66 kN.m at the ground floor.

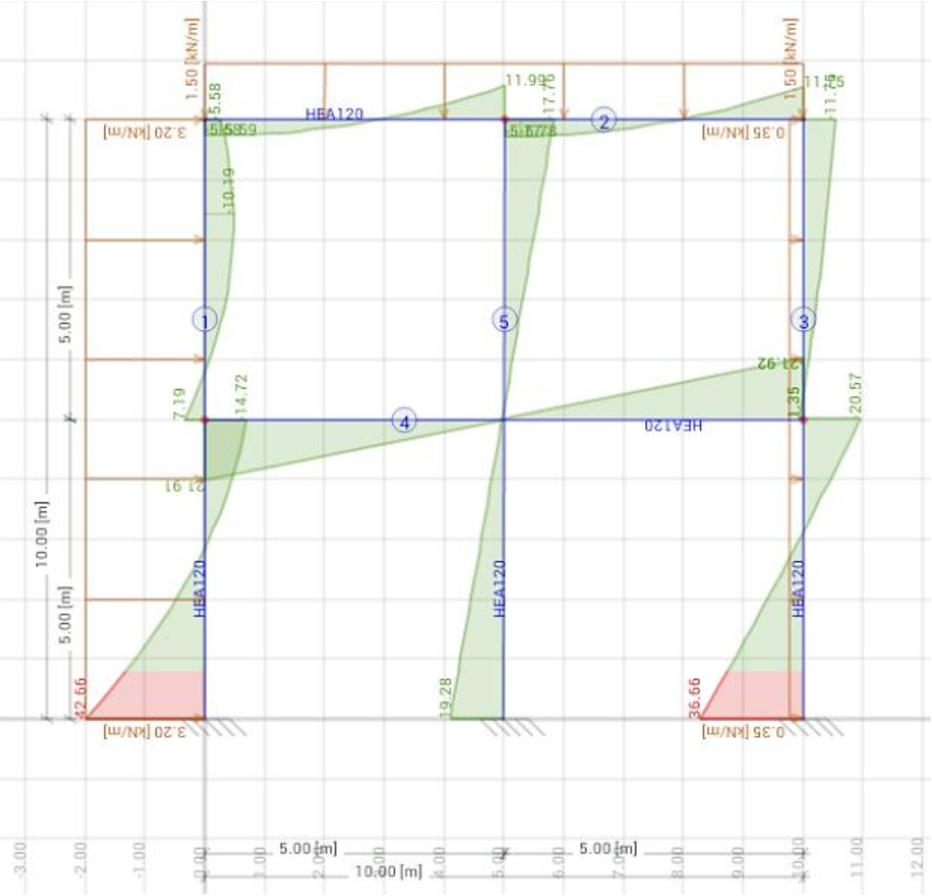


Figure 5.3.6: Bending moment diagram for design wind loading

Two design load cases (*1.2DL + 1.6LL and 1.35DL + 1.0LL*) were assessed based on a simplified sub-frame analysis utilising three load cases (see *Figures 5.3.7-5.3.12*) in order to determine the maximum moments and forces through the respective envelopes:

- Alternate spans loaded using ultimate loading and dead load only and using
- Ultimate loading throughout.

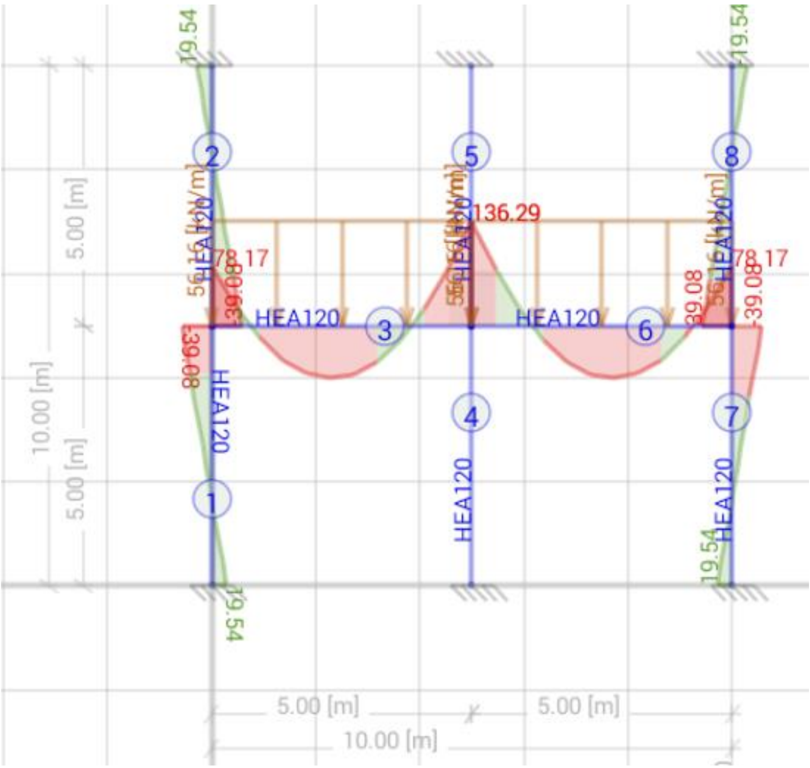


Figure 5.3.7: Simplified Sub-frame analysis 1.2DL + 1.6LL Case 1- Ultimate loading throughout

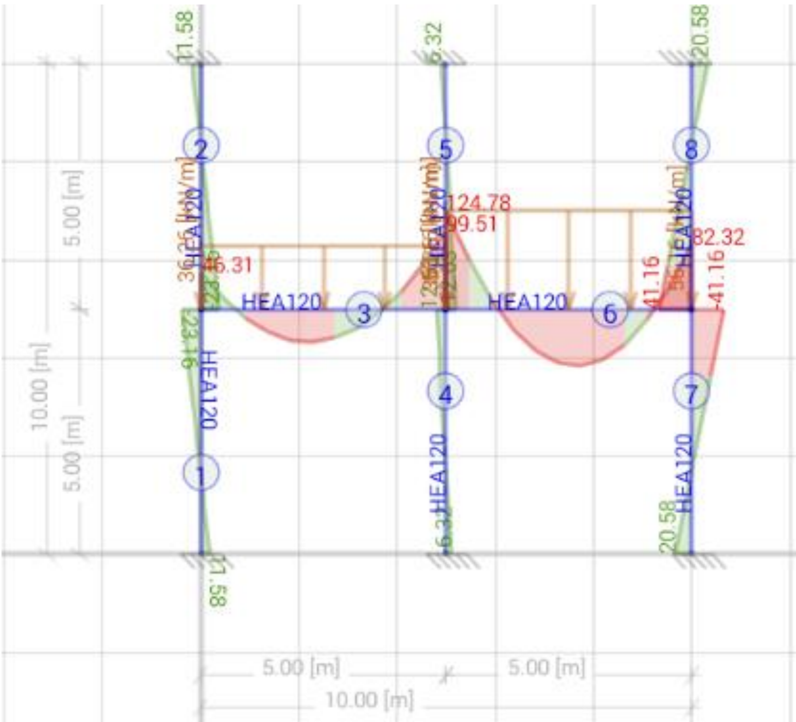


Figure 5.3.8: Simplified Sub-frame analysis 1.2DL + 1.6LL Case 2: Dead load and Ultimate load

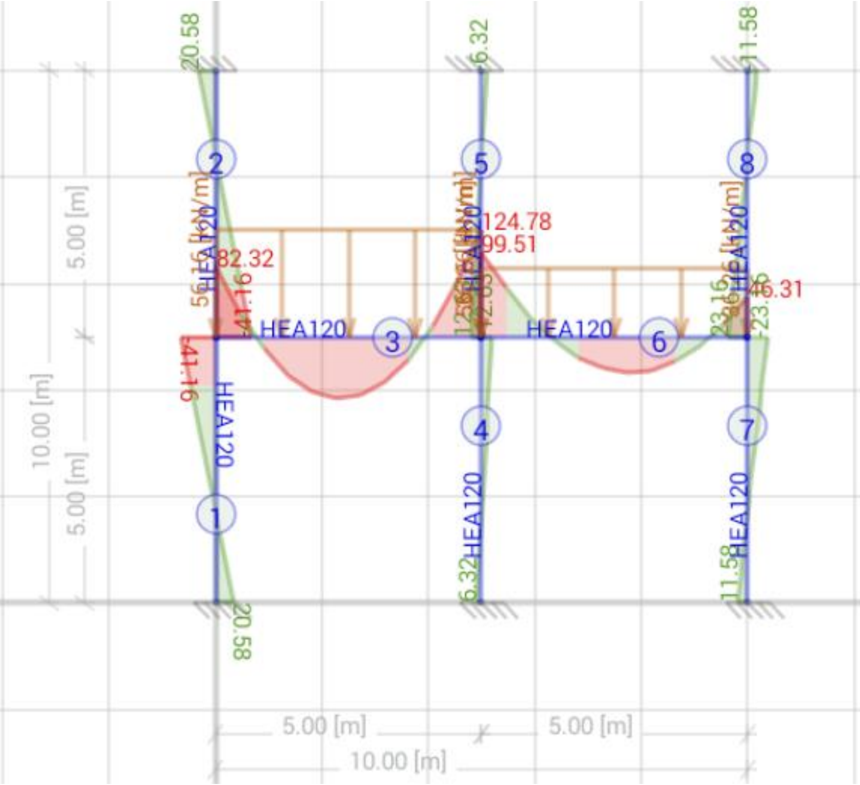


Figure 5.3.9: Simplified Sub-frame analysis 1.2DL + 1.6LL Case 3: Ultimate load and Dead load

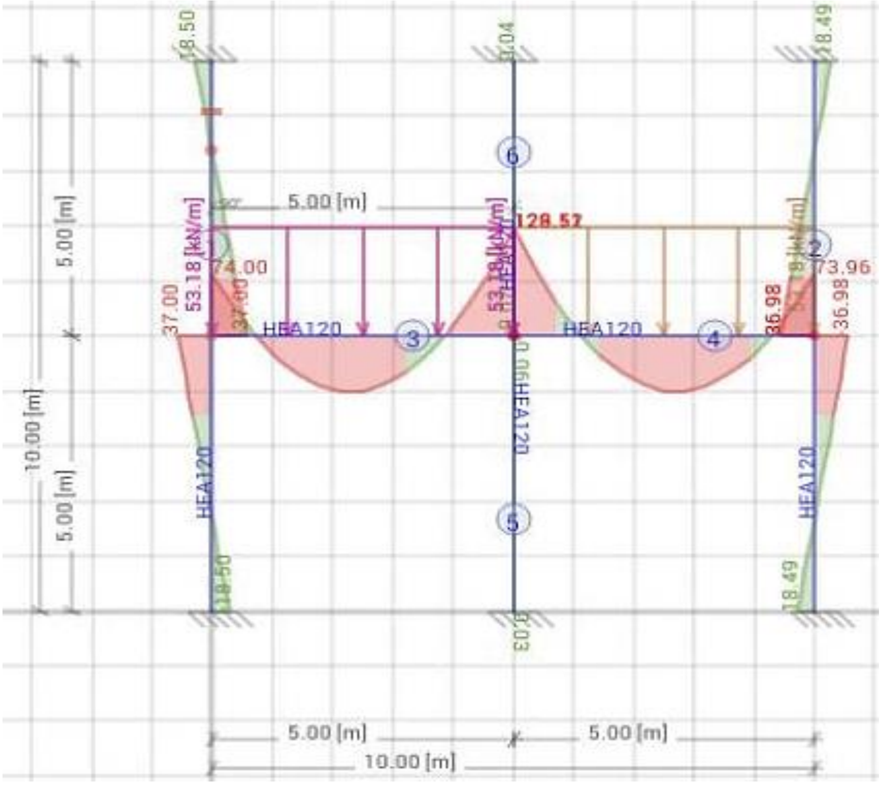


Figure 5.3.10: Simplified Sub-frame analysis 1.35DL +1.0 LL Case 1: Ultimate load throughout

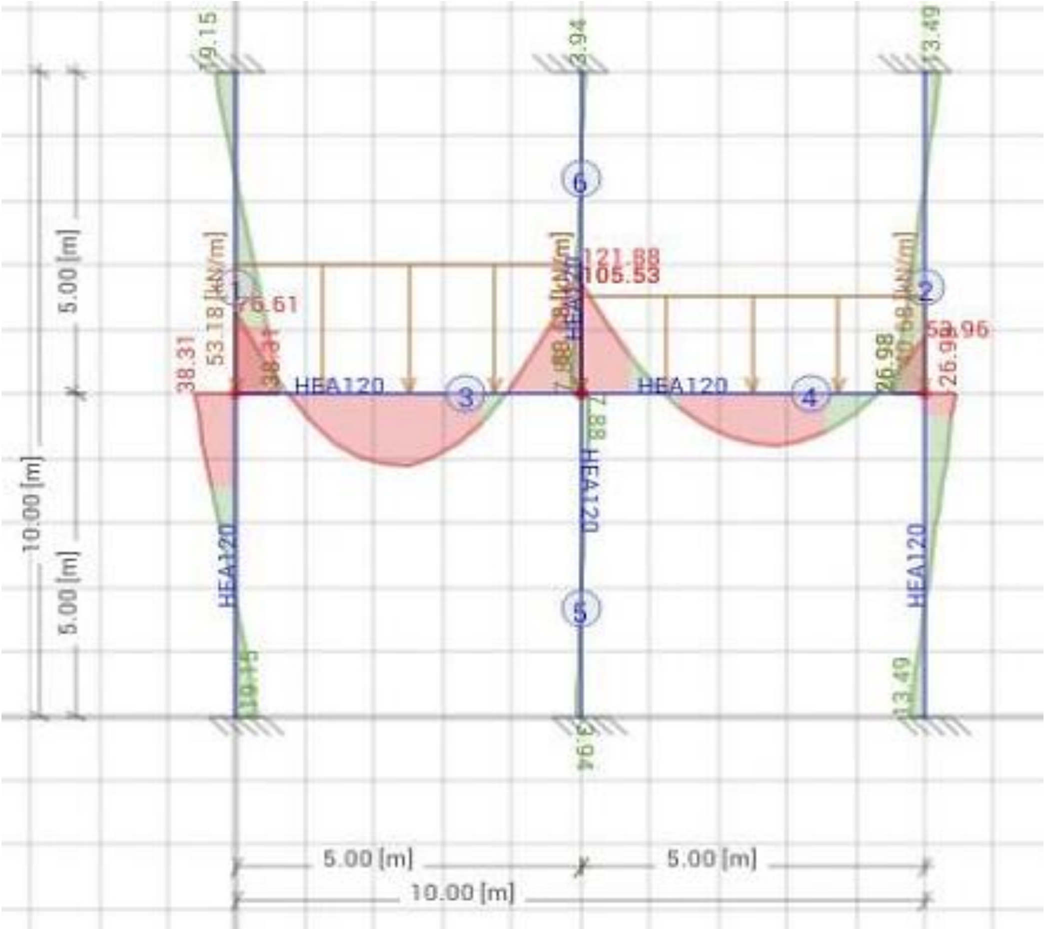


Figure 5.3.11: Simplified Sub-frame analysis 1.35DL +1.0 LL Case 2: Ultimate load and Dead load

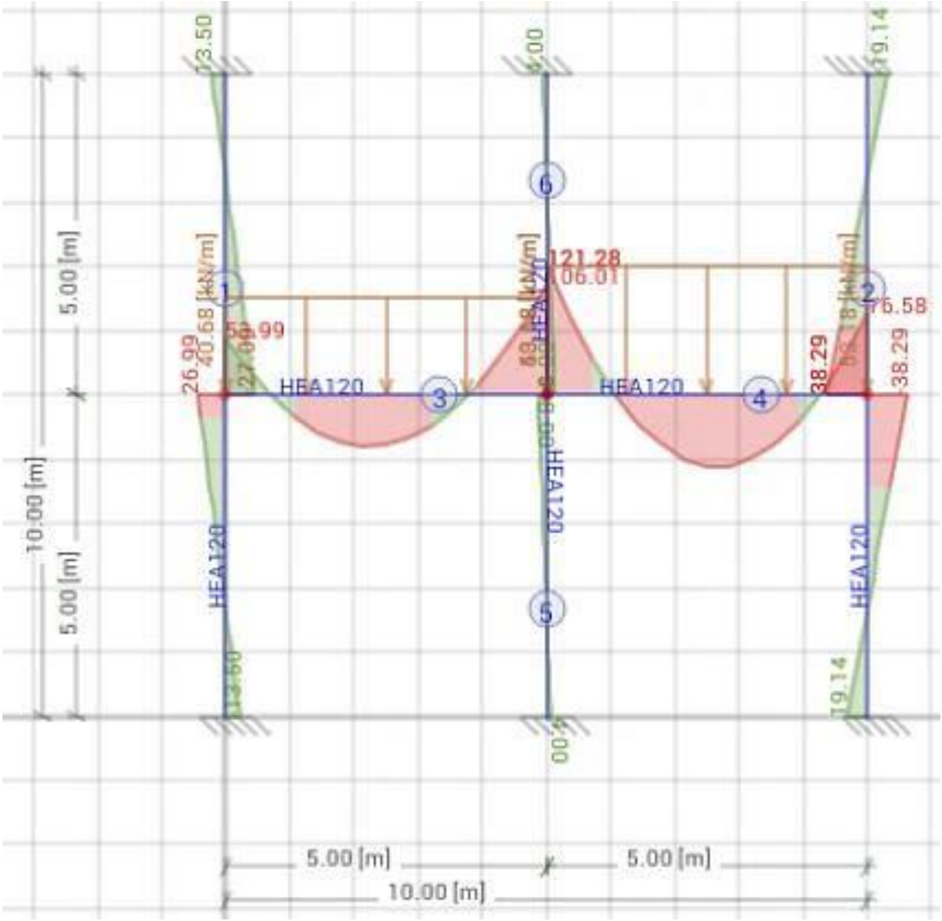


Figure 5.3.12: Simplified Sub-frame analysis 1.35DL +1.0 LL Case 3: Dead load and Ultimate load

The resultant analyses produced a maximum design moment of 158.20 kN.m for the beams and 83.73 kN.m for the columns. Utilising these moments, the structural elements were designed in accordance with SANS 10100-1 Code of Practice.

The slabs were designed as being two-way spanning. Initially the slabs were assumed to be 200 mm deep. Through calculations, it was found that a 250 mm deep would be adequate and was adopted. A concrete density of 25 kN/m^3 was utilised for the design. A 50 mm thick screed layer at a density of 23 kN/m^3, was applied as a finish. Together, these elements constituted a total dead load of 7.40 kN/m. An imposed live load of 2.5 kN/m^2, in accordance to SANS 10160-2, was applied to the slab. The largest factored load from the two load cases considered for the simplified sub-frame analysis i.e. the 1.2DL + 1.6LL load case and the 1.35DL + 1.0LL load case was calculated to be 12.88 kN/m. This was produced by the 1.2DL + 1.6LL load case, whereas the alternate load case produced a marginally smaller load of 12.49 kN/m. This force was later multiplied by the respective lengths of the slab and through the applicable calculations, it was found that the slabs would have to be designed to resist a moment of approximately 36 kN.m about the x-axis.

The concrete beams supporting the slabs were assumed to be 600 mm by 300 mm. Through calculation it was found to be adequate. The beams were required to resist a bending moment of 158.20 kN.m and a shear force of 152.03 kN. As a result, through further calculation it was found that the section would require 3Y25 high tensile steel reinforcing bars together with Y10 bars spaced at 400 mm in order to resist the bending moment and shear force respectively. The service load acting on the beam was calculated to be 45.61 kN.m. Utilising a modification factor of 1.55 and a basic ratio of 16, this loading produced an allowable deflection of 24.82 mm. Further calculations showed that the actual deflection amounted to 17.78 mm and henceforth, the section proved to be adequate.

The rectangular concrete columns were assumed to have a cross-section of 350 mm by 300 mm. Taking into account the 5 m floor to floor height together with the 600 mm beam depth, the effective height of the column on both the x and y axes was calculated to be 4.1 m. Due to the fact that the structure was designed to resist the lateral loading, the columns were designed as unbraced structural members and as a result the slenderness ratio was found to exceed 10 on either axis under consideration. As a result, the columns were designed as slender columns as opposed to short columns. Due to the geometry of the columns an analysis had to be performed on the column from an alternate direction to assess the structural behaviour of the column and ensure that the maximum design forces were in actuality, that which the structure was being design for. Following, the analyses, the columns were designed to resist an axial force of 152.03 kN. On completion of the relevant calculations its was found that the section size was adequate. Drawings of the structure together with the main elements of design can be found in *Appendix B.*

5.3.2.3 Post-green roof

Utilising the designed building, the process was repeated in order to determine the loading capacity. Following a top-down analysis of the structure, the additional carrying capacity of the structure was found to be 7 kN/m. This was limited to the capacity of the slabs, as through calculations these proved to fail prior to the failure of the beams and columns. This had highlighted the general consensus established in present literature that reinforced concrete structures have the potential to carry additional loading and hence, a potential green roof.

5.3.2.4 Summary

To assess the influence of concrete as a construction material and the associated implications with regard to the potential to retrofit a concrete structure with a green roof, a two-story beam and column structure was designed. Through various trials and errors, it was found that the loading acting upon the structure would be supported by means of 250 mm deep slabs, 600 mm x 300 mm beams and 300 mm x 350 mm columns. The loading types upon the structure involved dead loads, live loads and wind loads. The dead loads did not incorporate the load of a typical green roof structure. This was done as a means to determine the reserve capacity of the structure without including an additional load for a green roof in the design process. The analysis of the loading upon the structure involved a combination of two methods of analysis i.e. a complete frame analysis and a simplified sub-frame analysis. The frame analysis was performed utilising the design wind loading whilst the sub-frame analysis utilised the dead and live load combination. The results of the analysis produced a maximum moment of 158.20 kN.m for the beams and 83.73 kN.m for the columns. Following on from the preliminary design, the design process was repeated until failure of the structural elements in order to determine the structure's carrying capacity. The results of the calculations had shown that the structure's carrying capacity was limited to the capacity of the roof slabs. This comes as a result of the roof slabs failing prior to the other structural elements. The allowable additional loading i.e. the design load for a green roof was calculated to be 7 kN/m.

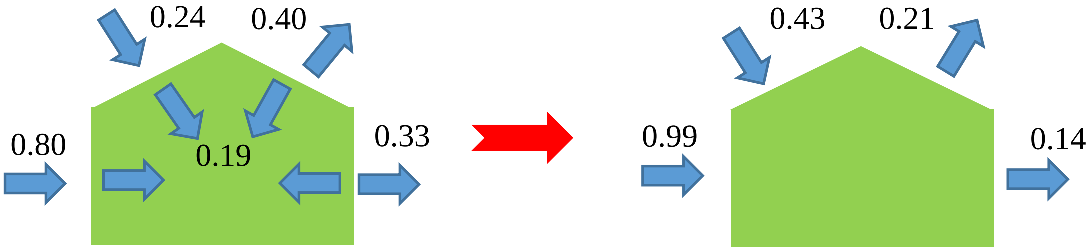
5.3.3 Low-cost housing

The results of the analysis with regard to the retrofitting potential in low-cost housing structural types is presented in the following chapter.

5.3.3.1 Wind loading:

Utilising the assumption that the structure would be located within the Waterloo area as identified in Chapter 3.4, an elevation of 70 m amsl was utilised to determine the peak wind pressure acting upon the structure. As a result, the peak wind pressure was determined to be 0.50 KPa A summary of the pressure coefficients together with the nett result between the internal and external pressure coefficients can be seen in *Figures 5.3.10-5.3.11*

Wind at 0°



Wind at 0°

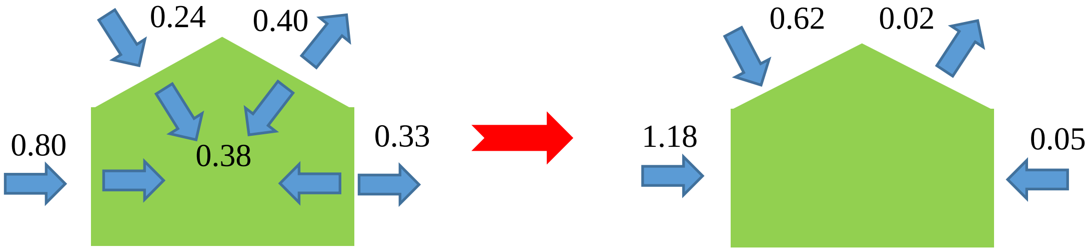


Figure 5.3.10: Pressure coefficients from low-cost housing design wind loading for wind at 0°

Wind at 90°

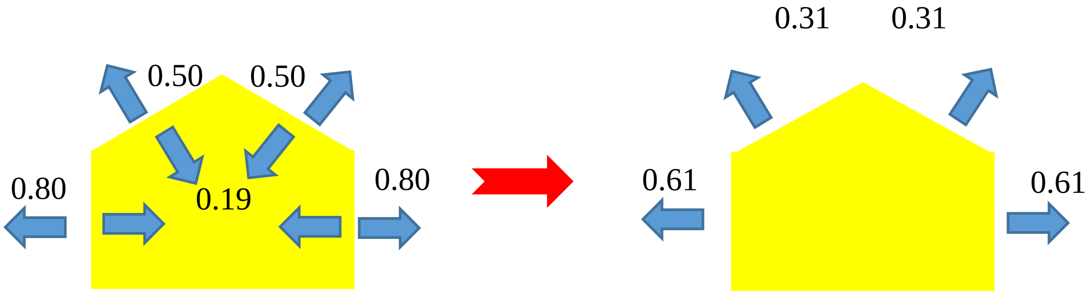


Figure 5.3.11: Pressure coefficients from low-cost housing design wind loading for wind at 90°

5.3.3.2 Roof battens

The roof battens on a low-cost house are designed to carry the weight of the roof tiles, water-proofing and the element's self-weight. Initially, for the design of the structure the roof battens were assumed to be 38 mm x 38 mm Grade 5 SA Pine timber beams. The relevant structural checks were carried out in order to assess if the section size had been suitable to carry the weight of the roof tiles and that of the waterproofing.

5.3.3.3 Truss analysis

It was found that the 0.9 x Dead Load + 1.3 x Wind Load load case was not the most onerous case due to the relatively small wind load. The truss was analysed according to the two other load cases i.e.:

1. 1.2 x Dead Load + 1.6 x Live Load
2. 1.35 x Dead Load + 1.0 x Live Load

Utilising the assumptions based on the material and typical structure that a low-cost house is generally comprised off, the ultimate load acting on the structure was found to be 4.06 kN/m. This load was based on a load case of 1.35 x Dead Load + 1.0 x Live Load that was comprised of a factored dead load of 3.81 kN/m and a live load of 0.23 kN/m. An imposed live load of 0.25 kN/m^2, in accordance with SANS 10160-2, was utilised for the live load based on the assumption that the roof structure would be used primarily for maintenance purposes. The roof truss comprised of 76 mm x 38 mm Grade 5 SA Pine beams.

Figures 5.3.12-5.3.13 are graphical representations of the forces acting in the roof truss in both design load cases. *Table 5.3.1* lists the respective members with the associated force acting within the member.

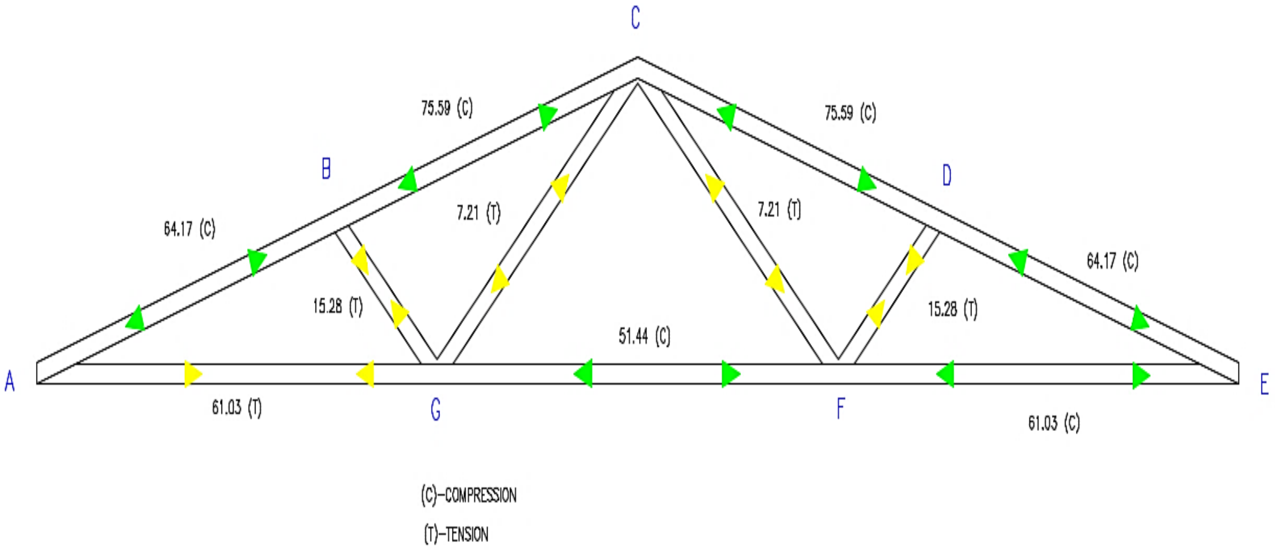


Figure 5.3.12: Member forces acting upon the roof truss from the 1.2DL + 1.6LL case.

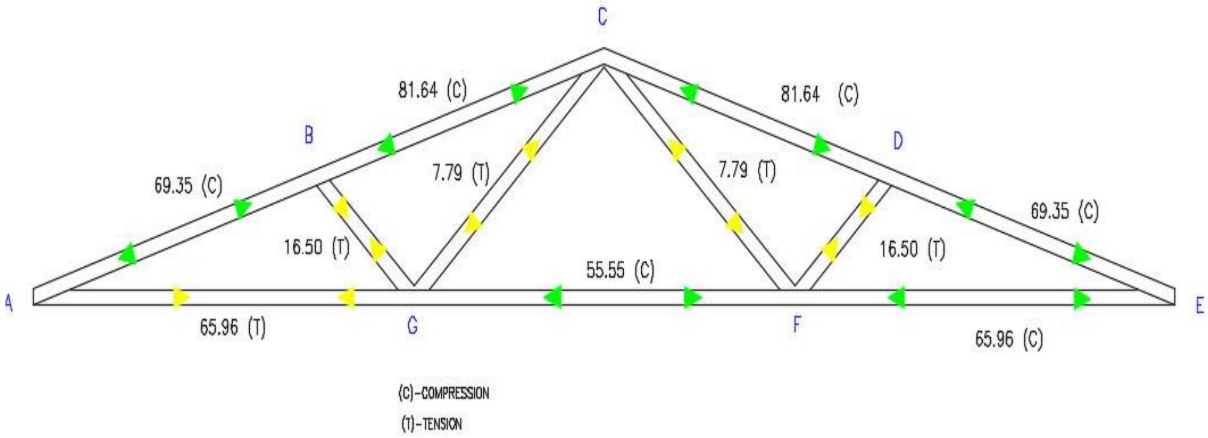


Figure 5.3.13: Member forces acting upon the roof truss from the 1.35DL + 1.0LL case.

The maximum member force acting in the truss amounted to 81.64 kN in compression. The symmetry of the truss allowed for calculations to be simplified on the basis that the forces on one half of the truss structure would be mirrored onto the other.

Table 5.3.1: Summary of member forces

Member	Force (1.2DL +1.6LL Case)	Force (1.35DL +1.0LL Case)
AB	64.17 Compression	69.35 Compression
BC	75.59 Compression	81.64 Compression
CD	75.59 Compression	81.64 Compression
DE	64.17 Compression	69.34 Compression
EF	61.03 Compression	65.96 Compression
FG	51.44 Compression	55.55 Compression
GA	61.03 Tension	65.96 Tension
GB	15.28 Tension	16.50 Tension
GC	7.21 Tension	7.79 Tension
FC	7.21 Tension	7.79 Tension
FD	15.28 Tension	16.50 Tension

5.3.3.4 Summary

To determine the potential of retrofitting low-cost housing with green roofs as a source of food security a design of typical low-cost house was conducted. The design incorporated the use of structural timber, predominately for the roof structure together with brick work for the encapsulation of the living area. The roof structure comprised of roof tiles, waterproofing and battens supported by a timber truss. The battens were first assumed to be 38 mm x 38 mm Grade 5 SA Pine. The members in the truss were assumed to be 76 mm x 38 mm Grade 5 SA Pine. Both elements were checked in accordance with the SANS code of practice. The repetition of the design process until failure of the structural elements was carried out in order to determine the carrying capacity of the structure. The results of which had shown that the carrying capacity of the structure is limited to the capacity of the roof battens as this was the structural element that had reached failure prior to that of the truss. As a result of the findings, green roof retrofitting upon low-cost housing structures is not entirely feasible without a form of structural upgrade. Drawings of the structure together with the main elements of design can be found in *Appendix C*.

The advantages of introducing green roofs on low-cost housing proves to be beneficial to those who reside in the property. Green roofs can reduce the storm water run-off from the properties and hence, prevent erosion around the property. Due to many low-cost housing developments being constructed on compacted ground, this will aid in reducing the potential effects that occur as a result of localised flooding and heavy rainfall events. Green roofs can reduce the temperatures within the structure and that of the surrounding areas. In addition, green roofs offer greater insulation. These may result in a better quality of life.

Often, due to the large scale and small spacing of low-cost housing developments, it is regarded as being unattractive. Green roofing can boost the attractiveness of the housing developments.

In a typical roof structure of a low-cost house the roof tiles and water-proofing layers are carried by the roof battens and this load is then transferred to the roof trusses as a point load. As a result, any additional loading upon the roof structure will be carried by the battens and then transferred to the trusses. For this reason, the weight of the green roof structure has to be limited to the carrying capacity of the battens. If the loading is greater than the carrying capacity of battens the structural element will fail. Therefore, the potential to retrofit green roofs onto low-cost housing is limited to the carrying capacity of the roof battens.

Another limitation to the implementation of green roofs on low-cost is accessibility. In order to utilise the green roof as a vegetable garden an individual would be required to perform regular maintenance and gardening techniques. However, getting from the ground level to the roof would require a device to allow efficient movement. The most cost-effective way would be to introduce a ladder. However, this will be impractical and hazardous to the aged population.

In an interview conducted with Clive Greenstone, a green roof specialist, the average green roof designed for the purpose of utilising as a vegetable garden is estimated to weigh approximately 200 Kg/m^2. Utilising this as a guideline, the structure would have to accommodate an additional load of 1.962 kN/m^2. As novel of an idea as it may be, retrofitting low-cost housing with green roofs intended for subsistence farming, can be considerably costly and as the name suggests, low-cost housing is designed to be as cost efficient as possible, whilst providing adequate housing to individuals.

Table 5.3.2 illustrates an array of typical vegetables that are typically utilised in subsistence farming. The table identifies the spacing between seeds (based on the recommended spacing of seeds from Starke Ayres, suppliers of vegetable, lawn and flower seed) and further presents the associated weight. The weight is based on the spacing and depth provided in the table and as such forms the estimated weight of the growing medium for every four seeds in accordance with the spacing. The estimated weight is based on the experimental green roof model utilised which had a volume of 8855 cm^3 and weighed 6.8 Kg unsaturated.

Table 5.3.2: Planting requirements for vegetables (after Starke Ayres, 2016)

Plant type	Depth (cm)	Lateral Spacing (cm)	Vertical Spacing (cm)	Weight (Kg)
Swiss Chard	2	20	60	1.84
Lettuce	0.5-1	25	40	0.38-0.77
Tomato	0.5-1	40	150	2.30-4.61
Cabbage	1	35	60	1.61
Pumpkin	2	70	150	16.13
Maize	2	30	90	4.15
Egg Plant	2	90	150	20.73
Herbs	0.5	25	25	0.24

Based on the findings presented in the table it is reasonable to assume that an individual will find subsistence farming impractical if the individual were to plant four seeds of a particular type of vegetable as a means of sustenance. Therefore, utilising this assumption, it can be said that the weight of the green roof will increase considerably with the introduction of additional seeds that conform to the recommended planting requirements.

5.3.4 Summary of experimental case studies

The case studies were done to understand the relationship between the structural materials and how they influence the overall structure in an attempt to better understand why most green roof systems are constructed over reinforced concrete structures.

From the three cases considered, it was found that the concrete structures had the greatest reserve capacity and hence, a higher potential of being retrofitted in comparison the other designs carried out. This was attributed to the properties of concrete i.e. it’s high load bearing capacity and particularly high strength in compression.

Due to the smaller load carrying elements in the roof structures of industrial and low-cost housing type structures, even though they are designed to be at an optimal, it is often the case that these elements are designed to carry small loads in the form of roof sheeting or roof tiles and as a result, limits the potential of having a greater reserve or additional load-carrying capacity. Hence, this influences the structure’s ability to be retrofitted with a reputable green roof structure without implementing a form of structural upgrade.

5.4 Overall results and discussion

The findings of the theoretical analyses suggest that older structures have the necessary capacities to carry and be retrofitted with substantially larger green roof systems. The findings of both studies suggest that of the structural material types available, reinforced concrete structures are the most well-suited structures to carry out or sustain a green roof retrofit system. It was also found that the choice of structural element influences in magnitude of any potential additional load. The studies have highlighted further that due to variation of structures there is no definite indication of a possible ability to retrofit with a green roof without going through the process of determining the current loading conditions and reserve capacities.

CHAPTER 6: TEMPERATURE ANALYSIS

6.1 Introduction

This chapter of the research presents the theoretical analysis that investigates various studies publicised in literature on the temperature effects of green roof systems and the findings of an experimental analysis carried out. These investigations were carried out with the aim of determining if there is a corroboration amongst the studies that could either prove or disprove the theory that green roof systems have the potential to reduce the temperature within a structure.

6.2 Theoretical Temperature Analysis

Publicised scientific literature with regard to the temperature reduction potential in green roofs was carried out to assess results and perspectives from studies that were unable to be produced practically in this study.

6.2.1 A study of green roofs and the associated climate

The success of a green roof is largely dependent on the climate that it is exposed to. Based on this fact it may be reasonable to assume that the climate has a large influence on the green roof and provides an array of benefits that varies per climatic condition. However, is a green roofs efficacy and purpose influenced by a variation in climate or a similar climate with a variation in location? This question was sought to be investigated by researchers, Pearce and Semaan (2016).

The primary purpose for green roof systems could largely be linked to the climatic conditions of the region within which it has been constructed. For instance, in climatic conditions that are deemed to be rainy the primary purpose of green roof systems could potentially be to promote stormwater management by reducing stormwater runoff. Whereas, on the contrary, in hotter climates green roof systems may be utilised to provide thermal comfort and increased energy performance through the reduction of a structure’s temperature.

To determine the influence of climate, the studies compared on three bases i.e.:

1. A comparison of two cities (Singapore and Rio de Janeiro, Brazil) based on equatorial climates in which, peak flow reductions were investigated.

2. A comparison of two cities (Loutraki, Greece and La Rochelle, France) based on warm temperature climates in which, indoor air temperature and the decrease in annual energy demand were compared
3. A comparison of three cities (Toronto, Canada, Lund, Sweden and East Lansing, USA) based on snowy, humid climates, compared annual stormwater reduction levels between the three cities.

Singapore and Rio de Janeiro are both said to have the same climate. A comparison of the results obtained from the studies performed in the two cities is presented in *Table 6.2.1*. In Rio de Janeiro the study of stormwater retention runoff from extensive green roofs was carried out on four test plots and observed over a period of nine months. In Singapore, the test was performed utilising three test plots over an observed five-month period. The study had determined that both locations produced similar peak flow reductions after the rainfall events, suggesting a similar annual stormwater retention could be expected at both locations.

Table 6.2.1: Comparison of green roof performance in Equatorial climates (after Pearce and Semaan, 2016)

Data Points	Singapore	Rio de Janeiro
Study Period	June 2012 – November 2012	January 2004 – September 2004
Average Annual Precipitation (mm)	2378	1278
Average High Temperature (°C)	30.7	29.8
Average Low Temperature (°C)	21	20.8
Stormwater Retention (%)	-	60.3
Peak Flow Reduction (%)	65	61

Table 6.2.2 compares the results of the thermal properties and energy performance studies carried out on extensive green roofs in Greece and France. The studies had determined that there was a decrease in the annual energy demand upon both structures at both locations.

Table 6.2.2: Comparison of green roof stormwater retention performance in warm temperature climates (after Pearce and Semaan, 2016)

Data Points	Loutraki, Greece	La Rochelle, France
Study Period	30 June – 17 August 2000	June – July 2003
Average Annual Precipitation (mm)	517	519.6
Average High Temperature (°C)	22.3	16.25
Average Low Temperature (°C)	10.3	11.25
Indoor air temperature decrease (°C)	2	2
Annual energy demand decrease (%)	4-7	6

The average rainfall retained by green roof systems was investigated over a predetermined amount of time in the respective cities presented in *Table 6.2.3*. The Table summarises the results obtained from the studies, concluding that there is a fluctuation in the annual stormwater reduction between the studies.

Table 6.2.1: Comparison of green roof stormwater retention performance in snowy, humid climates (after Pearce and Semaan, 2016)

Data Points	Toronto, Canada	Lund, Sweden	East Lansing, Michigan
Study Period	May 2002 – May 2004	July 2001 – December 2002	28 August 2002 – 31 Oct 2003
Average Annual Precipitation (mm)	475.2	587.6	806
Average High Temperature (°C)	13.3	11.75	14.1
Average Low Temperature (°C)	5.1	4.16	3.9
Annual flow volume (stormwater) reduction (%)	57	46	60.6

In conclusion of the study carried out by Pearce and Semaan (2016), the researchers conclude that the studies produced similar results with those studies having minor variations being attributed to the possible variation in time. In addition, it is evident that there is no direct relationship between climate and location.

6.2.2 Rome study: Green roof influence on the urban heat island effect

An assessment of existing literature has shown that green roofs have the potential to reduce the urban heat island effect. To assess the influence of green roofs on the urban heat island effect a study was conducted in the city of Rome utilising modelling software to apply green roofs to all the buildings within the identified study area (see *Figure 6.2.1*) and thereafter, utilising the software to reproduce the micro-climate and physical behaviour of urban areas.

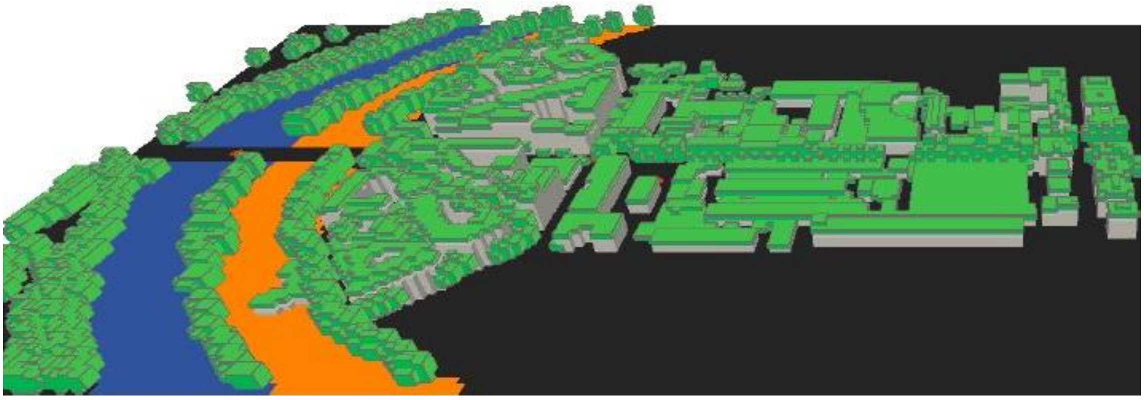


Figure 6.2.1: Distribution of green roof systems in Rome (after Basilicata, et al., 2016)

The results of the study suggest that there is an inversely proportional relationship between the effects of a green roof and an increase in solar radiation i.e. the effects of a green roof decrease with an increase in solar radiation. This is associated with a reduction in the moisture content of the green roof due to an increase in evapotranspiration. This was apparent in the study when solar radiation was at a maximum resulting in the green roof performing the same as a conventional system. The main results of the study however, showed that there was a further temperature reduction of 0.5°C in the morning and approximately 0.3°C at night, providing evidence of a reduction of the urban heat island effect (Basilicata, et al., 2016).

In addition, the study highlighted that adopting green roofs and with the air temperature reduction there is an induced variation in the building's energy performance. An analysis of energy performance of buildings within the study area resulted in a finding of a 2%

reduction in the overall energy saving, corresponding to an approximate 2.6 kWh/day saving.

6.2.3 A study into the energy requirements of extensive green roofs

A study was conducted by researchers Aneli et al. (2014), to investigate the energy requirements of a structure that has been retrofitted with an extensive green roof in terms of heating and cooling loads. The building under consideration is that of a single floor residential building in Sicily. The structure was constructed from reinforced concrete, with a reinforced slab of 25 cm. To assess the thermal performance a baseline was established. The building performance was assessed in both the heating and cooling periods. In calculation of the cooling period observations was conducted during the 1st of June to 30th September. The heating period, on the contrary, was conducted during 1st December to 31st March (Aneli, et al., 2014).

The results of the baseline assessment in both the heating and cooling periods have been presented in *Tables 6.2.4-6.2.7*. With reference to *Table 6.2.4*, which illustrates the results of the energy demand for cooling, a negative sign is an indication of heat loss whilst a positive sign is an indication of heat gain.

Table 6.2.4: Cooling energy demand (after Aneli, et al., 2014)

Thermal Fluxes (kWh)	June	July	August	September	Total
Transmission + Infiltration	-863	-455	-367	-703	-2388
Internal + Solar gains	1009	1025	1019	941	3993
Total cooling	189	-847	-977	-382	-2395

Table 6.2.5 illustrates the results of the cooling load analysis; a negative sign is an indication of heat loss whilst a positive sign is an indication of heat gain.

With regard to energy needed the negative sign is an indication that energy is needed to be extracted from the building. A positive sign is an indication that energy has to be provided to the building.

Table 6.2.5: Energy required for heating prior to green roof (after Aneli, et al., 2014)

Building with Green roof	December	January	February	March	Total
Transmission + Infiltration	-979	-960	-900	-880	-3717
Internal + Solar gains	1014	1029	1022	944	4008
Energy for heating	-44	-107	-207	-94	-452

The baseline assessment highlights that the overall energy demand from the building amounted to 1555 kWh for reasonable cooling and 2395 kWh to achieve total cooling.

To assess the savings achievable through the use of a green roof additional analyses were carried out. The assessment was carried out in the same time frame as the baseline study as a basis of comparison i.e. the cooling period (summer) was conducted during the 1st of June to 30th September. The heating period (winter), was conducted during 1st December to 31st March. The results of the study have been tabulated in *Tables 6.2.6-6.2.7.*

Table 6.2.6: Total cooling loading required with utilisation of green roof (after Aneli, et al., 2014)

Building with Green roof	June	July	August	September	Total
Transmission + Infiltration	-979	-960	-900	-880	-3717
Internal + Solar gains	1014	1029	1022	944	4008
Total cooling	44	-107	-207	-94	-452

Table 6.2.7: Total heating load required with utilisation of green roof (after Aneli, et al., 2014)

Building with Green roof	December	January	February	March	Total
Transmission + Infiltration	-2526	-2701	-2425	-2328	-9980
Internal + Solar gains	733	754	758	966	3210
Energy for heating	1840	1993	1707	1394	6934

The results of the assessment have established that the overall reasonable cooling load amounted to 269 kWh. However, to achieve total cooling, a load of 452 kWh would be required. With respect to the energy requirements, the requirement for heating amounted to 6934 kWh. In comparison to the baseline the heating demand was reduced by approximately 34%.

In addition, the study produced a daily analysis of the temperature profiles over a period of a month (see *Figure 6.2.2*). From the analysis, it is evident that the temperature profiles associated with the green roof are always lower than that of the traditional roof. The average temperature difference for the month between the superstructures (T_{SO}) of the two roof types is approximately 5.44°C. The maximum temperature difference was approximately 6.70°C with a minimum difference of 3.99°C. With reference to the substructure temperature (T_{Si}), the average difference for the month between the two roof types was approximately 3.89°C, with a maximum daily difference of 5.09°C and a minimum value of 1.74°C.

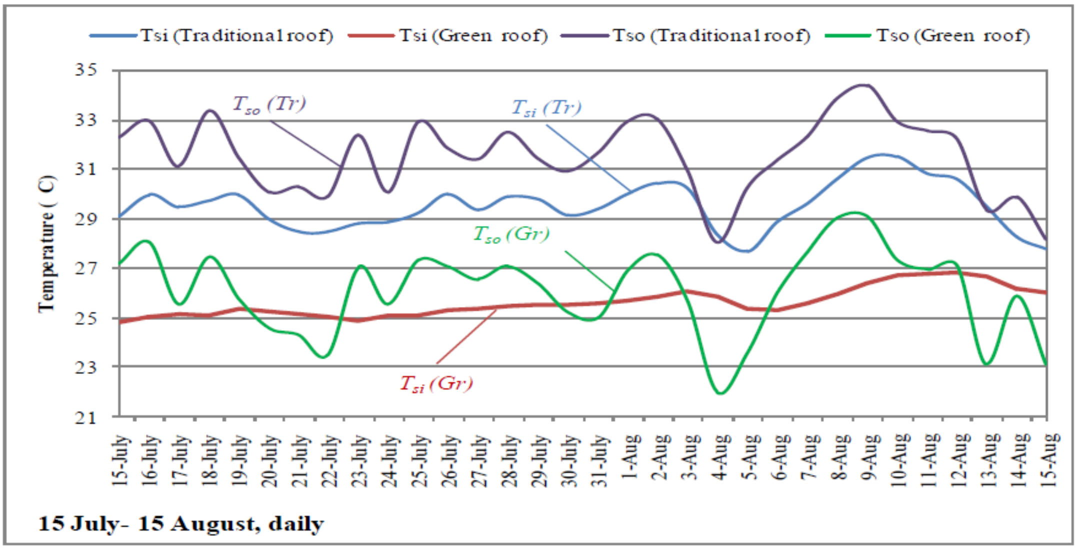


Figure 6.2.2: Daily super- and substructure surface temperature of the traditional and green roof (after Aneli, et al., 2014)

An analysis of the hourly temperature profile between the two roof types (see *Figure 6.2.3*) shows that the superstructure temperature of the traditional roof reaches a maximum temperature of approximately 45°C, whilst the substructure temperature reaches a maximum temperature of approximately 33°C. The green roof however, reaches a maximum temperature of approximately 33.5°C on the superstructure whilst the substructure reaches a maximum of 26.3°C. A temperature difference of 11.5°C in the superstructure and 6.7°C in the substructure of the two roof types, quantifying the fact that green roofs reduce the temperatures experienced within structures.

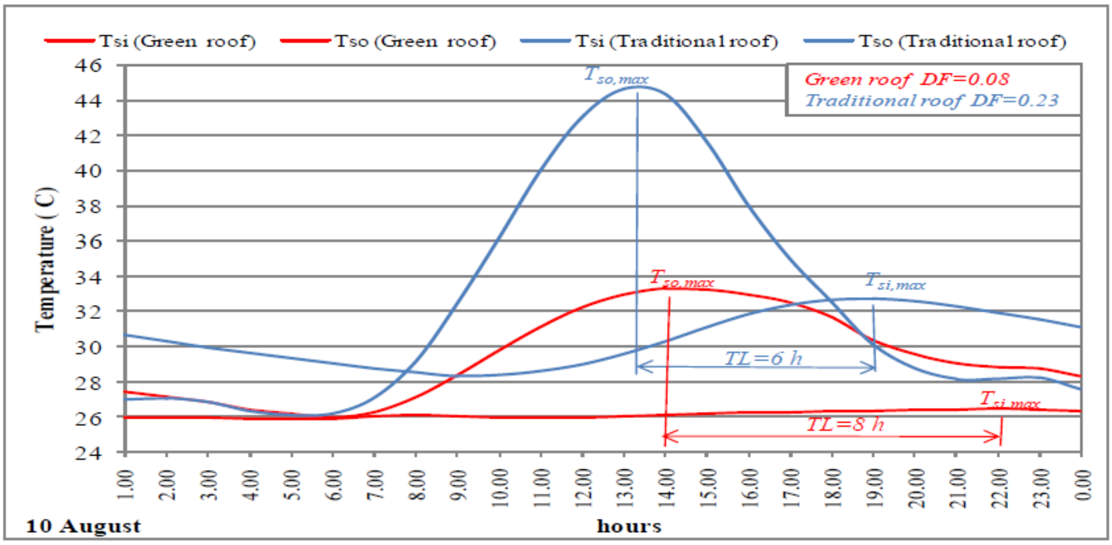


Figure 6.2.3: Hourly super- and substructure surface temperature of the traditional and green roof (after Aneli, et al., 2014)

In summary, the key findings of the study have found that the green roof utilised, had the potential to reduce the structure's cooling load by approximately 80% and the structure's heating load by approximately 34%. In addition, the study has highlighted that the use of a green roof results in a decrease in the substructure temperature of the associated structure and furthermore, results in a delay and attenuation of the outdoor heat wave resulting in a reduction in the average daily temperature between 12°C and 6°C.

6.2.3 Results and discussion

In conjunction with the theory presented in the literature review of this study, a review of various case studies in publicised literature has highlighted that green roof systems have the capability of reducing the temperature of the substructure of the building upon which the roof is constructed. The extent of the reduction varies per study due to the variation in the green roof systems (i.e. deeper green roof systems offer a greater reduction of temperature). The emerging trends however, provide evidence to suggest that green roofs offer a greater reduction in temperature when compared to conventional roof structures. The studies also suggest that the performance of green roofs, although present a slight variation in results, are not significantly influenced by different climates. In addition, due to the spread of the theoretical assessments, there is evidence to suggest that collective green roof systems have the potential to further reduce the urban heat island effect.

6.3 Experimental analysis

An experimental analysis was carried out to further investigate how a green roof effects the temperature of a structure in comparison to other roof types. In addition, the analysis would serve as an addition or act as evidence of contradiction toward the findings obtained from a study of existing literature.

The results of the temperature simulation from the various roof models are presented in the subsequent characters. *Appendix D* illustrates the data obtained from the various temperature analyses conducted.

6.3.1. Tiled roof

The tiled roof model comprised of a roof tile supported by a container (see *Figure 6.3.1*) the results of the experiment have been graphically represented in *Figure 6.3.2*. Data for the experiment was collected over a period of 8 days. The average difference in temperature for the roof model was found to be 0.9 °C. The maximum and minimum temperature difference of the model was found to be 2.6 °C and 0.1°C respectively.

Figure 6.3.1: Tiled roof model

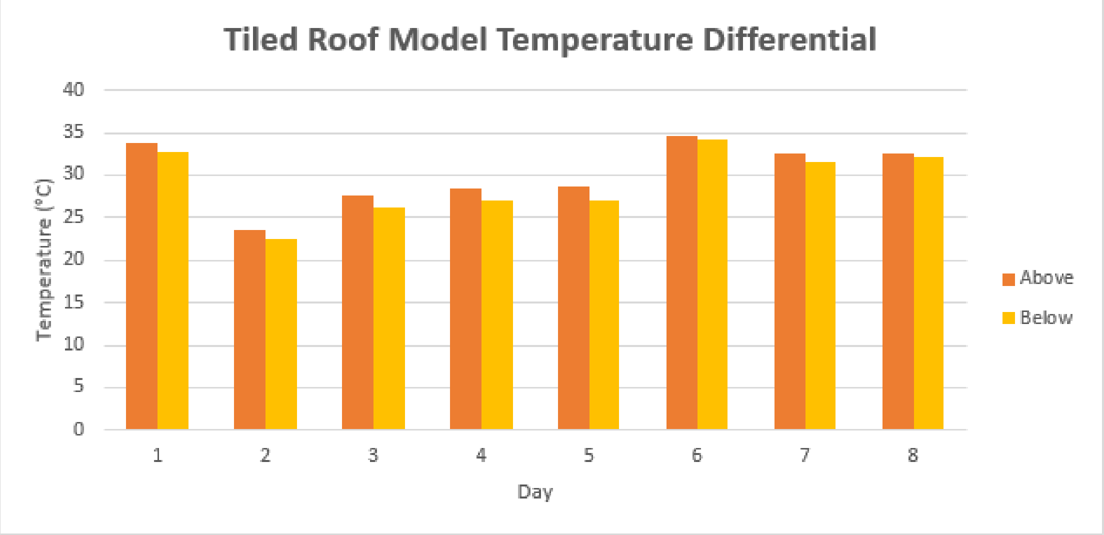


Figure 6.3.2: Temperature observed on the tiled roof model

6.3.2 Green roof

The green roof model utilised for the temperature analysis can be seen in *Figure 6.3.3*. Data for the green roof model was collected over a period of 6 days. The results of the experiment have been graphically represented in *Figure 6.3.4*. The average temperature difference above and below the roof model was found to be 1 °C. The extremities of the temperature difference showed a maximum temperature difference of 3.7 °C with a minimum temperature difference of 0.1 °C.

Figure 6.3.3: Green roof model

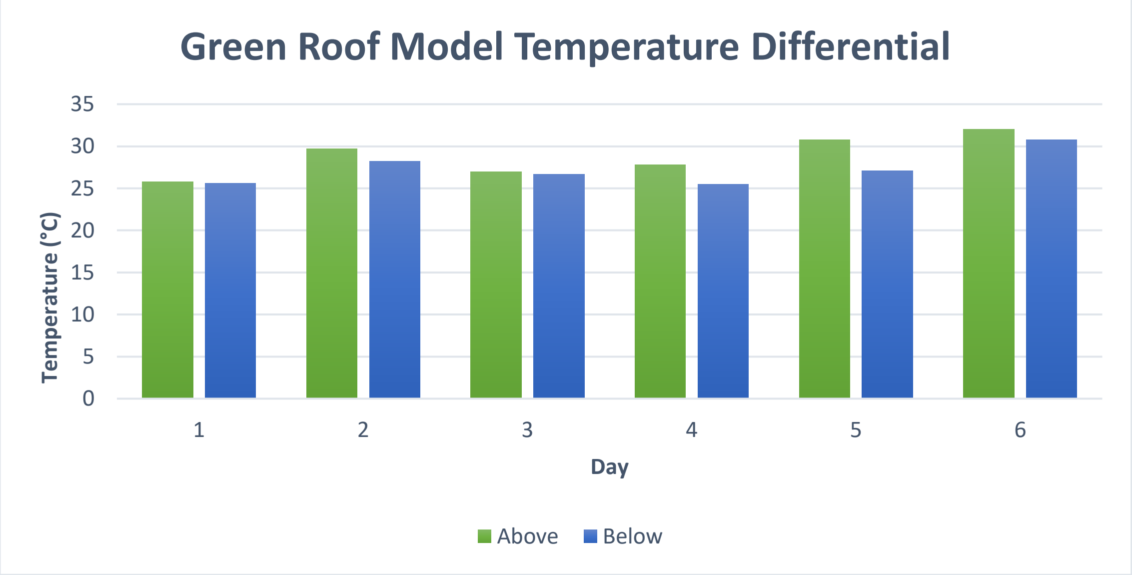


Figure 6.3.4: Temperature observed on the green roof model

6.3.3 Concrete roof

Figure 6.3.5 illustrates the concrete roof model utilised in the temperature analysis. *Figure 6.3.6* is a graphical representation of the results obtained from the 4-day temperature analysis. The average temperature difference above and below the concrete roof model was found to 0.7 °C. The extremities obtained from the analysis yielded a maximum temperature difference of 1.6 °C and a minimum temperature difference of 0.1°C.

Figure 6.3.5: Concrete Roof Model

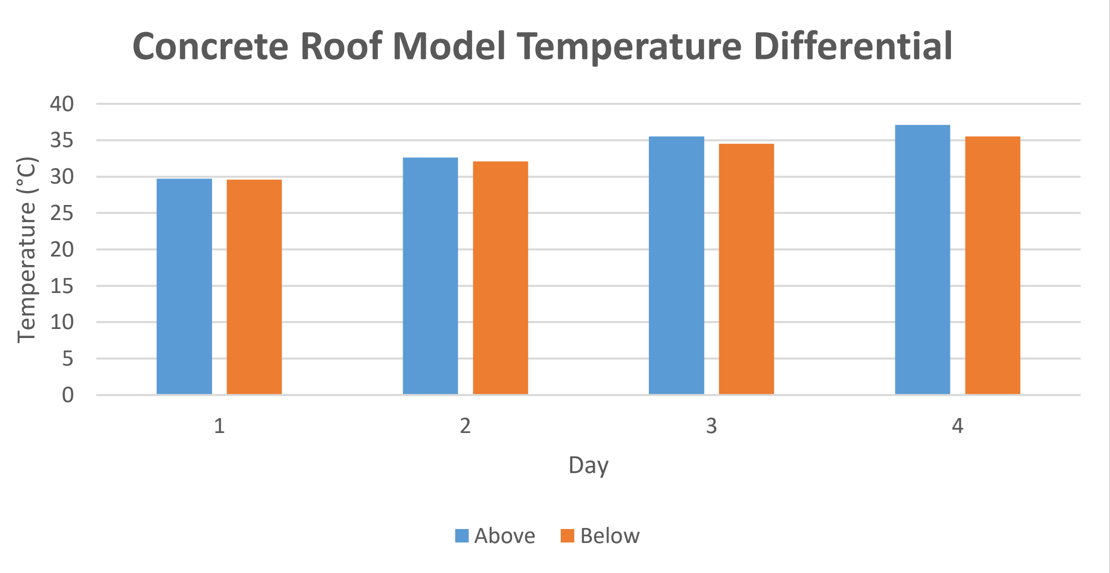


Figure 6.3.6: Temperatures observed on the concrete roof model

The variation in the number of days that data has been collected has been attributed to the presence and reoccurrence of inclement weather that has hindered the recording of data. The results of the experiment provide evidence to suggest that of the roof models, green roofs have a greater potential to reduce the temperature of the substructure as opposed to other conventional roof types. Theoretically, the deeper the green roof the greater the potential for heat reduction in the substructure. This is based on the absorption of incoming solar radiation by the growing medium.

The results of the experiment have shown that although there is a greater difference in temperature produced by green roofs, the results are not entirely significant and do not form an entirely consistent difference in temperature.

6.3.4 Shortcomings and limitations

It must be noted that the results of the experiment may not form an entirely accurate representation as there is potential for error. These errors may be attributed to the fact that the experiment does not take into account the effects of temperature retention through solar absorption of the containers and that of the concrete brick. Furthermore, due to the fact that the thermometers were placed upon the respective models and were subjected to air flow, the influence of the air flow had not been measured and could have potentially influenced the results of the experiment.

In addition, calibration or lack thereof, of the thermometer may have resulted in errors in the recorded temperature and as a result may have either under-read or over-read the temperature. However, the same thermometer and methodology was utilised for the experiments and if there does exist a degree of variation it was applied to all the roof models.

6.4 Overall results and discussion

The findings of both the theoretical and experimental studies have highlighted that green roof structures, in comparison to conventional roof structures, have the potential to reduce the temperature of the structure upon which the roof system is constructed and when utilised as part of a widescale project has the potential to reduce the urban heat island effect. The degree to which green roof systems reduce the temperature experienced within structures varies per green roof structure based on the depth of the growing medium layer within the green roof system. In addition, there is no direct influence to a green roof’s temperature reduction performance with respect to varying climates.

CHAPTER 7: STORMWATER RUNOFF ANALYSIS

7.1 Introduction

This chapter of the research presents an investigation into various studies publicised in literature based on the stormwater runoff potential of green roof systems. In addition, it presents the experimental analysis carried out utilising a simulated model. The primary aim of the investigation was to either prove or disprove the theory that suggests that green roof systems have the potential to reduce the stormwater runoff from a structure.

7.2 Theoretical runoff analysis

The theoretical runoff analysis involved the assessment of published scientific literature with regard to the stormwater runoff in green roofs. The assessment investigates various studies to produce a holistic assessment.

7.2.1 Hydrological modelling study of green roof retention performance

A study into the hydrological performance of single and long-term events in green roofs was carried out by Arnbjerg-Nielsen, et al., (2014). The researchers utilised a model that includes both the surface and subsurface components of storage in green roofs. These components represent the overall retention capacity of green roofs and is continuously re-established through the process of evapotranspiration. Validation of the model was achieved through the utilisation of 3 different extensive sedum type green roofs constructed in Demark. Data collection consisted of high resolution measurements of runoff, precipitation and atmospheric variables during a 2-year period from 2010-2012. The responses to hydrology from green roofs were quantified based on statistical analyses based on a 22-year long simulation utilising Danish climate data.

The study has shown that during the single events, the intensities of the runoff experienced at the 10-minute mark was reduced by between 10-36% for the associated 5-10-year return period and approximately 40-78% for the associated 0.1-1-year return period. For the same return periods, the associated runoff volumes were reduced by approximately 2-5% and 18-25% respectively (Arnbjerg-Nielsen, et al., 2014).

The study had determined that the annual runoff volumes amounted to approximately 43-68% of the total annual precipitation and the peak time delay varied between 0 to 40 minutes.

The key results of the study have shown that even with a few millimetres of storage, the mean annual runoff from a structure can be reduced by up to 20% in comparison to a traditional roof. In addition, it was found that there is no linear correlation between the mean annual runoff and storage.

7.2.2 Sheffield Study: Green roof potential to manage stormwater

A study carried out in the town of Sheffield in the United Kingdom to determine the potential of green roofs to manage urban stormwater was perfomed on a small-scale instrumented green roof system. The key findings of the study had determined that the average retention volume amounted to approximately 34% with an associated peak reduction volume of 57%. These volumes were influenced by the dry weather periods that had occurred during the duration of the study, mean rainfall intensity and rainfall depth (Stovin, 2010).

The researcher had found, through a detailed study of the relationship between rainfall and the associated runoff during the summer of 2007, that the performance of a green roof is dependent on antecedent moisture conditions. In addition, the structural assessment of flat roofs suggests that the feasibility of retrofitting a structure with a green roof may be feasible option, particularly in roofs constructed from concrete slabs.

Initial testing of the green roof model was carried out over a single day. In this simulation, the Authors utilised a 9.2mm rainfall event which produced a runoff of 3.55mm. This represents a 61% reduction in the stormwater volume. The study carried out throughout the English spring of the year 2006 had performed and monitored 11 rainfall events. The results of the study show that the average runoff volume amounted to 56% of the total rainfall, with a peak runoff volume of 43%.

Further studies carried out in the summer of the year 2007 had produced very different results from the previous study. The second study carried out by the authors was conducted during the months of June and July of 2007. The rainfall event experienced on the 11th of June was one that occurred following a prolonged dry period. During this rainfall event, 12.8mm of rainfall fell and due to the antecedent conditions, all of the rainfall was retained by the green roof. During the second rainfall event that occurred on the 13th of June, the event had a produced a total of 24.8mm of rainfall. A total of 16.1mm of rainfall was retained during the event, representing a 65% retention volume. The third rainfall event occurring on the 14th of June had produced a total rainfall of 74.4mm.

However, it was observed that the green roof system was still saturated, as only 5% of the total rainfall volume was retained. On the 15th of June, the study had observed negative retention due to drainage from the accumulated volume. In addition, the Authors state that the green roof system had failed to regain its moisture retention capacity over the subsequent days, with 27% of the total 24.8mm of rainfall being retained 24th of June and a surprising 0% of the total of 37mm of the total rainfall being retained on the 25th of June. The overall retention volume for the month of June had amounted to approximately 33% and 45% in July, due to a reduction in the extreme rainfall events.

The second study has highlighted the fact that green roofs cannot be seen as a standalone means to reduce the impact of stormwater runoff and the associated impact of extreme rainfall events. However, it can still be seen as control measure and can play a significant role in reducing the total runoff volume, with additional potential benefits to the quality of stormwater runoff.

7.2.3 Stormwater retention performance in three different climatic regions

A study carried out by researcher’s Hay et al. (2016), investigates the impact of different climatic regions on the performance of green roofs in terms of stormwater retention. Three identical green roof systems were located in London, Ontario (humid, continental climate), Calgary, Alberta (semi-arid, continental Climate) and Halifax, Nova Scotia (Humid, maritime climate). The study had produced results that indicated that regions with drier climates have a greater cumulative retention stormwater retention capacity by percentage. This was based on the findings that showed that Calgary, at 67%, had a greater percent retention when compared to both London, 48%, and Halifax, 34%. During the study period it was found that when comparing the retention capacities of the green roof systems based on the retained depth of stormwater, the city of London recorded a retained depth of 598mm, whilst Halifax and Calgary recorded 471mm and 411mm respectively. The researchers state that climatic impact was most evident in medium sized storms where antecedent moisture conditions (AMC), occurring at the beginning of the rainfall event, govern the retention performance of the green roof (Hay, et al., 2016).

With similar stormwater retention capacities found at all three sites utilised in the study for a given AMC, it has been established that AMC is an indicator of the retention performance of green roofs in any given climate.

The research had established that AMC can be seen as an excellent predictor of the stormwater retention capacities of green roofs. The findings from large rainfall events (those greater than 45mm) during the study, showed that the green roof retention averaged between 16%-29% in all cities.

The overall results from showed that green roofs in drier climatic conditions have a greater retention capacity due to the associated lower AMC in the growing medium. However, moderate to wet climatic conditions have a reduced retention capacity in comparison to drier climatic conditions but still provide a substantial reduction benefits (Hay, et al., 2016).

7.2.4 Long term stormwater performance study

Research conducted by researchers Berretta, et al. (2013), suggest that the retention capacity of a green roof system is dependent on the system's physical composition and is largely influenced by local climatic conditions, inclusive of rainfall characteristics and the restoration ability of the green roof system's retention capacity during dry weather periods.

The researchers developed a concept hydrological flux model to simulate the long-term runoff and drought risk, the likelihood of drought periods and the associated required irrigation in green roofs. In addition, the model links evapotranspiration rates to moisture content rates in the substrate of green roofs and validates the results utilising observed runoff data. Utilising the model, the volumetric retention capacities of green roofs in different climatic conditions were found to range between 19% in wet climates to 59% in dry climates. The simulation further considered retention performance per rainfall event and it was found that there was a significant decrease in the retention performance of green roof systems when considering high rainfall events in isolation (Berretta, et al., 2013).

A sensitivity study conducted during the research to further investigate green roof retention capacities suggests that green roof systems offer a reduction in retention capacities when these systems have a reduced moisture holding capacity and/or low evapotranspiration rates, whilst green roof systems offer strong drought resistance when they have high moisture holding capacities and low evapotranspiration rates (Berretta, et al., 2013).

7.2.5 Behaviour of moisture content in extensive green roofs

A study conducted by researchers Berretta, et al. (2014), to investigate the behaviour of moisture content in extensive green roof systems during dry periods has shown that a key parameter in the influence of stormwater retention capacities and hence, overall hydrological performance is that of evapotranspiration. The findings of the study were supported by the continuous in-field monitoring of moisture content from four green roof test models. Three of the models incorporated vegetated sedum and one model was left unvegetated. To measure soil moisture profiles and temporal changes in the moisture content of the substrate material in the study, water content reflectometers were installed at three different soil depths and recordings were taken at 5-minute intervals (Berreta, et al., 2014).

The results of the measurements showed a constant variation in the vertical profiles of moisture content with an increase in the moisture content levels at the deepest depths of the substrate material within the vegetated green roof system.

In terms of daily moisture loss rates the study has shown that both temperature and moisture content influence the daily rates with the presence of vegetation resulting in a higher daily moisture loss. In addition, when there was a reduction in soil moisture there was an associated reduction in moisture loss/evapotranspiration.

7.2.6 Summary

Case studies were investigated to establish the stormwater runoff potential of green roof systems carried out in various existing research studies. The key findings of the study have shown that in comparison to conventional roof systems, the properties of green roof systems allow for a greater reduction in stormwater runoff from structures. The extent to which these systems reduce the stormwater runoff varies based on the depth and efficiency of the growing medium layer of the green roof system and hence, the type of green roof system. In addition, to the growing medium, studies suggest that the retention performance is further influence by local climatic conditions and in particular rainfall characteristics, showing evidence that drier climatic conditions result in greater reduction performance in comparison to wet climatic conditions.

7.3 Experimental runoff analysis

The experimental runoff analysis was done on the basis of corroborating or contradicting the theory and adding to the findings of the studies found in literature.

7.3.1 Run-off model

The run-off model assesses the difference in the amount of simulated rainfall that is retained by the various roof models and that which escapes as run-off. The results of the experiment aimed to either validate or disprove the theory that suggests that green roofs have a higher potential to reduce storm water run-off. The results of the simulations are tabulated in *Table 7.3.1*. With reference to the Table (Trials A, B, C) it is evident that green roofs are capable of significantly reducing the volume of stormwater run-off, in comparison to the other roof types. The average run-off volume from the green roof model amounted to 270 ml. With reference to *Table 7.3.1*, the difference in run-off volume, as per the trials, is based on the variation in saturation of the green roof model. This highlights the fact that in periods of consecutive rainfall events the run-off from a green roof will increase. The findings of the experimental model provide further evidence suggesting that green roofs offer a greater reduction in stormwater runoff. However, this is not to be taken in isolation.

Table 7.3.1: Average run-off volume from roof models

Roof type	Run-off volume (ml)			Average Run-off Volume
	Trial			
	A	**B**	C	
Green	370	290	150	270
Concrete	950	970	940	953.33
Tile	920	950	930	933.33

Utilising the difference in average run-off volume between the green roof model and the other roof models, the potential carbon emission savings associated with the implementation of a green roof upon the other roof type has been quantified in *Table 7.3.2*. As explained previously, the carbon emission savings are based on the average volume of water that would be retained by the green roof, which had previously been run-off, and further reduces the need for hydration of the roof type through the use of potable water.

Table 7.3.2: Carbon emission savings from associated run-off

Roof model comparison	Difference in volume (ml)	Difference in volume (Kl)	Emission Factor ($\frac{Kg.CO2}{Kl}$)	Emission Savings (Kg. CO_2)
Green-Tile	663.33	0.000663	0.4091	0.000271
Green-Concrete	683.33	0.000683	0.4091	0.000280

The green roof model utilised to simulate run-off had a surface area of 0.081 m^2 (27 cm x 30 cm). From *Table 7.3.2* it can be seen that the green roof has the potential to produce a carbon emission saving of 280×10^{-3} $Kg.CO_2$ when utilised on a concrete roof and 271×10^{-3} $Kg.CO_2$ when utilised on a tiled roof. Utilising the results obtained from the run-off modelling tabulated in *Table 7.3.1*, a green roof with an area equivalent to 1m^2 will result in an average run-off volume of approximately 3.34 L from a total volume of 12.35 L.

Utilising the maximum average rainfall of 96.77 mm (see *Appendix E*) for the month of March and taking into account the assumed roof area, it is estimated that a maximum volume of 0.09677 m^3 will fall as precipitation in the city of Durban. Utilising the results from the experiment, it is estimated that a green roof surface area equivalent to 1 m^2 will result in a surface run-off volume of 26.12 L from the total volume of 96.77 L. This amounts to water retention of 70.65 L and effectively a carbon emission saving of 0.0289 $Kg.CO_2$. Subsequently, *Figure 7.3.2* is a graphical representation of the potential carbon emission savings associated with the average monthly rainfall for the various months of the year. In addition, it highlights the average rainfall volume for the respective month assuming a 1 m^2 roof area, together with the volume of rainfall retained and that which is lost through run-off.

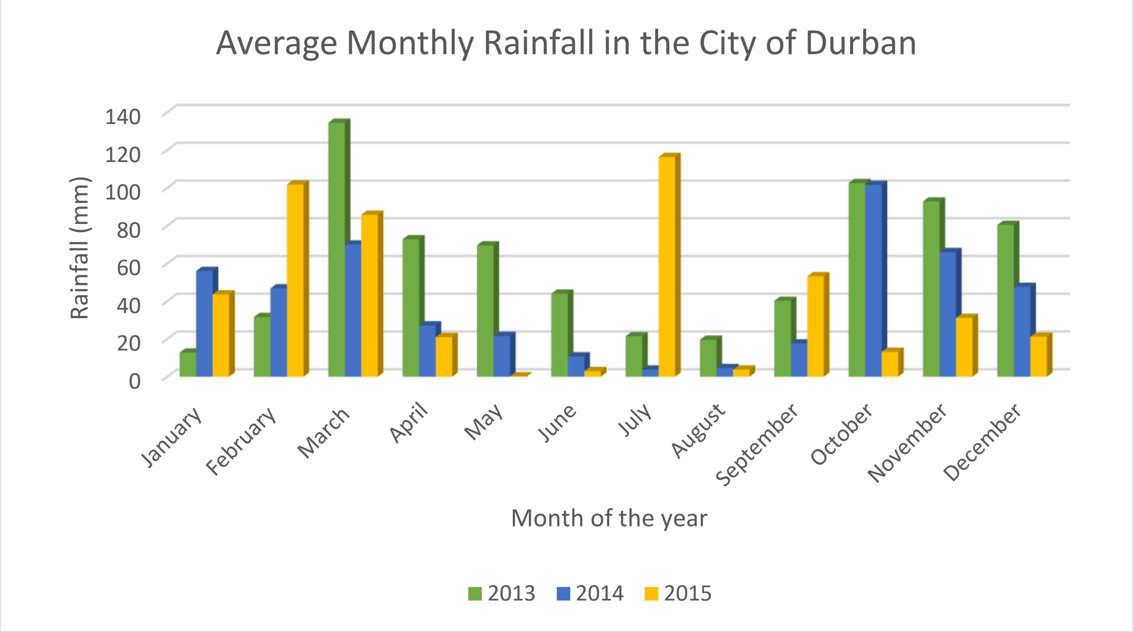


Figure 7.3.1: Average monthly rainfall in the City of Durban

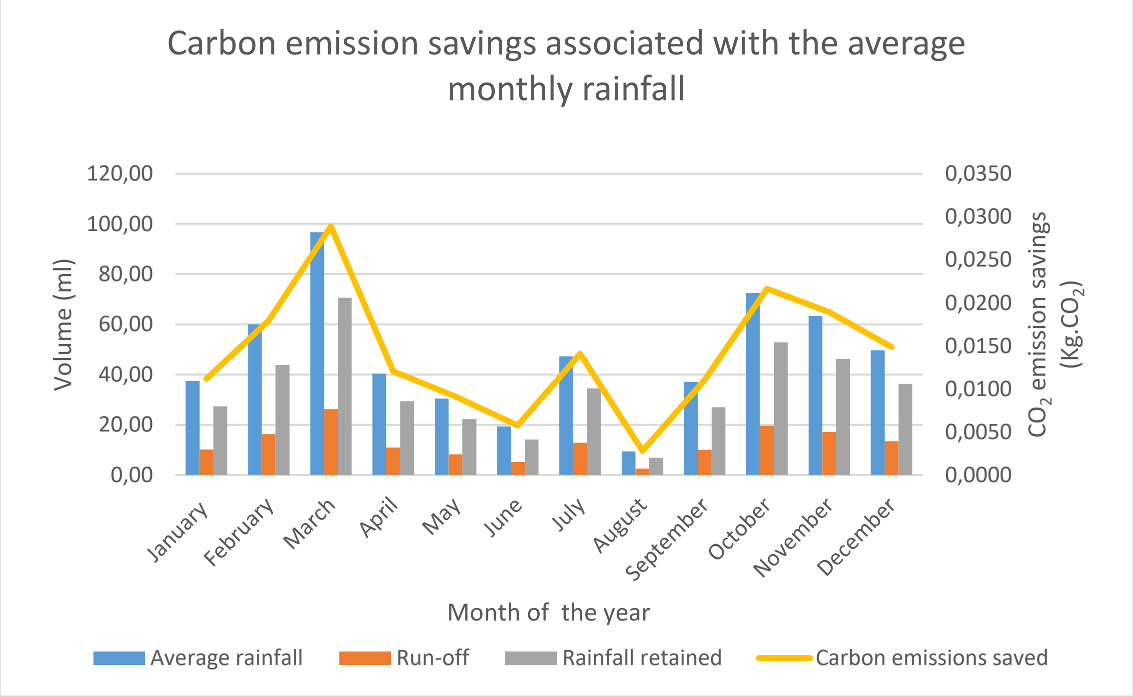


Figure 7.3.2: Carbon emission savings associated with the average monthly rainfall

With reference to *Appendix F*, which illustrates the raw data utilised to produce the graphical representation in *Figure 7.3.2*, the total carbon emission savings per year, resulting from a total rainfall volume of 563.43 ml that falls upon a green roof area of 1 m^2 and subsequently results in run-off and retained volumes of 152.28 ml and 411.15 ml respectively, amounts to 0.170 Kg.CO_2. This result is based on the findings of the experiment and has been modelled per square meter as a hypothetical scenario to allow for the determination of carbon emission savings for larger roof areas.

7.3.2 Green roofs vs rainwater harvesting

It can be argued that in terms of carbon emission savings associated with savings in water, green roofs may not yield the greatest carbon emission savings. Considering a rainwater harvesting system that is deemed ideal i.e. the total amount of rainfall that enters the catchment area, a structure's rooftop in this regard, run-offs the catchment area and is stored in the rainwater harvesting tank without any losses along the system. Assuming a catchment area of 1 m^2 and utilising the average rainfall illustrated in *Figure 7.3.1*, it was found that per year, a total of 0.231 Kg.CO_2 could be saved by harvesting a total of 0.536 KL of rainwater (see *Appendix G*). *Figure 7.3.3* illustrates the volume of rainfall that serves as the input volume to the catchment area based on the average rainfall per month. In addition, the figure illustrates the cumulative volume of rainfall that is harvested, assuming that the input volume forms part of storage each month and is not utilised. *Figure 7.3.4* is a graphical representation of the carbon emission savings associated with the harvested rainfall. Utilising these findings together with the results of the green roof carbon emission calculations it is evident that, in a square meter comparison, the use of a rainwater harvesting system results in a 0.061 Kg.CO_2 greater saving of carbon emissions. In addition, the volume of harvested rainfall is directly proportional to the size of the catchment area and therefore, results in greater savings. The same can be said for green roofs, however, green roofs are limited to the saturation point of the growing medium which conversely effects the carbon emission savings. This limitation implies that any additional water will result as run-off and hence, a loss in carbon emission savings. As a result, if an individual seeks to reduce their associated carbon footprint through savings in water, green roofs may not necessarily be the avenue that will result in the greatest savings.

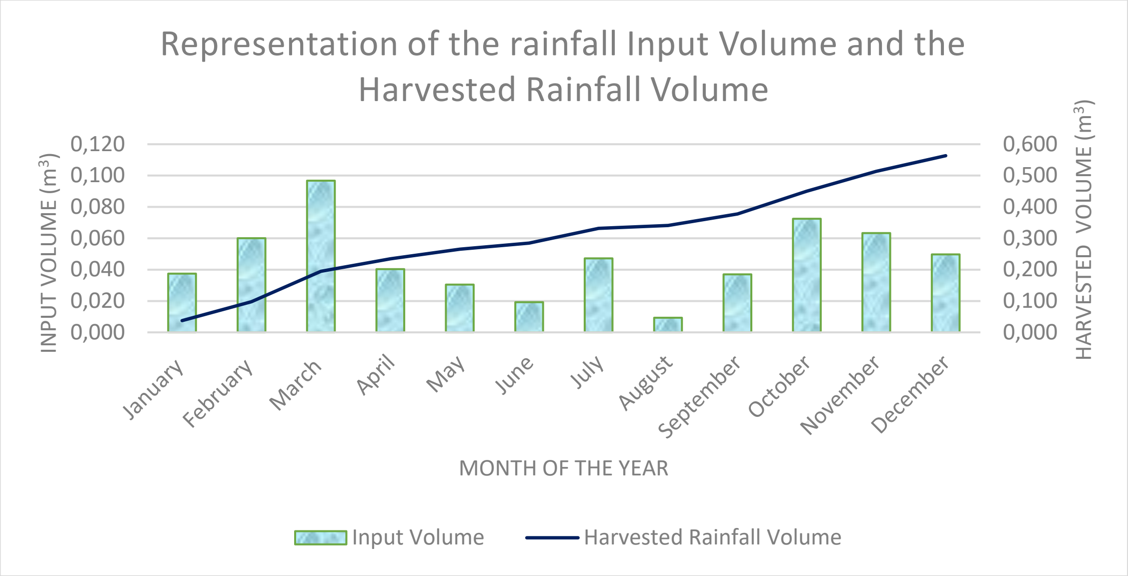


Figure 7.3.3: Representation of the rainfall input volume and the rainfall harvested volume

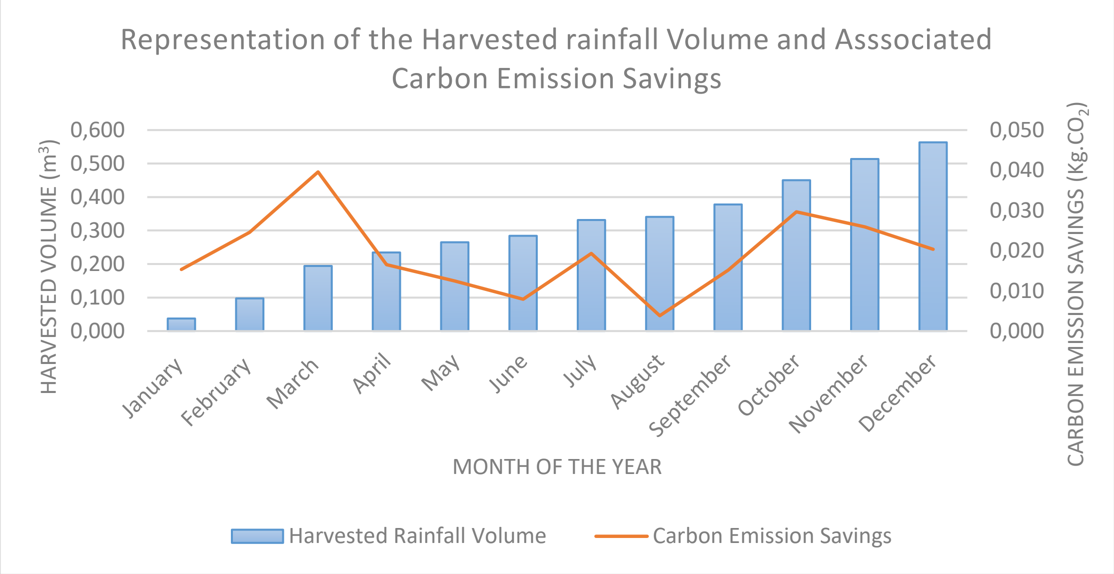


Figure 7.3.4: Representation of the volume of harvested rainfall and the associated carbon emission savings

7.4 Overall Results and Discussion

The combination of theoretical and experimental analysis has shown that green roof systems have the potential to significantly reduce the stormwater runoff from structures. The extent to which green roof systems reduce the stormwater runoff from structures is largely dependent on the retention capacity of the growing medium of the green roof systems and hence, is indirectly dependent on the depth/size of the growing medium. Furthermore, the findings of the study give evidence of the impact of climatic conditions on the stormwater reduction performance of green roof suggesting that green roofs in drier climates offer greater retention. If the primary aim for investment in a green roof system is to reduce or control stormwater runoff then a green roof will prove efficient provided that there are no prolonged rainfall events ensuring that the growing medium is never saturated.

CHAPTER 8: RETROFITTING POTENTIAL

8.1 Introduction

This chapter serves as a presentation of the investigations carried out on both a theoretical and experimental basis. The theoretical study was an investigation into the publicised literature with regard to the retrofitting potential of green roof systems onto existing structures. The experimental study utilises factors presented in literature to carry out an assessment into the green roof retrofitting potential. Both studies were carried out to determine the feasibility, scale and extent to which retrofitting can be conducted.

8.2 Theoretical retrofitting analysis

The theoretical retrofitting analysis combined the results of various published scientific literature in an attempt to assess the results of these studies to gain greater insight into the retrofitting potential of existing structures.

8.2.1 Barriers to green roof retrofitting

The findings of the research suggest that green roof systems have not accelerated or become a widely utilised phenomenon due to the lack of awareness and a poor perception from both governmental and public domains. In addition, the perceived higher costs of new green roof systems also act as a barrier to the development of green roof systems. This has been attributed to the cost estimates of green roof systems being quantified as twice as costly in comparison to standard roof systems and to the fact that the cost of retrofitting existing structures with green roofs are not readily available (Reed & Wilkinson, 2009).

The research was conducted with the aim of determining the potential of retrofitting existing buildings with green roofs in the CBD of Melbourne, Australia. In addition, to determining the potential the study aims to determine the number of buildings that are suitable to accommodate green roof structures. To achieve the aims set out by the researchers a compilation of a database comprising of various information pertinent to the suitability of 536 commercial buildings to undergo green roof retrofitting was undertaken. Each roof structure was assessed through criteria derived by the researchers through an extensive review of literature (Reed & Wilkinson, 2009).

The findings of the study have shown that only a relatively small proportion of the roof structures of the commercial buildings under consideration was suitable for green roof retrofitting. This was due, partly, to local climatic and rainfall conditions. In terms of a physical assessment, it was found that only a small proportion of the structures were found to be suitable to sustain green roof systems. The buildings determined to be suitable were found at low secondary locations, privately owned, ungraded or B grade buildings, structures constructed with concrete and those not being shadowed by adjoining properties (Reed & Wilkinson, 2009).

Of the 536 commercial buildings investigated in the study, it was found that a minor portion of the sample size are historical buildings. Based on this fact, these structures will have to comply with heritage guidelines and hence, regardless of the structure's suitability of the existing structure to sustain a green roof system, these were not considered as potential retrofit options. Of the remaining structures, it was found that most of the structures would require additional analysis whilst others were deemed readily suitable for retrofitting green roofs on existing structures. The study found that less than a third of the structures were overshadowed by other structures but still has acceptable exposure for possible green roof retrofitting. The remaining structures, over a third of those in consideration, are partially overshadowed by existing structures and would therefore, require a detailed assessment to determine if some of the structures have sufficient exposure to sunlight to ensure that vegetation in the green roof system survive.

Type of building construction, overshadowing of the roof structure and green roof options were the categories utilised in a correlation analysis carried out during the study to determine green roof adaptability to existing structures, the results of which had determined that, in comparison to other structures, concrete structures were more suited to sustain green roof systems. This is primarily due to the fact that concrete structures require minimum additional structural alterations to accommodate additional weight (Reed & Wilkinson, 2009).

The study took into consideration the ownership of each structure under consideration and found that most structures were privately owned within the CBD and hence, green roof policymakers would need to incorporate incentives to encourage green roof development.

Another large quantity of structures belonged to the institutional sector. However, with these structures it was deemed that owners would be more invested in developing green roof retrofits. The smallest ownership group within the sample was that of the government or education sector. Consideration toward green roof retrofitting within this sector is based on the availability of financial budgets.

The key findings of the study in relation to green roof retrofitting has shown that 15% of the commercial buildings in the study were suitable for potential green roof retrofitting. Of the total structures, only 3.1% of structures were not overshadowed and were deemed suitable in a physical basis for green roof retrofitting. In addition, it was found that concrete structures were more suited for green roof retrofitting. In terms of ownership, most structures deemed feasible for green roof retrofitting on the basis of sustaining life in a green roof system were privately owned.

The study highlights that commercial structures, particularly those with concrete as a primary construction material are potentially more suitable for green roof retrofitting. It further highlights that if retrofitting were to be undertaken within the CBD of a city, most structures will be privately owned and hence, a more concerted effort would be required in convincing individuals to invest in green roof systems.

8.2.2 Green roof retrofitting

The researcher Stovin (2010), states that older buildings possess the potential to have a higher capacity when compared to structures that were constructed in the last 30 years. This is due to the potential initial overdesign and associated building regulations. The researcher goes on to state that a large number of medium-rise office buildings in the United Kingdom support flat concrete roofs that could potentially accept a green roof without any structural modification. However, even if this may be accurate, it is a broad statement to make without knowing the current loading conditions and highlights the fact that there is no definite indication and high uncertainty with regard to the retrofitting potential of a structure without a structural analysis.

A study of the Ryokka project in the United Kingdom, which has a long-term aim of retrofitting of as much of the roof structure as practically possible. The building upon which the project is being carried out has three structural roof types i.e. reinforced concrete, a steel frame and a timber frame. A preliminary structural analysis was carried out to determine the viability of retrofitting a variety of green roof systems onto these three types of material. The research had found that the concrete roof had an estimated carrying capacity of 8-10 kN/m^2 (Stovin, 2010).

The highest level of the roof structure comprised of universal steel beams, upon which profiled steel decking with plywood had been laid. Initial calculations found that the primary beams had an estimated carrying capacity of 2.98 kN/m^2. The researchers assumed that if the existing beams were retained, the associated loading inclusive of a retrofitted extensive green roof is estimated at approximately 2.67 kN/m^2. This results in a marginal allowable additional load. In addition, the research had found that the timber frame roof also had a marginal allowable additional load however, further assessments were required to determine the strength of the timber (Stovin, 2010).

The findings of the research highlight that retrofitting of existing structures can be considered for roof structures other than that of concrete. However, detailed structural assessments would be required to determine the allowable carrying capacity.

8.3 Experimental assessment

Following on from the theoretical assessment an experimental assessment was conducted to further investigate the potential of retrofitting structures with green roofs.

8.3.1 Retrofitting potential

The findings of the research presented previously was utilised to determine the average number of existing structures that, in principle, would be suitable for retrofitting with green roofs. The factors utilised and taken into account in classifying a structure as being suitable for retrofitting were:

- Predominately a concrete structure, typically a commercial building type
- Older construction date
- Flat roofs
- Structures with ballasted roofs
- Position of building
- Location of building
- Orientation of the roof
- Height above ground
- Roof pitch

The assessment had begun by investigating the suitably of structures within office parks and the focus was later shifted to a city scene, with the central business district of the City of Durban being the primary study area. Illustrated in *Figures 8.3.1* and *8.3.2* are the structures identified as being potential green roof retrofit structures. The Westway Office Park (see *Figure 5.8.1*) contains 16 potential retrofit structures. Inclusive in the 16 structures are 9 structures with ballasted rooftops. This indicates that without further calculations the structures have the capacity to carry a green roof with the saturated weight equivalent to that of the stone upon the structure.

Figure 8.3.1: Potential green roof retrofit structures at the Westway Office Park (Source: Google Earth, 2016)

The Ridgeside Office Park located at the uMhlanga Ridge, KwaZulu-Natal (see *Figure 5.8.2*) had been assessed based on the factors highlighted previously. From the assessment 19 structures were identified as potential retrofit structures. In addition, 16 of the potential structures contained ballasted rooftops indicating a definite practicality in retrofitting the structures with green roofs.

Figure 8.3.2: Potential green roof retrofit structures in the Ridgeside Office Park (Source: Google Earth, 2016)

As highlighted in the literature review, the central business districts are often areas with the highest temperatures recorded and in conjunction with the activities taking place in the vicinity, produces large amounts of carbon emissions. Therefore, assessing the potential for mitigation methods such as green roofs are paramount in the fight against climate change. *Figure 8.3.3* illustrates an aerial view of the Durban City CBD. The figure forms a graphical representation of the typical rooftops that can be found within the CBD. It is evident that most structures are high rise structures and contain flat roofs. In addition, utilising Google Earth to obtain the Figure proves beneficial on the basis that the software allows for a 3D rendering of the structures, enabling an individual to determine if the potential roof structure will be overshadowed by neighbouring buildings.

A large number of the structures within the CBD are relatively old buildings and have typically been constructed utilising reinforced concrete. *Figures 8.3.4-8.3.6* are graphical representations of three city blocks within the city isolated for study to determine a general consensus with regard to the potential of retrofitting structures within the CBD with green roofs.

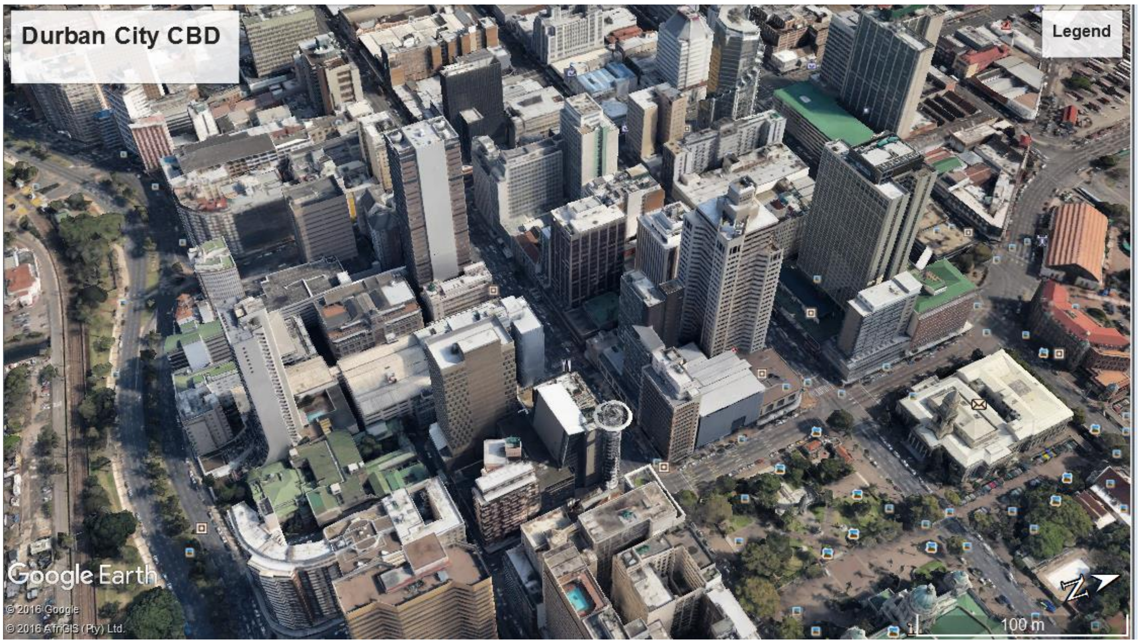


Figure 8.3.3: Aerial view of the typical rooftops within the Durban City CBD (Source: Google Earth, 2016).

Figure 8.3.4: Green roof retrofit potential study zones (Source: Google Earth, 2016).

Figure 8.3.5: Aerial view of the structures in Blocks 1 and 2 identified as being potential green roof retrofit structures (Source: Google Earth, 2016).

Figure 8.3.6: Aerial view of the structures in Blocks 3 identified as being potential green roof retrofit structures (Source: Google Earth, 2016).

The results of the assessment had established that from the three city blocks considered, a total of 38 structures were identified as being potential green roof retrofit structures. With reference to *Appendix H*, which contains the roof areas of these structures, as estimated from Google Earth, the average roof area was found to be approximately 845 m^2. *Table 8.3.1* presents the results of the study isolated per block under consideration.

Subsequently, in an average block area of 38741.3 m^2 within the CBD, an average of 14 structures has the potential to be retrofitting with a green roof.

Table 8.3.1: Results of the green roof retrofit assessment

Study Area	Area (m^2)	No. of potential retrofit structures	Average green roof area (m^2)
Block 1	33353	12	1118
Block 2	36761	9	1687
Block 3	46110	22	352,77

Utilising the results of the prior assessment into the suitability of retrofitting structures with green roofs, an assessment into the potential carbon emission savings that can be achieved, was carried out. The focus was given to the retrofitting potential of structures within the CBD on the basis that the CBD is an area that has the potential to make the greatest impact in the fight against climate change. However, it must be noted that the CBD is also an area with that buildings with owners that would require a significant amount of convincing to implement green roofs.

Figure 8.3.7 is a graphical representation of the potential carbon emission savings that can be achieved utilising a green roof with the equivalent area to that of the average roof area identified previously. The graph takes into account the average rainfall and the associated rainfall volume that will fall onto the roof area. In addition, it illustrates the resultant stormwater run-off and retained rainfall volumes. The total carbon emission savings that can be achieved from the installation of an 845 m^2 green roof, that retains a total of 347 m^3 of rainfall, amounts to approximately 142 Kg.CO$_2$ per year (see *Appendix I* for detailed data).

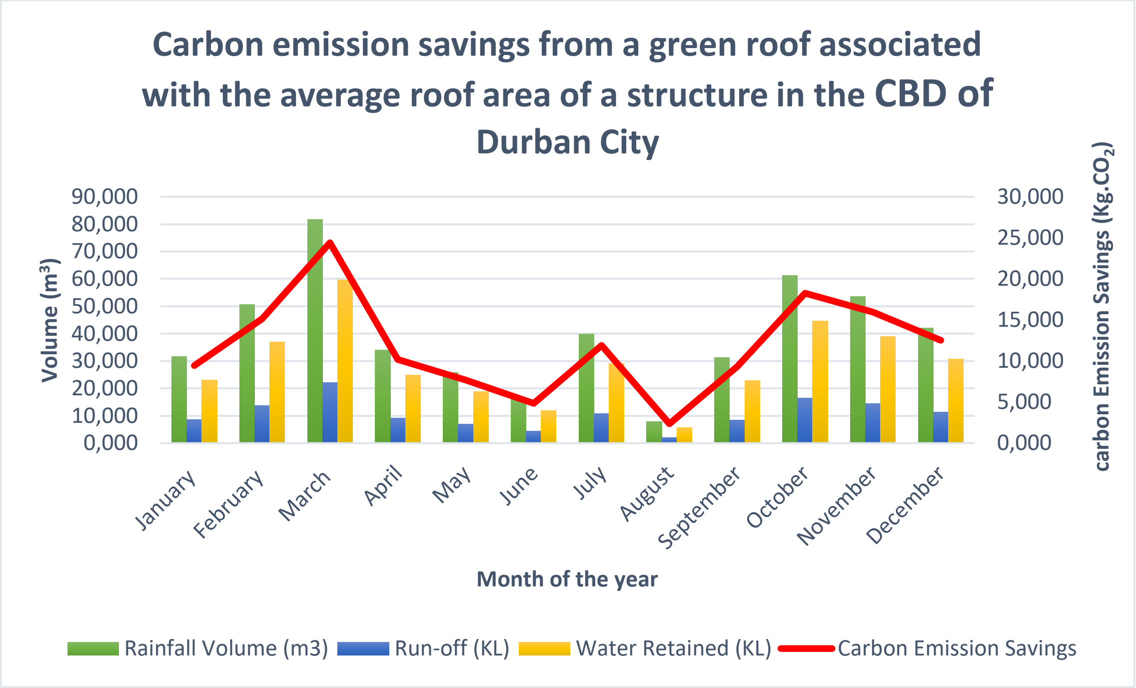


Figure 8.3.7: Carbon emission savings associated with the average CBD roof area

CHAPTER 9: LIFE CYCLE ASSESSMENT/COST-BENEFIT ANALYSIS

9.1 Introduction

Both a qualitative and quantitative investigation was carried out to determine the life cycle of a green roof and the associated cost-benefit in comparison to conventional roof systems. This chapter serves as a presentation of the findings of the investigations.

9.2 Theoretical

Due to various constraints imposed on this study, an assessment of publicised scientific literature investigating the life cycle and cost-benefit of green roofs was carried out to assess the findings of these studies in an attempt to identify findings that were not achieved through practical measures in this study and present a holistic argument.

9.2.1 Life-cycle cost–benefit analysis of extensive vegetated roof systems

Research carried out by Carter & Keeler (2008), to determine a life-cycle and cost-benefit analysis for extensive green roof systems in the Tanyard Branch urban watershed (see *Figure 9.1*) in the American state of Georgia, combined construction costs from an establish green roof test site with experimental storm water retention and building energy utilisation data to achieve the aims of their study. The results obtained from the study were later compared to conventional roof structures. The key findings of the study have established that the net present value associated with an extensive green roof is approximately 10%-14% greater than that of conventional roof systems. However, if the net present value of construction costs associated with an extensive green roof were to be lowered by 20% then the green roof system would be lower than that of a conventional roof system.

Figure 9.1.1: Tanyard Branch Urban Watershed (after Carter & Keeler, 2008)

The researchers had determined that the green roofs would differ based on structural and locality considerations. It is for this reason that an average cost of R1310.265/m^2 (based upon costs obtained from manufacturers) per green roof system was utilised.

The sensitivity analysis of the study utilised a 4% discount rate applied over a 40-year period (the design life of a green roof system) and upon quantification of the discounted costs and associated benefits, the total cost of installation associated with an extensive green roof system within the entire watershed study area amounted to R226 472.02 (see *Table 9.1.1*). However, the total cost of utilising a traditional roof system instead, amounted to R177 588.20 (see *Table 9.1.1*). This shows an approximate 28% increase in costs when utilising a green roof system. However, the researchers assumed an equal stormwater distribution across the entire watershed study area and with that, determined that the associated social (public) benefits would amount to R27 088 779.05 with a social (public) net present value of R199 383 236.30. The benefits of utilising green roof systems in the entire watershed was determined per respective categories, presented in *Table 9.1.2.*

Table 9.1.1: Green roof VS conventional roof NPV (after Carter & Keeler, 2008)

	Private Roof (R)		**Total Public roofs in study (R)**	
	Conservative	Average	Conservative	Average
Green roof costs	1 191 120,15	894 911,57	226 472 017,53	170 152 862,80
Green roof benefits	79 483,64	157 081,98	27 088 779,05	41 889 338,54
Green roof NPV	1 111 636,35	737 829,59	199 383 238,48	128 263 524,26
Conventional roof NPV	935 161,84	935 161,84	177 805 700,33	177 805 700,33
Green/conventional roof cost ratio	1,19	0,79	1,12	0,72

Table 9.1.2: Green roof benefits from a social (public) perspective (after Carter & Keeler, 2008)

Green roof benefit	**Unit benefit (R/m^2)**
Avoided BMP cost	74.75
Energy	3.05
Air Quality	0.91
Total social benefits	78.71

Conservatively, this proved to be approximately 12% greater than that of conventional roof systems. However, on average it was found that due to the benefits of green roof systems, these roof systems proved to be cheaper in the long term than that of conventional roof systems.

In addition to the study performed at a public scale, the researchers carried out an analysis to determine a cost-benefit analysis to building owners. Utilising the same methodology as the previous case, the results of the analysis showed that the nett present value of a green roof system would be much higher to a building owner that in comparison to a conventional roof system. The researchers utilised a 929 m^2 roof area as the test model for the analysis and had found that the total cost of constructing a green roof amounted to R1191.94/m^2 whilst, the cost of a conventional roof amounted to 935.16/m^2 for the same roof area. However, the associated green roof benefits to the building owner *Table 9.1.3* amounts to 18.87% more in comparison to the conventional roof system.

Table 9.1.3: Green roof benefits from a private perspective (after Carter & Keeler, 2008)

Green roof benefit	Unit benefit (R/m^2)
Stormwater utility credit	0.33
Energy	3.05
Air Quality	0.91
Total private benefits	4.29

The study has shown that although green roofs have a higher construction cost attached to them initially, the benefits associated with green roof systems that conventional roofing do not offer, make the systems more cost efficient in the long term. In addition, the study shows that from a private aspect, the associated benefits are much higher.

9.2.2 Life cycle assessment of extensive green roofs in Lisbon

The experimental findings of the research carried out by (Alves, 2015) suggest that extensive green roof systems present no advantage over the conventional roof system utilised in the study at an individual scale. This is based on the data demonstrating that the green roof system consumes a higher energy load throughout its life cycle. However, an analysis of the utilisation of extensive green roof systems at an urban scale shows that these systems consume less energy over their lifespan, as a collective, therefore, proving to be advantageous over the conventional roof system. This was partially attributed to the indirect reduction in the urban heat island effect, consequently reducing the impacts on the environment. These findings have allowed the researchers to go on and state that green roof systems can be utilised as a potential avenue for mitigation interventions for issues experienced in the urban areas. The researchers utilised a German software package that allowed for the modelling of the life cycle assessment in accordance with the ISO 14040 standard.

The study found that there was an approximate 4.2 kg.CO_2.eq./m^2 positive impact at an individual scale. On an urban scale the equivalent carbon emission savings were estimated to be more than the emissions emitted by a new light motor vehicle that has travelled over 300 million kilometres. An additional factor that was found to play a large part in the impact of life cycle is the indirect temperature decrease effect through the heat island effect.

On a long-term scale, extensive green roof systems prove to be sustainable. However, with the progression of time, it was found that the constituent materials may need to be replaced with materials that are prove to be more sustainable and environmentally friendly.

9.2.3 Life-cycle cost-benefit analysis of green roofing systems: Installation on Atlanta public schools

Research conducted during a study carried out Whatley (2011), had found that studies conducted in Oregon in the united states of America, comparing the life cycle costs of a single conventional roof and that of a single green roof over a period of 60 years, resulted in the green roof system amounting to approximately 7% more than the conventional roof over the period. The analysis took into account factors such as extension of roof life, savings from energy and stormwater reduction.

In another study investigated by the researcher, it was found that when considering low installation costs of a green roof and associated high environmental benefits of a single green roof project conducted in the state of Michigan, the return on investment was determined to be 11 years.

When comparing green roofs in the context of sustainability, utilising metrics as opposed to measures of a monetary basis, the findings of these studies show that relative to the life cycle and embodied energy of various materials green roof systems have a significantly higher environmental benefit in comparison to conventional roof systems.

9.3 Experimental

In an attempt to produce a cost-benefit analysis associated with the use of a modular green roof, the cost of the single module created for the purposes of this study (see *Appendix J*) was projected to a cost per square meter. The module utilised for the study did not contain waterproofing or a filter layer, however, this was added to the projected cost on the basis that these elements should be incorporated onto a module utilised on a roof structure to prevent damage to the structure and to further reduce the contaminants entering the storm water network. As a result, *Table 9.2.1* presents the hypothetical cost of a basic modular green roof per square meter.

Table 9.2.1: Estimated cost of a basic modular green roof.

Green roof component	Cost (R/m^2)
Vegetation	672
Growing medium	245
Filter fabric	200
Waterproofing	260
Module	384
Total	1761

Utilising the data presented in *Table 8.3.1* and the average roof area of the structures with the potential to be retrofitted with a green roof, as highlighted in *Chapter 8.3*, the potential cost of a green roof of that magnitude is estimated to be R1 488 045,00. This is a significant cost and does not take into account the cost of labour and any other additional expenses.

The result of the temperature analysis showed that the average temperature difference between the green roof and that of the other roof types under consideration, amounted to 2°C. Subsequently, assuming that if the green roof, highlighted above, is installed and that it results in a 2°C lower cooling potential than prior to its installation and further assuming that the structure utilises a 12000 BTU air-conditioner, which is equivalent to 3.5 kWh, takes approximately 5 minutes to cool a square meter by 2°C (SFGATE, 2005), the potential saving as a result, amounts to R338 per day based on a kWh cost of R1.3928, as per the eThekwini Municipality charge. As a result, the cost of implementing the green roof project will result in the project’s payback period i.e. the period after which the green roof becomes profitable based on the associated savings, being approximately 12 years (see *Appendix J*). However, this represents the savings associated with electricity only. Therefore, factoring in the savings obtained based on the retention of water from the green roof that, as a result, serves as a substitute to the use of potable water for the equivalent volume. The savings per year amounts to R5422.87 based on a retained volume of 347.62 KL of water at a cost of R15.60 per KL as per the eThekwini Municipality. Subsequently, the total savings through both, water and electricity amount to approximately R128 793.00 per year. This results in the projects payback period becoming 11.5 years.

9.4 Overall Summary

Considering the results of both studies it can be said that green roof systems have a greater cost-benefit ratio than that of conventional roof systems. Furthermore, it was established that green roof systems are most beneficial to private building owners as opposed to the general public structures. The typical design life of a green roof system is said to be 40 years. When utilised on a structure this represents an extension in the life of the roof system and a greater saving based on the fact that a conventional roof would potentially require renovation at the end of its 20-year design life. However, constituent material of a green roof may need to be replaced during the design life to ensure maximum efficiency.

The studies provide evidence to suggest that although green roof systems have a higher initial cost of construction, their added benefits across its longer design life make the structures more beneficial in the long term. The return period of a green roof structure depends largely on the magnitude of the benefits it offers and this in turn depends on the size and type of green roof system being utilised. In addition, typically, the benefit categories that are utilised to quantify savings are reductions in building energy requirements, reduction in stormwater runoff, and to a lesser degree air quality. However, in certain instances, stormwater runoff reduction benefits depends on whether local regulations allow for compensation if a structure is said to reduce its stormwater runoff.

CHAPTER 10: CONCLUSION AND RECOMMENDATIONS

10.1 Conclusions

The realities of climate change are evident in daily life. Given the slow rate of change, often these changes are not noticeable instantaneously but becomes evident through prolonged periods such as seasonal changes. Due to the increase in negative associations with climate change, new methods of mitigation are explored in various fields. In the structural field, the concept of ‘green building’ is fast being adopted as the norm in all aspects of new design. However, with existing structures suitable measures to optimise the efficiency and minimise the carbon footprint of the structure are being explored. One such measure is the introduction of green roofs.

Various research has highlighted that not all structures are suitable to adopt a green roof therefore, an investigation into the structural implications associated with the potential of retrofitting structures with green roof as a potential mitigation method toward the various issues highlighted in the study was carried out. This thesis had investigated different construction materials together with typical types of structures that exist today. In addition, it has assessed both quantitative and qualitative aspects of research, in an attempt to provide a compelling argument. For residential type structures, it was later decided to assess the potential of retrofitting low-cost housing with green roofs for the primary purpose of utilisation as a food garden. This was done not just as a means of alleviating the magnitude of the carbon footprint and the strain on storm water management networks but as a potential means of empowering people through ‘green structural engineering’. Society has many problems and requires a collective effort in trying to resolve them.

The most significant challenge in this thesis was obtaining building plans. Often designers are bound by ethical practice to refrain from the distribution of client plans without their express permission. Furthermore, when plans were available it was often that of architectural plans. As a result, without structural plans it makes the determination of the carrying capacity of an existing structure increasingly difficult. In addition, without structural plans the structural engineer has considerable difficulty in performing an assessment similar to those underlined in the ISO 13822 code or through general “good practice” methods, for an existing structure. In the event where building and more specifically, engineering plans do not exist, various methods have to be undertaken. These often increase the cost of the project. For instance, to determine the structural properties of slabs, where applicable, will involve taking core samples to determine the slab thickness and concrete strength. To determine the amount of reinforcing will involve carrying out rebar surveys. As a result, this has highlighted the fact that proper, relevant data, forms the baseline of all retrofit investigations. Without which, the project progress will be impeded and may further result in inaccurate representations of a structure's carrying capacity which, in itself, has serious consequences.

One of the benefits of utilising green roofs is the reduction in temperature it promotes. Extensive research, as highlighted in Chapter 2.9 and 2.10, has suggested that green roofs have the potential to reduce the urban heat island effect and lower a structures temperature. An attempt was made to thoroughly test the accuracy of this theory by undertaking both quantitative and qualitative experimental procedures.

With the quantitative approach taken, similar results were found amongst the studies represented in Chapter 6.2 and the general consensus that green roofs do have the potential to reduce the temperature within the structure upon which they are constructed, was achieved. Key findings of the studies have shown that a variation in climate had no significant impact on the temperature reduction performance of green roofs (Pearce & Semaan, 2016). However, further studies show that with an increase in solar radiation there is a resultant decrease in the temperature reduction performance of a green roof system due to the process of evapotranspiration that results in a green roof performing comparatively similar to a conventional roof system (Aneli, et al., 2014).

The reduction of temperature within a structure is estimated to result in a reduction of the cooling and heating loads of the associated structure. Consequently, this results in a reduction of the carbon footprint of the structure. There was no consensus to the extent to which green roof systems reduce the energy performance of a structure as there is variation amongst studies but it has been estimated that green roofs can reduce the cooling load by as much as 80% and the heating load by up to 34%.

Essentially, green roofs work on the principal of forming a barrier between the roof system of the structure and the incoming solar radiation. Furthermore, the nature of green roofs act to slow down and disperse the incoming solar radiation throughout the green roof system. It has become apparent, based on these factors, that the performance and magnitude to which a green roof can reduce the temperature depends largely on the type of green roof system, with the heavier, denser, intensive green roof systems contributing significantly higher reduction rates than that of extensive green roof systems.

Despite this study not being able to investigate and determine the effects that green roofs have on the urban heat island effect through practical measures, there are numerous scientific studies that suggests that green roof systems have the potential to reduce the urban heat island effect, as presented in Chapter 6.2. However, the reduction of the urban heat island requires the collective use of green roofs within a city to make a noticeable impact. In addition, more research investigating this phenomenon would benefit the scientific community. Suggestions on research investigating the effect of the collective use of different green roof systems on the urban heat island is recommended.

From the more qualitative experiment conducted, it was evident that there is correlation between the findings of previous studies presented in Chapter 6.2 and the results experimentation presented in Chapter 6.3 of this study. Although a greater accuracy was placed on the findings of the theoretical case studies due to the inherent errors associated with the experimentation carried out, the results of the experimentation adds to the theory suggesting that when compared to other materials, green roofs have the potential to reduce the heat experienced in the sub-structure. However, although there was considerable variation amongst studies, it was determined that green roofs have the potential to reduce to the temperature of the substructure by a further 2°C -12°C, when compared to other roof types.

It is based on these collective findings that the theory suggesting that green roof systems reduce the temperature of a structure, amongst other key performance indicators, holds true. This suggests that green roof systems may be an avenue to explore as a potential mitigation measure against climate change and a further means to reduce costs and a structures carbon footprint.

Another acclaimed benefit of green roofs was the systems’ ability to reduce the rate of stormwater runoff from the associated structure. Theory presented in Chapter 2.10 suggests that green roof systems reduce the stormwater runoff from structures, the findings of both the assessments carried out in Chapters 7.2 and 7.3 show that this holds true. However, a higher degree of accuracy was placed upon the assessment of the publicised experiments due to the reduced error amongst the studies, that was comparatively higher in the experimental assessment of this study.

The findings of the assessment highlighted in Chapter 7.2 show that the magnitude of the reduction of stormwater is dependent on the depth of the growing medium and effectively, the type of green roof system. Consequently, there was noticeable variation amongst the studies suggesting that green roofs can reduce stormwater run-off by between 20%-67%. A key finding however, showed that the runoff reduction rate from a green roof system was progressively reduced as the system neared saturation. This implies that in periods of extended rainfall, the efficiency of the stormwater runoff from a structure with a green roof will become comparatively similar to a conventional roof system. This idea was corroborated with the findings of the stormwater reduction performance of green roofs in different climates where the key findings suggest that a green roof system was more efficient in reducing stormwater runoff in a drier climate than it in comparison to a wet climate. This was attributed to infrequent rainfall and hence, the failure of a green roof system to attain complete saturation (Hay, et al., 2016).

The results of the experiment conducted and presented in Chapter 7.3, add to the findings of the assessment of the publicised studies highlighted in chapter 7.2, as it shows that the green roof produced a substantially smaller run-off when compared to the tiled and concrete roofs. This was based on the ability of green roof to retain water, the magnitude of which, again, was found to be dependent on the growing medium layer. However, like the assessed publicised studies, the runoff rate from the structure increased when the green roof system attained saturation.

Proving that green roofs have the ability to reduce temperature and stormwater of a structure is excellent motivation for the use of green roofs but is only beneficial if the structure can sustain a green roof. With the aim of understanding the structural implications surrounding the ability of a structure to sustain an additional load and essentially investigating if this additional load is adequate to carry the load of a green roof system and hence, attaining the retrofitting potential of the structure, it is evident that the ability to retrofit an existing structure with a green roof is a function of various factors. Primarily, it involves the structure having the necessary additional carrying capacity and thereafter, factors that influence the suitability and feasibility of a green roof installation at a particular location have to be considered. These include but are not limited to, as previously highlighted in the study, building location, proximity to tall structures and the roof slope. These factors working together is the primary identification of whether a structure can be retrofitted.

There are many parameters that influence the carrying capacity of a structure and each one is dependent on a further parameter. The current carrying capacity and hence, any additional load carrying capacity is dependent on the structural elements that constitute a structure. This in turn, is dependent on the structure's designer and their choices, as well as the codes of practice governing the designer's choices. Subsequently, it has become apparent from the study that parameters such as span, material strength, the use of alternate support structures, etc., each play a vital role in the carrying capacity of a structure. In addition, it was determined that deflection of an element is often the limiting criteria in member selection. As a result, the carrying capacity of a structure is influenced and essentially becomes a function of these parameters of a structural element and in particular, deflection.

Without performing any additional structural assessment, there are two methods that may identify potential structures that can be retrofitted with a green roof. However, structural assessments will still need to be performed at a later stage, prior to any development in the prospective project. These methods include a comparison of a building with similar structural properties that contains a green roof with one that is intended to be retrofitted, to serve as an indicator of the retrofitting potential or those structures that contain ballast roof structures. However, the findings of this study have highlighted that there is no conclusive method of identifying or singling out a structure that is suitable for retrofitting, unless it has been allowed for in the preliminary design.

However, an emerging trend discovered during the study, has highlighted that there is a higher likelihood of a concrete structure having the necessary additional load carrying capacity to sustain a green roof system in comparison to other structural types.

By establishing that the ability to carry an additional load is entirely dependent on the choices made by the designer it is understandable that under the guidelines of the relevant code of practices there is an expectation that the choice of element made by the designer will be greater than the required load, resulting in the element being able to carry a significantly higher load than it has been designed for. However, although there exists the possibility that each element chosen in the structure has the ability to carry a higher load than the design load, the design load of a green roof structure will be limited to smallest load carrying element provided that this element will be directly affected by any changes in the loading.

The study has identified a directly proportional relationship with the additional structural carrying capacity/reserve capacity and the age of the structure i.e. the older the structure the most likely it is to have a higher additional carrying capacity.

The findings that older buildings have a greater reserve capacity in comparison to newer structures were attributed to the variation in building practices and design codes. Of particular importance, was the magnitude to which these additional load carrying capacities compare. The findings have shown that older buildings not only have the capacity to carry a green roof system but an intensive green roof system at that i.e. a much heavier system. The heavier system implies a deeper growing medium and hence an increased benefit in terms of temperature and stormwater runoff reductions. Furthermore, there is corroboration with this fact and the ISO 13822 code that suggests structures built years ago, utilising “good practice” maybe be overdesigned for.

Based on the findings of the older buildings, the use of factors of safety may, to some extent, result in a structure being over-designed for. Updates to codes of practice may highlight that structures have a greater additional load carrying capacity. However, this requires further investigation.

Ideally, to avoid additional costs and damage to the green roof structure, green roofs should be constructed on flat rooms for maximum efficiency. In addition, the utilisation of modular green roofs proves to be the most efficient means of constructing a green roof. This is based on the parameters of cost, efficiency, practicality, ease of installation and disposal at the end of the design life.

From this study, it has been noted that in order to perform an accurate structural assessment of an existing structure to determine a reserve capacity, where applicable, there are items that are needed. These include:

- Structural drawings

Drawings are needed on the basis that they contain important information with regard to the structure. In addition, it provides the structural engineer with a means to carry out relevant structural calculations and provide a graphical representation of the structure, highlighting positions of structural elements. However, this is only pertinent if the structure was constructed in accordance with the plans, any deviation from the plans without documentation could result in an incorrect analysis of the structure in the future.

- Initial investigation

By conducting an investigation of the existing structures in terms of the condition of the structural elements the structural engineer would be able to determine how safe the structure actually is at the moment and may be able to predict how safe the structure will be in the future, based on the identification of cracks, corrosion, visible deformations, etc.

- Design codes

The identification and familiarisation, if unknown, for the respective structure is vital in assessing the existing structure. Utilising an alternate code to assess a structure could result in inaccurate determination of the structure's carrying capacity.

- Analysis

The structure should be analysed in both the ultimate and serviceability limit states.

- Site visit

A site visit would allow for a visual assessment of the existing structure.

- Non-destructive tests

Non-destructive tests are to be performed to obtain further evaluation of materials and components within the structure.

In an attempt to thoroughly test hypotheses and investigate the proposed aim put forward in this study, various studies and methodologies were utilised. The presentation of the findings achieved in the study has highlighted various factors, some unexpected whilst others were expected. Although, there is significant room for growth, this study has explored various avenues and attempted to produce an unbiased scientific study and, in the process, has answered the research question and met the aims and objectives set out.

10.2 Recommendations

Green roof retrofitting has an array of potential for investigation. It is a study that can spread across a variety of different fields that can be combined for a given research scope. This study has highlighted the fact that there are numerous gaps in research that involve green roof systems and it is therefore recommended that the following areas be investigated further:

- Plant selection

Plants utilised in green roofs are often considered based on availability, theme of the green roof system. Currently the only guidelines to assist in selection come from that of German research. As such, research into creating guidelines on plant selection so that more alternatives are made available without being limited to a singular source. More research is required to investigate plant types that will be suitable for use in green roof systems that are often subjected to shaded conditions. In addition, research is required in the field of plants that will be effective in reducing the number of contaminants and nutrients that escape through a green roof system and enter a storm water network.

- Run-off water quality

As research shows green roof systems serve as sources of water retention. However, little is known about the quality of the water that enters into a storm water network from a green roof system. According to Oberndorfer, et al., (2007), research shows that due to a green roof system containing organic matter, water being discharged contains contaminants and nutrients high in nitrogen and phosphorous and can result in this water becoming an added or new source of pollution.

- Degree of water treatment that is required

Following on from the research into the quality of the runoff water, research into the degree to which this water requires treatment prior to it being of potable quality should be investigated.

- Air quality

Oberndorfer, et al., (2007), states that apart from the documentation of indirect benefits of a green roof system on a structures energy and carbon emissions savings, little research has been conducted on the potential of utilising green roof systems on the basis of producing better quality air.

- Retrofitting potential and structural implications:

Most sources of research associated with green roof systems contain little to no research on the effects and implications of green roof systems on existing structures. Often research suggests that a structural engineer should be consulted in order to determine all structural related queries. Although this should be done at all times, further research is needed on guidelines and expectations when retrofitting or designing a structure with the intention of adding a green roof, in order to provide some understanding of the associated basic concepts, expectations and consequences of improper structural workmanship. As such, research should be conducted into topics such as:

  - Temperature effects on structural elements (expansion and contraction of material) due to an addition of a green roof
  - A study into how much longer the addition of a green roof will extend the lifespan of a structure's roof system
  - The influence of a structure's roof system on its carrying capacity. i.e. how truss systems compare with beam and column systems.
  - The influence of a structure's span on the carrying capacity.
  - The influence of a structure's section sizes on the carrying capacity.
  - Measures of introducing cost efficient structural upgrades to accommodate green roofs.

- Biodiversity implications and ecosystem creation:

Due to the nature of green roof systems, they can be considered as a method of bioengineering. Further research is required into the potential benefits of green roof ecosystems and the associated environmental implications and biological interactions. This topic allows for interdisciplinary research (Oberndorfer, 2007)

- Benchmarking

From the research conducted it has become apparent that there are no benchmarks with regard to green roof performance in terms of temperature and stormwater runoff reduction and in addition, the benchmarking of carrying capacity in a structure. However, due to the variation amongst structures the latter benchmark would be significantly difficult to produce. Developing benchmarks would allow for comparison between the performance of the current green roof system and that of international and local best practice.

- Education and Social acceptance

From a social study point of view, there has been little to no research on the social acceptance toward green roofs. There is no indication of how the average individual views green roofs and their willingness to make a concerted effort in implementing one. This highlights the fact that only individuals who are aware of the potential benefits and quite possibly, who can afford to implement them, do so.

- Government intervention and incentives

Following on from the previous point, there is no incentive for the utilisation of green roofs. In South Africa, the government subsidies the installation of solar powered geysers on many low-cost housing projects and other home owners who install them as a personal cost incurred, receive rebates from the power utility, Eskom. However, there is no similar scheme for green roof systems. In addition, apart from an incentive programme there is no government endorsed education programme promoting the utilisation of green roof systems. As a result, the reasoning as to why this is the case may form the basis of an investigation for future studies.

- The future of low-cost housing

Earlier research in this study has indicated the number of RDP, low-cost homes delivered by the South African Government. It has also indicated the percentage of the population living in poverty in the country. Green roof systems can give people a means of food security in the least. However, structural limitations imposed on low-cost housing developments hinder the utilisation of green roof systems resulting in green roof systems being structurally and impractically inadequate. For this reason, it is recommended that a study into the design of new low-cost housing that has the structural capacity to carry a green roof for the purpose of utilisation as a vegetable garden, be investigated. A suggested avenue of investigation is the retrofitting of shipping containers as the potential future low-cost housing model.

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Appendix A

Industrial Building Drawings

Appendix B

Commercial Building Drawings

Appendix C

Low-Cost Housing Drawings

Appendix D

Data obtained during the temperature analysis

Table D1: Green roof temperature analysis data

Green Roof					
Day	***Time***	***Date***	***Above***	***Below***	***Difference***
1	12:00	2016/10/18	25,8	25,6	0,2
1	13:00	2016/10/18	25,8	25,1	0,7
1	14:00	2016/10/18	23,2	23	0,2
1	15:00	2016/10/18	21,7	21,6	0,1
1	16:00	2016/10/18	20,8	20,2	0,6
2	12:00	2016/10/19	29,7	28,2	1,5
2	13:00	2016/10/19	29,2	29,1	0,1
2	14:00	2016/10/19	27	25,2	1,8
2	15:00	2016/10/19	25,1	23	2,1
2	16:00	2016/10/19	23,7	23,5	0,2
3	12:00	2016/10/20	27,8	27,6	0,2
3	13:00	2016/10/20	27	26,7	0,3
3	14:00	2016/10/20	26,5	26	0,5
3	15:00	2016/10/20	25,1	25	0,1
3	16:00	2016/10/20	24,6	23,6	1
4	12:00	2016/10/21	32,4	31,9	0,5
4	13:00	2016/10/21	33,5	31,4	2,1
4	14:00	2016/10/21	29,4	28,6	0,8
4	15:00	2016/10/21	27,8	25,5	2,3
5	12:00	2016/10/22	30,8	27,1	3,7
5	13:00	2016/10/22	29,5	27,2	2,3
5	14:00	2016/10/22	27	26,6	0,4
5	15:00	2016/10/22	26,8	26	0,8
6	12:00	2016/10/23	31,9	29,9	2
6	13:00	2016/10/23	32,4	29,9	2,5
6	14:00	2016/10/23	32	30,8	1,2
6	15:00	2016/10/23	27,9	27	0,9
6	16:00	2016/10/23	25,1	24,5	0,6

Table D2: Concrete roof temperature analysis data

Concrete Roof					
Day	***Time***	***Date***	***Above***	***Below***	***Difference***
1	12:00	2016/10/22	29,7	29,6	0,1
1	13:00	2016/10/22	29,9	29,4	0,5
1	14:00	2016/10/22	28,9	28,5	0,4
1	15:00	2016/10/22	26,9	26,6	0,3
2	12:00	2016/10/23	32,6	32,1	0,5
2	13:00	2016/10/23	32	31,9	0,1
2	14:00	2016/10/23	30,5	29,2	1,3
2	15:00	2016/10/23	28,3	28	0,3
2	16:00	2016/10/23	26,9	25,4	1,5
3	12:00	2016/11/03	35,5	34,5	1
3	13:00	2016/11/03	32,5	31,9	0,6
3	14:00	2016/11/03	30,7	30,4	0,3
3	15:00	2016/11/03	27,1	26,7	0,4
3	16:00	2016/11/03	26,5	26	0,5
4	10:00	2016/11/21	37,1	35,5	1,6
4	11:00	2016/11/21	38,8	37,5	1,3
4	12:00	2016/11/21	39,4	38,5	0,9
4	13:00	2016/11/21	39,6	38,1	1,5
4	14:00	2016/11/21	36,4	35,4	1
4	15:00	2016/11/21	34,7	33,8	0,9
4	16:00	2016/11/21	33,9	33,8	0,1
4	17:00	2016/11/21	32,4	32	0,4

Table D3: Tiled roof temperature analysis data

Tiled Roof					
Day	**Time**	**Date**	**Above**	**Below**	**Difference**
1	11:30	2016/10/16	33,8	32,8	1
1	12:30	2016/10/16	27,8	27,5	0,3
1	13:30	2016/10/16	25,7	24,7	1
1	14:30	2016/10/16	22,1	21	1,1
1	15:30	2016/10/16	21,9	21,3	0,6
2	13:00	2016/10/17	23,5	22,6	0,9
2	14:00	2016/10/17	21,3	20,9	0,4
2	15:00	2016/10/17	19,8	19,6	0,2
2	16:00	2016/10/17	21,8	19,2	2,6
2	17:00	2016/10/17	18,8	18,6	0,2
3	12:00	2016/10/18	27,7	26,3	1,4
3	13:00	2016/10/18	25,7	24	1,7
3	14:00	2016/10/18	24,6	23,4	1,2
3	15:00	2016/10/18	22,5	22,1	0,4
3	16:00	2016/10/18	20,7	20,6	0,1
4	12:00	2016/10/19	28,5	27,1	1,4
4	13:00	2016/10/19	28,7	26,7	2
4	14:00	2016/10/19	28,3	26,9	1,4
4	15:00	2016/10/19	25,6	25,4	0,2
4	16:00	2016/10/19	23,3	23	0,3
5	12:00	2016/10/20	28,6	27,1	1,5
5	13:00	2016/10/20	26	25,3	0,7
5	14:00	2016/10/20	27,8	26,7	1,1
5	15:00	2016/10/20	25,5	24,1	1,4
5	16:00	2016/10/20	24,3	23,4	0,9
6	12:00	2016/10/21	34,7	34,2	0,5
6	13:00	2016/10/21	34,6	33,8	0,8
6	14:00	2016/10/21	33	32,3	0,7
6	15:00	2016/10/21	31,8	30,9	0,9
6	16:00	2016/10/21	27,8	27,5	0,3
7	12:00	2016/10/22	32,6	31,6	1
7	13:00	2016/10/22	29,8	29,1	0,7
7	14:00	2016/10/22	29,3	27	2,3
7	15:00	2016/10/22	27,7	27,2	0,5
8	12:00	2016/10/23	32,5	32,2	0,3
8	13:00	2016/10/23	31,5	30,5	1
8	14:00	2016/10/23	30,5	29,7	0,8
8	15:00	2016/10/23	30,3	29	1,3
8	16:00	2016/10/23	26,3	26	0,3

Appendix E

Rainfall Data from the City Engineers Complex

Table E1: Rainfall Data from the City Engineers Complex

Rain Gauge Station: R04-Cityeng				
Month	***2013***	***2014***	***2015***	***Average***
January	12,8	56	43,6	37,47
February	31,6	46,8	101,8	60,07
March	134,5	70	85,8	96,77
April	72,8	27,2	21	40,33
May	69,6	21,6	0,2	30,47
June	44	10,8	3	19,27
July	21,4	3,8	116,4	47,20
August	19,6	4,6	3,8	9,33
September	40,2	17,6	53,2	37,00
October	102,6	101,6	13,2	72,47
November	92,8	66	31,2	63,33
December	80,4	47,6	21,2	49,73
Total	**722,30**	**473,60**	**494,40**	**563,43**

Appendix F

Data utilised to determine carbon emission savings from a 1m^2 green roof

Table F1: Data utilised to determine carbon emission savings from a 1m^2 green roof

Month	***Average Rainfall***	***Run-off***	***Rainfall Retained***	***CO_2 saved***
January	37,47	10,13	27,34	0,0112
February	60,07	16,23	43,83	0,0179
March	96,77	26,15	70,61	0,0289
April	40,33	10,90	29,43	0,0120
May	30,47	8,23	22,23	0,0091
June	19,27	5,21	14,06	0,0058
July	47,20	12,76	34,44	0,0141
August	9,33	2,52	6,81	0,0028
September	37,00	10,00	27,00	0,0110
October	72,47	19,59	52,88	0,0216
November	63,33	17,12	46,22	0,0189
December	49,73	13,44	36,29	0,0148
Total	**563,43**	**152,28**	**411,15**	**0,17**

Calculations

1. Run-off

37.47mm ÷ 1000= 0.03747m

$\therefore 0.03747\text{m} \times 1\text{m}^2 = 0.03747\ \text{m}^3 = 37.47\ \text{L}$

From the run-off analysis:

0.081 m^2 yields 270 ml of run-off from 1 L

∴ 1m^2 yields 3.334 L of run-off from 12.35 L

∴ 1m^2 results in 10.13 L of run-off from 37.47 L

2. Rainfall Retained

= Average Rainfall-Run-off

Eg. 37.47 L – 10.13 L =27.34 L

3. CO_2 Saved

= Rainfall Retained (KL) × Carbon Emission Factor (0.4091)

Eg. (27.34 L ÷ 1000) × 0.4091 = 0.0112 Kg.CO_2

Appendix G

Carbon emission savings obtained from harvesting rainwater from a 1m^2 roof area

Table G1: Carbon emission savings obtained from harvesting rainwater from a 1m^2 roof area

Month	*Average Rainfall*	*Input Volume*	*Harvested Volume*	*Carbon Emission Savings*
January	37,467	0,037	0,037	0,015
February	60,067	0,060	0,098	0,025
March	96,767	0,097	0,194	0,040
April	40,333	0,040	0,235	0,017
May	30,467	0,030	0,265	0,012
June	19,267	0,019	0,284	0,008
July	47,200	0,047	0,332	0,019
August	9,333	0,009	0,341	0,004
September	37,000	0,037	0,378	0,015
October	72,467	0,072	0,450	0,030
November	63,333	0,063	0,514	0,026
December	49,733	0,050	0,563	0,020
Total	**563,433**	**0,563**	**3,691**	**0,231**

Calculations

1. Input Volume

=Average Rainfall (m) × Catchment Area (m^2)

Eg. (37.467mm ÷ 1000) × 1 m^2 = 0.037 m^3

2. Harvested Volume

= Sum of Input Volume for preceding months at month of consideration

Eg. Harvested volume for March = (0,037 + 0,060 + 0,097) =0.194m^3

3. CO_2 Saved

= Input Volume (KL) × Carbon Emission Factor (0.4091)

Eg. (0.037) × 0.4091 = 0.015 Kg.CO_2

Appendix H

Roof areas of the structures identified as potential green roof retrofits

Table H1: Roof areas of the structures identified as potential green roof retrofits

	Block 1	**Block 2**	**Block 3**
1	305	4471	262
2	1142	4545	651
3	500	492	317
4	1911	1722	238
5	380	497	236
6	606	853	263
7	2719	751	219
8	2212	1119	238
9	1140	734	229
10	534		281
11	1490		262
12	482		622
13			424
14			340
15			402
16			710
17			711
18			155
19			187
20			349
21			266
22			399
Total	**12**	**9**	**22**
Average Area	**1118,42**	**1687,11**	**352,77**

Appendix I

Carbon emission savings associated with the average CBD roof area

Table I1: Carbon emission savings associated with the average CBD roof area

Month	***Average Rainfall (mm)***	***Average Rainfall (m)***	***Rainfall Volume (m3)***	***Run-off (KL)***	***Water Retained (KL)***	***Carbon Emission Savings***
January	37,467	0,037	31,659	8,557	23,103	9,451
February	60,067	0,060	50,756	13,718	37,038	15,152
March	96,767	0,097	81,768	22,099	59,668	24,410
April	40,333	0,040	34,082	9,211	24,870	10,174
May	30,467	0,030	25,744	6,958	18,786	7,686
June	19,267	0,019	16,280	4,400	11,880	4,860
July	47,200	0,047	39,884	10,779	29,105	11,907
August	9,333	0,009	7,887	2,132	5,755	2,354
September	37,000	0,037	31,265	8,450	22,815	9,334
October	72,467	0,072	61,234	16,550	44,685	18,280
November	63,333	0,063	53,517	14,464	39,053	15,976
December	49,733	0,050	42,025	11,358	30,667	12,546
Total	**563,433**	**0,563**	**476,101**	**128,676**	**347,425**	**142,132**

Calculations for the above table follows the same methodology as Appendix G with the only exception being the roof area (845m^2)

Appendix J

Green roof cost and Cost-Benefit Analysis Calculations

Table J1: Green roof module cost

Item	**Cost (R/0.081m^2)**
Module	32
Potting Mix	20.40*
Vegetation	56**
Total	108.40

*Potting Mix was purchased in a 10Kg bag at R30 per bag. However, only 6.8Kg of the bag was utilised per module.

**Vegetation was purchased per tray of seedlings at R14 per tray. A total of four trays were required per module.

Cost-Benefit Analysis Calculations:

Electricity:

12000 BTU = 3.5 kWh = 3500 Watt-hour

∴Assuming a 5-minute usage per day= (5 ÷ 60) h × 3.5 kWh

=0.292 kW

Cost of electricity within the eThekwini Municipality = R 1.3928 per kWh

∴Saving per square meter = 0.292 × 1.3928

= R0.41 per day

∴Saving on an 845 m^2 green roof = 0.41 × 845

= R338/day = R10140/month = R123370/year

Repayment period = Cost ÷ Savings

= R1488045,00 ÷ R123370

= 12.06 Years

Water:

Utilising the run-off calculation method identified in *Appendix F*, 845m^2 results in a retained volume of 7.62 Kl from every 10.40 Kl.

∴ Utilising the sum of the average rainfall for the city of Durban, identified in *Appendix E*, which amounts to 563.33mm per year, the total input volume of rainwater amounts to 476.10 Kl per year.

- $(563.43 \div 1000) \times 845\text{m}^2 = 476.10\text{ Kl}$

∴The total retained volume = $(476.10\text{ Kl} \div 10.4\text{ Kl}) \times 7.62\text{ Kl}$

= 347.62 Kl per year

∴Savings per year = $347.62\text{ Kl} \times \text{R}15.60/\text{Kl}$

= R5422.87