THE INTEGRATION OF BUILDING INFORMATION MODELLING (BIM) AND LIFE CYCLE ASSESSMENT (LCA) FOR BUILDINGS IN SOUTH AFRICA

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PREFACE

The candidate's supervisor, I, Dr. Elena Friedrich, hereby agree/ ~~disagree~~ to the submission of this thesis:

[redacted]

Dr. Elena Friedrich

DECLARATION – PLAGIARISM

I, Razan Osman, Student Number: 212500019, hereby declare that the research reported in this dissertation, titled "*The integration of Building Information Modelling (BIM) and Life Cycle Assessment (LCA) for buildings in South Africa",* is my original research, except where clearly specified and referenced. The research submitted is based on my own efforts of data collection, any contributions by organizations has been acknowledged.

I understand the implications of plagiarism and hereby state that this dissertation has not been submitted for any degree at any other University. I accept that any breech of academic integrity may have consequences, by signing this declaration I affirm the authenticity of the research and that it upholds the academic ethics and morals of the University of Kwa-Zulu Natal.

Signed:

[redacted]

Razan Osman

ABSTRACT

Anthropogenic growth has catapulted the effects of global warming and the building sector is at the forefront of emissions, responsible for approximately 37% of carbon dioxide emissions into the atmosphere (UNEP, 2022). This research addresses the need for South Africa to reduce carbon dioxide emissions in the building sector and investigates the integration of Building Information Modeling (BIM) and Life Cycle Assessment (LCA) as a framework for achieving lower carbon emissions for buildings. It also explores the adaptation of the Green Star SA rating tool to effectively incorporate LCA criteria. The research objectives include: 1) evaluating the use of BIM and LCA as a decision-making tool for improving the environmental performance of office buildings, 2) examining the interoperability of BIM and LCA through case studies, 3) identifying potential hotspots in buildings where improvements can be made and developing an improvement analysis, 4) establishing criteria for a BIM-LCA framework for Green Star SA, and 5) identifying motivations and barriers to adopting BIM-LCA in South Africa.

To achieve these objectives, One Click LCA and Revit Software were used to evaluate a BIM-LCA framework of two case studies. The first case study used an existing building typical of BIM models prevalent in South Africa, with a low Level of Development (LOD), whereby the only material modelled was concrete of varying strength. The second case study was theoretically structured with a high LOD, and all major building materials included. Integrated BIM-LCA models were developed for both case studies. The results showed a similar order of magnitude, with respect to the environmental burdens of lifecycle stages. The operational energy of both buildings had the most significant impact on the environment followed by the materials used. This is due to the concrete frame of both buildings and the dependency on non-renewable energy (i.e., coal) to generate electricity in South Africa. The findings indicate that the BIM-LCA framework provides valuable information by quantifying environmental contributions, helping with optimizing alternatives. A reduction of carbon emissions could be achieved for both case studies and a series of interventions were evaluated. The integration of LCA with BIM showed promising results even for the case study with a low LOD and it can enable designers to incorporate and quantify specific environmentally and socially responsible interventions. However, insufficient data can be a major barrier for implementation in South Africa and may affect the validity of results depending on the type of building and the data included. For the Green Star SA LCA criteria were developed and the award of 3 points for conducting an LCA with a BIM LOD of 300 is proposed.

The acquisition of data will be improved if LCA criteria are incorporated into the Green Star SA rating tool, thereby providing motivation for material manufacturers and the building industry alike to release more specific LCA information. This research also suggests ways of improving the interoperability of BIM-LCA in the local context and expresses the importance of developing a local database for Environmental Product Declarations (EPDs) and the establishment of a BIM-LCA platform for knowledge sharing.

ACKNOWLEDGEMENTS

"All praise is due to Allah, the most gracious, the most merciful, the all-knowing, all wise"

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LIST OF ABBREVIATIONS

- AEC – Architecture, Engineering and Construction
- AP – Acidification Potential
- BEM – Building Energy Modelling
- BIM – Building Information Modelling
- BOQ – Bills of Quantities
- BREEAM – Building Research Establishment Environmental Assessment Methodology
- DGNB – German Sustainable Building Council
- DTT – Distance to Target
- EP – Eutrophication Potential
- EPC – Energy Performance Certificate
- EPD – Environmental Product Declaration
- GBCSA – Green Building Council of South Africa
- GBRT – Green Building Rating Tools
- GFA – Gross Floor Area
- GHG – Greenhouse gases
- GIFA – Gross Internal Floor Area
- GSSA – Green Star South Africa
- GWP – Global Warming Potential
- HVAC – Heating, Ventilation and Air-Conditioning
- IEA – International Energy Agency
- IFC – International Foundation Class
- INDC – Intended Nationally Determined Contribution
- IPCC – Intergovernmental Panel on Climate Change
- ISO – International Organization for Standardization
- LCA – Life Cycle Assessment
- LCI – Life Cycle Inventory
- LCIA – Life Cycle Impact Assessment
- LEED – Leadership in Energy and Environmental Design
- LOD – Level of Detail
- MCDM – Multi-Criteria Decision Making
- MEP – Mechanical Electrical and Plumbing
- NDC – Nationally Determined Contribution
- OCLCA – One Click Life Cycle Assessment
- ODP – Ozone Depletion Potential
- PCR – Product Category Rules
- SANS – South African National Standards
- STV – Sustainable Target Value
- TRACI – Tool for the Reduction and Assessment of Chemicals and other Environmental Impacts
- UNEP – United Nations Environmental Programme
- WGBC – World Green Building Council

Chapter 1 - Introduction

1.1. Background of research

The environmental impacts from buildings and construction activities are significant and wide ranging and include air emissions, waste generation, noise pollution, resource consumption and water pollution (Ametepey and Ansah, 2015). In this context, the concept of "sustainable buildings" emerged. In 1987, the Brundtland Commission defined the term sustainability as "meeting the needs of the present without compromising the needs of the future". As time progresses, people have become increasingly aware of their ecological footprint and the importance of sustainable development. The notion of "Green Buildings" (GB) cultivated due to excessive environmental pollution and the depletion of resources was brought about by the "energy crisis" of the 1960s and 70s (Mao, 2009). These buildings were developed as an intervention in reducing the environmental impact and the dependency on non-renewable resources (Ding, 2008). Consequently, the establishment of institutions that monitored and assessed Green Buildings, such as Green Building Councils, became effective with their use of environmental assessment methods. Through these councils, each country adopted individual Green Building Rating Tools (GBRTs), with regional priorities, that measure sustainable efforts and award Green Building certifications. These tools aim to incorporate assessments on a variety of environmental aspects linked to buildings including materials, energy use and associated emissions (including greenhouse gas emissions). With the effects of global warming becoming more significant, there is an increasing need to reduce such emissions.

It is estimated that the carbon dioxide emissions from the building industry accounted for 37% of the total energy-related CO_2 emissions for 2020 (IEA, 2021).The United Nations Environment Programme, UNEP, has expressed the importance of a whole life-carbon approach as another methodology of environmental assessment, especially in striving for net zero carbon, with primary focus on emissions related to construction, operational emissions, and the functional use of buildings (UNEP, 2022). For an effective sustainable building strategy, the entire life cycle of buildings should be considered. Life Cycle Assessment (LCA) as defined by ISO 14040 standards, is a technique for investigating all aspects of a product's environmental impact from its' inception to its' end. It is a holistic framework that represents the data of each component to improve the environmental impacts associated with an entire product, system or activity. The LCA of a building includes analyzing data from the raw acquisition of building materials, the transportation of materials, the construction phase, the operating phase and the recycling or demolition phase of the building (Cavalliere et al., 2018). The application of LCA on buildings, is a relatively new development that began in the 1980s and hence, there is always more room for research and expansion (Guinée et al., 2011).

Detailed LCAs require numerous data sets for all life cycles stages of a building. In many cases, the intricate precision of the scientific data makes it difficult to extract, as the building life span could surmount to 50 years or more. It is for this complexity of data and time intensity that LCA's of buildings were commonly avoided in the past (Bueno and Fabricio, 2018). Nevertheless, LCA's have been proven to provide a good estimate and can quantify the environmental consequences for the entire lifecycle of a building. More recently, simplified applications of LCA for buildings are emerging. Therefore, the development of a simplified LCA can provide the Architecture, Engineering and Construction (AEC) industry with the tools required to decrease potential emissions. Simplified versions of LCA involves the development of general databases on building materials, energy and construction processes as well as automated software that are easy to use. One of the ways in which this may be further developed is by integrating Building Information Modelling (BIM) with simplified LCA tools, to make LCA's available to non-LCA professionals involved in the design of buildings.

BIM is a project management tool that provides information on all aspects of building design. It is often only associated as a 3D visualization tool; however, it can include all stages of the building process, i.e., the architectural plans, structural plans, Mechanical, Electrical and Plumbing (MEP) as well as interior design. It is, therefore, regarded as a potential 6D tool, encompassing many levels of interdisciplinary project management (Mtya, 2019). Particularly, linking the visual elements of a building with the materials and associated quantities needed can be automated even in the initial planning stages. Therefore, the integration of LCA and BIM could provide the AEC industry with the tools required to incorporate environmentally conscious designs by evaluating the environmental impacts of different options early in the project. Sustainable buildings can be designed in a more environmentally friendly, cost-effective, and efficient manner provided that the stages are planned, and targets are set. For example, for carbon dioxide emissions, Sustainable Target Values (STVs) can be incorporated into the carbon emission benchmarks and included with these tools (Russel-Smith et al., 2014). The significance of the initial stages of design have been reiterated in many studies (Azhar et. al, 2011). Errors and alterations at later stages do not only give rise to financial liabilities but could also harm the environment. Hence, the importance of the integration of LCA and BIM software during the initial stage of the design process cannot be overlooked (Genova, 2019). It is for this reason that incentives for conducting building LCA's should be included in GBRTs.

Green Star South Africa (GSSA) is the sustainability rating tool responsible for awarding Green Building Certifications in South Africa. It was developed to promote and advocate sustainable buildings and rate them in accordance with environmental impact categories. It is a tool that has been adapted from Green Star Australia, to address the prevalent local environmental concerns. It includes categories that address the issues related to energy, emissions, water, and materials (Green Star SA, 2014). Despite the GSSA efforts to increase sustainable buildings, the adoption rate remains relatively low in South Africa (Dosumu and Aigbavboa, 2021). Sustainable buildings address key environmental impacts, such as reducing greenhouse gas emissions, improving energy and water efficiency, and minimizing resource depletion (Liu et al., 2022). However, the building sector continues to face challenges in reducing carbon emissions due to factors such as high upfront costs, lack of incentives and regulatory measures, limited awareness and expertise among stakeholders (Windapo, 2014).

1.2. Problem Statement

One of the largest contributors to global warming is exhibited within the building sector. Although global pressure has resulted in a heightened sense of environmental awareness in comparison to the past; there are insufficient measures to reduce carbon emissions and other important impacts from buildings (Wang et al., 2021). Combatting climate change requires innovative efforts and a more robust approach towards developing and implementing regulations, as well as towards voluntary initiatives in the building industry (Fawzy et al., 2020). The increasing population and urbanization will undoubtedly result in an increase in building and associated operations, thereby putting additional pressures on an already fragile system (PRB, 2023). The COVID-19 pandemic resulted in a temporary reduction of carbon emissions due to the decrease of building operations by 10% (IEA, 2021). However, the lack of systematic change, has resulted in a relapse of high emissions (UNEP, 2022). Therefore, to maintain a more lasting effect in the reduction of emissions; it is essential for the building sector to abide by environmentally conscious building practices and to adopt a whole-life carbon approach in its' design. It is especially important for developing countries to incorporate such an approach due to the rise of urbanization.

South Africa is a developing African country with a population of approximately 61 million people which is projected to increase to 75.5 million people by the year 2050 (Worldometers, 2023). It is one of the largest contributors of carbon dioxide emissions on the continent due to its heavy reliance on coal produced energy (Green Star SA, 2014). Globally, South Africa was rated as the 14th largest contributor for 2021, emitting 435 million metric tons of carbon dioxide, due to fossil fuel combustion and industrial use (Statista, 2022). The South African building sector was responsible for 23% of greenhouse gas emissions (UNEP SBCI, 2009). The built environment incorporates long lasting infrastructure whereby decisions and investments made in the present can have long lasting effects. This implies that current choices have the potential to create a long-term reliance on carbon-intensive investments that can persist for decades (Boshoff and Mey, 2020).

Therefore, there is a necessity for a simplified whole life carbon approach to building design that focuses on reducing carbon emissions. Although, various international Green Building Rating Tools (GBRTs) have incorporated LCA approaches into their sustainability criteria, South Africa, has yet to implement such measures. The South African Green Star exhibits a limited scope for the use of LCA as a decision-making tool. While it indirectly addresses certain life cycle stages in some instances, there is no criteria for conducting building LCAs. Furthermore, there is limited consideration for the selection of materials, despite awarding points for responsible sourcing. The accreditation system does not take into consideration the energy and GHG emissions related to the material production stage, transportation, construction and end of life stage. This is a limitation that should be addressed for the future.

1.3. Research Question

The research problem highlights the importance for South Africa to reduce its carbon dioxide emissions within the building sector. This raises the research questions of:

- Can the integration of BIM and LCA be used to achieve lower carbon dioxide equivalent emissions in buildings in South Africa?
- If yes, can the Green Star SA be adapted to include LCA criteria effectively?

1.4. Aims and Objectives

This thesis aims to investigate a possible BIM-LCA framework for the South African context. It seeks to explore the interoperability of BIM and LCA software in the design stage of buildings. The main aim of the research is to evaluate a BIM-LCA integration methodology for South Africa by examining the carbon dioxide equivalent emissions and to investigate if and how the tool can be used to reduce the emissions from office buildings. It is also intended to provide recommendations to optimize the process as a decision-making tool for designers and provide a possible building improvement intervention.

The objectives for the thesis are:

1. To investigate LCA and BIM as a decision-making tool for improving the environmental performance of office buildings within the local context with regard to GHG reduction potentials.
2. To explore the interoperability and integration of BIM and LCA with regard to case studies.
3. To identify potential hotspots and provide an improvement analysis of buildings.
4. To conduct a comparative analysis of the various International Green Building Rating Tools such as BREEAM, LEED, Green Star South Africa and Green Star Australia in relation to BIM and LCA.
5. To provide criteria on a BIM-LCA framework for Green Star SA by determining a point system for achieving environmental impact reductions.
6. To determine the local advantages and disadvantages of the BIM-LCA integration.
7. To determine the possible motivations and barriers of the BIM-LCA adoption in South Africa.

1.5. Scope of Research and Methodological Approach

To achieve these aims and objectives, the scope of the study was set to investigate office buildings within the province of Kwa-Zulu Natal, South Africa. Furthermore, the emphasis of the LCA was on global warming and the other environmental impacts like acidification only mentioned.

The following methodological approach was followed:

- Identify the research gap, motivation for the study, research question and expected outcomes.
- Conduct a literature review – Research the existing literature on the integration of BIM and LCA and identify the various tools and guidelines used.
- Select the BIM and LCA tools –Select the tools most appropriate to the study based on the information gathered from the literature review, the scope and availability of data.
- Select Case Studies – to be representative for the South African context regarding the Level of Details (LOD) available.
- Data collection – Collect the necessary data for the BIM models and LCA, this includes quantitative data and qualitative data as in interviews with various structural and architectural consultancies to determine current BIM practices in South Africa. It also includes data sources and assumptions made, when data was not directly available.
- Develop the BIM model – Based on the selected BIM tool and data collection, develop the BIM model to include material components and project information relevant for the LCA case studies. The output of the BIM model is used then as an input into the LCA.

- Conduct the LCA analysis – Using the selected LCA tool, perform the LCA analysis based on the output from the BIM model. Determine the environmental impact of each lifecycle stage.
- Conduct an improvement analysis – Determine the various improvement measures that may be implemented or followed to reduce the impact of buildings.
- Interpretation of results – Analyze the results and compare the environmental performance of the various lifecycle stages and improvement measures.
- Benchmarking – Validate the results through comparisons with other studies and provide recommendations on how to reduce the impact of buildings.

1.6. Structure of Dissertation

The dissertation follows a quantitative and qualitative research approach, it is divided into 5 chapters with the following headings:

- **Chapter 1 - Introduction**: Provides the background of the study, motivation and problem statement. It discusses the concept of Green Buildings and the importance of a whole life carbon approach to reduce the environmental impact of buildings. It thereafter introduces the niche topic of BIM-LCA integration and formulates the research question followed by the aims and objectives.
- **Chapter 2 - Literature Review:** This chapter provides the theoretical foundation of the research through a critical review of past journals, dissertations and articles. It describes the broad concept of sustainability and narrows down to core areas related to GBRTs, LCA and BIM analysis. It also compares the various GBRTs with respect to LCA and provides insight into the carbon emission benchmarks and highlights the value of a simplified BIM-LCA approach in sustainable design. Lastly, it summarizes the previous research conducted and delimits the research gap this study aims to address.
- **Chapter 3 – Methodology**: The methodology includes a description of the approach followed to obtain the results, from the planning phase to the conclusion. It includes two case studies and uses BIM software (AutoDesk Revit) and LCA software (One Click LCA) to investigate interpretation and analysis for each case study.
- **Chapter 4 – Results and discussions**: The results are based on the analysis explained in the methodology. This section includes the numerical data and graphical representation of the environmental impact categories included in the environmental profiles of the two case studies. It also includes an improvement analysis and emphasis is placed on the carbon dioxide emissions calculated. The discussion provides insight into the results. The motivation and barriers in

implementing sustainable construction and BIM-LCA interpretation in South Africa are also discussed.

- **Chapter 5 – Conclusion**: The conclusion summarizes the main results. It reassesses the effectiveness of the study to address the research question as well as the aims and objectives. Recommendations are also provided.

Chapter 2 – Literature Review

2. Introduction

The literature review presents the theoretical framework underpinning this research. It analyzes previous scholarly articles, journals, dissertations, and books to present the background, define important concepts, and to provide the basis for analysing the results. As such this chapter provides the theoretical details of each component of the thesis which includes the environmental impacts of the construction industry, the need for change, Green Buildings, the international Green Building Rating Tools (GBRT), Green Star SA, LCA of buildings the LCA methodology, LCA Software, BIM, REVIT software, BIM-LCA integration, and similar case studies published.

2.1. Environmental Impacts of the Building Sector with emphasis on GHG emissions

The anthropogenic emissions caused by urbanization have significantly contributed to environmental degradation; and the building and construction industry is considered an important contributor. The wider environmental effects of the construction industry include habitat destruction, air pollution, soil erosion, deforestation, noise pollution and construction waste (Ijigah et al., 2013). Buildings contribute to a wide range of environmental impacts for example:

- Negative impacts due to air pollution can be caused directly (e.g. direct air emissions from stoves and furnaces in buildings) and indirectly (e.g. emissions from the electricity generated to be used in buildings). These emissions include GHG as well as other pollutants like sulphur and nitrogen oxides and these depend on the types of fuels combusted (IEA, 2022). GHG are considered particularly important as over one third of global GHG emissions are due to buildings (IEA, 2022). Other emissions like the nitrogen and sulphur oxides can also cause impacts and contribute to other problems like acid rain and acidification of soils and waters (Pawlowski, 1997).
- Negative effects on aquatic systems are also recorded as buildings can contribute to eutrophication and algal blooms through inadequate stormwater runoff design, discharge of wastewater, landscaping and associated use of fertilizer and pesticides (Kobeticova and Cerny, 2019).
- Negative effects on soils and changes in land use are cause by the expansion of urban zones with more buildings being constructed on natural areas but also by the densification of existing urban areas, where buildings displace green parks and recreational environments. These changes not only lead to habitat loss and decreased biodiversity, but they also contribute to an increase of land surface temperatures of urban areas (Song et al., 2020).

- Deterioration of the stratospheric ozone layer is caused by Fluorocarbons and the older Chlorofluorocarbons (still in use in some developing countries). Buildings contribute to the depletion of the ozone layer by emitting such substances due to air-conditioning, refrigeration and building insulation (Filippo et al., 2022).
- Buildings use non-renewable and renewable resources and statistics showed that they account for one-sixth of world's freshwater withdrawals, one quarter of the wood harvested and two-fifth of the world materials used globally (Sandanayake, 2022). For example there is a significant amount of water used in the production of concrete and Miller et al. (2018) showed that 1.7% of the global water consumption was used to produce concrete in 2012. Furthermore, by the year 2050, 75% of the water demand used for concrete production is projected to occur in water stressed countries (Miller et al., 2018). This is locally relevant as South Africa is such a country.

In addition to the effects of buildings the impacts of the construction sites and the processes involved in erecting these buildings need to also be considered. Construction sites are known to generate and contribute to a variety of diverse environmental issues ranging from noise, dust, air pollution, water pollution to waste generation and numerous other concerns. Sandanayake (2022), in a review, identified 3795 references dealing with this topic. However, it is considered that even though a large amount of research is conducted with regard to the environmental impacts of the construction of buildings, most of the estimation and approximation is observed in this life stage and this is also valid for air emissions including GHG emissions (Sandanayake, 2022).

In the current context of global warming and climate change, GHG emissions and in particular the emissions of CO_2 are considered important and the building sector is causing considerable contributions (WGBC, 2023). These are predicted to increase in the future due to population growth but also due to increased urbanisation rates which are directly linked to an increased demand for buildings and associated infrastructure (Boshoff and Mey, 2020). Zhao and Zhang (2017) showed that for China for the last 30 years every increase of 1% in urban population resulted in an increase of 1.4% in national energy use and associated GHG emissions and this can be traced back to buildings (urban sprawl) and transportation. In particular the area occupied by buildings in Chinese cities increased fivefold and this trend is predicted to continue. In South Africa a similar evolution is observed with population increasing at about 1% annually and urbanisation increasing at a rate of 1.97% per year (UN-Habitat, 2023). Urbanisation reached about 67.8% of the population in 2021 (Statista, 2023). This is mirrored in the increase of GHG emissions from construction as showed in the last published GHG inventory for the country, where manufacturing and construction industries had the 3rd highest contribution in South Africa after energy production and transportation (National GHG Inventory, 2020). Globally the build floor area is projected to increase with the highest rate to be experienced by the developing countries, expected to account for 80% of the growth (UNEP, 2022) and the African continent (Statista, 2016). Therefore, for South Africa as the largest GHG emitter of the continent it is important to measure and mitigate such emissions.

The COVID-19 pandemic saw a positive decline in global emissions, albeit a short one. According to the UN's 2022 Global Status Report, emissions, especially in the building sector have rebounded, creating a large set back towards sustainability goals. The building industry consumes 36% of global energy and it is responsible for 37% of the total energy-related carbon dioxide emissions as illustrated in Figure 2.1 (UNEP, 2022).

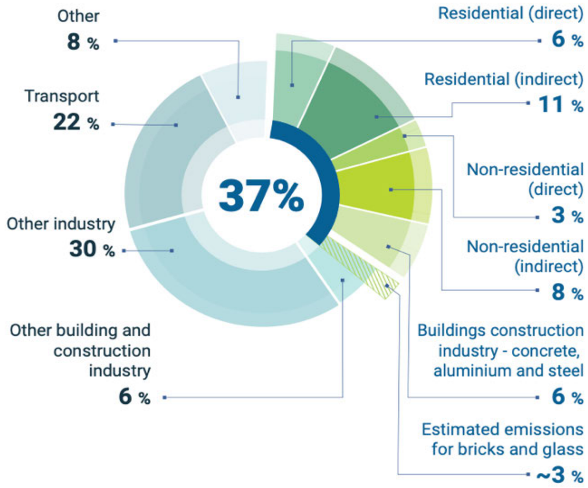


Figure 2.1. Global energy related CO_2 emissions (UNEP, 2022)

2.2. Energy associated GHGs and sustainability goals for the building industry

Energy consumption and associated GHG emissions are linked to all life stages of a building and in order to reduce them it is important to understand how they occur. These are divided into three types: embodied energy, operational energy and end of life energy (Najjar et al., 2017 & WGBC, 2023):

- Embodied Energy and GHG emissions – Energy that is needed in the acquisition and processing of raw materials to manufacture the building materials and transport them to the construction site. This phase also includes construction site activities and the transportation of waste materials thereof. Associated GHG emissions are linked to the type of energy used.
- Operational Energy and GHG emissions – Energy associated with the use stage and maintenance of a building. This refers to the energy consumed after the building is occupied and functioning, which includes lighting, Heating, Ventilation and Air-condition (HVAC). The energy utilized while the building is occupied can be determined using Building Energy Modelling (BEM) or by direct measurements.

- End of Life Energy and GHG emissions – Energy consumed during the demolition or waste processing of the building, the disposal energy is the relevant energy consumed during this phase and will lead to associated emissions.

For each of the life stages of a building the types of energy and the types of GHG emissions will vary and in this context the concept of carbon footprint of buildings has emerged. Even though there are many definitions of the "carbon footprint", in essence it is a metric which aims to total all GHG emissions over the different life stages of a building and express the results in CO_2 equivalents. This is possible by using the Global Warming Potential of different GHG gases. Fenner et al. (2018) reviewed the application of this concept and highlighted that here are different methodologies and standards used currently, and that variations exist leading to some inconsistencies. They also defined 4 life stages of a building similar to the WGBC (2023), however their definition and the terminology varies slightly as the embedded GHG emissions are called product stage (i.e. GHG from producing the construction materials) and they define a construction stage which the WGBC does not. Also Fenner et al. (2017) consider that maintenance and replacement is part of the operational stage of a building. Standards developed for GHG accounting for buildings have helped not only in a consistent definition of life stages but also in standardising calculations procedures. Most notably the ISO 14047, PAS 2050 and EN15804 are used internationally to calculate GHG emissions from buildings in a consistent way (Fenner et al., 2018).

Considering actual GHG emissions Fenner et al. (2018) showed that for most of the studies reviewed, the operational stage of buildings usually has the highest impact, and represents over 70% of all GHG emissions of buildings. These emissions are directly related to the use of energy in buildings and depend very much on the type of energy used in different national electricity grids. For example, countries relying on coal (such as South Africa) as the main source for electricity generation will have higher GHG emissions per kWh produced and used, whereby countries that use more renewable energy sources (e.g. geothermal, wind or solar) or nuclear energy will have lower GHG emissions per unit of energy (Scarlat et al, 2022). The review by Fenner et al. (2018) also shows that the embodied emissions from materials are dominated by concrete and steel and the GHG emissions associated with materials can become important when the operation GHG emissions are reduced through zero carbon interventions. The end of life GHG emissions are less important and can be further reduced through disassembly and reuse of materials (Fenner et al., 2018).

It is evident that the life cycle energy use of buildings varies and is highly dependent on the case study, the database available and the region in which the case study exists. Azari (2019) attempted to aggregate a range of LCA results with regards to the embodied energy of a building and the operational energy. Table 2.1 summarizes these ranges for residential and office buildings.

Table 2.1: Range of embodied energy in buildings (Azari, 2019)

Year	**Authors**	**Data basis**	**Embodied energy**
2007	Sartori and Hestnes	60 buildings	2-38% for conventional buildings 9-46% in low energy buildings
2010	Ramesh et al.	73 residential and office buildings	10-20 %
2016	Chastas et al.	90 buildings	6-20% conventional buildings 11-33% passive buildings 26-57% low energy buildings 74-100% net zero energy buildings

Figure 2.2 illustrates pie graphs that highlight the percentage ranges of embodied energy and operational energy of 4 types of buildings, conventional, passive, low energy and net zero energy. It indicates that the higher the embodied energy of a building is throughout its life span, the closer it was to achieving net zero emissions (Azari, 2019) as the operational energy (and associated emissions) is reduced.

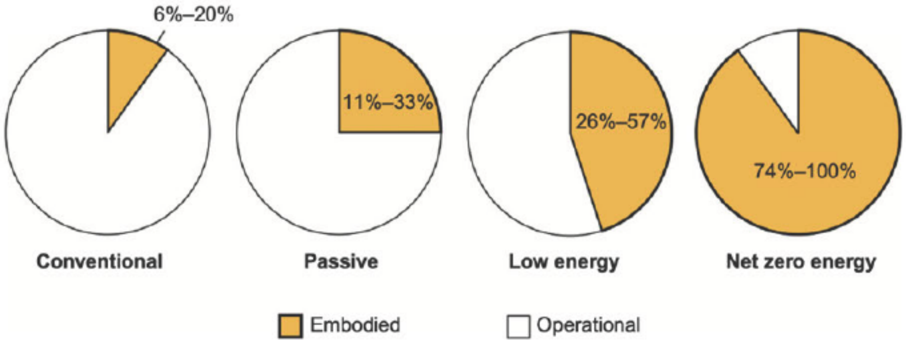


Figure 2.2: Graphs showing the various share of embodied energy in buildings (Azari, 2019)

Once GHG for buildings are calculated and reported there are different mitigation measures that can be put in place. To judge the success of such measures constant recalculations are needed in order to compare. The most effective mitigation measure to reduce GHG emissions as described by the World Green Building Council (WGBC) is through the optimization of embodied energy and operational energy. The materials associated with the embodied energy should have a positive effect on the operational energy and the best way to accomplish this is through design planning. Figure 2.3. illustrates that the highest carbon reduction potential may be obtained during the planning and design stages of building projects. Making design changes during the later stages of a project incur additional costs and lead to a waste of resources.

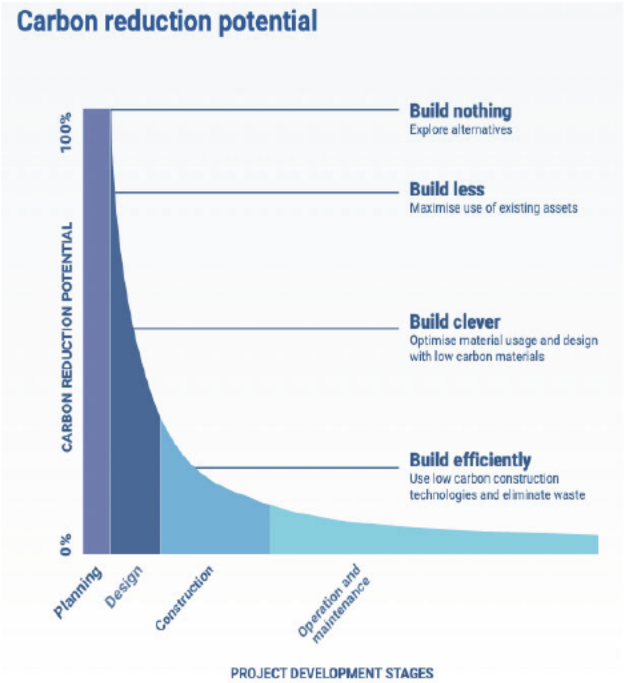


Figure 2.3: Carbon Reduction Potential from stage design process (HM Treasury: Infrastructure Carbon Review, 2013)

2.2.1. Global Warming Targets

Eradication of the adverse effects of the building industry is nearly impossible to accomplish, these may however, be significantly reduced through mitigation. The urgency of the matter has been highlighted by the IPCC in their special report of global warming of 1.5°C. The IPCC (2018) proclaims that decarbonization and net zero emissions would have to be accomplished by the year 2050 to limit global warming to 1.5°C above pre-industrial levels. The target of 1.5°C has been postulated based on historical trends dating back to the pre-industrial era (IPCC, 2018). Emissions would have to be reduced by 43% by 2030 (IPCC, 2018). The building industry presents a large opportunity to limit the effects of global warming (UN Habitat, 2016).

The Nationally Determined Contributions (NDC) is a strategy adopted by the parties of the Paris Agreement to reduce their emissions and to review policies and enhance them every 5 years accordingly (IPCC, 2018). Unfortunately, insufficient measures are implemented by countries in their NDC's to reduce their carbon footprint in the building industry. South Africa for example, is one of the few developing countries to submit an Intended NDC, whereby one of its main targets is to limit emissions to between 398 and 614 metric tons of carbon dioxide equivalents between the years 2025 and 2030 (SA's INDC, 2015). However, these measures are broad, with no specific sectors or action plans mentioned, and they are considered insufficient to meet the targets set out by the IPCC (Climate Action Tracker, 2022).

As seen in the literature, the theoretical concept of emission reduction has been established, guidelines have been developed and, in many countries, policies are in place. However, pragmatically seen, reduction efforts have been stagnant in many countries. Since GHG emissions are linked to the consumption of energy, the energy building standards and the codes associated might be used for mitigation (Boshoff and Mey, 2020; Reed et al., 2011). South Africa's SANS 10400 building code regulates energy usage through requirements for thermal insulation, building orientation, and lighting based on building class and energy zones. The intended 66% energy trajectory for 2029-2030 has been normalized to 2021 levels, but to align with the IPCC's Global Warming Targets, a lower energy target is required (Boshoff and Mey, 2020). The challenges presented in upholding the building energy codes include data collection and monitoring and ensuring that the codes are being implemented.

2.2.2. Challenges and opportunities for energy interventions and GHG reductions in buildings

Energy efficiency plays a crucial role in building performance, and to mitigate energy consumption, different countries have adopted various energy codes and regulations. The difficulty in implementing global mandatory building energy codes is a result of socio-economic limitations. Hence, many developing countries have adopted no new policies or have adopted voluntary policies. Figure 2.4. depicts the status of building energy codes in each country. Further challenges in implementing detailed energy building standards, is the diversity of climate. In Europe, approximately 35% of buildings are over 50 years old (Europa, 2018), rendering their energy performance inefficient and outdated. Hence, the European Union has amended their NDC’s to introduce the Renovation Wave Strategy. For a better quality of life and for cleaner energy, the strategy seeks to modernize and increase the renovations of older buildings. This proposal among other measures aims to reduce building emissions by 60% by the year 2030 (Europa, 2018). Countries would have to plan their strategies based on their respective climate. European countries undergo harsher winters and consequently their building energy performance would differ from the African and Australian continent where air-conditioners are linked to hot and warmer climates.

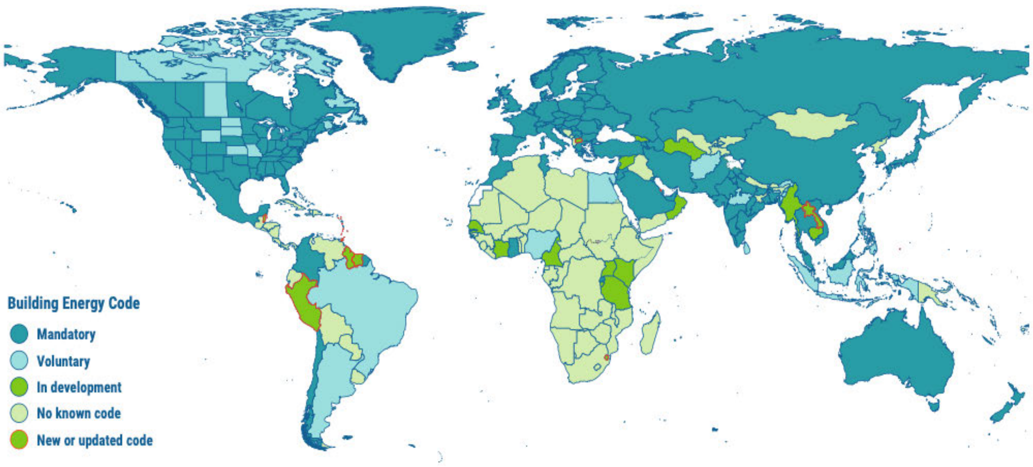


Figure 2.4: Building energy codes by country sourced from IEA, 2021

In developing countries, many sustainability challenges are due to inadequate funding. The International Energy Agency (IEA, 2023) estimates that 80% of the residential floor area growth is in developing countries where unfortunately, many of the countries have not committed to a distinctive action plan of reducing emissions. Despite the challenges faced by the African continent with the building sector, therein lies many opportunities. Africa is rich in renewable energy sources; the integration of renewable energy would significantly reduce emissions and resolve issues related to inadequate energy (UNEP, 2022). To facilitate a positive outcome a series of recommendations have been developed by international organisations.

UNEP's latest Global Status Report for Buildings and Construction, (2022), has provided the 9 following recommendations for overcoming challenges related to achieving sustainability goals related to energy and GHG emissions:

1. A roadmap and strategy should be established towards achieving Net Zero by the WGBC.
2. Mandatory building energy codes should be implemented using the NDC guidelines and policies
3. Governments should commit to the expansion of energy efficiency investments
4. The AEC sector should develop zero-carbon strategies for new and existing buildings.
5. Carbon dioxide emissions should be reduced throughout the material value chain.
6. An increase in research investment to accelerate progress towards decarbonization.
7. Policies should incorporate a life cycle approach that focuses on the embodied energy and operational emissions of materials.
8. Policies should also incorporate the shift to circular economies.
9. Countries that are quickly growing should commit to increasing investment towards energy efficient designs and green construction.

To achieve these recommendations a series of interventions and decision-making tools are needed, considering all life stages of a building.

2.3. Decision-making tools in civil engineering design and the incorporation of environmental factors

Decisions are taken in all engineering projects and in particular the decisions taken during the design stage can influence all stages of a building. In the engineering design process, decisions follow a 5-step model whereby a problem is defined, information is collected, solutions and alternatives are determined, the most suitable design is selected and finally the decision is evaluated and reflected upon (Han and Shim, 2019).

Good decisions are intrinsically dependent on the information available; inadequate data may often lead to costly choices and poor decisions. For example, asbestos was a common building material in the past, until its adverse effects on human health were discovered (Gutiérrez et al. 2023). It is for this reason that developments of regulations and codes in design have been established over time to simplify decision-making and implement better design choices. These guidelines provide practitioners with limitations that decrease complexities, or the scope may become too vague and difficult to process (Jalaei et al. 2015). Furthermore, civil engineering designs incorporate environmental factors to combat climate change through 3 strategies characterized by (Illankoon et al., 2019):

1. Knowledge – based - Uses existing guidelines
2. Rating schema - Uses frameworks to calculate the sustainability outline (Green Building Rating Tools)
3. Performance based – focuses on life cycle analysis and energy performance (LCA).

The first two strategies are based on limited quantified data and rely mainly on qualitative assessments; they are checklists that work as a guideline. The environmental measurement of buildings can attain meaningful progression through a hybrid strategy of all three methodologies that include:

- Multi-Criteria Decision Making (MCDM)
- Sustainable Target Values (STV) and Benchmarks
- Life Cycle Assessments and,
- Green Building Rating Tools (GBRTs).

These will be discussed in the following sections.

2.3.1. Multi-Criteria Decision Making (MCDM)

An essential methodology to decision-making in design that analyses information, establishes a criteria and alternatives, and consequently determines the most feasible solution is known as Multiple-Criteria Decision Making (MCDM) (Tan, 2021). The MCDM methodology assists practitioners with decision-making by breaking down issues into smaller steps and in some cases provides a system framework using a mathematical model (Si, 2016). Based on the objectives, the designer can determine alternatives and rate them in accordance with the selected MCDM methodology.

The selection of an appropriate method is often dependent on the characteristics of the project (the scale of the project, the data, the number of alternatives, etc.) (Arroyo et al., 2016) with the most common of the methods used being the Analytic Hierarchy Process (AHP) method (Campos-Guzman, 2022; Torkayesh et al., 2022). The MCDM method can be applied to all engineering disciplines and is a systematic approach that encourages making informed decisions under complex circumstances. Combining MCDM and LCA allows the designer to prioritize the objective, be it, reducing energy consumption, reducing GHGs, reducing material consumption, etc. Sanchez-Garrido et al. (2022) combined MCDM with a lifecycle approach to derive sustainability scores for buildings and energy use and associated emissions where one criterion is used.

2.3.2. Sustainable Target Value (STV) and Benchmarks

STV is a goal-oriented approach, its principle relies on quantifying a sustainable target and then proceeding to design a project to meet that target. This method assists in abiding by the purpose and not compromising on the objective. Russel-Smith (2014) proved that a progressive sustainable target value assessment is a great early intervention tool that can prevent harmful environmental impacts and increase the amount of design alternatives considered for buildings. The study involved 5 teams designing a University Building in various locations and with different sustainability targets. The results showed that adopting an STV life cycle analysis, resulted in a decrease of the environmental impact of the operational phase through an iterative process. The STV strategy limits the scope of design to prioritize sustainability, resulting in innovative designs (Russel-Smith, 2014). Similar results and conclusions were reported by Silveira and Alves (2018) on the use of this approach for the design of green buildings in California, in addition they mention many other advantages that can be achieved.

Although closely related terms, STVs and Benchmarks differ in their fundamental purpose, STVs are specific sustainability goals, whereas Benchmarks are moreover a frame of reference. They often compare the performance of buildings to a set of industry standards; for example, in South Africa, notional buildings refer to a reference building that complies with the clauses stipulated in the South African National Standards (SANS) 204: *Energy Efficiency in Buildings.* Most benchmarks are based on similar concepts of standard buildings designed by the respective GBRT's project team and are not based on scientific imperatives. These standard buildings often depict scenarios whereby minimal or no sustainable measures are undertaken to indicate the improvements made by new sustainable buildings, this however, demonstrates little progress towards achieving the reduction targets set out by the Intergovernmental Panel on Climate Change (IPCC) (Abdelaal, 2021).

One of the most accurately presented benchmarks has been researched by Abdelaal, (2021), with the New Zealand residential housing sector. The research follows that benchmarks should be established by comparing the impact of buildings to the reduction targets set out by the IPCC. Essentially, it combines

STV by planning for the desired sustainability target year, as opposed to comparing to an arbitrary building. It utilizes the Distance to Target (DTT) approach, whereby the weighting factor equation is used to determine the benchmark by dividing the environmental impact categories reference year to the target year (Seppala and Hamalainen, 2001). Abdelaal's (2021) methodology although valid and applicable, cannot be implemented without adequate data of the impact categories reference year, therefore, currently notional buildings are used in the absence of such data. However, given the ongoing climate change emergency, it is highly recommended to gather more data and develop plans for more ambitious benchmarks and targets.

2.3.3. Life Cycle Assessment (LCA) – Broad Overview

The purpose of LCA is to determine the environmental consequences and social impact of a product, process or service throughout its existence by examining a 'cradle to gate' approach (Friedrich, 2007). It provides a scientific approach of understanding and subsequently reducing anthropogenic emissions by incorporating all life stages associated carbon emissions, including buildings. It is considered as a performance-based methodology that allows for the most-informed decision, by providing a holistic framework of all life stages. LCA, further described in Section 2.6, includes 4 phases: Goal and scope definition, inventory analysis, impact assessment and interpretation. Environmental life cycle approaches can be used with MCDM and STVs in decision making for the design of buildings that are more environmentally friendly. These are complex decision-making tools which despite many of their advantages might not be easy to implement in day-to-day design practice (Silveira and Alves, 2018). A more uncomplicated approach is the use of GBRTs for design. However, the challenges associated with GBRTs include an arduous documentation process and high costs related to certification (Windapo, 2014).

2.3.4. Green Building Rating Tools (GBRT)

A green building is defined as a building that effectively reduces negative impacts on the environment; operates in an efficient manner to reduce water and light consumption, improves air quality and makes use of renewable energy. Nowadays, the value of a building is directly related to its sustainability. Green Building Rating Tools (GBRTs) have been developed to assess how effective a green building is in its efforts to meet sustainability goals. The tools are an important aspect of managing a building as it measures the operational and maintenance needs and caters for the building whilst focusing on reducing energy consumption (Reed et al., 2011).

GBRTs vary throughout the world; the difficulty in creating a standardized international rating system stem from different environmental factors and regulations such as topography, building codes, population size, land area, climate and building stock (Reed et.al, 2011). Figure 2.5. depicts the rating tools present in different countries.

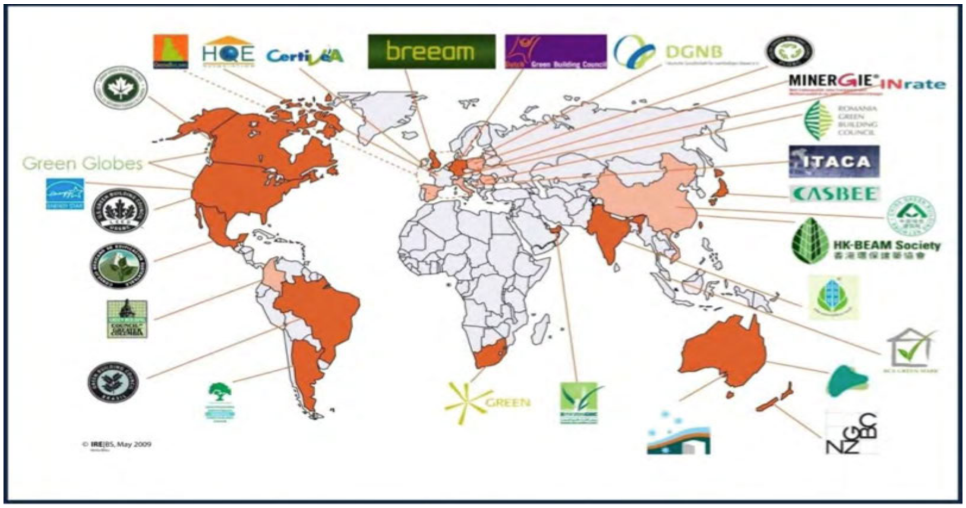


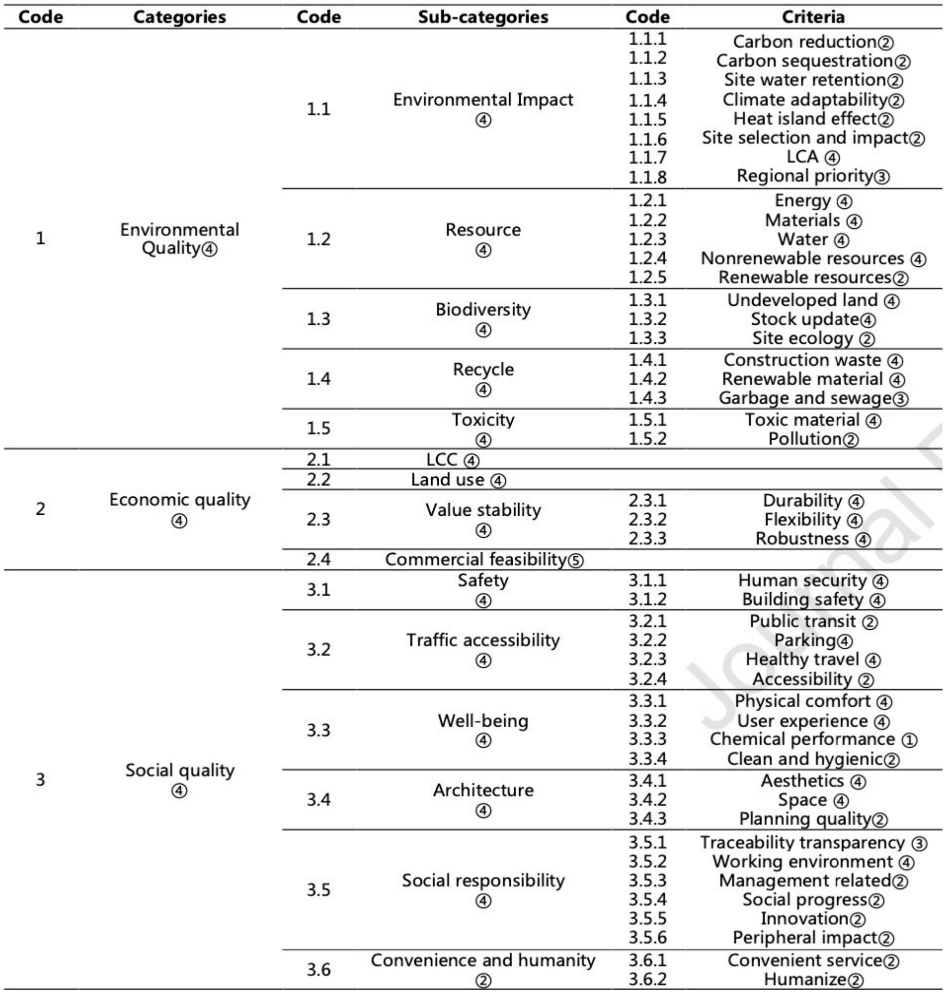
Figure 2.5: Global Sustainable rating tools (Reed et al., 2011)

The national rating tools developed are considered variations of the three main rating tools, namely LEED (Leadership in Energy and Environmental Design - American rating system), BREEAM (Building Research Establishment Environmental Assessment Method- European rating system) and Green Star (Australian rating system). Most of the remaining rating tools (see Figure 2.5) have modified these three systems to suit their respective countries. The challenges sometimes encountered when rating green buildings are related to the bureaucracy and exorbitant costs of certification (Reed at al., 2011). The framework that exists however, is a good indicator of sustainability and promotes sustainability initiatives. It is a detailed process composed of extensive checklists and there are three phases in sustainability rating (Usman and Abdullah, 2018):

1. Indicator phase – The initial phase classifies and organizes the performance factors of buildings into different groups.
2. Scoring phase – Awards points to the various performance factors.
3. Rating phase – Assesses the scoring system and rates the building accordingly.

The GBRT’s essentially aim to measure the three pillars of sustainability i.e., environment, society and economy (Bernardi et al., 2017). According to Baohua et al. (2020), there is an imbalance of scoring on societal and economic factors, with priority given to the environment. The environment is undoubtedly an essential component; however, its counterparts are also important as they are all linked and directly proportional. Baohua et al. (2020) further went on to develop a unified framework when assessing sustainable buildings as depicted in Table 2.2.

Table 2.2. Framework showing the criteria of the three sustainable pillars incorporated in GBRT's (Baohua et al., 2020)



Code	Categories	Code	Sub-categories	Code	Criteria
1	Environmental Quality④	1.1	Environmental Impact ④	1.1.1	Carbon reduction②
				1.1.2	Carbon sequestration②
				1.1.3	Site water retention②
				1.1.4	Climate adaptability②
				1.1.5	Heat island effect②
				1.1.6	Site selection and impact②
				1.1.7	LCA ④
				1.1.8	Regional priority③
		1.2	Resource ④	1.2.1	Energy ④
				1.2.2	Materials ④
				1.2.3	Water ④
				1.2.4	Nonrenewable resources ④
				1.2.5	Renewable resources②
		1.3	Biodiversity ④	1.3.1	Undeveloped land ④
				1.3.2	Stock update④
				1.3.3	Site ecology ②
		1.4	Recycle ④	1.4.1	Construction waste ④
				1.4.2	Renewable material ④
				1.4.3	Garbage and sewage③
		1.5	Toxicity ④	1.5.1	Toxic material ④
				1.5.2	Pollution②
2	Economic quality ④	2.1	LCC ④		
		2.2	Land use ④		
		2.3	Value stability ④	2.3.1	Durability ④
				2.3.2	Flexibility ④
				2.3.3	Robustness ④
		2.4	Commercial feasibility⑤		
3	Social quality ④	3.1	Safety ④	3.1.1	Human security ④
				3.1.2	Building safety ④
		3.2	Traffic accessibility ④	3.2.1	Public transit ②
				3.2.2	Parking④
				3.2.3	Healthy travel ④
				3.2.4	Accessibility ②
		3.3	Well-being ④	3.3.1	Physical comfort ④
				3.3.2	User experience ④
				3.3.3	Chemical performance ①
				3.3.4	Clean and hygienic②
		3.4	Architecture ④	3.4.1	Aesthetics ④
				3.4.2	Space ④
				3.4.3	Planning quality②
		3.5	Social responsibility ④	3.5.1	Traceability transparency ③
				3.5.2	Working environment ④
				3.5.3	Management related②
				3.5.4	Social progress②
				3.5.5	Innovation②
				3.5.6	Peripheral impact②
		3.6	Convenience and humanity ②	3.6.1	Convenient service②
				3.6.2	Humanize②

From the criteria summarized in Table 2.2, it is evident that energy and materials as well as carbon reduction and sequestration are incorporated to different degrees in the GBRT. As buildings are designed to score well for these criteria to obtain certification, the GBRT can influence the design process towards more environmentally friendly performing buildings.

2.3.4.1. BREEAM

BREEAM was launched in the United Kingdom in 1990 and it has since become an international rating tool reaching over 74 countries (BRE Group, 2023). The international technical manuals are divided according to life cycle stages: new constructions are managed by the technical manual SD250, version 6, which addresses all design aspects related to the pre-building phase. There are 9 environmental categories that are assessed: management, health and wellbeing, energy, transport, water, resources, resilience, land use and ecology and lastly pollution (BREEAM, 2021). The rating benchmarks are assessed according to outstanding, excellent, very good, good, pass, acceptable and unclassified.

2.3.4.2. LEED

LEED is another international rating tool that was established by the US Green Building Council (USGBC) in 1994. The current version in use is LEED v4, that focuses on encouraging growth in 6 main categories: location and transport, sustainability sites, water efficiency, energy and atmosphere, materials and resources and indoor environmental quality (LEED v4, 2013). The results are rated as certified (40 points), silver (50 points), gold (60 points) and platinum (80 points). The goals behind LEED certification include promoting sustainability, protecting the environment and resources as well as improving human health (LEED v4, 2013).

2.3.4.3. Green Star

Green Star is a voluntary Australian green building rating tool launched in 2003, that uses 8 categories (Responsible, healthy, resilient, positive, places, people, nature and leadership). The categories are subdivided into credits each addressing an initiative. A Green Star "Certified" rating does not expire post-construction. The ratings are accredited according to numbers: 4, 5, or 6 stars. There are minimum credits that must be met to qualify for submission, these credits are not awarded points but are rather deemed as requirements. The key features of Green Star aim to address the Paris Agreement goals set out by the UN and responds to sustainability trends and is updated accordingly (Green Star Buildings, 2021). As observed BREEAM, LEED and the Green Star rating tools incorporate a basic simplified lifecycle approach in their structure, but the importance placed on different building impacts varies.

2.4. South African Green Building Rating

2.4.1. Green Building Council of South Africa (GBCSA)

The World Green Building Council (WGBC) is a non-profit organization that promotes and advocates for green buildings. There are over 70 countries registered and each of them follow their own independent rating tools. The WGBC works with member bodies to assist in achieving the UN's global goals for sustainability. The WGBC's strategy for Advancing Net Zero (ANZ) carbon emissions in building is by adopting a whole life carbon vision. South Africa is one such country that has an established membership with the WGBC since 2007. The GBCSA operates across the building sectors; in residential, commercial and public domains. They educate South African businesses on the importance of green buildings by offering training workshops and campaigns, they also offer courses to individuals within the industry to become Accredited Professionals (AP). An AP guides their company in applying to the GBCSA using the respective rating tool (GBCSA, 2017).

2.4.2. Green Star South Africa

The rating tool adopted by South Africa is based on the Green Star Australia rating tool. The alterations have been made to suit the South African Mediterranean and sub-tropical climate; and to cater to South African resource priorities (GBCSA, 2017). This dissertation focuses on office buildings; therefore, the assessment follows the criteria of the Green Star SA Office v1.1 developed in 2014.

The South African Green Star technical manual for offices provides background information, guidance, and documentation requirements for certification. Certification eligibility is dependent on 4 factors: spatial differentiation, space use, conditional requirements, and the timing of certification (Green Star SA, 2014). The technology and tools surrounding sustainability and green buildings are dynamic, consequently the Green Star SA Office v1.1 technical manual, is also dynamic and updated according to developments made in the field. The tool was established to encourage sustainable initiatives and to promote integrated whole building designs (GBCSA, 2017). Its environmental impact categories include 9 categories (Management, Indoor Environmental Quality, Energy, Transport, Water, Materials, Land Use and Ecology, Emissions and Innovation) that have been further described in Appendix 7. These categories apply the MCDM methodology to assign scores to the various criteria described in the categories.

Assessment Scoring System:

Each of the categories are broken down into criteria or credits. They represent an environmental initiative and points are awarded according to each credit. A percentage is then calculated for each category and a weighting factor is then applied. Figure 2.6. represents the procession of assessment credits.

Figure 2.6: Procession of assessment credits in the Green Star SA Office technical manual v1.1. (Green Star SA, 2014)

1. $Category\ Score = \frac{Number\ of\ points\ achieved}{Number\ of\ points\ available}$

2. $Weighted\ Category\ Score = Category\ score \times\ Weighting\ Factor \times 100$

The total score is based on the sum of the weighted category scores (maximum = 100 points) in addition to any innovation points awarded (maximum points = 5). The rating of the scores is ranges from one star which is not eligible for formal certification, to six stars being the highest and recognized for "World Leadership" (Green Star SA, 2014).

Weighting Factor:

The weighting factor for each category varies according to the localized context. Each country differs in its' importance of environmental concerns. The South African Green Star rating tool, when compared to the Australian tool, has elected to prioritize the categories of water, emissions, and materials. Water has been prioritized in South Africa due to the perennial constraints experienced with erratic and often unpredictable rainfall (GSSA, 2014). Emissions, another factor that is a focal point has been prioritized due to South Africa's heavy reliance on coal-produced energy. The non-renewable source of energy is a major emitter of carbon dioxide (CO_2), ranking South Africa, as one of the highest CO_2 contributors in the region (GSSA, 2014). Lastly, materials are prioritized to encourage the recycling and reuse of materials. As such this rating system acknowledges the different life stages of a building but in a very simplified manner. Therefore, for more information on these stages and their potential environmental impacts, more detailed environmental life cycle assessments are needed.

2.5. Life Cycle Assessment (LCA)

The concept of LCA was developed in the 1970's when the availability of non-renewable raw materials was under scrutiny which consequently led to the need for environmental quantification of products and services (Bayer, et al., 2010). The International Organization for Standardization (ISO) provided the essential guidelines towards defining the main concept and the LCA methodology (Almezeraani, 2021; ISO 14040, 2006). The guidelines follow the following standards (Najjar, et al., 2017):

- ISO 14040 identifies the principles and framework
- ISO 14041 identifies the goal definition and inventory analysis
- ISO 14042 addresses the Life Cycle Impact Assessment (LCIA)
- ISO 14043 provides the interpretation of the Life Cycle

There are three levels of LCA: conceptual, simplified and detailed (Vosloo et al., 2016). The conceptual level is the most basic form of an LCA, it is not used for public distribution and is intended to provide a rough insight. The simplified LCA, is more detailed than its counterpart and may consist of generic information that is based on literature. It has a more limited scope and may be based on specific components or environmental impacts of the LCA process. And lastly, the detailed LCA is the most dependable as it consists of a thorough and detailed analysis of the entire life cycle (Vosloo et al., 2016).

2.5.1. Workflow of LCA

According to ISO 14040, the process based LCA approach consists of four essential phases. These phases, illustrated in Figure 2.7, form a structured workflow for obtaining LCA results. They include defining the goal and scope, conducting an inventory analysis, performing an impact assessment, and lastly, interpreting the findings.

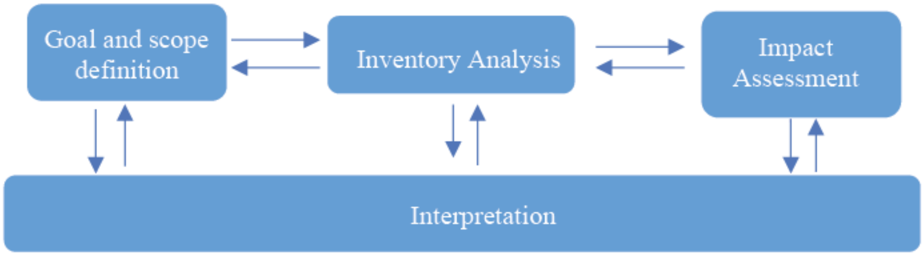


Figure 2.7: Workflow of the four phases in LCA (ISO 14040, 2006)

Lotteau et al. (2015) provided a description of the criteria when considering an LCA review on a neighbourhood scale. The criteria, shown in Table 2.3, offers a description of the steps involved within the four phases.

Table 2.3: Description of the 4 phases in LCA (adapted from Lotteau et al., 2015)

LCA Phase	**Qualitative Criteria**	**Quantitative Criteria**
Goal and Scope Definition	- Goal definition - System boundaries - Life Cycle steps considered	- Functional Unit - Geographic Location - Assumptions made - Limitations - Lifetime or period of analysis
Life Cycle Inventory (LCI)	Inputs and Outputs of the system	- Materials and energy consumed (Input) - Emissions (Output)
Life Cycle Impact Assessment (LCIA)	- LCIA method selected - Impacts and damages considered - Classification - Normalization (optional) - Weighting (optional) - Aggregation (optional)	- Primary energy consumption data - Climate change impact data - Characterization
Interpretation of Results	- Mono or multi criteria - Sensitivity check	Contribution analysis, identification of hotspots

2.5.2. Goal and Scope Definition

The Goal and Scope phase defines the system boundaries and sets out the objectives, the most important part of this phase is defining the functional unit (Friedrich et al., 2007). According to the SimaPro's Introduction to LCA, (2016), the first phase is intended to address questions such as:

- Reason for the LCA – Is the reason for the LCA intended to prove a hypothesis or provide information regarding a product or service?
- Define the product - What is the purpose of the product or service?
- Define the functional unit – what is the reference for the LCA study? What is the value that describes the purpose of the system?
- Data and data quality requirements, assumptions and limitations – What are the data requirements? What are the assumptions made?
- The target audience – Who is intended to benefit from the LCA? Will it be on a commercial scale for industry, private or for research purposes?
- The type and format of the report – What should be the format of the report? Will it include visualization aid?

The scope of the LCA entails methodological choices, assumptions and boundaries. It is an iterative process and can be adapted according to information that is made available. The system boundary can be linked with geographical factors, time, the natural environment or a technical scheme. It is inter-related with the inputs and outputs of the life cycle inventory. It is for this reason that it may be amended at a later stage depending on the LCI (Bauman and Tillman, 2004).

2.5.3. Life Cycle Inventory (LCI)

The second phase (Life Cycle Inventory) is the data collection phase whereby for the system investigated, information is gathered regarding the raw materials and the energy consumed (ISO 14040, 2006; Lotteau et al., 2015). The outputs are also determined based on the system boundary. Figure 2.8. depicts a flowchart describing the system boundary and LCI.

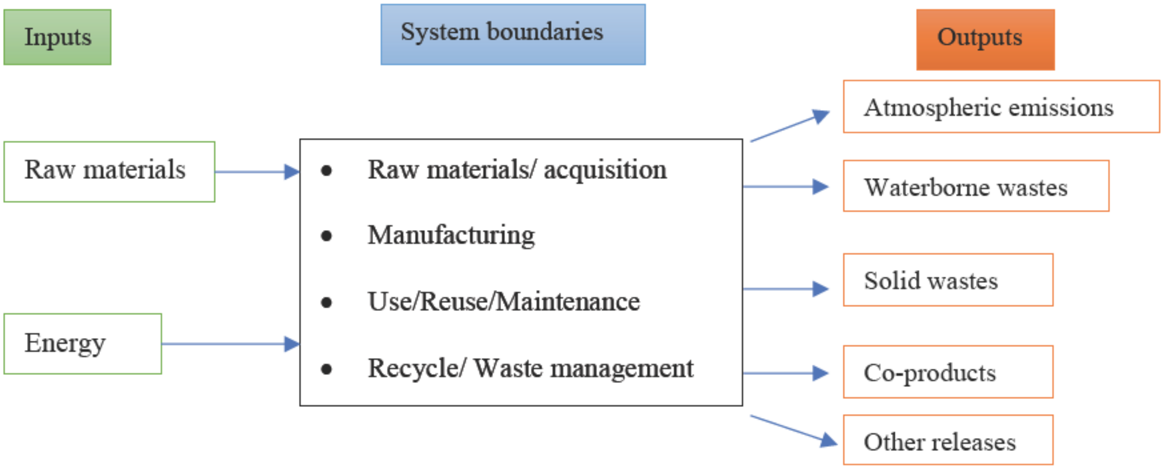


Figure 2.8: Input, System boundary and Output processes included in LCA (adapted from SimaPro, 2016)

There are various databases that have been established whereby LCI information is available and regularly updated for users. These databases often consist of product, processes, material or service information regarding life cycles (Ciroth and Burhan, 2021). Although there are many databases; only a few focus on construction materials and have integrity of data, of important note, are the Ecoinvent database and GaBi database (Martinez-Rocamora et al., 2015). Due to the availability of multiple databases, it becomes difficult to definitively compare LCA results and even with databases such as Ecoinvent and GaBi, there are disparities, creating complexities for comparisons (Pauer et al., 2020).

2.5.4. Life Cycle Impact Assessment (LCIA)

The third phase (Life Cycle Impact Assessment) converts the data from the previous phase into quantifiable environmental results. The ISO 14040 (2006) standards on LCA specify that the inputs and outputs from the inventory must be classified in terms of their contribution to the environmental impact categories selected. Classification which is the assignment of LCI results to the impact category, is followed by characterization and in this step for global warming, the GHG contribution is multiplied by a characterization factor. This factor expresses the contribution of the GHG emission under one reference unit, and for global warming specifically in carbon dioxide equivalent emissions (SimaPro, 2016). The emissions are subsequently calculated to the same unit and summarized for each impact category resulting in one score. There are various characterization methods which differ in their use of environmental impact factors and conversion factors, these include: the CML method, TRACI, PEF, ReCiPe and numerous others (Dong et al., 2021). One of the reasons why LCA is considered to be a complex undertaking is due to the confusion regarding LCIA methodologies, particularly, which impact category to focus on (Feng et al., 2023). Each of the methodologies adopt a different approach towards their inclusion of impact categories. To decrease the complexities of Building LCA, Feng et al. (2023) proposed a list of environmental impact factors considered to be a priority group, these include: “Global Warming Potential, Ozone Formation and

Human Health, Fine Particulate Matter Formation, Ozone Formation and Terrestrial Ecosystems, Terrestrial Acidification and Terrestrial Ecotoxicity."

Table 2.4 shows the six the environmental impact categories according to European standards EN 15804 (EN, 2019) and EN 15978 (EN, 2011) of the built environment. These are: climate change, ozone depletion, photochemical ozone creation, acidification, eutrophication and depletion of abiotic resources (Lotteau et al., 2015). Lastly. the LCIA phase also includes elective steps, namely, normalization, grouping and weighting. These use additional weighting procedures and are optional in the ISO LCA methodology (ISO, 2006).

Table 2.4. Impact categories and description (One Click LCA, 2015)

Impact category	**Unit**	**Description**	**Area of Protection**
Global warming potential (GWP) (greenhouse gases)	kgCO_2 eq	Describes changes in local, regional, or global surface temperatures caused by an increased concentration of greenhouse gases in the atmosphere. Greenhouse gas emissions from fossil fuel burning has been strongly correlated with two other impact categories: acidification and smog. Often called "carbon footprint".	Human and Ecosystem Health
Acidification potential (AP)	kgSO_2 eq	Describes the acidifying effect of substances in the environment. Substances such as sulfur oxides and carbon dioxide dissolve readily in water, increasing the acidity, which contributes to global phenomena such as freshwater and ocean acidification (IPCC 2014).	Ecosystem Health
Eutrophication potential (EP)	kgPO_4-eq	Describes the effect of adding mineral nutrients to soil or water, which causes certain species to dominate an ecosystem, compromising the survival of other species and sometimes resulting in die-off of populations.	Ecosystem Health
Ozone depletion potential (ODP)	kgCFC_{11}eq	Describes the effect of substances in the atmosphere to degrade the ozone layer, which absorbs and prevents harmful solar UV rays from reaching Earth's surface.	Human and Ecosystem Health
Photochemical Ozone Creation Potential (POCP)	kgC_2H_4eq	Describes the effect of substances in the atmosphere to create photochemical smog. Also known as summer smog. This is an important pollutant affecting human health and ecosystems.	Human and Ecosystem Health
Abiotic Depletion Potential (ADP)	MJ, net calorific value	Describes the depletion of fossil fuel and other non-renewable resources.	Natural Resources

2.5.5. Interpretation of results

The fourth and final phase (Interpretation of results) should provide meaningful insight into the results obtained from phase 2 and 3 which are all on dependent on the goal and scope of the study. As such the main contributors to each score and from each life stage should be quantified and compared. It should be inclusive of recommendations, limitations and deductions made (Lotteau et al., 2015). The interpretation aims to provide critical information regarding the implications and significance of the LCI results which allows for the information to be used in accordance with the following key factors:

1. Identification of potential hotspots – interpretation of results helps to identify hotspots which are areas that incur significant environmental consequences or resource consumption (Mirabella et al., 2019).
2. Comparison and benchmarking – the interpretation of results allows for the comparison of findings with established reference values or benchmarks, which serves as a foundation for setting targets (Dong et al., 2021)
3. Sensitivity analysis – examining how LCA results change by altering input parameters, which leads to the identification of patterns and influential factors (Pannier et al., 2018)

2.6. LCA of Buildings

The LCA of buildings is primarily utilized as a valuable tool to assess and enhance the environmental performance of buildings and promote the use of sustainable materials. Building LCA is defined as the scientific approach of the impact quantification a building has on the environment throughout its lifecycle (One Click LCA, 2021). Through the evaluation of a building's lifecycle environmental impacts, it enables stakeholders to focus on energy consumption, greenhouse gas emissions, water usage, and waste generation to reduce impacts. By analyzing various design options, material selections, and operational strategies, building LCA supports informed decision-making to minimize environmental footprints, optimize resource efficiency, and promote sustainability. It also provides opportunities for design improvements, through using eco-friendly materials and circular economy principles (Fnais et al., 2022). Overall, the broad application of building LCA facilitates a comprehensive and sustainable approach to building design, construction, and management, aligning with global initiatives to address climate change and achieve Sustainable Development Goals (SDGs). While building LCA presents many opportunities for design improvements and building efficiency, it does have drawbacks related to comparability. Many building LCA case studies cannot be compared to one another, due to the varying goal and scope definitions, building uniqueness, disparate lifetime of buildings, LCIA methodologies and databases used (Borg, 2001 and Dossche et al., 2017).

Mora et al. (2020), conducted a systematic literature review of the various BIM-LCA integration techniques of buildings, highlighting the many ways in which scholars have used different analysis parameters. For example, the design stage in which the LCA was conducted, the software tools used, the databases, the functional unit, the environmental impact categories and the LCA phase. Some researchers such as Bueno et al. (2018), focused on the early design stages of building elements (wall and roofing system) whereas others such as Santos et al. (2019) focused on the detailed design stage of the entire building. In this regard, building LCA is considered highly flexible with the key parameters used, allowing researchers to shed light on the various aspects of a building. This flexibility is considered advantageous in South Africa, where there is limited data, allowing professionals to apply parameters based on the data available.

As shown in Section 2.2, buildings have different life stages, and these have been further classified by European Standards EN 15978 (EN, 2011) to describe each of the stages using the alphabetical sequence depicted in Figure 2.9. A1 – A3 is associated with the product life cycle stage, A4-A5, with the construction stage, B1- B7 is related to the operational use stage of the building and C1-D describes the end-of-life stage.

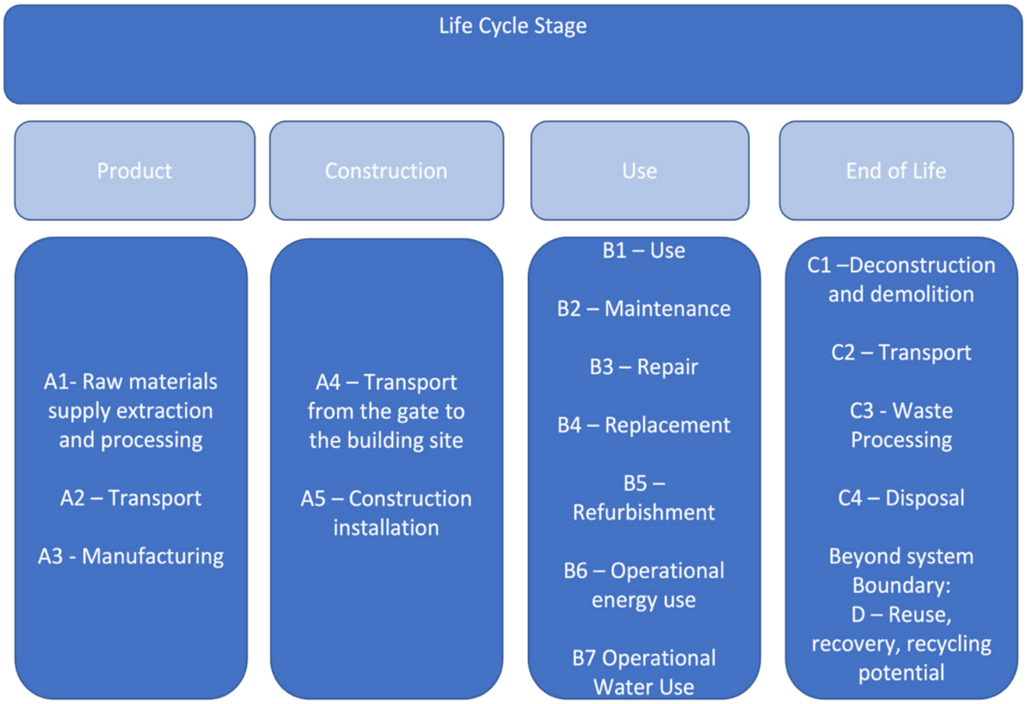


Figure 2.9: The Building Life Cycle Stages (Casini, 2022)

The consequences of climate change have led countries to place primary emphasis on reducing the impact of the Use Stage or the Operational energy phase (B1 and B6). This is because it has been shown to have the most detrimental effect on the environment in the long term (Chong et al., 2017 & Fenner et al., 2018). Therefore, in many instances, this phase is regulated through energy codes and standards (Izaola et al., 2023). However, operational energy use and its associated environmental impact can be reduced over time, whereas the effects of embodied energy cannot be reversed (De Wolf et al., 2017). Hence, it becomes essential to analyze all phases to formulate an effective and holistic sustainable building strategy.

More recently, emphasis has also been placed on examining the early stage of building designs as these can influence all lifecycle stages (Röck et al., 2018). The application of this, however, presents uncertainties due to the number of variables that exist during the initial phases. The influx of research regarding early stages have thus increased due to the sustained efforts to decrease embodied impacts as early as possible during the design process, focusing on prevention rather than mitigation (Anand and Amor, 2017). These research areas have been enabled through the technological advancement of Building LCA tools (Tushar et al., 2019).

2.6.1. LCA tools used in the Building Sector

A wide range of LCA tools have been developed to perform an LCA analysis. The LCA tools that provide an extensive and detailed LCA report include SimaPro and GaBi, these tools although highly reliable are considered time consuming, expensive and require LCA expertise (Fnais et al., 2022). It is for this reason that simplified LCA tools have been developed, tools such as Open LCA, One Click LCA, Tally and eToolLCD Plugin. In recent times these tools have made significant advancements in the form of Plugins, as seen in Table 2.5. LCA Plugins facilitate the operation of a secondary software (LCA Plugin) within a host software (BIM software), essentially serving as an extension to the capabilities of BIM software to carry out a specific task.

Table 2.5: The various simplified LCA tools used for buildings

LCA Plugin	Description	Release date and last update	Cost
One Click LCA	- One Click LCA is an automated web-based software that can be used as a Revit plugin or stand-alone product. - Provides LCA and Life Cycle Costing (LCC) - Provides instant Green Certification (LEED, BREEAM, etc)	12/07/2016 and 21/02/2023	- Free educational version - Commercial cost is individually priced
Tally	- Determines the environmental impact of buildings and provides a comparative analysis of design alternatives. - User-friendly - Contains a Tally database that uses GaBi	15/06/2017 and 25/06/2020	- Free educational version - Commercial cost is individually priced
eToolLCD Plugin	- Consists of a template library that allows the users to link materials information - Adaptable; identifies changes made by the user and updates automatically	20/02/2019 and 06/10/2020	- Free for non-commercial use - Commercial use is individually priced, and pricing is available per project
CarboLife Calculator	• Determines the embodied carbon of a building using specific databases or independently defined data • Creates 3D visualizations	09/04/2021 and 13/09/2021	Free

The LCA Plugins were developed in recent times which exemplifies the technological progress made towards environmental management. All the Plugins provide free educational versions, suggesting that there is still room for academic progress. All the Plugins either use Environmental Product Declarations (EPDs) or generic data for the product stage (A1-A3). An EPD is defined as a declaration of a product's lifecycle emissions. It abides by the standards and guidelines highlighted in Table 2.6. Lasvaux et al. (2015) compared generic data to EPDs and found deviations in environmental impact categories, hence, OCLCA (2021) recommends the use of EPDs to increase the validity of results, as these are more specific and reliable. However, even amongst EPDs of the same material, there are differences; and LCA results are highly dependent on the material selected and its associated EPD (Tozan et al. 2022). The differences may largely be attributed to the standards that govern the Product Category Rules (PCRs) of EPDs, whereby inconsistencies are shown in the interpretation of ISO 14040/44 (Weidema, 2014). Therefore, it becomes important to avoid comparisons of products that are based on varying assumptions (Dossche et al. 2017). Even with all the variances and the difficulty of comparisons, EPDs allow for environmental transparency of products and promote environmental consciousness. And the availability of EPDs in the African region are largely lacking; with only approximately 26 EPDs belonging to the South African Building Industry (Global Green Tag, 2023).

Table 2.6. International and European standards that govern LCAs (OCLCA, 2021)

Cornerstone Standards	Construction works specific standards	EPD standards
ISO 14040 (fundamentals for LCA)	EN15978 – LCA standard for construction projects (European standard, basis for all EU regulations)	ISO 14025 – cornerstone standard for all kinds of EPDs
ISO 14044 (fundamentals for LCA)	ISO 21929-1 and ISO 21931-1 (less used LCA standards)	EN 15804 (EPD data) and EN 15942 (EPD format) (European standard, basis for all EU regulations) ISO 21930

2.7. Green Building Rating Tools and use of LCA

The various GBRTs have acknowledged the importance of LCA for whole building design and towards the reduction of GHG emissions. Subsequently, many GBRTs have incorporated it to their certification schemes on some level or another. There are, however, many differences in terms of how LCA is assessed, variances are observed in the scope, system boundaries and the scoring. Furthermore, some have approached LCA with more rigor than others, for example, the German GBRT, Deutsche Gesellschaft für Nachhaltiges Bauen (DGNB), assigned 8% of the scoring to LCA. It has clearly defined the LCA scope to include all lifecycle phases, provided procedural guidelines and criteria with 10 environmental indicators measured (Veselka et al., 2020). For the purposes of this research, the following GBRTs will be assessed with respect to LCA: BREEAM, LEED, Green Star Australia, and Green Star South Africa. Table 2.7 compares these various GBRTs with respect to their LCA incorporation.

Table 2.7. BREEAM, LEED and Green Star Australia comparison with respect to LCA (adapted from Veselka et al., 2020)

GBRT	Category	Credits	Carbon Reporting	Points	Benchmark
BREEAM	Materials	Life Cycle Impacts	Yes	5	None
LEED	Material and resources	Building Life Cycle Impact Reduction	Yes	4	Yes
Green Star Australia	Positive Category	Life Cycle Impacts	Yes	2	Yes
Green Star South Africa	Materials	LCA	No	0	No

The BREEAM, LEED and Green Star Australia GBRTs incorporate LCA and the "cradle to gate" approach, however, there are variances with respect to the weighting of points and benchmarks (Abdelaal, 2021). BREEAM awards the highest points for the use of LCA, specifically 5, but there is no established benchmark for their evaluation. Furthermore, these points are optional, and certification can be awarded without it. However, energy use and carbon emissions are necessary criteria to achieve certification. The LEED scheme awards a maximum of 4 points and assesses 6 impact categories with emphasis on the Global Warming Potential (GWP) impact category and stipulates that its' reduction is mandatory to achieve points. The points are awarded in accordance with a 10% impact reduction of 3 categories (GWP included) when compared to a baseline. The baseline, which is used as a benchmark for comparison, is a reference building that is comparable in its' dimensions, functionality and location (USGBC, 2023). Similarly, Green Star Australia also specifies a baseline building for comparison. It awards a total of 2 points for LCA which are also optional. The three GBRTs have a list of approved LCA tools that can be used for assessment. Further discussion on the LCA accreditation system for the international GBRTs can be found in Appendix 8, however, in this dissertation greater emphasis has been placed on Green Star South Africa to understand the scope of Life Cycle Thinking (LCT) and is examined in the next section.

2.7.1. Green Star South Africa

The importance of incorporating the embodied carbon of a building throughout its lifecycle has been recognized by Hoffman et al., (2020) who conducted an analysis of Green Star SA. Currently, Green Star SA does not have an LCA criteria, it does however encourage it and has plans to include it in the updated version to be released later in 2023. Although there is a lack of LCA criteria, the Green Star SA does incorporate a more basic approach, in the form of LCT. LCT refers to the mindset of including a holistic environmental approach, and this is observed in Table 2.8. whereby the only relation to LCA may be observed indirectly through the embodied and operational emissions section, more specifically under the Energy category and Materials category. For the Energy category, GHG emissions are prioritized and is the only impact factor considered, a significant number of points (20) are awarded for reducing the operational energy of the building and the associated GHG emissions. The Materials category promotes the use of recycled and reused materials, and it encourages the use of materials that are sourced locally, thereby decreasing transport distances. Therefore, it becomes evident that the tool has the basic concept of LCA, and it recognizes the importance of incorporating LCA criteria for an improved assessment of Green Buildings.

Table 2.8. The Green Star SA embodied and operating GHG emissions (Green Star SA, 2014)

Emission	Category	No.	Credit	Carbon Reporting	Points
Embodied Emission	Energy	ENE-1	Greenhouse Gas Emissions	Partly	20
	Materials	MAT-2	Building Reuse	No	5
		MAT-3	Reused Materials		1
		MAT-5	Concrete		3
		MAT-6	Steel		3
		MAT-8	Sustainable Timber		2
		MAT-9	Design for Disassembly		1
		MAT-10	Dematerialization		1
		MAT-11	Local Sourcing		2
Operating Emissions	Energy	ENE-3	Lighting Power Density	No	4
		ENE-5	Peak Energy Demand Reduction		2
	Water	WAT-1	Occupant Amenity Water	No	5
		WAT-3	Landscape Irrigation		3
		WAT-4	Heat Rejection Water		4
		WAT-5	Fire System Water Consumption		1

When comparing the Green Star SA with the other international GBRTs it is evident that further development is required in terms of LCT and LCA. To accomplish this, would require the inclusion of LCA criteria that involves the incorporation of LCA methodologies, data requirements and benchmarks. Additionally, guidance and knowledge resources should be provided to project teams and Accredited Professionals (APs) to promote the use of LCA as a decision-making tool within the South African building industry. The integration of LCA and BIM, can facilitate the entire process and the next section delves into the topic of BIM and addresses how it can be used to simplify the LCA of buildings.

2.8. Building Information Modelling (BIM)

The definition of Building Information Modelling (BIM) often differs between scholars. Wang and Chong, (2015), and Mathews, (2015), describe it as a collaborative means to share building information throughout a building's lifecycle; thereby solidifying its advantages in facilitating the LCA decision-making process. Other researchers emphasize its efficacy in building visualization (Gu and London, 2010). Mtya (2019), combined the terminologies and proposed the definition as "detailed computable information about a facility in digital accessible format". The concept is relatively new, and its evolution mirrored the overall advances in digitalization as applied to the design of buildings. This was made possible by developments in software (i.e., applications and platforms) and hardware (processing power). Historically in 2002, the introduction of BIM was proposed by Autodesk, to supersede 2D software and provide 3D visualization of buildings (Bew and Richards, 2008). It was found, however, that more information would be required to produce a 3D component, for example, the addition of a component, a door or window, would compel further information regarding its properties, size, material used, color etc. (Gamayunova & Vatin, 2015). With technological progress, this subsequently gave rise to the 7D BIM capabilities exhibited in Figure 2.10 (adapted from Cervosek, 2011).

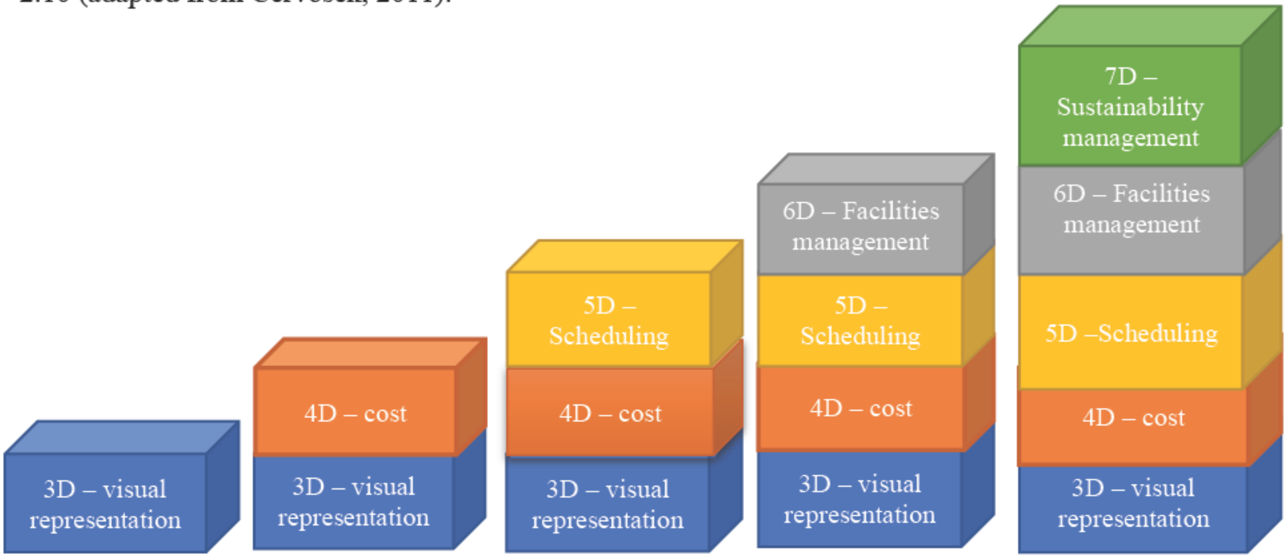


Figure 2.10. Progression of BIM to 7D capabilities (Cervosek, 2011)

As can be seen in Figure 2.10, the 7D sustainability management component is a recent addition to the capabilities. As with any widely used process, product or service, the development of BIM called for an international standard or guideline that would form as a basis for users. ISO 19650 was subsequently created to manage information over the entire lifecycle of a built asset utilizing BIM. Overall, BIM allows the user to create simulations and modify them according to design criteria, saving time, energy and resources (Mtya, 2019). It interlinks the design of architects with the structural components of engineers to the building components of contractors and the Mechanical, Electrical and Plumbing systems (MEP). It has reduced fragmentations and simplified the design and building process by being a means of communication between disciplines using a Common Data Environment (CDE) (Calitz, 2021). Each key member of a building project benefits from the use of BIM differently as shown in Figure 2.11.

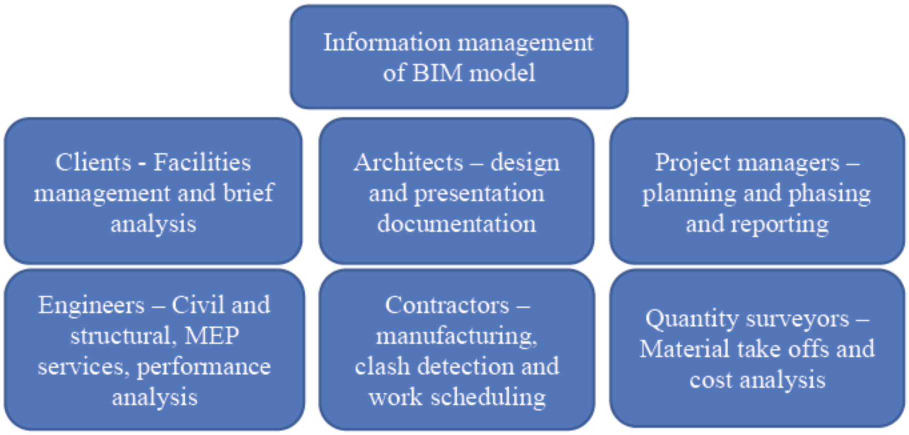


Figure 2.11. How BIM is used by the various key members of the construction industry (Ismail, 2019)

The AEC industry has seen a major shift towards the use of BIM primarily due to the interoperability between various entities. Mtya, (2019), summarized the perceived benefits of BIM from previous literature as:

- Design information is direct and succinct which improves the workflow
- Decreases the need for re-assimilation of data
- Provides live synchronization of project information, reducing time and cost
- Supports maintenance operations by enhancing logistics and supply chains
- Automated process- checking and analysis

Furthermore, another benefit of BIM can be observed in its' crucial role of facilitating the pursuit of Green Building certification. The pursual of Green Building certification has been deemed a laborious, costly and complex process (Dosumu et al., 2021). One of the reasons for the complexity of certification is associated with the acquisition of data (Mtya, 2019). Building projects are fragmented, with data stored often at different times, in different companies, through various subcontractors and professionals in the field. BIM stores the majority of the information regarding the materials to a high level, this includes: the type of structural material, family, color, volume and thicknesses of materials. Users can modify this information according to their project and can even include manufacturer details through shared parameters. It can include the Bill of Materials and Bill of Quantities, and the extraction of such information is simple and readily available through material takeoff schedules and quantity take off schedules. The live synchronization and collaboration of data possible within BIM has further simplified the pursual of Green Certification. Gandhi and Jupp, (2014), found that 66% of the Green Star Building certification requirements may be assessed by using BIM. Abdelaal (2021) reported that 67 out of the 120 points in the New Zealand Homestar rating system could be accomplished using BIM. Therefore, its importance needs to be underlined even if it is used at lower levels of detail.

2.8.1. BIM Software

Over the years BIM has seen significant improvement in its technological advancement, from its visualization capabilities, transitioning from 2D to 3D, to its clash detection capabilities, allowing for improved coordination and the minimization of errors during the design and construction phases. BIM software can be classified into 6 groups: Architectural, Structural, Construction, MEP, Sustainability and Facilities Management (Kalfa, 2018). The various BIM software applications and the respective fields are highlighted in Table 2.9.

Table 2.9: Various BIM Software used by different groups within the Building Sector (adapted from Kalfa, 2018)

Architecture software	
• Revit • ArchiCAD • Vectorworks Architect	• Bentley Architecture • RhinoBIM (BETA)
Structure Software	
• Revit • Bentley Structural Modeler	• Bentley RAM • Tekla Structures
Construction Software	
• Navisworks • Solibri Model	• Tekla BIMSight • Bentley ConstructSim
Mechanical Electrical Plumbing (MEP) Software	
• Revit • Bentley Hevacomp Mechanical Designer	• Digital Project MEP Systems Routing • Fine HVAC + FineLIFT + FineELEC
Sustainability Software	
• Ecotect Analysis • Green Building Studio • Eco Designer	• IES Solutions • Bentley ConstructSim
Facilities Management	
• Bentley Facilities • FM: Systems FM: Interact	• EcoDomus

As seen in Table 2.9, each field exhibits a particular preference for a certain software, for architects and structural engineers, the most widely used BIM software is ArchiCAD and Revit (Kalfa, 2018). While there is no definitive right or wrong way to utilize the various software, its' effectiveness often depends on its strength in performing specific tasks. This is predominantly why preferences for software usage can vary among companies, industries and even countries. There is, however, an open file format called Industry Foundation Classes (IFC) which allows for the exchange of models across different software packages, this will be further discussed in Section 2.9.1.

2.9. BIM- LCA Integration for Buildings

BIM-LCA integration refers to the incorporation of BIM capabilities which are used for visualization and assimilation of data, with LCA methodologies for the quantification of the environmental impact of buildings. Essentially, BIM is used as a quantitative inventory input for LCA to determine the quantitative environmental output. The integration is an initiative to reduce the harmful environmental effects associated with urbanization by facilitating the decision-making process to prioritize sustainability of buildings. BIM-LCA integration can be used for various practical applications that include:

- Material and product selection – Allows for designers to make more informed decisions by taking into consideration the embodied emissions associated with the product stage of materials, which in turn enables the selection of sustainable materials (Xue et al., 2021).
- Energy performance analysis – Provides opportunities to reduce building operational energy by using Building Energy Modelling (BEM), to assess the impact of building orientation, smart ventilation and sustainable energy sources (Asare et al., 2020).
- Waste management – Provides opportunities for recycling, reusing and optimizing a waste management strategy.
- Water management – Enables the evaluation of the lifecycle water footprint and provides opportunities to minimize water consumption and improve water management strategies (Haddad et al., 2022) (Xue et al., 2021).
- Renovation and retrofitting – Enable designers to create sustainable design alternatives and select the best alternative for renovation and retrofitting, that reduces resource consumption and waste generation (Dauletbek and Zhou, 2022).

Overall, the best use of BIM-LCA integration is during the early design stages where it is cheaper to implement changes. According to Najjar et al. (2017), approximately 60% of time is wasted during the initial design stages due to lack of clarity and scope definition, poor communication, inefficient iterative design process, among other reasons. The integration of BIM-LCA is a means to reduce the time spent on the conceptual phase by improving the iterative design process to provide sustainable design alternatives (Bueno et al., 2018). While ideally implementing the BIM-LCA integration during the initial design stages is optimal, it can also be challenging because of the inherent uncertainties regarding data variability and material selections (Feng et al., 2022).

Table 2.10. describes each of the BIM and LCA parameters that should be considered during a particular phase of the lifecycle to achieve the desired objectives set out for a particular building phase.

Table 2.10. Parameters to be considered during building phases (adapted from Najjar et al., 2017)

Building Phase	**BIM Parameters**	**LCA Parameters**	**BIM – LCA Integration**	**Objective**
Conceptual Design	Design Alternatives	Building Materials and transportation data	Sustainability requirements and targets	Sustainable designs and reduced embodied impact
Construction Phase	Structural details of building	Construction machines data	Sustainable practices	Environmentally conscious practices, reduced construction impacts and less energy
Operation, Maintenance and Repair	HVAC system specifications, lighting and appliances	Operational energy data	Simplified analysis of building phase	Cost and energy efficiency and reduced GHG emissions
Demolition Phase	Simulate demolition	Impact assessment	Predict disposal energy	Recycle and safe demolition

The BIM parameters are dependent on the Level of Development (LOD) of a building. LOD is defined as the level of detail of the BIM model, and it establishes the composition of a project at different development stages. It encompasses two fundamental elements: the geometric representation, which pertains to the visual aspect of the project, and the attached data that provides additional information about its elements (Building Design, 2017). Various countries rate LOD differently, in the US for example it is rated according to five rating levels that is: 100, 200, 300, 400, 500 (Reinhardt and Bedrick, 2015). However, in the UK, it reaches a rating level of 700, and for the purposes of this study, the UK LOD system will be utilized as illustrated in Figure 2.12. A level 100 LOD describes an abstract model, and the amount of detail increases until level 500, an as-built model. A level 100 LOD could be defined vaguely with no dimensions, simply a model with a surface. A level 200 LOD could have dimensions, quantities and sizes. As the LOD progresses, the level of details in specifications increases leading to greater confidence in calculations as many uncertainties are resolved until it reaches LOD 700 that incorporates all stages including the deconstruction and reuse of building materials. Santos et al. (2019) recommend an LOD of 200 or 300 for a simplified LCA methodology.

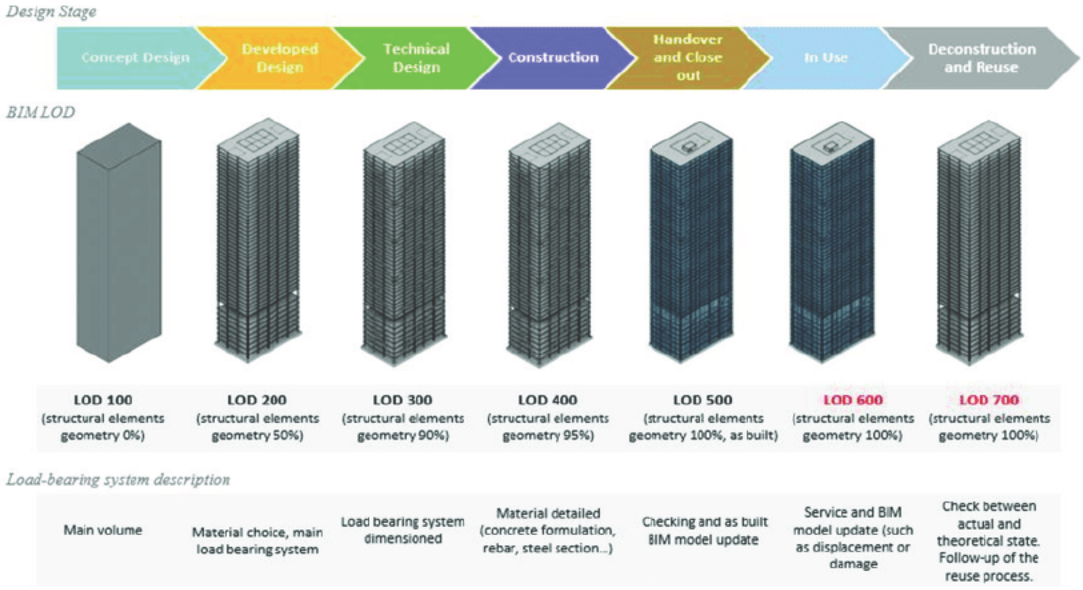
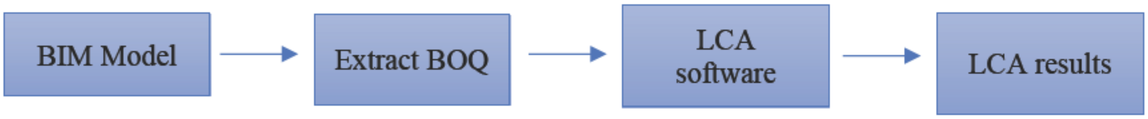


Figure 2.12: The range of LOD during the various stages (Bertin et al., 2020)

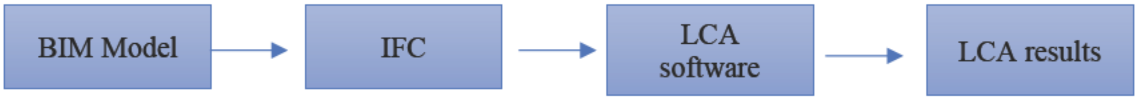
2.9.1. Methodologies of BIM-LCA integration

There are various BIM-LCA integration methodologies that can be followed to reduce the environmental impact of buildings. These methodologies are best implemented during the early design stages to facilitate the decision-making process for the AEC industry to achieve sustainability goals. Several researchers have examined different methodologies for integrating BIM and LCA, these include: Obrecht et al. (2020), Mora et al. (2020), and Wastiel's and Decuypere (2019). Among these studies, Wastiel's and Decuypere provided a notable summary where they outlined and explained the five distinct approaches for BIM-LCA integration:

1. Bill of Quantities (BOQ) – This strategy uses the BIM model to extract the BOQ data and link it to the LCA profile in the LCA software. It is currently the most used approach.



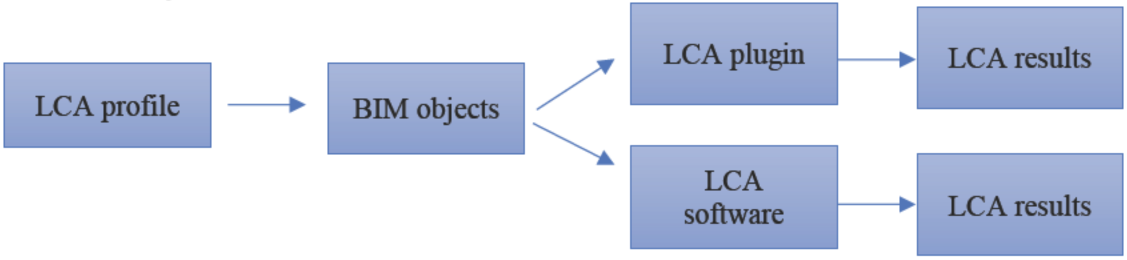
2. Industry Foundation Classes (IFC) – IFC as defined by Wastiel's and Decuypere (2019) is an open file format that exchanges BIM models between software tools from various suppliers. This method essentially transmits the BIM model into the LCA software via the IFC. The geometrical parameters of the BIM are identified, and material quantities are determined and then linked to the LCA profile by the user.



3. BIM viewer – The third strategy involves an intermediate viewer which maintains the 3D geometry and subsequently links the LCA profiles to the material quantities. This method facilitates an iterative process.

4. LCA Plugin – The LCA plugin method allows for the entire LCA process to be conducted within the BIM software. The plugin calculates the LCA results.

5. LCA enriched BIM objects – The LCA profile in this strategy is predetermined and combined within the BIM objects from the beginning. The user would be able to see a reference to the LCA data of a component whilst modeling. This strategy is the most ideal as designers would have LCA information prior to selecting building components, however, any material changes may prove to be laborious and time consuming to edit. Although the LCA profile is associated to the BIM object, further steps to determine the LCA results are required. One could either opt to use the LCA plugin or LCA software to conduct the analysis.



The 5 approaches may be used interchangeably depending on the project. Factors such as the BIM environment (architectural or structural), LOD and iteration requirements are important to ascertain before proceeding with a strategy. Revit architectural for example consists of more details than Revit structural, i.e., interior finishes, curtain walls, etc. and therefore has a higher LOD. High LOD's require more iteration and details and therefore, strategy 1, 2, or 4 may be used. A project with a low LOD has the option of utilizing strategy 2, 3 or 4 as they are more geometrically inclined (Wastiel's and Decuypere, 2019).

2.9.2. Previous research on BIM-LCA integration

Safari and AzariJafari (2021), conducted a systematic literature review on all the existing BIM-LCA integration papers. They emphasized on the reliability of studies and provided comparisons. They identified the four components that must be considered and carefully analyzed in every BIM-LCA integration to decrease discrepancies:

1. Level of Development (LOD) –Safari and AzariJafari, (2021), have determined that defining the LOD and design phase is essential in increasing the reliability of results. The higher the LOD, the lower the uncertainty associated and deviation of results.
2. Functional Unit –Failure to accurately determine the functional unit could lead to discrepancies. The functional unit in previous literature varied greatly (Safari and AzariJafari, 2021). It was often defined as the entire building or building element, however, as the name suggests, the functional unit should be selected in accordance with its function. The function of the building is dependent on the occupancy and building performance (Safari and AzariJafari, 2021).

3. Lifespan - The lifespan of a building should be ascertained based on each phase; for example, the construction phase could surmount to 3 years, the building phase could be 40 years and the demolition phase could be 7 months. However, the majority of the BIM-LCA integration and Green Building Rating Tools, stipulate an overall lifespan for office buildings as 50-60 years.
4. System Boundary – The system boundary is based on each individual project and most importantly based on the data that is available which is a key factor contributing to the variations among different studies. The system boundary should consider intricate details of all the building phases, including the materials selected during the product stage, as well as data related to energy use during the operational phase, and data related to reuse and recycling during the demolition phase.

Table 2.11 presents a summary of further research on BIM-LCA integration, with a focus on evolving concepts rather than providing an inclusive list.

Table 2.11. Research on BIM-LCA integration and associated findings

Reference	Year	Research Summary
Basbagil et al.	2012	The study assessed the material choice and component thicknesses to determine the lowest embodied impact. The purpose of the research was to identify building component hotspots that may be analyzed by designers to improve and assist in the environmental decision-making process. The study aggregated the designs to determine the GWP of buildings by considering different material components and thicknesses. The assessment of the operational phase included only Maintenance, Repair and Replacement (MRR). The results found that the embodied impact due to the MRR were small and that the cladding material and thickness selection were significant.
Najjar et al.	2017	Compared modern building materials to typical building materials in Brazil. The results interpreted that in modern buildings, curtain wall mullions and walls were responsible for 89% of the Global Warming Potential (GWP) and 80% of the primary energy demand (PED). Whereas in typical buildings, the walls accounted for 57% (GWP) and 75% (PED), the windows accounted for 6% (GWP) and 8% (PED). The Demolition phase however, found that modern buildings benefitted the environment more than the typical buildings.

Rock et al.	2018	Established a common granularity between the bill of quantities in BIM (using Autodesk Revit software) and LCA data (Swiss SIA MB 2032 pre-calculated dataset). This allowed for the automation of BIM and LCA; a common naming convention was essential towards exchanging information. The workflow used the functional unit of the impact per square meter on Building Elements ($m^2{}_{BE}$) to create a visual representation of the results and identify potential hotspots. The results found were that the external walls, partition walls and the floors were accountable for the highest GWP.

In summation, each of the articles determined the effect of a particular material or element's impact on the environment, with specific focus on the GWP. There was limited information with regards to the Level of Development (LOD) of a BIM model and its relation to LCA results. However, one such study by Habert et al., (2020) researched this relationship and found that there was an over-estimate of GWP during the early design stages whereby the LOD was low. There was also limited information regarding studies conducted in Africa. Crippa et al., (2020) conducted a systematic literature review and found that the majority of the BIM-LCA integration studies were from European countries, with no published articles in Africa. However, to date, there has been one article by Santos et al., (2020), that determined the LCA of a high rise building in Morocco. It therefore becomes important to research the topic of BIM-LCA integration further in Africa.

2.9.3. Existing Gaps and Challenges of BIM-LCA integration

The lack of adequate data in the BIM database poses a challenge to BIM-LCA integration, primarily due to varying global socio-economic circumstances. Developing countries, in particular, show less inclination to gather data on BIM-LCA integration. The diverse range of building materials across countries further complicates the creation of a comprehensive database, necessitating significant efforts from software developers, the AEC sector, and manufacturers. The implications of inadequate data result in less accurate results. One potential solution to address this challenge is to establish country-specific BIM-LCA task forces dedicated to data collection. Thereafter, the database should be updated regularly to include more information on building materials and properties (Anand and Amor, 2017).

A lack of commonality between the datasets also presents as a challenge, which may cause significant variations in LCA results. The root cause of which is due to the varying naming conventions implemented by companies when modelling on BIM software due to company preference. The implications of which includes a complex list of building materials that is not user friendly, resulting in more inaccuracies and possibly selecting the wrong building material. The solution would be to create a common naming convention for all building materials.

Another challenge includes the interoperability of BIM and LCA although there have been significant efforts for improvement, there have been studies that reported data loss when transferring information (Obrecht et al., 2020). The onus is on the users to report instances of data loss so that software developers can upgrade the software, address issues and fix bugs.

Further challenges include uncertainties within the LCA process, uncertainties in terms of data, construction materials, methodologies and approaches (Rezai et al., 2019). There are also uncertainties in terms of the changes that could be potentially made after the initial design phase, changes by stakeholders or building owners, human error during the construction phase, all of which could decrease or nullify the validity of results (Habert et al., 2020). Academics should incorporate uncertainty analyses into their studies so that the level of uncertainties can be identified and reduced. Furthermore, a follow up on the LCA analyses should be conducted i.e., a comparison of the pre-design phase and the post-construction phase which significantly assists in understanding and improving the LCA of buildings.

Zimmerman et al., (2021), investigated BIM-LCA integration within the industry practice. They conducted in depth interviews with medium and large consulting companies in Denmark. Some of the important challenges faced include inaccuracies of modelling. Often, the LCA practitioner is not the one that has created the model, human error occurs, and it therefore decreases the quality of the LCA analysis. Another common challenge encountered pertains to extracting data which must be obtained from suppliers, subcontractors, past projects, other engineering disciplines or even literature. This can sometimes cause delays and be time consuming. A possible solution to this is the use of a Common Data Environment (CDE) such that information may be stored on a shared server and easily accessible to all participants. Zimmerman et al. (2021) further mentioned that the automation of the BIM-LCA integration may lead to a lack of transparency and consequently errors. Therefore, the optimum extent of automation must be established to increase efficiency.

2.10. The South African Situation

South Africa is a developing nation with large disparities exhibited within the society. It is therefore quintessential to establish a BIM-LCA framework that is feasible in terms of both cost and time. The onus is on key stakeholders, such as the government and the Green Building Council of South Africa (GBCSA) to provide motivation for the AEC industry in the pursuit of sustainable buildings. According to Cao et al., (2014), motivation to design more sustainably in developing countries is best implemented through authoritative pressure. This comes in the form of Green Building accreditation for sustainable buildings and could even come in the form of the Carbon Tax. South Africa has already implemented a Carbon Tax policy in 2019 that follows the "polluter pays principle", however this policy is only for selected industries and excludes the building industry (IMF, 2023). The inclusion of the building industry to the Carbon Tax policy has the potential to promote a stronger commitment towards reducing building related GHG emissions, however, it might increase costs.

Additionally, the South African government has implemented other measures for environmentally conscious practices, such as Energy Performance Certificates (EPCs). Since December 2020, it has become mandatory for new buildings to disclose their energy expenditure and submit an EPC, this initiative encourages companies to actively monitor their energy consumption. It includes an energy performance scale that considers the occupancy, geographic location of energy zones, energy sources and building occupancy (SANEDI, 2023). Similarly, guidelines and mandates may be developed on GHG emissions to provide a holistic environmental outlook of buildings locally and the BIM-LCA integration can help in this process.

The implementation of any framework requires an assessment of current practices and the challenges that could potentially be encountered. It is, therefore, important to acquire information about current trends and how other countries have incorporated BIM integrated LCA frameworks. The distinction between current global practices may consequently motivate and expedite change within South Africa. The challenges that could be encountered locally in implementing a BIM-LCA framework to determine the environmental impacts of buildings are divided into two parts: the environmental sustainability challenges in South Africa's building sector and the challenges associated with BIM-LCA integration. The biggest challenge common to both components is the lack of knowledge, expertise and incentives (Windapo, 2014).

2.10.1. Environmental Sustainability Challenges in South Africa's Building Sector

Despite efforts to improve the sustainable standing of the country, implementation has been gradual (Oke et al., 2016). The consensus of previous scholars in terms of what the biggest challenges for South Africa include:

- Insufficient affordable sustainable materials - Windapo (2014) found that sustainability is driven by economic ambitions, without the provision of affordable sustainable materials and stakeholders would not be encouraged to pursue sustainable construction.

- Inadequate knowledge and technology - Dosumu (2021) deduced that the dominant factor inhibiting sustainability progression was a lack of knowledge and technology.
- Lack of legislation and incentives – The government plays an important role in establishing a status quo and providing social benefits towards excellence, inadequate interest and monitoring by the government is a crucial inhibitor (Windapo, 2014; Dosumu, 2021 and Marsh et al, 2019)
- Weak economy – Dosumu, (2021), reported that developing countries in general, struggled to prioritize sustainability due to financial constraints.

2.10.2. BIM and LCA Challenges in South Africa

The increasing interest in BIM and the acknowledgment of its' benefits, has led to some research in South Africa to investigate the reason behind its limited implementation. Mtya, (2019) and Calitz, (2021), conducted a thorough analysis of the state of BIM adoption rates and found the following commonalities in limiting implementation:

- Inadequate BIM competency in education sectors and in practice
- Insufficient research
- High capital costs and uncertainty regarding the returns
- Lack of legislation
- Social resistance to change traditional processes
- Inadequate support by key drivers: government, stakeholders and education sectors.

The attributional construct of LCA is time consuming and requires expertise and competency. However, consistent research has led to the simplification of such methodologies. In South Africa, there is limited interest in the topic and little incentive to understand it better and implement it. In first world countries there is legislative pressure on manufacturers to provide more environmental data on their products, necessitating the need for ecolabels and EPDs. Such initiatives are lagging in developing countries such as South Africa, for example, the development of an EPD database is only in the initial stages. The LCA challenges in the country is predominantly due to the absence of data and the lack of willingness to share data (Friedrich et al, 2017). It also includes similar barriers to BIM, in that there are limited LCA professionals, a lack of knowledge and technology. Some of the challenges faced by the GBCSA to implement LCA in its Green Star rating tool and to advocate for Life Cycle Management include "additional costs, limited local data and limited knowledge of the benefits" (Anderson, 2022). However, there are current drivers to pursue BIM-LCA integration, these include:

- Benefits of BIM-LCA integration – Sustainable development of Buildings, improved decision making, cost and resource efficiency.
- Pressure to adopt BIM-LCA integration- As previously discussed in this chapter, international GBRTs have adopted LCA criteria to their accreditation systems, this serves as a driver for South Africa to adopt a similar approach.

2.11. Summary of Literature Review

In this chapter, significant concepts and prior academic research related to the research topic were explored, emphasizing the correlation of three key areas: Green Buildings, Life Cycle Assessment (LCA), and Building Information Modeling (BIM). Figure 2.13 illustrates the interrelation of these topics. Green Buildings are characterized by energy-efficient designs that prioritize sustainability. LCA serves as an environmental assessment methodology that empowers designers to make more informed decisions about the environmental performance of buildings. GBRTs worldwide, including BREEAM, LEED, and Green Star Australia, incorporate and implement LCA to varying degrees. However, it is worth noting that the criteria within these tools are still evolving and not fully inclusive. Extensive research is currently underway to enhance and expand the LCA criteria. In South Africa, the development and research of LCA is still in progress and not established. South Africa's lagging progress on the LCA of buildings, highlights the need for an LCA criteria and the acquisition of LCA related data. BIM functions as a project management and 3D visualization tool that streamlines the design process of Green Buildings and can simplify the implementation of LCA methods and can potentially aid in local LCA applications for buildings leading to more environmentally friendlier designs and better overall environmental performance of buildings. However, the integration of BIM with LCA has not been researched in the local context and this study aims to fill that gap.

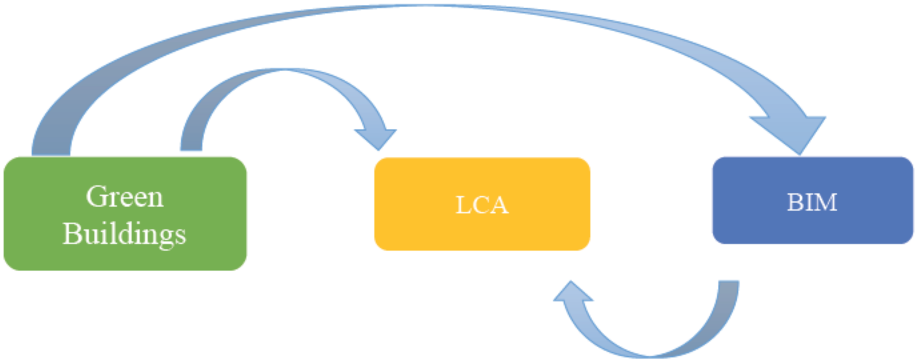


Figure 2.13. The interrelation of Green Buildings, LCA and BIM.

Chapter 3 – Methodology

3.1. Introduction

The integration of BIM and LCA is a relatively new approach to ascertaining the environmental impact and carbon footprint of buildings. This chapter gives an overview of the methodology followed for this research. As such, it included the conceptualizing and planning of the research to determine the BIM and LCA tools to be used in performing the LCA analysis. It provides a description of how the study was conducted which includes a description of the case studies, scope, assumptions made, system boundaries and a brief description of the LCA data that was used. The steps in the analysis process used to obtain results are also included.

3.2. Methodological Overview

The main methodological steps as presented in Figure 3.1 are described in the upcoming sections.

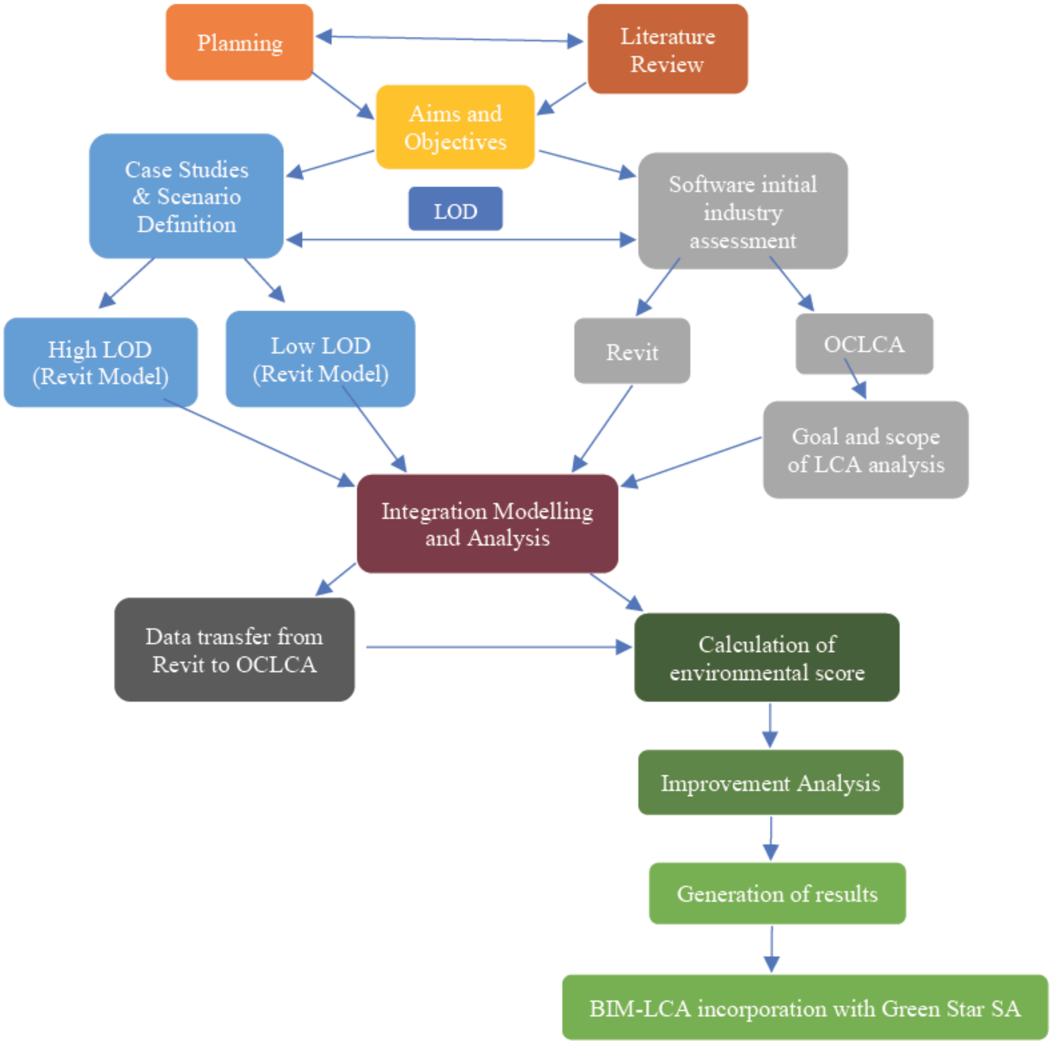


Figure 3.1. Methodological Overview

3.3. Planning and Literature Review

The planning phase of the methodology involved laying the groundwork, establishing the motivation for the study and subsequently determining what was feasible given the limited BIM-LCA experience in South Africa. This phase also established that only a limited number of Revit case studies in South Africa that included a high LOD existed, which created the need for a second case study. The research question, aims and objectives were set, and a comprehensive literature review followed thereafter. The literature review involved extensive searches and the input of key words that included BIM-LCA integration, building LCA, GBRTs and LCA into academic search engines such as Google Scholar, ScienceDirect, ResearchGate, Springer and MDPI. Following these searches, a compilation of articles, journals, theses, etc. were examined, and only pertinent information that aligned with the research objectives was selected.

3.4. Evaluation of software to be used

The evaluation of software involved an iterative approach, wherein various software options were assessed and selected based on their functionalities and capacity to meet the research's aims and objectives. The primary phase involved gathering information with respect to BIM and determining the best software that would simultaneously satisfy the constraints of the building sector and environmental LCA requirements. The outcome of this phase was determined through the literature review and seeking the guidance of engineering industry practitioners. The selection of BIM software was more extensive in comparison to the LCA software to be able to establish current industry practices. Thereafter, an evaluation of the various LCA tools was also conducted to be able to integrate the two software platforms.

3.4.1. BIM and Revit Evaluation

In the initial step to select the most appropriate tool, a series of interviews were conducted with professionals to determine which BIM software was locally preferred and used. The interviews, which were semi-structured in their approach, also provided a more in-depth understanding of current BIM practices in sustainable building designs in South Africa. These findings will be further discussed in Chapter 4. The interviews also served the purpose of identifying suitable case studies that could be utilized in the integration process. The interview questions which have been included in Appendix 9, targeted professionals as highlighted in Table 3.1.

Table 3.1. Description of professionals participating in the interviews

Interviewee	Title	Company
Person A	Digital Lead	AECOM
Person B	Digital Lead	AtkinsRéalis
Person C	Senior Revit Modeler	WSP in Africa
Person D	Senior structural engineer	Zutari Consultancy
Person E	Junior structural engineer	Zutari Consultancy
Person F	Senior Architect	Roy Hardie Architects
Person G	BIM manager	Studio 3B
Person H	Sector Manager: Bridges and Buildings	MPAMOT
Person I	Sustainable Building Consultant - Architect	Solid Green Consulting

Table 2.9 of the Literature Review, presented an overview of the various BIM software identified during the theoretical research. Among the available options, Autodesk Revit emerged as the most widely used software (Carvalho et al., 2020) due to its collaboration capabilities and its ability to store material properties. It was chosen for this study due to several factors including:

- Project Information - The software can store a significant amount of information in its Type Properties.
- Automation of procedures – Through the use of Dynamo which is a built-in visual scripting application that compliments Revit by creating algorithms that automate repetitive tasks.
- Flexible data- Adaptability of material data is demonstrated through the modification of shared parametric components. For example, if a particular material does not exist on the software or there are changes in its properties, it can be created or amended in accordance with the project.
- Inter-disciplinary Platform – Revit facilitates projects through the coordination of Structural, Architectural and MEP disciplines.
- It includes several plugins that simplify a wide range of applications such as energy modelling, LCA, reinforcement design using Naviate rebar, clash detection, etc.
- Project management – Revit can carry projects from the conceptual phase through to construction by allowing designers to generate detailed 3D models, create construction documentation, and collaborate with stakeholders throughout the project lifecycle. This process is facilitated by using a construction cloud feature called BIM collaborate.
- Real-time project synchronization – Changes made by various users can be made visible instantaneously thereby facilitating the collaboration of a project team and reducing fragmentation and repetitive tasks.
- It also provides a cost estimate and a logical sequence to any project, thereby promoting transparency amongst all project members.

- It also depicts 2D views for engineers and architects to specify details and annotations.
- Free – Revit has a free student version.

3.4.2. LCA and One Click LCA Evaluation

The various LCA software available on the market were discussed in Table 2.5 of the Literature Review. The evaluation of these software choices was conducted iteratively, the author initially explored SimaPro for analysis, however, it was found to be more product/process oriented, and although it could conduct a detailed LCA analysis, it required more data, expertise and time. The commercial version was also considered expensive, priced at an annual subscription of R113 932. Considering the research objectives, a feasible option for South Africa was required, this necessitated a software that was easy to implement, allowing professionals with limited LCA knowledge to incorporate it into the building design process.

Therefore, SimaPro and GaBi were both excluded from consideration due to their similar functionalities and both options were expensive. The next iteration was based on OpenLCA, and while the software itself was free and easily accessible, additional data from sources like Ecoinvent had to be purchased separately. The final selected software for this study was the web-based software, One Click LCA (OCLCA), as it was specifically aligned to conduct building LCA, and it should integrate seamlessly with Revit. In addition, the following reasons also contributed:

- Flexibility of data input – Material data can be manually added or edited during any stage of the project.
- Compatibility with BIM and Building Energy Modelling (BEM) software – OCLCA is compatible with AutoDesk Revit, ArchiCAD and Bentley.
- Vast database – The OCLCA software has a large database that includes Ecoinvent and GaBi, and it contains some South African data or applies a localization factor in the case of missing data. It also has a large EPD database and EPD generator.
- Time validity of database – The software values the validity of data by providing warnings for expired data.
- Other Software Integration - It supports various software integrations to import data, these include Grasshopper, Design Builder, Tekla, Trimble, Rhino, IES-VE, IDA ICE, Solibri, gbXML and Excel.
- Quick and efficient – The software provides the results quickly and its web-based feature does not use up significant computer processing memory, thereby saving time.
- Free – The software has a free student version

- Widely Used - OCLCA is used in over 120 countries and supports over 60 certifications (OCLCA, 2021)
- Contains Add-ons - It also has add-ons such as Carbon Designer, Net-Zero Carbon, Building Circularity, Site Designer, Compliance tools, Life Cycle Costing and Interior Design Carbon.
- User-friendly interface – The software is easy to navigate and use.

The environmental impact factors of building materials have been included in LCA databases, such as Ecoinvent and GaBi. However, most databases contain limited information for South Africa and Africa in general. To tackle this limitation, some tools such as the One Click LCA software developed a localization factor to compensate for the lack of data in many regions; whereby formulas are used to determine the impact of a material by considering the electricity required for material production and the local electricity generation impact factor (One Click LCA, 2021). Therefore, despite the limited data in the African region, a scientific estimate can still be determined using One Click LCA for a building throughout its' life stages.

3.5. Case Studies

Accomplishing the aims and objectives of the research necessitated the selection of a case study to test the framework and offer a concise report on how results were obtained. The author contacted large companies in Durban, namely: AECOM, Studio 3B, Royal Haskoning DHV, WSP, Arup, Zutari, Hatch and MPAMOT. However, there were few companies that responded and of those, Zutari was the only company to offer a case study. The case study provided was completed in 2020 and was designed for the client, commercial developers, Zenprop Properties, the occupying tenants were Rewardsco. Several attempts to obtain the Bill of Quantities (BOQ) and energy expenditure reports from Zenprop Properties were made to check the validity of results, however, this was not provided due to confidentiality reasons. In addition, the case study was modelled with a single building material, concrete, and subsequently, had a low LOD, this necessitated a second case study with a high LOD. The author re-created a model of the second case study, following a Udemy course outline and expanded on the scope of building materials. The overview of the case studies, scenario definitions as well as the advantages and disadvantages are described in the following sections.

3.5.1. Case Study 1 – Rewardsco Building (Zutari)

3.5.1.1. Overview of Building

The case study obtained from Zutari (Pty) Ltd. analyzes Block B office development of the Rewardsco Building, which provides commercial space for offices, sales centers and training facilities. The Rewardsco Building demarcated in red on Figure 3.2. is interconnected to Block A, the Blue Earth Industries Building, by a bridge, and is part of three buildings in the Umhlanga Arch. It is located at 2 Ncondo Place, Umhlanga Ridge, eThekwini Municipality and is situated on climate zone 5 (sub-tropical coastal weather conditions). The service life according to Zutari Consultancy is 50 years. The overall cost of construction was valued at R92 million, and the building has been certified by the Green Building Council of South Africa (GBCSA) for its green design. It has sub-meters that monitor energy usage to identify possible energy reductions and an efficient rainwater harvesting system. Figure 3.2 provides an aerial view of this building.

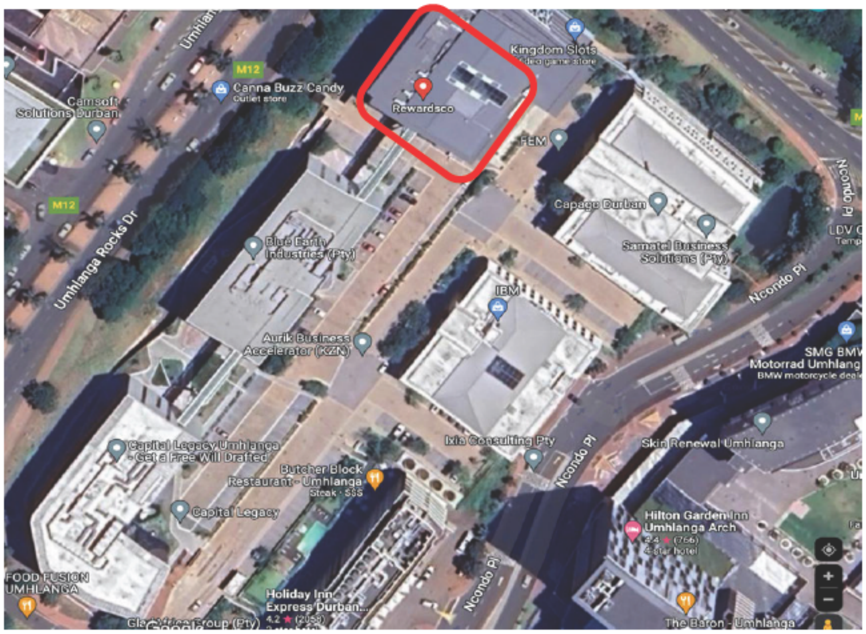


Figure 3.2. Site location of the Rewardsco Building

Building	Rewardsco Block B
Project Address	ERF 3144, Precinct 1, Block B
Project Number	505442
Architects	Hilton Lawrence Architects
Structural Designers	Zutari Consultancy
Sustainability Consultant	Solid Green Consulting
Contractor	Trencon
Client	Zenprop Properties

3.5.1.2. Building Fabric, Space Breakdown and Foundations

The external walls of the Rewardsco Building use a combination of glazed aluminium curtain walls and concrete bricks as illustrated in Figure 3.3. The curtain frame of the building utilizes double glazing, with a 6mm solar E plus material and an air gap of 6mm with vertical spandrel panels. The exterior wall construction is made up of 230mm bricks with a thermal value (R) of 0.679. The building has 4 floor levels with a total internal area of 4 329.33 m^2 according to the BIM model. The internal floor is made up of 300mm thick concrete with a lower thermal value (R) of 0.535. The concrete roof is flat and composed of three layers, a 300mm cast concrete, 50mm lambda board and a 50 mm roof screed. The layout of each floor is depicted in Appendix 1. Each of the floors has an ablution area, and the ground floor otherwise termed the podium, is a reception area, catering for the lobby and canteen. The first and second floor consist of office space and the third floor is made up of office space and a coffee shop.

Figure 3.3. Rewardsco Building – Street View

The building has 3 basement car parking levels which have been partially excluded from the study due to the guidelines stipulated in the Green Star SA's rating tool. According to the supplementary area technical clarification (GEN00-T-OB1-0001) of the Green Star SA office v1.1, car parking should not be included in the Gross Floor Area. The foundation of the Rewardsco Building has been included, but the foundation supporting external areas have been left out. The foundations are made up of a Franki pile system as displayed in Table 3.2. with a concrete strength of 30MPa.

Table 3.2. The pile system for the foundation

Pile Caps	Dimension	Quantity
Franki Driven 1H Pile Cap	900 x 900 x 900 deep	16
Franki Driven 1H Pile Cap	900 x 1400 x 900 deep	1
Franki Driven 2H Pile Cap	2300 x 900 x 1200 deep	66
Franki Driven 3H Pile Cap	2300 x 2100 x 1100 deep	26
Franki Driven 4H Pile Cap	2300 x 2300 x 1100 deep	11
Franki Driven 5H Pile Cap	2900 x 2900 x 1200 deep	7
Franki Driven 6H Pile Cap	4100 x 2500 x 1700 deep	2
Piles	Diameter	
Franki Pile (medium)	410mm	1
Franki Pile (heavy)	520mm	238
Franki Pile (heavy)	610mm	7

3.5.1.3. Energy Consumption

The Green Report and energy consumption data for the Rewardsco Building was obtained from Solid Green Consulting using the Design Builder Energy Software. This data was instrumental to calculate the carbon dioxide emissions of the Rewardsco Building during the building use stage. It was subsequently compared to a notional building designed using SANS 204. A notional building serves as a reference building, comparable in size and location, however, it is designed with no sustainability measures, allowing for a comparison between sustainable and conventional buildings. The energy consumption of the building is made up of an HVAC system, lighting, domestic hot water, miscellaneous equipment and lifts services. The total electricity use equated to 618 727 kWh/year (excluding external areas and the car park lights) and the energy usage was 174.3 $\mathrm{kWh/m^2/year}$. As part of the Green Star rating conditional requirements, the building's energy use must be compared to a notional building. The notional electricity use was calculated and determined to be 875 055 kWh/year and the energy usage was 239.6 $\mathrm{kWh/m^2/year}$. The total energy consumption improvement for the building was 51% when compared to the notional building. This improvement awarded the Rewardsco building 10 points under the category of Greenhouse Gas Emissions (Green Star SA – Office Design v1.1 manual) for reducing the carbon emissions associated with energy usage.

The tenant lighting was reduced significantly due to the optimization of building orientation and lack of overshadowing, thereby maximizing daylight. The lighting of the actual building only required 3.82 $\mathrm{W/m^2}$ whereas the notional building required 11 $\mathrm{W/m^2}$. Furthermore, the building reduced energy consumption by installing occupancy sensors which saved 15% of lighting power density. The HVAC system composed of water-cooled chillers with a basement cooling tower to improve ventilation; the chillers essentially supply fresh air to the Fan Coil Units (FCUs), this in turn circulates fresh air throughout different levels of the building. The fresh air rates of the actual building equated to 13.9 l/s/person and the notional building equated to 7.5 l/s/person.

3.5.1.4. Scenario Definition for Case Study 1

The Rewardsco case study consists of two scenarios:

Scenario I – Current Rewardsco Building:

The first scenario is composed of the Revit model acquired from Zutari Consultancy, it is unchanged and is taken as is to represent the typical BIM models prevalent in the local context. The energy consumption data utilized has been acquired from the Green Report. This scenario has a low LOD of 200 because only one material choice is defined, i.e., concrete. In addition, it has high certainty, due to the building already being designed and constructed.

<u>Scenario II – Improved Rewardsco Building</u>

The analysis for improving the Rewardsco Building involves modifying material constituents to reduce the building's embodied emissions. Since only concrete is modeled as the structural material, the improvement in this case involves incorporating recycled content into the concrete. Furthermore, this scenario explores the impact of reducing the energy consumption by 10%. There are existing sustainability measures already implemented in the Rewardsco Building that were undertaken as part of the Green Building interventions. The existing design remains fixed and cannot be altered, but minor adjustments can still be made to achieve a further 10% reduction in energy consumption.

3.5.2. Case Study 2 - Udemy Building

3.5.2.1. Overview of Building

The second case study is fictitious and has been modelled following a Udemy Course Outline. Udemy is an online educational platform that provides courses on Revit modelling. The affordable nature of the course and its detailed content on how to model an office building was selected for the second case study. Whereby 2D AutoCAD drawings were used to create a 3D representation as illustrated in Figure 3.4.

Figure 3.4: Udemy Building modelled on Autodesk Revit

The location of the building has been selected based on the Rewardsco Building, that is, under climate zone 5. The building consists of 4 floors, a roof and a top roof. The Gross Internal Floor Area (GIFA) equated to 925.617 m^2 and the external areas of the building (the balconies and roof)) equated to 370.81 m^2. The structural foundation system composed of 28 reinforced concrete footings that supported the column necks and columns. The building fabric is composed of external walls with concrete masonry and insulation materials, as well as a curtain wall. The building is intended for use as a commercial office space, and its service life has been chosen to align with the Rewardsco Building, which is set at 50 years.

3.5.2.2. Scenario Definition for Case Study 2

Scenario III - Udemy Building

In this scenario, the structural components used are based on the Udemy course outline. However, the author expanded the scope by incorporating additional building materials to increase the LOD. These additional materials included a curtain wall, insulation materials, windows, roofing bitumen and internal walls. It's important to note that this approach had a high LOD of 400, because 95% of the materials were defined. However, it had low certainty, as it was carried out during the early design stage when design changes were still possible. The inclusion of a higher LOD that encompassed a wider range of building materials facilitated a more comprehensive assessment of the integration framework. However, it lacked in providing empirical information, the energy consumption of the building for example was extrapolated to provide a calculated estimate based on the South African National Standards (SANS).

Scenario IV – Improved Udemy Building

The improvement conducted on the Udemy Building aimed to identify sustainable alternatives for materials and explore strategies to reduce operational energy consumption. In this scenario, the energy consumption used demonstrated a 50% reduction, similar to the reductions observed in the Green Report for the Rewardsco Building. The analysis examined different approaches to achieve this reduction. However, a limitation of this scenario was the inability to calculate the actual operational energy based on the recommended consumption reduction measures. Table 3.3. provides a summary of the various scenarios utilized in the methodology.

Table 3.3. Scenario definitions for both case studies

Scenario	Description	Comments
Scenario I	Rewardsco Building model obtained from consultancy	Low LOD (200), high certainty
Scenario II	Improvement of Rewardsco Building	Low LOD (200), high certainty
Scenario III	Udemy Building as modelled following course outline, including more building materials	High LOD (400), low certainty
Scenario IV	Improvement of the Udemy Building	High LOD (400), low certainty

3.6. Integration Modelling

The integration modeling process began by creating the model using Revit Software as the primary tool. Subsequently, the quantitative material output of the Revit model was used as input for the OCLCA software, and validation checks were performed. The integration modelling can be divided into two sections: low LOD specific to the Rewardsco Building and high LOD specific to the Udemy Building. In the first case study, minimal adjustments were made to the Revit model. This involved excluding the external areas and the basement car park. On the other hand, the second case study required more extensive modeling efforts as the building was modelled from scratch.

Table 3.4 provides explanations for the terminology used in this section, which encompasses a combination of BIM and OCLCA terms, as well as terms introduced by the author. The nomenclature employed aims to clarify and define these terms for better understanding.

Table 3.4. Nomenclature used in the methodology

Nomenclature	Definition	Source
Family	Represents an object or component within a building model	Revit Software
Type Properties	Describes the properties or characteristics of the material or family type	Revit Software
Shared Parameters	Defined by the user to create or store data about a family type and can be accessed by multiple users	Revit Software
Composite Material	Refers to a material that has multiple layers, for example, a wall that has various layers (insulation material, bricks, vapour membrane, etc.) is referred to as a composite material	Revit Software
Material Takeoff Report	Represents a Bill of Quantities	Revit Software
IFC	Industry Foundation Classes – refers to an open file format that allows collaboration between different software.	Revit
Potential Hotspots	Areas considered to have high carbon dioxide equivalent emissions	Author
LCA checker	Assesses and ensures the reliability of the data input	OCLCA
Environmental Product Declarations (EPDs)	EPDs are an environmental declaration of a product that includes its' LCA results.	OCLCA

3.6.1. Integration with Low LOD for Rewardsco Building

The integration with low LOD is for BIM models that have very limited building materials specified. It is intended to be typical to the South African situation, whereby BIM is not utilized to its full potential. The 3D model obtained from Zutari was not modelled based on the request of the client and was, therefore, not part of the employment contract deliverable. It was modelled by the consultancy for internal purposes and the project relied solely on 2D AutoCAD drawings for construction.

3.6.1.1. Revit Procedure

Figure 3.5 illustrates the Rewardsco Building, which was modeled using Revit Software. In the initial step, the author determined the building's scope, whereby the basement car parking was excluded from the model, as per the specifications outlined in the Green Star SA technical manual.

Figure 3.5. Revit model of the Rewardsco Building

The scope of the building model is listed in Table 3.5. This excludes steel reinforcement, curtain walls, internal finishes, building fittings and furnishings which were not modelled by Zutari. These components could have provided further validation checks and could have highlighted the difference between a high LOD and low LOD analysis. However, the Bill of Quantities (BOQ) could not be sourced by the author although several requests have been made to the companies having this information. A material takeoff report was conducted of the components available on the Revit model, whereby the family, type and exact quantities of materials were determined. Further specification of the building material was added to the type properties, this included adding the strength of concrete.

Table 3.5. Building elements of Rewardsco Building

Element	Included	Comments
Frame	*Yes*	Concrete frame
Upper floors	*Yes*	3 upper floors
Roof	*Yes*	Flat roof
Stairs	*Yes*	Concrete stairs
External walls	*Partial*	Curtain walls have not been included in the model
Windows & external doors	*No*	Not included in the model
Steel reinforcement	*No*	Not included in the model
Internal walls and partitions	*No*	Not included in the model
Internal doors	*No*	Not included in the model

3.6.1.2. Transfer from Revit to OCLCA

A student version of OCLCA had been obtained, and an LCA plugin downloaded to Revit. The plugin is composed of two parts, LCACloud and LCARevit. LCACloud redirects the designer to conduct functions outside of Revit as a web-based software, whereby the data is exported to the website. The advantage to this feature is that it does not require high computer processing power, which decreases the time used for integration. LCARevit on the other hand, permits the user to conduct all data integration and provides LCA results within Revit. The advantage to LCARevit is that it facilitates the filtering of data and allows the user to trace the building material by isolating the structural element within the model, it also facilitates the transferal of MEP data and the lighting system. The student version, however, is restricted to the use of LCACloud only, this necessitated the longer method of conducting validation checks to ensure the correct quantities were being exported to the OCLCA software.

3.6.1.3. Data Input

The automatic input of data entails using the Revit model to extract information such as the bill of materials and quantities. One Click LCA has simplified the entry of data through this method, saving time and effort. However, if the building is not modelled accurately or material information is missing or misspelt, it leads to the need of manually mapping the material information. The software then remembers the selections made under the manual mapping for future imports. The step-by-step guidance for importing the data from Revit Software to OCLCA has been included in Appendix 4.

The data on the production of the construction materials used are obtained from various databases, predominantly Ecoinvent and GaBi. The software recommends the use of specific EPDs for building materials. Where there is a lack of EPDs, other EPDs may be used and the OCLCA software applies a localization factor to create generic data for the region using the following equations:

$$\boxed{\textbf{\textit{Equation 1}}: \mathrm{CF} = \left(\left(\mathrm{A}_{\mathrm{original}} \times \mathrm{B}_{\mathrm{original}}\right) - \left(\mathrm{A}_{\mathrm{target}} \times \mathrm{B}_{\mathrm{target}}\right)\right) \times \mathrm{C}}$$

- CF = Compensation Factor
- A = Efficiency of the electricity use
- B = Impacts of electricity
- C = The electricity required to produce the material

$$\boxed{\textbf{\textit{Equation 2}}: \mathrm{CI} = \mathrm{OI} - \mathrm{CF}}$$

Where CI = Compensated Impact and OI = Original Impact

The software ensures the time validity of data by adhering to the European Standards of EN 15804 which indicates that EPDs are valid for a period of 5 years, if data is older than 5 years, the software flags it with a warning, recommending that another EPD should be utilized. Furthermore, the verification of the EPD is always included as either third party verified as per ISO 14025 standards or internally verified by OCLCA. The software also specifies the EPD standards and guidelines adhered to, that is, either EN15804 or ISO 14040.

3.6.1.4. Model Checker

The model checker assists in reviewing the data after it has been imported from Revit or any other BIM software. The importation process could result in uncertainties arising and the model checker requests further clarification. The points that may arise either include a warning or an error or information that is required to be amended as described further in Table 3.6. The most common issue encountered within this study included an error, with implausible thickness, whereby the dimensions were not imported, and the thickness of material was zero. This error was rectified by tracing the material and element ID to the Revit model to establish the thickness or volume.

Table 3.6: One Click LCA types of issues encountered with data transfer from Revit to OCLCA

Type and name of issue	Description	Recommended Action
Error: Implausible thickness	The thickness does not correlate to the material, for example steel studs could be mapped to a resource with solid steel, the thickness of which is usually less than a few centimeters thick.	Download the excel file and check the issues tab, inspect the rows that consist of the error and verify the thickness by examining the model. The recommended action is dependent on the outcome found: - The material may be named incorrectly which has resulted in inaccurate mapping. This issue may be rectified by changing the material name within the Revit model or by modifying the excel file and updating the corrected data. - If the thickness appears to be inaccurate, the dimension may be corrected under excel or the Revit model and updated to the LCA software. - There is also an option to decide later regarding the issue, in which case it will reappear in the questionnaire page and may be handled accordingly.
Warning: Generic Definitions	Data cannot be mapped accurately as the material name contains generic terms such as "default".	The recommended action is to either name the material correctly or manually map the material name to the dataset.
Information: Unidentified data	This issue means that the OCLCA import mapper could not recognize the data and map it accurately.	A choice must be made regarding which dataset to map the materials, after which, the OCLCA software will remember it for future scenarios.

3.6.1.5. Completeness and Quality Checker and Summary of Steps

The LCA checker, provides a grade for the quality of data imported, which is ranked in alphabetical order, with A, being of the highest quality and F, the lowest. The check description provides a project value and a threshold value which is indicative of the embodied impacts for the GIFA, under the scope provided. The threshold value has been determined by OCLCA through the analysis and comparison of numerous buildings, these buildings are predominantly situated in Europe. It will indicate for example that the foundation mass for the building type and area is either too low or too high. It will also indicate whether there are too few materials or a high dominant single material. Exceptions to the threshold value may occur in which case this may be validated by the user. The disadvantage to the low LOD case study was the limited building material data. Only concrete elements were modelled to provide the shape and geometry of the actual building, thereby providing limited insight into the embodied energy stage of all structural components such as steel reinforcement among other building materials.

Figure 3.6. highlights the summary of the steps undertaken in the low LOD integration process. The advantages to low LOD are that the integration process is quicker due to limited materials and the mapping of materials being less intensive. The disadvantage is the level of uncertainty created due to the number of materials that have been excluded.

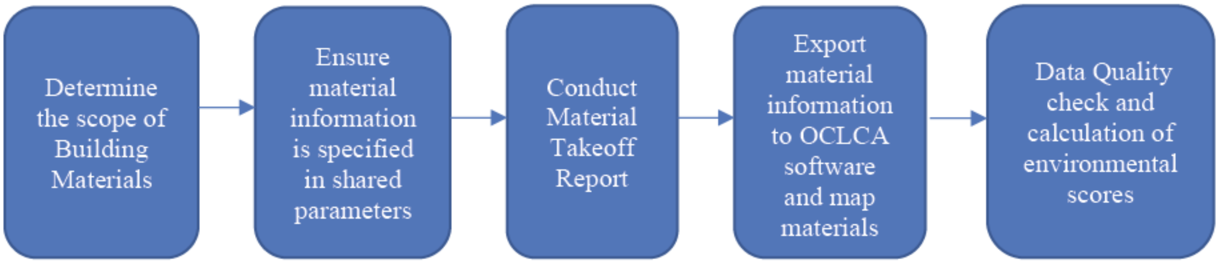


Figure 3.6. Summary of steps involved in low LOD integration

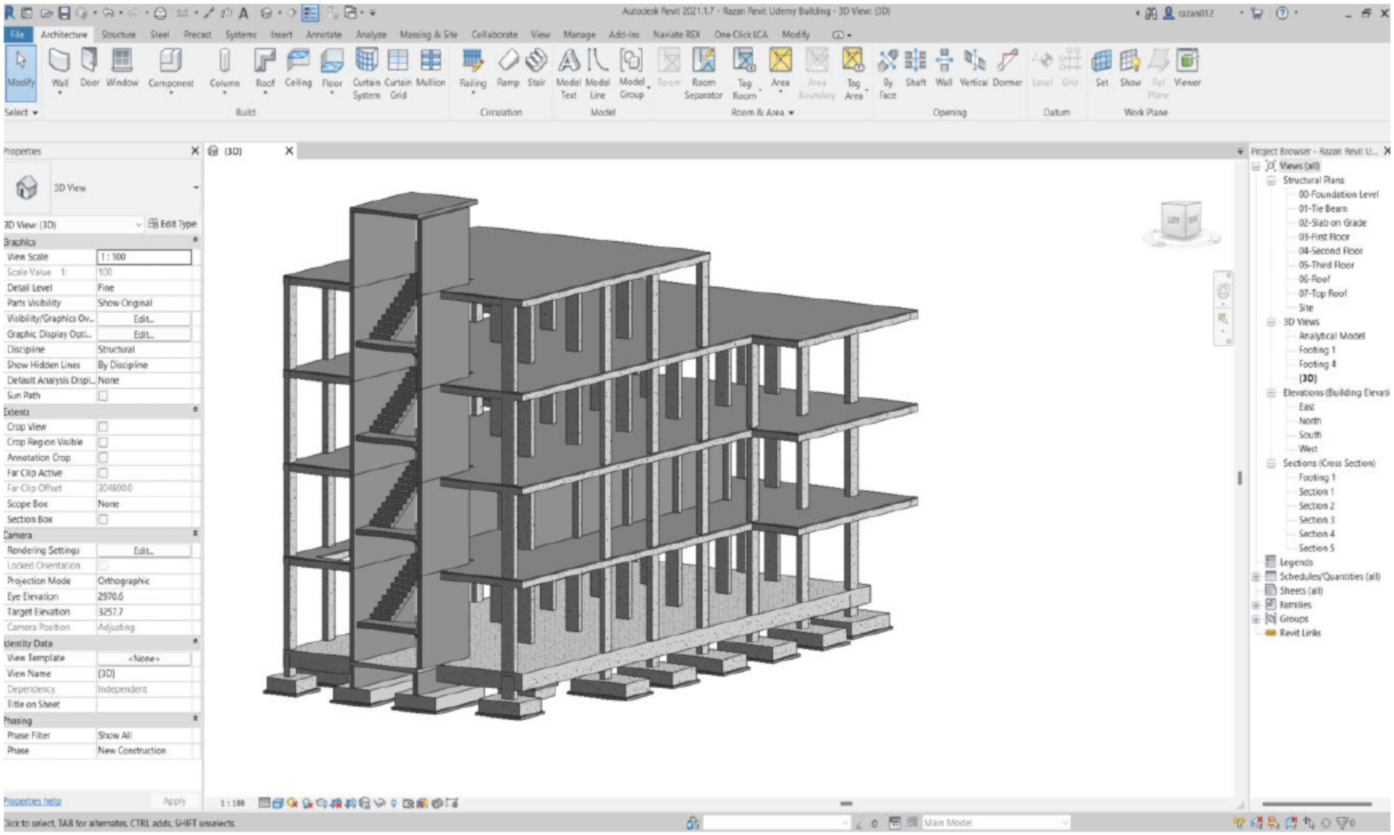
3.6.2. Integration with high LOD for Udemy Building

The integration with high LOD followed the same approach as the low LOD, however the Revit modelling and the mapping of materials was more intensive.

3.6.2.1. Sequence of Revit Modelling

The initial stage of the project involved setting the project parameters under the metric system. Thereafter, crucial to the design of any building was the setting of grids and levels to establish the bearings. The structural components of the building as shown in Figure 3.7, were modelled using the following sequence:

1. The plain concrete and structural footings – 28 footings were modelled following 9 various dimensions, two of which consisted of shear walls.
2. Column neck and tie beams – There were 27 columns that followed 2 different dimensions, i.e., column 1 and column 2 dimensions.
3. Slab on grade and columns – A 150mm slab on grade was modelled using the boundary lines of the building.
4. Stairs – cast in place, monolithic stairs, were modelled including a landing to connect the four floors.
5. Structural slab and beam system – included the modelling of joists and girders.
6. Structural walls and concrete model completion.
7. Reinforcement of footings (See Figure 3.8) – the structural rebar was modelled for the beams, slab on grade, columns, walls and stairs.



3D View: {3D}

Graphics	
View Scale	1 : 100
Scale Value 1:	100
Detail Level	Fine
Parts Visibility	Show Original
Visibility/Graphics Ov...	Edit...
Graphic Display Opti...	Edit...
Discipline	Structural
Show Hidden Lines	By Discipline
Default Analysis Displ...	None
Sun Path	☐
Extents	
Crop View	☐
Crop Region Visible	☐
Annotation Crop	☐
Far Clip Active	☐
Far Clip Offset	304800.0
Scope Box	None
Section Box	☐
Camera	
Rendering Settings	Edit...
Locked Orientation	☐
Projection Mode	Orthographic
Eye Elevation	2970.6
Target Elevation	3257.7
Camera Position	Adjusting
Identity Data	
View Template	<None>
View Name	{3D}
Dependency	Independent
Title on Sheet	
Phasing	
Phase Filter	Show All
Phase	New Construction

Click to select, TAB for alternates, CTRL adds, SHIFT unselects.

Figure 3.7: Udemy structural elements of model

The structural reinforcement depicted in Figure 3.8 and Figure 3.9, was initially modelled manually using Revit, thereafter, a Naviate plugin was utilized to automate the process. The plugin used a window to facilitate the rebar modelling by allowing the user to input rebar specifications and dimensions used for the upper bars, lower bars, short and long directions as well as the dowels and stirrups. This decreased the time used for rebar modelling when compared to the time used for the manual modelling of each individual rebar.

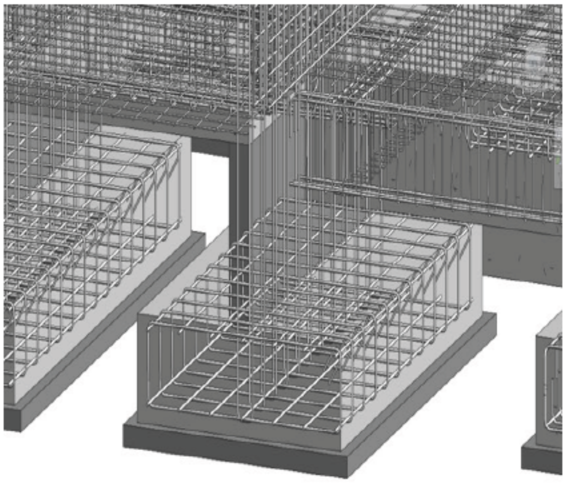


Figure 3.8: Footing reinforcement modelled on Revit

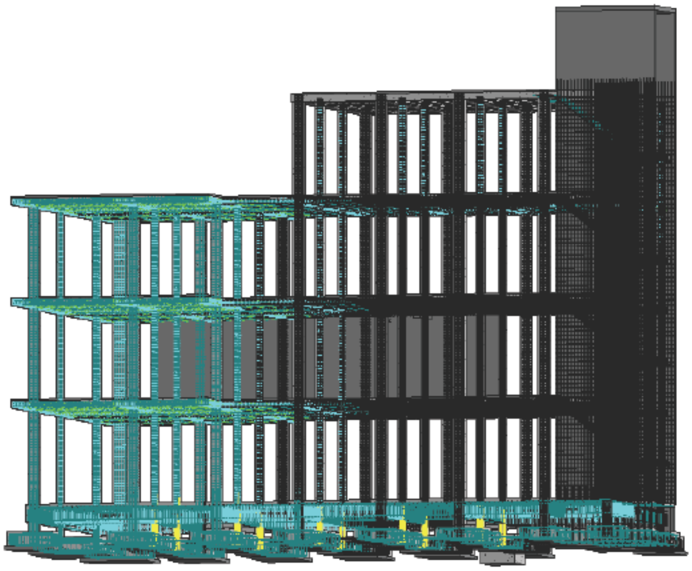


Figure 3.9. Reinforcement of Udemy Building modelled on Revit

The Udemy course consisted of Revit links to the architectural and MEP model. These were loaded on to the structural model and the discipline of the Revit file was consequently altered from structural to coordination. This allowed the user to bind the links and work interchangeably between all disciplines (Architectural, Structural, Mechanical, Electrical and Plumbing). An interference check was conducted to detect any clashes. The check detected some clashes between the MEP and structural elements; the structural components were amended but keeping the structural integrity was a priority. A dynamo script was conducted to create openings in the walls where clashes were detected with the ducts, this reduced the amount of concrete used. The clashes that involved the MEP and structural columns could not be amended, in a real-life project, these clashes would be reported to the MEP team whereby alterations would be made to suit the structural components. However, for the purposes of this research, the location of these clashes was deemed to not affect the environmental modelling of the building. Clashes were also found between the architectural components, the windows clashed with some of the structural columns. The location of the windows was consequently adjusted to remove clashes. The designer also amended the architectural model by creating a curtain wall system to increase the natural daylight entering the building and therein decreasing the artificial light consumption. In addition, the user modified the components of the wall to suit the location. Durban has sub-tropical weather, with humid summers and mild winters. Expanded polystyrene insulation (EPS) was used for the external cavity walls with precast concrete elements. The internal walls were modelled to include gypsum wall boards, metal studs and rock wool insulation for acoustic purposes as illustrated in Figure 3.10 and Figure 3.11. To model the internal walls and depict the positions of the metal studs, the curtain wall feature was used, and the structural materials of the mullions and panels were amended under the Type Property settings.

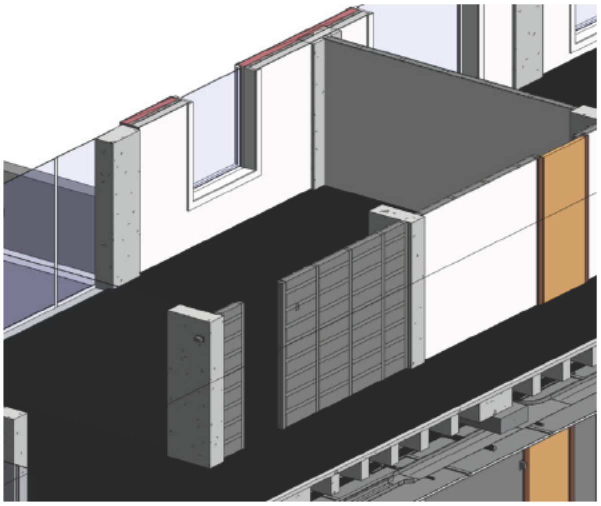


Figure 3.10. Internal walls modelled using metal studs and rock wool insulation

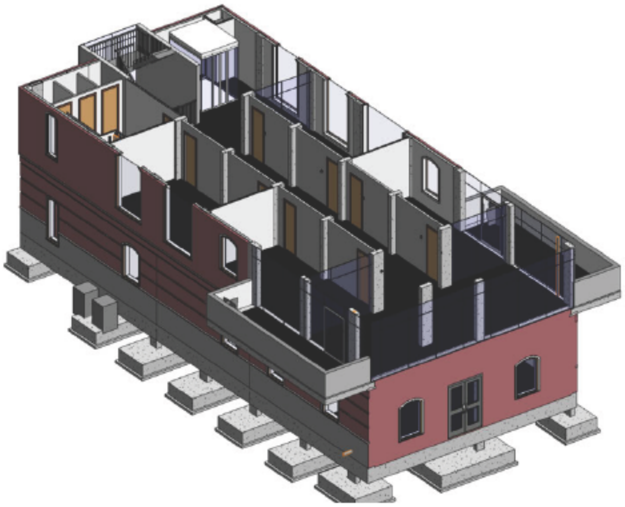


Figure 3.11. Internal walls modelled on Revit

3.6.2.2. Transfer from Revit to OCLCA

The same Transfer from Revit to OCLCA as for the Rewardsco Building was followed to obtain the results for the Udemy Building. However, the mapping of materials was more intensive and required further assessment of materials. The hierarchy for mapping materials included firstly matching the material with the exact EPD from the manufacturer, if the EPD is unavailable, then select the closest match from manufacturers typically used in the country, and if that is not possible then select generic data from the same country or other countries. The majority of the building materials, such as the suspended ceilings, aluminium and insulation materials lacked local EPDs, therefore the author was required to compare the various materials from different countries and assess which material aligned best. Furthermore, although a localization factor was applied, there were various options to choose from. The criteria for selecting the closest generic match included examining the material description, qualities and its strength properties in accordance with the project requirements, thereafter prioritizing countries that had similar electricity generation factors to South Africa.

The building energy consumption was calculated using the South African National Standard (SANS) 10400 XA:2021: energy usage in buildings. The annual maximum energy consumption for the class occupancy of office buildings with a north-faced building orientation is 95 kWh/m^2/a. The annual water consumption was not included in the study and the transportation distances to the construction site were assumed based on the One Click LCA software assumptions. The LCA software imported 106 rows of data from the BIM model which reduced to 94 rows after grouping. It classified the information in accordance with their IFC classes, the data was grouped under the following classifications slab, door, external wall, foundation, window, beam, column, internal walls, finish and surface. It also included a classification termed other, this included information that could not be classified under a particular group, such as paint.

The stairs, lighting and HVAC components were modelled on Revit, however, the OCLCA software did not automatically import them on the student version. The software imports the information based on the IFC class, and these components did not have material definition, to edit these parameters, would require a full version of the OCLCA software whereby the user can select which information should be imported. The components were subsequently not imported, however, the OCLCA software contained generic mappings for the elements based on the area of the building, these were subsequently included. For example, the software had mappings for stairs based on the number of floors and the material used to construct the stairs. Ultimately, generic mappings were utilized on the OCLCA software for the stairs, lighting and HVAC components.

3.6.2.3. Data Quality Check and Summary

The same model checker and completeness and quality checkers were applied for the integration with a high LOD. However, because of the high number of building materials, the mapping process and data checks were more intensive. The software identified 23 issues with the filtered datasets, these included implausible thicknesses, generic definitions and composite materials. The implausible thicknesses were due to the thickness of paint and vapour retarders (damp proofing membrane) which had a 1mm thickness, these materials were not defined under the Revit type properties as membrane layers, the issue was rectified under the BIM model and the user reimported the data. Once the materials were defined as membrane layers on Revit and reimported, the OCLCA software mapped the information correctly and the data was included. The issue of generic definitions was also rectified by returning to the Revit model and tracing the material that had a generic definition, which was the concrete material located in the footing, the user defined the material accurately and specified the strength, after which the OCLCA software recognized the mapping and included the data accordingly.

The composite material issue was due to the walls and the structural rebar. The walls were modelled with detail to specify the metal studs, the insulation materials and the various layers of the cavity walls, however the OCLCA software requires that composite materials be avoided. To rectify the issue of composite materials, the user would have to follow one of two options:

1. Revisit the BIM model and change the element to have a broader definition, for example: the external wall should be modelled as concrete and defined as an external wall under the type properties. Thereafter, the user would have to use the correct mapping on the OCLCA software by defining the type of wall and materials used.
2. Manually map the composite materials on the OCLCA software and validate the checks using the material takeoff feature on Revit to ensure that the quantities of the materials are accurate. For the Udemy Building, option 2 was followed and the quantities were validated.

To retain the integrity of the BIM model and the high LOD, the user, applied option 2 and manually mapped the composite materials on the OCLCA software. This option was also selected because it avoids the use of composite materials on Revit, thereby simplifying the integration process. Overall, the summary of steps followed for the integration with high LOD has been included in Figure 3.12:

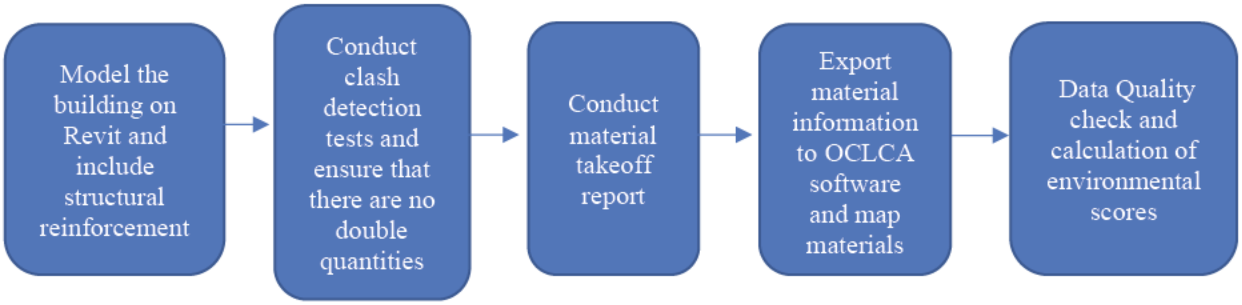


Figure 3.12. Summary of steps involved in high LOD integration

3.7. LCA analysis and Environmental Profiles

Once the integration steps outlined in Section 3.6 have been carried out and the data transferred to OCLCA meets the prescribed quality checks, the OCLCA software can conduct and provide a more accurate LCA analysis. The initial stage involves defining the goal and scope of the analysis in order to generate environmental profiles and conduct the improvement analysis.

3.7.1. Goal and Scope of LCA analysis

3.7.1.1. Goals of LCA analysis

The goals of the LCA analysis were as follows:

1. To quantify the environmental impact of both case studies over their entire lifecycles.
2. To assess the environmental impact and identify potential hotpots for environmental impact reduction.
3. To develop an improvement analysis based on the potential hotspots for both case studies.
4. To evaluate the potential integration of BIM and LCA in the local context.
5. To create a link between BIM integrated LCA and the Green Star Rating Tool to establish a LCA weighting category.

3.7.1.2. Scope of LCA Analysis

A comprehensive LCA would ideally include all life cycle stages of a building as per EN 15978 standards illustrated in Figure 3.13, which shows the life cycle stages and the associated alphabetical and numerical nomenclature. The Product and Construction Process Stage of buildings range from A1-A5 and include the processing of raw materials, their transportation to the manufacturing plant, manufacturing, transportation of the material to the construction site and construction site activities. The Use stage of the building ranges from B1-B7 and include the operational energy use, operational water use, maintenance, replacement and refurbishments. The End-of-Life Stage range from C1-C4 and include the deconstruction, transport to waste site, waste processing and disposal of materials. The final stage, D, indicates the Potential Benefits through recovery, recycling and reuse of building materials, it is considered as supplementary information and is a cradle-to-cradle approach which becomes important for building circularity. However, for this research it has not been included in the scope.

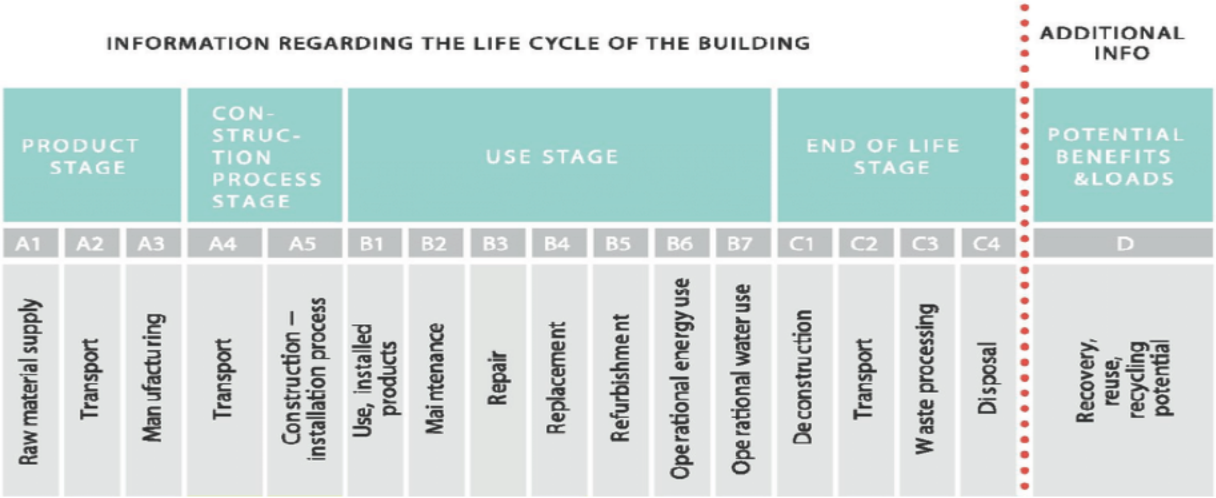


Figure 3.13. Building Life Cycle Stages as per EN 15978 Standards

Due to limited data, the MCDM ideology was applied (see Section 2.3.1) which states that effective decision-making is rooted in breaking down complex systems into smaller steps. The research methodology therefore aimed to prioritize the impact of the following life cycle stages as per EN15978:2011.

- The embodied emissions associated with the Product Stage (A1-A3) and the transport of materials to the construction site (A4) phase.
- The emissions associated with the Use Stage of the building, specifically the Replacement of materials (B4) and the operational energy consumed (B6)
- The emissions associated with the End-of-Life Stage, specifically Waste Processing (C3) and Disposal (C4).

The goals and system boundaries for the scenarios are further illustrated in Table 3.7:

Table 3.7: Goals and System Boundaries for the study

Case Study	Scenario	Goal	System Boundary
Rewardsco Building	I - Rewardsco Building	Assess the environmental profile and identify potential hotspots for environmental reductions	A1-A4, B4, B6, C3 and C4
	II – Rewardsco Improved	Compare to Scenario I and assess the environmental impact reductions	A1-A4, B4, B6, C3 and C4
Udemy Building	III – Udemy Building	Assess the environmental profile and identify potential hotspots for environmental impact reductions	A1-A4, B4, B6, C3 and C4
	IV – Udemy Improved	Compare to Scenario III and assess environmental impact reductions	A1-A4, B4, B6, C3 and C4

When analyzing the Udemy Building, it is important to note that while B2 (maintenance) is included in the analysis, it primarily reflects B4 (the replacement) of materials rather than the specific maintenance schedule. This distinction arises due to insufficient information available regarding the maintenance schedule for the building materials.

3.7.2. LCAs and the Generation of Environmental Profiles

The LCA results are achieved through the classification of environmental impacts and the determination of which impacts are relevant. There are many environmental impact factors which are classified as midpoint indicators or endpoint indicators. These indicators may be described as a "cause and effect" type of relationship (Bare et al., 2012). The midpoint method defines the environmental impact, which is the cause, for example Global Warming Potential (GWP) and the endpoint describes the effect or the harm, such as human toxicity and cancer (Reap et al., 2008). The endpoint indicator is more difficult to quantify and has a higher level of uncertainty, it is for this reason that midpoint indicators and methods are predominantly used to quantify the environmental impact associated with buildings. These indicators may be determined through several methods which are not mutually exclusive and are dependent on the scope, application and geographical location. The most widely used characterization methods include the ReCiPe, TRACI and CML methods:

- ReCiPe (Relevance and impact of characterization factors) – This method summarizes many indicator scores to 18 midpoint indicator scores and 3 endpoint indicator scores. It is mostly used in the SimaPro software and is product-based (Pré, 2023).
- TRACI (Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts) – This method has 7 environmental impact categories for buildings and is specific to the North American region (OCLCA, 2021).
- CML (Center for Environmental Science, Leiden University) – This method has 6 environmental midpoint indicator scores for buildings and has global applications excluding the North American region. Endpoint scores can also be modelled; however, they are less precise and require more assumptions (Koch et al., 2022)

The Life Cycle Impact Assessment (LCIA) method used in this research is the CML method (Leiden University, 2016). As mentioned in Section 2.5.4, the data is first classified in accordance with the impact category followed by characterization. The GHG contribution is converted to one reference unit using a characterization factor which summarizes each impact category resulting in one score. It includes 6 impact categories as shown in Table 3.8. Emphasis was thereafter placed on the GWP impact of the building and carbon dioxide equivalent emissions due to the prominence of the climate impacts.

Table 3.8: Midpoint indicators utilized in the OCLCA software as per the CML method (OCLCA, 2021)

Environmental Impact Category	Unit	Description
Global Warming Potential (GWP)	Kilogram of carbon dioxide equivalent emissions (Kg CO_2e)	When the quantity of greenhouse gases in the atmosphere increases, the GHG effect is enhanced and the atmospheric layers near the earth are heated up, resulting in climate change.
Acidification Potential (AP)	Kilogram of sulfur dioxide equivalent emissions (Kg SO_2e)	When acidifying substances react with water and falls as "acid rain" causing increased acidity of waters and soils.
Eutrophication Potential (EP)	Kilogram of phosphate equivalent emissions (Kg PO_4e)	An excessive supply of nutrients generates unwanted plant growth in water ecosystems, for example the growth of algae which results in the death of fish.
Ozone Depletion Potential (ODP)	Kilogram of Chlorofluorocarbon-11 equivalent emissions (Kg $\mathrm{CFC11}_e$)	Depletion of the stratospheric ozone layer which protects flora and fauna against the sun's harmful UV-A and UV-B radiation.
Formation of ozone in the lower atmosphere	Kilogram of Ethene equivalent emissions (Kg Ethene_e)	Contributes to the formation of ozone in the lower atmosphere (summer smog) which is damaging to the respiratory system but also affects plants and crops.
Total use of primary energy excluding raw materials	Megajoules (MJ)	Sum of use of non-renewable energy excluding non-renewable primary energy resources used as raw materials, and use of renewable primary energy excluding renewable primary energy resources used as raw materials.

The term "carbon dioxide equivalent emissions" (CO_2e) refers to the total emissions of greenhouse gases (GHGs) released into the atmosphere, which contribute to global warming (Brander, 2012). GHGs consist of a combination of various gases, with the IPCC (2022) specifically highlighting six of them: Carbon Dioxide, Methane, Nitrous Oxide, Hydrofluorocarbons, Perfluorocarbons, and Sulphur Hexafluoride. The combination of these gases under a common unit provides an outlook into the overall environmental impact regarding global warming. This is possible by applying global warming potentials (which measures the global warming effect of each gas in relation to a reference gas, in this case, CO_2) (IPCC, 2022). For the purposes of this study, it is essential to differentiate between the following two terminologies and units:

- Overall carbon dioxide equivalent emissions from the building (tonnes CO_2e)
- Yearly carbon dioxide equivalent emissions from the building throughout its lifetime divided by the Gross Internal Floor Area (GIFA) expressed per m^2 per year (Kg CO_2e / m^2/yr)

The difference between the two lies predominantly in the unit of measure, the contribution to global warming does not take into consideration the GIFA and the assessment period and is the summation of

GHGs for the overall project (OCLCA, 2021). To avoid misconceptions, the carbon dioxide equivalent emissions (tonnes CO_2e) from the project will be referred to as Global Warming contributions.

3.7.3. Generation of Embodied Carbon Benchmarking

The embodied carbon benchmarking of the OCLCA software evaluates the project's embodied carbon dioxide equivalent emissions per square meter (according to the gross internal floor area) in relation to other building projects that have used the software (One Click LCA, 2021). The scope of the benchmarking adopts a cradle to grave approach that includes most of the life cycle stages (A1-A4, B4-B5, C1-C4) except operational energy (B6), the focus is predominantly placed on the environmental performance of the materials utilized in the building. To generate the benchmark values, the software relies on the data input of other building projects that have been submitted to the software. The data is aggregated in accordance with the building type (i.e., an office building) and with the geographical location (either regional benchmarking or country specific). There was no data available for South Africa, which led the author to assign a global region which had a sample size of 400 international office buildings. The goal of the benchmarking is to provide users with a relative indication of how their building project performs in comparison to other buildings. This can help users identify areas for improvement and set targets for environmental embodied emissions. However, these global buildings might be situated (most likely) in other climatic zones and might only give a rough estimation for local benchmarking. Therefore, for this research only the procedure and the functionality in the BIM-LCA integration was tested and interpretation was limited.

3.7.4. Improvement Analyses

The improvement analysis for both the high and low LOD case studies involves changing the building materials and/or the material constituents to more environmentally friendly alternatives. The objective is to measure the extent of environmental impact reductions and assess the tool's effectiveness in achieving those reductions. The software includes a feature to provide alternative sustainable materials, however, if there is a lack of data in the region, no alternative materials will be recommended. It, therefore, relies on the user to apply their own knowledge of materials to be able to determine sustainable alternatives and assess how effective the sustainable changes are in reducing the environmental impact. To accomplish the improvement analysis, potential hotspots for environmental impact reductions were identified. Through the identification of potential hotspots, potential interventions are possible to reduce environmental burdens, these should then be compared to the original design to determine its efficacy.

One Click LCA does not calculate the energy performance of the building, Revit, however, can perform energy modelling and analysis with the addition of a plugin called AutoDesk Insight. Although, Building Energy Modelling (BEM) can be performed, this research focuses on the environmental impact of reducing the energy use rather than on the methodology deployed to achieve energy reductions.

Therefore, for the purposes of this study, the following assumptions were made regarding the operational energy reductions:

- Rewardsco Building (Low LOD and high certainty) – 10% reduction in operational energy, this value has been selected as the building has already achieved a 51% reduction in operational energy as per the Green Report, and the design remains fixed. Furthermore, a 10% reduction can still be achieved through mitigation measures and changes in behavior (Mantesi et al., 2022).
- Udemy Building (High LOD and low certainty) – 50% reduction in operational energy, this value has been selected because the design has not undergone any improvements regarding environmental performance, therefore the potential to achieve reductions is higher. The reductions may be achieved through various measures which will be discussed in the next chapter.

To generate the LCA of the improvement analysis, the following steps are involved for both case studies:

- Identifying potential hotspots for environmental impact reduction.
- Determining sustainable alternatives to the most contributing materials to global warming.
- Research was conducted to explore operational energy reduction measures with the aim of identifying the most effective and feasible means to enhance the environmental performance of the two case studies.
- Copying the As-Built Materials to a new design.
- Editing the components therein to replace materials, resetting the LCA parameters accordingly and re-mapping where necessary.

3.7.5. Additional features possible

The OCLCA software also has other features included that allow for further calculations, this includes the Baseline feature. It refers to the starting point against which the environmental performance of a building or project is compared. It represents the conventional or standard condition and serves as a reference for evaluating improvements. By defining the baseline, users can assess the sustainability benefits of design choices and make informed decisions. The baseline is conducted during the initial stages, and it is during this conceptual phase that designers may potentially set carbon targets.

3.8. Green Star SA incorporation of BIM-LCA

GBRTs criteria and a series of assumptions were used to establish the relationship between BIM, LCA and the Green Star rating tool. The common factor that relates BIM, LCA and Green Building rating tools is the Level of Development (LOD) of the building modelled in BIM. As illustrated in Figure 3.14, the LOD plays a significant role as it determines the level of detail and accuracy of information in the model, which impacts the availability and reliability of data for LCA analysis. Theoretically, a higher LOD provides more detailed information, improving the accuracy of LCA assessments and aligning with the criteria of Green Building Rating Tools. By incorporating a higher LOD, practitioners can enhance the quality of LCA results and effectively evaluate a building's environmental performance in more detail.

Figure 3.14: The interrelation of BIM, LOD, LCA and Green Star

There is insufficient research in South Africa and Africa in general regarding BIM based LCA of buildings. The inadequate regional information of the field has led the author to apply specific weightings for the Green Building Certification Accreditation based on Global Green Building Rating Tools, specifically, BREEAM, LEED and Green Star (Australia). To develop a weighting for LCA in Green Star SA, it is important to answer the following questions in Chapter 4 of the Results:

- What is the Level of Development (LOD) that should be targeted to achieve reliable LCA results? The Level of Development should be based on the ranges (level 100 – level 700) described in Figure 2.11 of the Literature Review Chapter which showed the level of detail presented in a BIM model. The relationship between LOD and LCA results were determined by comparing the various scenarios of Case Study 1 and Case Study 2. The author then recommended a LOD to be followed for the purposes of Green Star Certification in South Africa.
- What should be the criteria for Green Star SA's BIM-LCA integration? The criteria for Green Star SA is based on Multi-Criteria Decision Making (MCDM) principles, it involves identifying various internationally established GBRT criteria, such as BREEAM, LEED and Green Star SA, as alternative options. These alternatives are then compared based on their compatibility, relevance and applicability to the local context in South Africa.

Figure 3.15 provides an overview of the analysis of the study, illustrating how the two case studies and the comparison of other GBRTs criteria, contributed towards determining the BIM-LCA criteria in the developed Green Star SA rating tool.

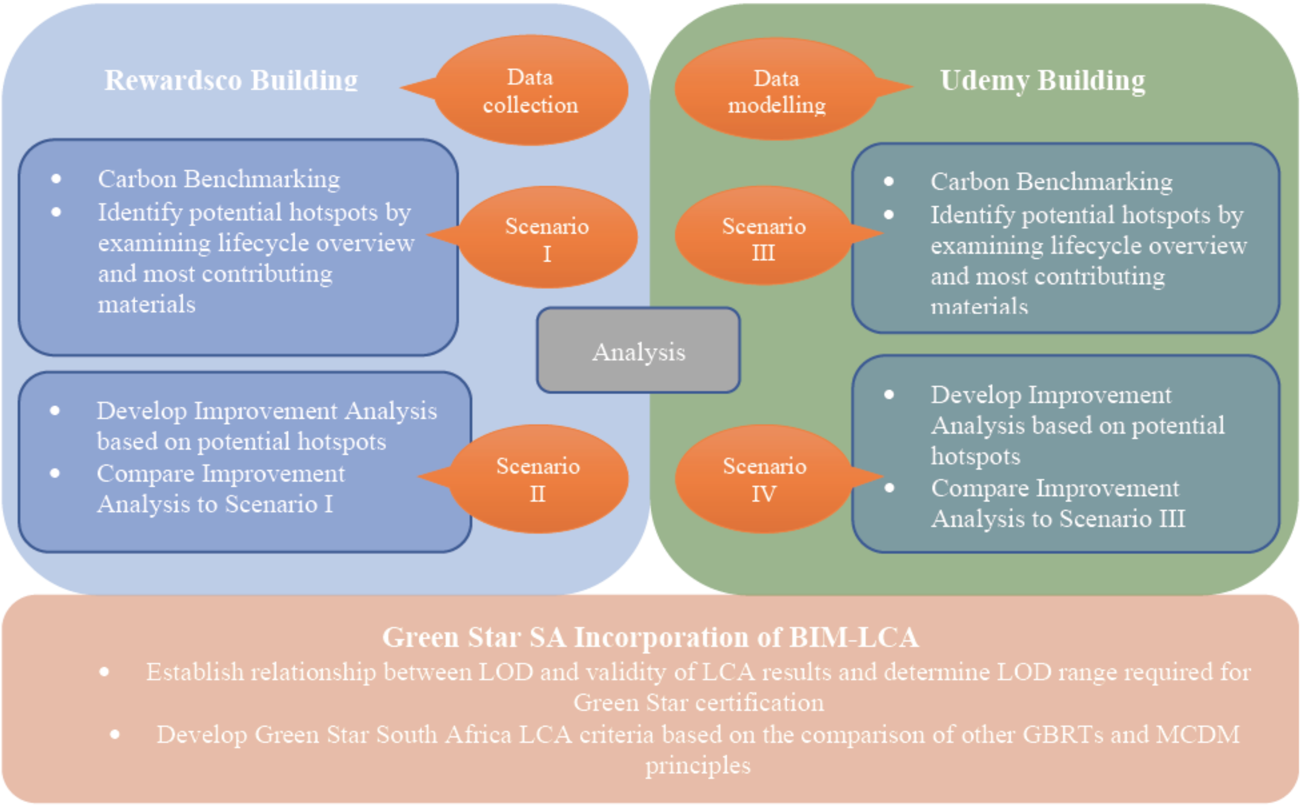


Figure 3.15. Analysis overview and Green Star SA incorporation

3.9. Analysis of BIM-LCA and the local situation

The discussion and analysis of the BIM-LCA framework has been presented by identifying the advantages and disadvantages of the framework; thereafter, determining the possible motivations and barriers regarding its wide scale implementation in South Africa. The advantages and disadvantages of the BIM-LCA framework have been determined based on the following factors:

- The efficacy of the framework- the effectiveness of the framework in quantifying and reducing the environmental impact of buildings.
- The quality of data and LCA results – the ability of the framework to provide valid data sources and meaningful results.
- Time and cost effectiveness – the time taken to conduct an LCA analysis as well as the affordability of software is taken into consideration.

- The use of software and its interoperability – compatibility of Revit and OCLCA is assessed.

The BIM-LCA dynamics and current practices within South Africa have been summarized through an extension of the interviews that targeted the professions previously mentioned in Table 3.1. with the addition of technical consultants from building material manufacturers. In addition to enquiring about the BIM software used, the interviews also focused on providing insight on the adoption of BIM, LCA, sustainable buildings and EPD availability in South Africa. These interviews were not designed to be statistically representative of the entire construction sector, but to give an insight on how BIM is currently used in the local context. These statistics were done by Mtya (2019) and support the BIM adoption, capability and maturity of consulting and construction companies in South Africa. The interview findings of this research were consolidated with previous research to determine the potential motivations and barriers for local BIM-LCA implementation.

3.10. Assumptions, Uncertainties and Limitations

Due to constraints in the study (including time and data), the research necessitated that certain assumptions be made resulting in a degree of uncertainty.

3.10.1. Assumptions and Uncertainties

The assumptions made in the research included:

- The modes of transport were assumed based on the materials, for example, concrete was transported via a concrete mixer truck.
- The transportation distances of the materials to the construction site were assumed to be 60kms for all materials in both case studies and the return trip for the transportation was omitted. These distances were assumed based on the Ecoinvent background data for transport.
- The end of life which includes, the waste treatment scenario and default waste treatment method were also assumed for each individual material based on Ecoinvent background data.
- Assumptions were made regarding the material choices for Case Study 2, these included: 1. An external cavity wall with EPS insulation 2. Internal walls with metal studs or timber studs and rock wool insulation 3. Roofing bitumen material
- The energy consumption assumptions for Case Study 2 were made in accordance with SANS 10400 based on the building class and energy zone. This results in average energy consumption values rather than exact values which introduces some degree of uncertainty to the results.

- In both Case Studies, material mapping assumptions were employed, utilizing primarily South African data while also incorporating global data due to data limitations. In instances where specific EPDs or regional South African data were lacking, materials were mapped to global EPDs that closely matched the properties of the respective materials.

One of the contributors to uncertainty is related to the Rewardsco case study, the inclusion of only concrete in the Revit model and the consequent lack of other building materials, creates a large uncertainty regarding the embodied carbon dioxide emissions. However, this is typical of how Revit is used in South Africa. Another contributor to the uncertainty of results may be attributed to the assumptions made regarding the mapping of materials. Due to the limited data available in South Africa, mapping materials to the closest alternative creates a level of uncertainty because these alternatives might be produced slightly differently from the local ones. Although the generic data is inclusive of a localization factor to account for a lack of regional data, there remains a degree of uncertainty associated with it, partly due to the technological differences in the manufacturing of materials and the energy source used. In addition, the inclusion of predominantly European Building Data in the embodied carbon benchmarking introduces uncertainty, particularly concerning the average service life of the building, which is assumed to be 60 years. The OCLCA discloses the level of uncertainty associated with each material under its environmental profile by including the approximate percentage variation in dataset, termed Q Metadata. The Q Metadata adopts the Carbon Leadership Forum (CLF) methodology which calculates the variation associated with "product specificity, plant specificity and manufacturer specificity" for a given data point (OCLCA, 2021).

3.10.2. Limitations

The limitations are divided in accordance with the Case Studies investigated. The limitations that constrained Case Study 1, the Rewardsco Building, predominantly include a lack of data. These are further summated as:

- Lack of construction site activities data – Attempts to obtain this data have been made with the contractor, however, there was a lack of interest and motivation to provide such information.
- Lack of Bill of Quantities (BOQ) – The BOQ would have disclosed the material manufacturers and the material quantities. It was planned to use this to check the Revit calculated BOQ. It would have provided an extra check in the modelling process. Numerous attempts were made to obtain the BOQ from the Quantity Surveyor, however, they were contractually obligated to seek permission from the client (commercial developers) when sharing any information. Although a non-disclosure agreement was signed by the author, details regarding the BOQ were not obtained.

- Lack of transportation distances – Due to the lack of manufacturer details, the transportation distances could not be determined which lead to their assumptions as discussed in Section 4.10.2.
- Lack of real-time energy consumption data – The Rewardsco Building had sub-meters installed and attempts to obtain electricity and water consumption data were made, however, the tenants also required the approval of the owners of the building (commercial developers), which was subsequently not granted.
- Lack of maintenance and replacement data - Attempts to obtain this information were also made but to no avail. Therefore, informed assumptions have been made based on literature.
- Lack of water consumption data - The OCLCA software also includes a water consumption input possible in the operation stage, however this was omitted from the study.

The limitations due to Case Study 2, Udemy Building included:

- Lack of empirical data – The fictitious nature of the study resulted in a lack of manufacturer details, a lack of transportation distances, energy consumption and maintenance data. This resulted in certain assumptions being made, for example, the energy consumption data further discussed in Section 4.10.2.
- Lack of contextualization – The building was not modelled in accordance with the South African climate, i.e., the insulation materials utilized could have been more specifically tailored to suit the eThekwini region.

General Limitations:

- Lack of South African EPDs - The manufacturers data would have facilitated the data mapping process, allowing the user to link the materials to the EPD. However, the lack of South African EPDs remained a large limitation to the study. South Africa is still developing in its technological advancement and sustainability efforts, therefore, there is limited EPD data. The author discovered that there were only four South African EPDs available on the OCLCA database, all from the manufacturing company Saint-Gobain Africa. These included EPDs for plasterboard, mineral wool and glass wool insulation. However, upon reaching out to Saint-Gobain Africa directly, the author learned that there were actually two additional EPDs that were not listed on the OCLCA database. Subsequently, the author contacted OCLCA to request the addition of these EPDs to the database.
- One Click LCA limitation - The inability to see calculations on the OCLCA software, resulted in researching and re-calculating several values for validation.
- Although the software includes the maintenance and replacement lifecycle stage it is more a reflection of the replacement stage determined through the service life of materials.

3.11. Summary of Methodology

The research objective set out to address how the integration of BIM and LCA could be used to decrease the CO_2 equivalent emissions in office buildings as well as establish a BIM-LCA criteria for Green Star SA incorporation. The methodology described in this chapter employed a sequential mixed approach through the initial collection of data, industry software assessment, case studies and a comparison of GBRTs to provide an estimation on the Green Star SA criteria. The methodological approach is considered sufficient to analyze the CO_2 equivalent emissions and provide an improvement analysis to the case studies to assess potential emissions reductions. However, the primary limitation of the methodology was the limited availability of data in South Africa. To address this, the OCLCA tool provides generic data to supplement the analysis. Although the data limitation and the assumptions made throughout the study introduced some level of uncertainty, given the study's objective of investigating BIM-LCA integration for sustainable building design, the level of uncertainty was deemed acceptable. As more studies of this nature are undertaken, as well as through internal and international drivers, it is hoped that more data will be collected for South Africa leading to future studies that are more locally representative.

Chapter 4 – Results and Discussion

4.1. Introduction

This chapter presents the data findings and analysis of the LCA results obtained from the OCLCA software using the methodology described in the preceding chapter. It endeavors to assess the efficacy of the BIM-LCA framework and whether it is feasible for civil engineering designers to use it as a sustainability tool. It provides the LCA results for the two case studies and their respective scenarios. It includes the identification of potential hotspots, environmental profiles, carbon dioxide emissions of the buildings per life cycle stage as well as the most contributing materials. The results were compared to literature to gauge their validity. An improvement analysis is also included. Furthermore, the results of the analysis, the framework and the shortcomings were assessed and compared to literature. The implementation of BIM-LCA integration within South Africa was examined and compared to other countries and the associated challenges summated.

4.2. LCA Results and Discussion

4.2.1. Rewardsco Building LCA Results

The Rewardsco Building had a low LOD, with the only building material modelled being concrete of variable strength (i.e., normal strength 30Mpa and high strength 60 MPa). The overall data quality of the Rewardsco Building had a low grade of F (see Section 3.6.1.5) due to incomplete materials, and the user found inconsistencies in the material quantities exhibited between the Revit model and the OCLCA software. The LCA software doubled the area quantities of the BIM model and in many cases, the thicknesses of materials were 0. This issue was rectified by creating material takeoff reports on Revit for all elements and re-entering the volumes for the building materials on the LCA software. After rectifying the issue, the final overall grade was D due to the low number of materials, and a single dominant input of concrete.

Table 4.1 presents the LCA results for each impact category in accordance with its lifecycle stage. The "Construction materials" or product stage (A1-A3) and the "Energy consumption" or operational stage (B6) are identified as the most important environmental contributions, with the former having the highest environmental effect across all impact categories. The lowest contributions across all categories may be attributed to the “End-of-life stage” (C1-C4) and “Transportation to Site” (A4). The distance for A4 was set at 60kms using a concrete mixer truck, and although emissions were considerably low, the author notes the importance of sourcing materials from proximity to the construction site to avoid higher emissions. The maintenance and material replacement lifecycle stage (B1-B5) has been omitted for the Rewardsco Building because concrete is considered to have a long service life (BCIS, 2006).

Table 4.1. Rewardsco Building, Scenario I environmental scores for each lifecycle stage

Life Cycle Stage		**Environmental Impact Category**					
		GWP ($t\ CO_2e$)	AP ($t\ SO_2e$)	EP ($t\ PO_4e$)	ODP (Kg CFC11e)	Formation of Ozone of lower atmosphere ($t\ \text{Ethene}_e$)	Total use of prim. energy excl. raw materials (MJ) ($\times 10^6$)
A1-A3	Construction Materials	2 384.25 (5.8%)	7.98 (2.2%)	1.42 (1.6%)	0.05 (18.9%)	0.30 (2.5%)	11.77 (2.7%)
A4	Transportation to site	138.92 (0.3%)	0.20 (0.1%)	0.04 (0.0%)	0.02 (8.3%)	0.02 (0.2%)	2.12 (0.5%)
B6	Energy consumption	38 175.23 (93.6%)	355.15 (97.6%)	84.73 (98.2%)	0.19 (66.1%)	11.67 (97.2%)	415.56 (96.3%)
C1-C4	End of life	98.42 (0.2)	0.58 (0.2%)	0.12 (0.2%)	0.02 (6.7%)	0.01 (0.1%)	2.17 (0.5%)
	Total	40 796.82 99.9%	363.91 100.0%	86.31 100.0%	0.28 100.0%	12.00 100.0%	431.61 100.0%

Figure 4.1 displays the building's contribution to GWP for each lifecycle stage. B6 (energy use) demonstrates a 93.6% contribution to GWP, followed by 5.8% attributed to the A1-A3 (materials) stage. This is an underestimation as many materials have been left out. The embodied environmental impact makes up a small portion of the global warming impact when compared to the operational phase of the building, however this value is expected to be higher when including more building materials to the BIM model. The B6 (energy use) value is the most significant one due to the use of electricity which spans over 50 years. Eskom is the energy company responsible for providing 90% of energy across South Africa (Eskom, 2021). It predominantly utilizes coal, which is non-renewable, to produce energy, hence, the environmental emission factor for electricity in South Africa is high. The local electricity emission factor of 1.2 Kg CO_2/kWh is subsequently responsible for the high GWP in the B6 (energy use) lifecycle stage.

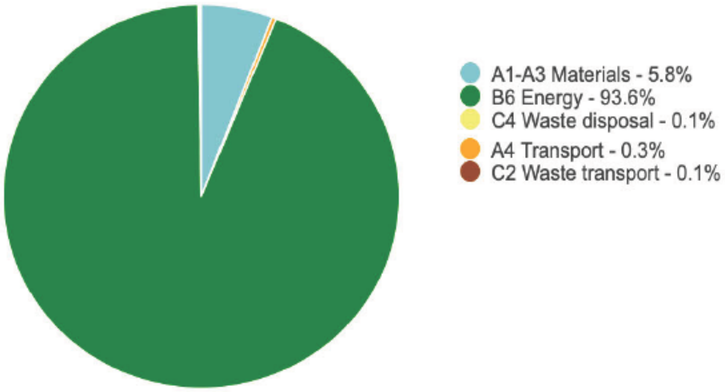


Figure 4.1: Contribution to Global Warming per lifecycle stage

The transport (A4), waste transport (C2) and waste disposal (C4) make up the smallest portion of the global warming impact, when combined equate to only 0.58%. Petrovic et al., (2018) also found that the lifecycle stages A4 (transportation) and C1-C4 (end of life), had smaller impacts when compared to A1-A3 (materials) and B1-B5 (maintenance and replacement), however, these were determined for single family houses in Sweden. In a more suitable context with reference to office buildings, Najjar et al. (2017), confirmed that the most environmentally impactful lifecycle stage was the operational one followed by the construction of materials. The study compared the difference between modern building materials (Type A) and typical building materials (Type B), the B6 (energy use) contributed 86% and 95% of the global warming potential. The A1-A3 (materials) contributed 10% and 4% for Type A and Type B respectively. Therefore, the results obtained even by modelling a low LOD building with an incomplete material list in Revit produced LCA results of the same order of magnitude as in the literature. This shows that even incomplete Revit models as those used in South Africa might have value when used for a BIM-LCA integration for concrete dominated buildings.

Scenario I had a carbon dioxide equivalent emission of 223.42 Kg per square meter per year. which may be compared to the emissions found in the Green Report provided by Solid Green Consultancy (Appendix 6). The Actual Building and Notional Building reported carbon dioxide equivalent emissions of 209.20 and 287.50 (Kg $\mathrm{CO_2e}$ /$\mathrm{m^2/yr}$) respectively. The Notional Building was higher than the results found in Scenario I by 64.08 $\mathrm{Kg\ CO_2e\ /\ m^2/yr}$, this is due to the Notional Building having a higher energy consumption value which did not include any sustainable measures. And Scenario I was higher than the Actual Building by 14.22 Kg $\mathrm{CO_2e\ /\ m^2/yr}$ due to the addition of embodied energy attributed to the concrete. If other materials were included in the case study, the values expected would be even higher, as this result is an underestimation. The proximity of values, however, observed in Scenario I and the Actual Building results indicate that the OCLCA tool is reliable. The author found that the proximity was attributed to the use of the same electricity environmental impact factor from the Ecoinvent Database of 1.2 Kg$\mathrm{CO_2}$/kWh.

Figure 4.2 presents the embodied carbon benchmark for the concrete used in the Rewardsco Building, which is assigned a Grade E ranking and has a CO_2 equivalent emission per square meter of 718 (kg $\mathrm{CO_2e/m^2}$). If other materials were included the emissions would have been higher. The emissions for concrete is still considered relatively high and the author found that the elevated value is closely linked to the environmental impact factor associated with concrete. According to the OCLCA software, the Global Warming Potential (GWP) of producing concrete with a strength of 30Mpa is reported as 270.88 kgCO_2e / m^3. It's worth noting that the most recent available data on the GWP of concrete production in South Africa dates back to 2010, which is considered outdated according to EN standards. However, this data indicated a GWP value ranging between 215 and 240 kgCO_2e / m^3 for a typical concrete mixture (Theodosiou, 2010). Therefore, given the expired nature of the South African concrete data, it is challenging to definitively determine whether the GWP value of 270. 88 kgCO_2e / m^3 was overestimated. It can, however, be likened to China, a country that also relies heavily on coal produced energy, the concrete GWP in China equated 270 kgCO_2e / m^3 (Miller et al., 2016).

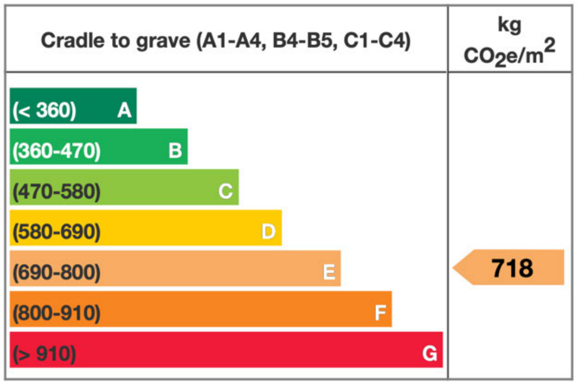


Figure 4.2: Embodied carbon benchmark for Rewardsco Model

It is also important to note that the embodied carbon benchmark calculates the service life of the building as 60 years, regardless of the input, this creates an uncertainty in results, due to the service life of the Rewardsco Building being 50 years. Furthermore, the benchmark is based on global data with a sample size of 400 office buildings, this global data, however, is predominantly from Europe and excludes South Africa and African countries in general. This is due to the largely limited use of the software in the African region. The benchmark is dependent on the users input to create a sample size; it is, therefore, considered important for Africa to engage with the OCLCA software to be able to create a more accurate embodied carbon benchmark for the local context. Hence, currently, this calculation is only of limited value in the country but it can gauge how local buildings compare with international ones with regard to GHG from different life stages of a building.

After interpreting the environmental scores based on the incomplete material inventory of the Rewardsco Building, the potential hotspots for environmental reduction were identified as:

1. Reducing the Energy Consumption of the building – by switching off appliances outside of working hours. Alternatively, energy could be reduced by creating a flexible working schedule where occupants could work remotely from home on certain days where feasible.
2. Sourcing more environmentally friendly concrete - Concrete is made up of coarse and fine aggregates, water and cement. The bulk of carbon dioxide emissions associated with concrete is due to the production of cement which is highly energy intensive (Muigai et al., 2012). Therefore,

one of the ways in which the environmental impact of concrete may be reduced is through the incorporation of recycled binders. The use of recycled binders in concrete involves using waste concrete powder found in construction and demolition waste and although the maximum percentage of recycled binders in the OCLCA is 40%, the optimum amount is 30% (Petrov and Zaharieva, 2020). However, for the Rewardsco Building this intervention is too late as it is already built. This was included for theoretical modelling purposes only in order to investigate the BIM-LCA integration.

Therefore, the improvement analysis involved reducing the energy consumption by 10% and changing the mapping of concrete strength to include 30% recycled binders to safeguard the strength and water properties of the concrete. The overall environmental reductions across the 6 impact categories have been illustrated in Figure 4.3 and the GWP results have been summarized in Table 4.2. Essentially, increasing the recycled binders in cement by 20% resulted in a 23.13 (Kg CO_2e/m^2) decrease in carbon dioxide equivalent emissions, which equated to a decrease of GWP by 4 223 tonnes CO_2e. The embodied carbon benchmark improved to Grade D (607 Kg CO_2e/m^2) from Grade E which is still an underestimation but a good example of an intervention and how improvements can be quantified even with an incomplete data set. The implications of the uncertainties on the validity and reliability of the LCA results could contribute to a higher margin of error. A sensitivity analysis could mitigate the implications, however, for the purposes of this thesis, the margin of error was deemed acceptable.

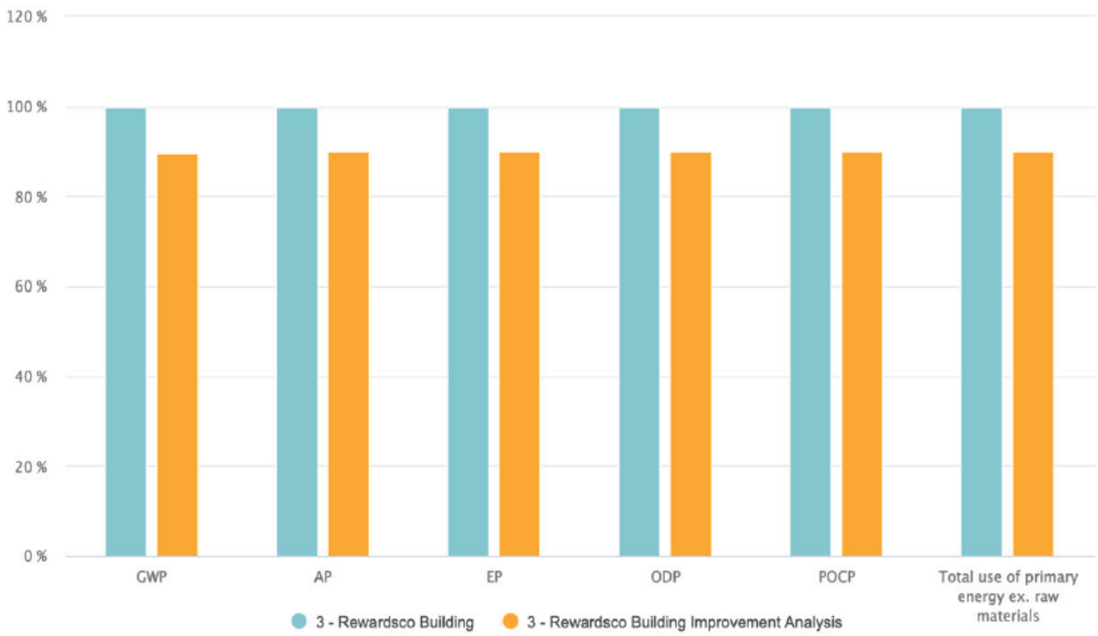


Figure 4.3: Environmental Reductions of Rewardsco Building across all impact categories

Table 4.2: Carbon dioxide equivalent emissions comparisons between Scenario I and II

	GWP (Tonnes CO_2e)	Total carbon dioxide equivalent emissions for the GIFA and assessment period (Kg CO_2e/m^2)	Embodied carbon benchmark (Kg CO_2e/m^2)
Scenario I - Rewardsco Building	40 797	223.42	718
Scenario II- Rewardsco Improvement	36 574	200.29	607

4.2.2. Udemy Building LCA Results

The Udemy Building had a higher LOD of 400, and was modelled with LCA parameters in mind, whereby the modeler ensured that the materials were defined under the type properties of the Revit Software and the quantities were validated using the material takeoff feature on Revit. In summary, the building materials included:

- Concrete (Strength 30Mpa)
- Structural rebar
- EPS insulation for cavity walls and vapor retarders
- Glass and aluminum for curtain panels and windows
- Ceramic and porcelain tiles
- Gypsum wall boards
- Precast concrete masonry and bricks
- Metal studs and rock wool insulation for internal walls and ceilings

Due to the lack of local EPD data, the mapped materials included a large amount of generic data which were mapped to the closest match, further highlighting the need for South African EPD data. The complete list of the relevant mappings for the materials have been included in Appendix 5 along with the associated embodied environmental impact. The mapping of these building materials involved aligning them with generic data based on their type properties and strength. Furthermore, when selecting the data, preference was given to the country with a similar electricity generation factor to South Africa. The overall grade for the data quality was A, indicating that the number of materials and their masses were reliable in comparison to other international buildings in the existing OCLCA database.

Table 4.3. represents the environmental scores for the impact categories of Scenario III in accordance with the lifecycle stage. A similar trend is observed in the Udemy Building when compared to the Rewardsco

Building with respect to the lifecycle stages considered to be most environmentally detrimental across all impact categories, except for the ODP. The energy consumption lifecycle stage (B6) has the highest environmental impact, followed by the construction materials (A1-A3), however, unlike the Rewardsco Building, an additional lifecycle stage is included for the Udemy Building, B1-B5 (maintenance and replacement), which is associated with the service life of materials. This is because the Udemy Building has more construction materials, some of which have a shorter service life that require replacement after several years. B1-B5 (maintenance and replacement) is ranked third followed by A4 (transport) and C1-C4 (end of life) across all impact categories, except ODP. The environmental impact category that is considered the outlier in this case study is the ODP, whereby the most environmentally influential lifecycle stages are attributed to A1-A3 (materials) and B1-B5 (maintenance and replacement). This necessitated further analysis, in determining the reason for the differences. One of the advantages of the software is that it provides the breakdown of the contribution of each material based on the impact category, allowing the user to trace the material, which was found to be the metal studs in the internal walls.

Table 4.3. Udemy Building, Scenario III - environmental scores for each lifecycle stage

Life Cycle Stage		**Environmental Impact Category**					
		GWP (t CO_2e)	AP (t SO_2e)	EP (t PO_4e)	ODP (Kg CFC11e)	Formation of Ozone in the lower atmosphere (t Ethene$_e$)	Total use of prim. energy excl. raw materials (MJ) (× 10^6)
A1-A3	Construction Materials	636.05 (7.6%)	3.40 (4.6%)	0.93 (5.2%)	0.29 (47.2%)	0.21 (8.1%)	5.70 (6.2%)
A4	Transportation to site	13.46 (0.2%)	0.02 (0.0%)	0.00 (0.0%)	0.00 (0.0%)	0.00 (0.1%)	0.22 (0.2%)
B1-B5	Maintenance and material replacement	305.96 (3.7%)	2.51 (3.4%)	0.59 (3.3%)	0.28 (46.2%)	0.16 (5.9%)	4.69 (5.1%)
B6	Energy consumption	7 384.26 (88.4%)	68.70 (91.9%)	16.39 (91.3%)	0.04 (5.8%)	2.26 (85.8%)	80.38 (88.0%)
C1-C4	End of life	14.02 (0.1%)	0.08 (0.1%)	0.02 (0.0%)	0.00 (0.4%)	0.00 (0.0%)	0.36 (0.4%)
	Total	8 353.75 (100.0%)	74.71 (100.0%)	17.94 (100.0%)	0.61 (100.0%)	2.63 (100.0%)	91.36 (100.0%)

There was no South African data for metal studs in internal walls, this was subsequently mapped to European data from Saint-Gobain, specifically "Gypframe metal framing components for gypsum plasterboard". The metal framing components are manufactured by using hot-dip galvanized steel coil which is made from iron ore using a Blast Furnace or Blast Oxygen Furnace, it is then pickled and coated in zinc (EPD Saint-Gobain, 2016). The high ODP value for the A1-A3 (material) phase may be attributed to the energy intensive process of manufacturing the metal studs as well as the chemical additives used in the pickling process. And the high ODP corresponding with B1-B5 (material and replacement) is due to the limited-service life of the material being 30 years.

Figure 4.4 shows the GWP contribution per lifecycle stage of Scenario III further. The total carbon dioxide equivalent emissions from Scenario III equated to $128.87\ \mathrm{kg}\ \mathrm{CO_2e/m^2}$. B6 (energy use) contributed 88.4% of the GWP. The second most contributing impact is due to A1-A3 (materials) with 7.7% impact. The most contributing materials included the concrete, responsible for 33% of the embodied environmental impact. Although the amount of reinforcement steel rebar used in the project was significantly less than the concrete, it produced 181 tonnes of $\mathrm{CO_2e}$, responsible for 28.5% of the GWP contribution; it has a high contribution because it is mined, processed, and manufactured using a large amount of electricity and has a high emission factor. It differs from aluminum in the recyclable potential as its strength properties are an important factor. When recycling steel, it is 100% recyclable, however, it is often required to undergo the smelting process again to produce a new product with specific strength properties. Although the mining process in the recycling of steel is excluded, the product still requires a lot of energy even when being recycled (SA Metal Group, 2023). It is therefore recommended to optimize the ratio of concrete to steel during the design phases to reduce the embodied energy.

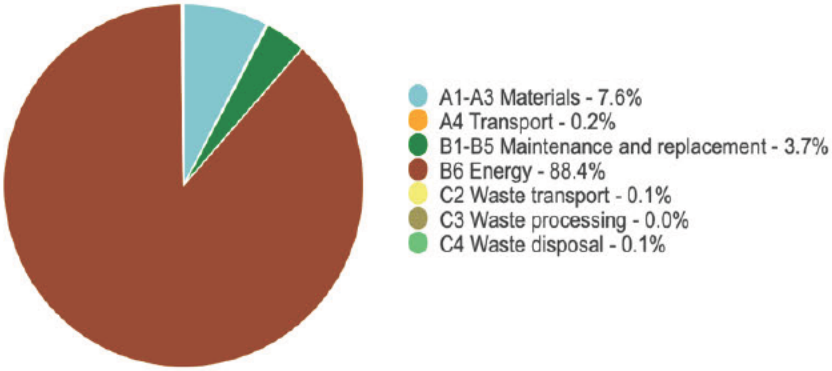


Figure 4.4. Contribution to Global Warming per lifecycle stage for Scenario III

The aluminum frame curtain wall was responsible for third highest contribution to GWP with 13.5%. The curtain wall panels are also highly energy intensive with high emission factors due to the manufacturing of glass and the mining and manufacturing of aluminum (Joshi, 2018). Although curtain wall assemblies have a high carbon footprint, both the glass and aluminum components are 100% recyclable (Joshi, 2018). Najjar et al., (2017) also highlighted the differences between using modern building materials and conventional materials in walls. The research found that the GWP for walls and curtain mullions in modern buildings were 80% whereas typical buildings were 57%; however, the curtain walls fared better in the demolition phase due to its high recyclable potential. Furthermore, the curtain wall panels decrease the energy consumption of a building by increasing the natural lighting (Liu and Wang, 2000). These trade-offs need to be further investigated in the local context.

Finally, the maintenance and replacement (B1-B5) life cycle stage had a 3.7% impact on GWP. The impact is predominantly due to B4 – the replacement of materials because of the short service life of certain materials. The metal framing components for gypsum and the steel ceiling baffle system with acoustic inserts had a service life of 30 years or lower. Although there are various techniques to prolong the service life of materials, it is highly recommended to select suitable materials during the onset of the project that have a high service life and can thereafter potentially be recycled. Overall, the embodied carbon benchmark ranked the materials with Grade E as shown in Figure 4.5. and the embodied carbon dioxide equivalent emissions of the materials equated to 770 kg $\mathrm{CO_2e}/m^2$. The improvement analysis therefore aims to improve on this ranking based on identifying the potential hotspots for environmental reduction.

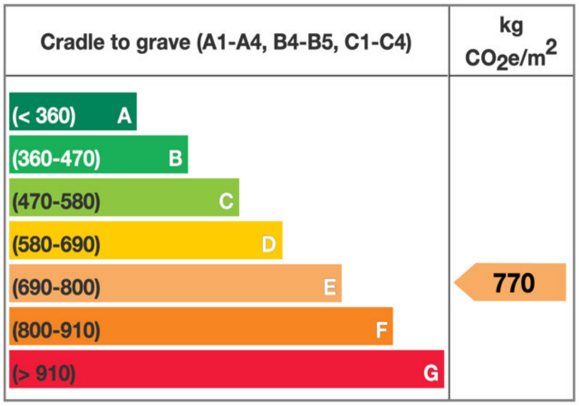


Figure 4.5. Embodied carbon benchmarking of materials for Udemy Building

The potential hotspots based on the environmental profile, lifecycle overview and most contributing materials for the Udemy Building were identified as:

1. The operational energy phase (B6) had the highest impact on the lifecycle: Recommendations to improve the operational energy phase have been provided in the Improvement Analysis, however, to be able to see the improvement measures would require an energy simulation on a BEM software, which is not included in the scope of this study. However, the author explores a 50% reduction of the SANS code in energy consumption to determine the GWP impact.

2. The material stage had the second highest (A1-A3) impact: concrete, steel, steel ceiling baffle system and the metal framing components used for the internal walls were the identified hotspots. The steel ceiling baffle system with acoustic inserts had a short service life span of 12 years according to the EPD, it was therefore considered a hotspot. It can, however, be prolonged through various measures such as coating and surface protection, nevertheless, it is generally recommended to select materials that have a longer service life. The metal framing components were also considered a hotspot because of the shorter life span of 30 years. The metal studs in the internal walls had a relatively high ODP value, it was considered essential to find a sustainable alternative.

The improvement of the theoretical building was accomplished through material substitutions and the use of recycled content. The OCLCA software has a feature to show users sustainable alternatives to the most contributing materials of GWP. This feature, however, is very limited for the localized context and showed no benchmarked alternatives for the materials selected in the project. Therefore, the user incorporated the following changes based on the identified hotspots:

- The metal studs in the internal walls were substituted with wood studs which have the same strength properties.
- The steel ceiling baffle system was substituted with another steel ceiling system that had a lower density and no acoustic inserts.
- The recycled content in binders for concrete increased by 30%, which according to Tereza, (2018), is the optimum amount of recycled content that does not affect the strength properties.
- 97% recycled steel was used. According to the European Steel Association, steel is 97% recyclable. The "SA metal group" is one of the leading metal recyclers in the region that recycle steel by re-smelting from scrap yards. It is therefore technically feasible for South Africa to use 97% recycled steel in reinforcement, provided that it is re-smelted to create new steel with specific strength properties.

The 50% reduction in energy consumption calculated using the SANS code may be achieved through the implementation of various measures which include the installation of:

- Energy efficient air-conditioners and heating equipment
- LED lights as opposed to incandescent or fluorescent lights
- Sensors that switch off lighting, computers and office equipment after hours
- Solar panels to reduce the dependency on non-renewable sources of energy
- Sub-monitors to track the expenditure of energy and find potential hotspots to reduce energy

- Furthermore, the reduction of energy consumption is also largely dependent on the social norms and practices; the effect of education and awareness of tenants to reduce energy is largely under-estimated. Another solution may be found in developing a hybrid-work schedule for employees, the effect of the COVID-19 pandemic saw significant energy consumption reductions of up to 50% when compared to pre-pandemic times (Mantesi et al., 2022); therefore, flexible work schedules may be incorporated to the office building ethos. Through the implementation of such measures, energy consumption may be reduced by 50%, this factor was used to determine the carbon dioxide equivalent emissions and environmental impact factor for Scenario IV.

The improved Udemy Building exhibited reductions across all impact categories as illustrated in Figure 4.6, which highlights the reductions between Scenario III and IV. Table 4.4 shows the reductions of the carbon dioxide equivalent emissions and embodied carbon benchmark. The carbon dioxide equivalent emissions of Scenario IV equated to 67.32 kg $\mathrm{CO_2e/m^2}$/year which dropped from 129.04 kg $\mathrm{CO_2e/m^2}$/year. The GWP potential for the project reduced from 8 364 tonnes $\mathrm{CO_2e}$ to 4 364 tonnes $\mathrm{CO_2e}$. Scenario IV demonstrates that by changing the materials to more suitable and eco-friendly alternatives, the embodied carbon ranking improved from a Grade E to a Grade C. Although the overall ODP was low, (less than 1 kg CFC11e), it was found that the initial high ODP in Scenario III, was due to the selection of materials in the internal walls, which used hot dip galvanized/ zinc coated steel for the metal studs. For the improvement analysis, this material was substituted with timber studs, resulting in the significant ODP reduction. It is for this reason that the importance of weighting the environmental impact of material choices must be highlighted for designers in the building industry.

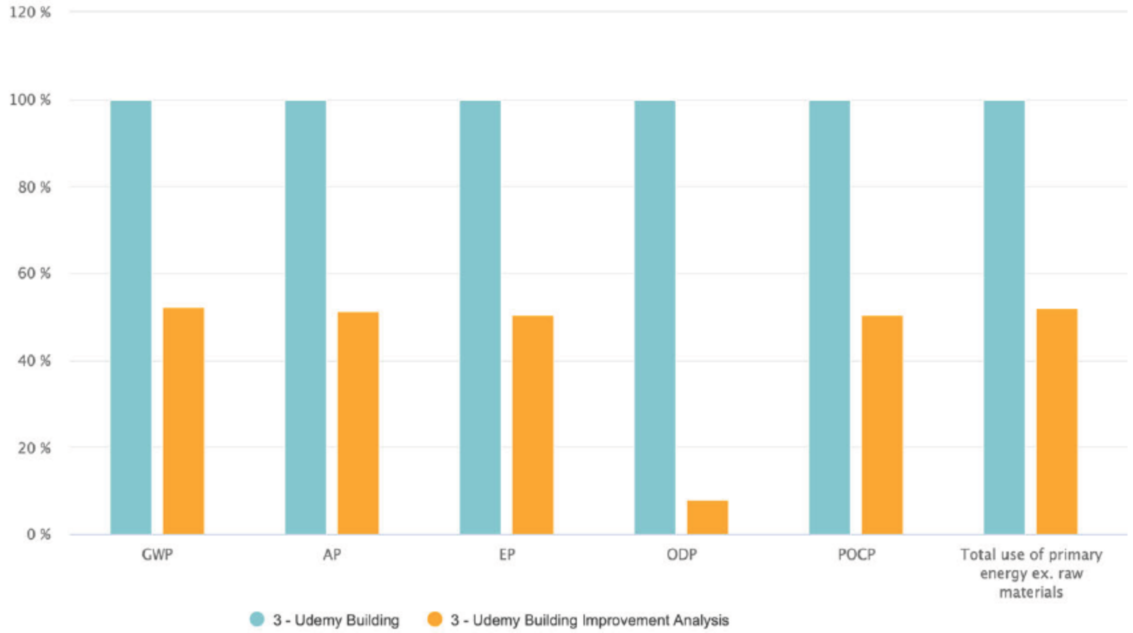


Figure 4.6. Environmental impact reductions for the Udemy Building across all impact categories

Table 4.4. Carbon dioxide equivalent emissions comparisons between Scenario III and IV

	GWP (Tonnes CO_2e)	Total carbon dioxide equivalent emissions for the GIFA and assessment period (Kg CO_2e/m^2)	Embodied carbon benchmark (Kg CO_2e/m^2)
Scenario III – Udemy Building	8 364	129.04	770
Scenario IV- Udemy Improvement	4 364	67.32	540

4.2.3. Overall Discussions

It is considered important to gain an understanding of the underlying causes behind the reductions in both case studies. The Rewardsco Building showed reductions of approximately 10% across various categories, while the Udemy Building achieved reductions in the range of 49%, excluding the ODP. These values may be strongly linked to the reduction in operational energy, for the Rewardsco Building, the operational energy was reduced by 10% and the Udemy Building by 50% respectively. Hence, emphasizing the directly proportional relationship of operational energy consumption and the subsequent environmental impact, highlighting the significance of the B6 (energy use) lifecycle stage. While material selection is undoubtedly important and has an effect on B6 (energy use), the key to achieving substantial change lies in actively reducing the operational energy consumption of buildings. In addition, it becomes important to focus on how the energy in B6 (energy use) is sourced. South Africa's heavy reliance on coal generates a high environmental impact factor, further exacerbating the emissions associated with B6 (energy use). The South African government has already expressed its plans for transitioning towards cleaner sources of energy by targeting natural gas in the short-term (IOL, 2023). Natural gas like coal is also non-renewable, however, its environmental emissions are lower and more aligned with the sustainability goals of the country. Nonetheless, long term goals and investments should be allocated towards renewable sources of energy.

The Rewardsco Building, with an incomplete dataset, demonstrated that the material percentage contribution towards GWP was 5.8% and the energy consumption was 93.6%. The Udemy Building with a more complete dataset, had contributions of 7.6% and 88.4% respectively. Rucińska et al., (2020) conducted a study on 11 office buildings in Poland and determined that the range for materials was 6-11% and the energy use was 79-93%. Although, this is representative of Poland, which has a different climate, it does provide insight into the range that may be expected for office buildings. Therefore, although underestimated, the bulk of embodied emissions for the Rewardsco Building might have been included due to the nature of the building which depends heavily on concrete. The importance of the material, however, should not be overlooked. Various studies have determined that concrete is the major contributor towards emissions especially in concrete frame buildings, whereby it accounts for 70% of carbon dioxide emissions among major building materials (Bhagat & Savoikar, 2021). Overall, both case studies, despite the varying LOD, showed the major lifecycle contributors to be energy consumption (B6) and construction materials (A1-A3). Previous research on similar buildings also confirms that these are the most influential lifecycle stages (Carvalho et al., 2020; Najjar et al., 2017). The percentage contributions from the case studies investigated are within the range of those calculated in the literature (see Table 2.1) for energy conventional buildings in general and Rucinska et al. (2020) for office building emissions. The transport and end of life stages are low contributors, both of which are not affected by the LOD of the Revit model. Therefore, it may be said that, regardless of the LOD, the BIM-LCA framework was effective in determining the most influential lifecycle stage, given the dominant quantities concrete in a concrete-frame building and the associated environmental impacts calculated. Nonetheless, LOD is considered important in providing more accurate LCA results, especially in the case of Green Building Certification which will be further discussed in Section 4.3. Further research is needed to determine whether the same conclusion is valid for steel frame buildings and other types of buildings.

4.2.4. Additional features - Baseline

The baseline for the Rewardsco Building, Scenario I, was determined because it had a low LOD and limited number of materials. The carbon footprint of the baseline yielded a result of 492 Kg $\mathrm{CO_2e}$ /m^2. It showed that the element contributing the most to the carbon footprint was attributed to the floor slabs. For the Rewardsco Building, the floor slab is made up of 300mm concrete with no specifications regarding insulation. However, the OCLCA tool automatically simulated a floor slab with 300mm concrete and 250mm thick EPS insulation as per European data. This shows that the carbon footprint for the Baseline is over-estimated due to the thickness of insulation. It also underlines that local conditions and designs are important for accurate LCA results when using BIM-LCA integration. The second element contributing the most to a high carbon footprint is the external walls which are automatically generated according to European data and common practices. The components of the Baseline's external wall consist of brick with running bond, masonry mortar, 50 mm mineral wool insulation, brick with running bond, masonry mortar, render, smoothed and painted and paint. Whereas the external wall components for the Rewardsco Building described in the Green Report are 230mm bricks and a curtain wall assembly. This figure further demonstrates the over-estimation of the Baseline and again highlights the importance of local data in the BIM-LCA integration.

It is important to note, that the Baseline values may be amended to suit the project, the author initially sought to ascertain how accurate the Baseline would be when set to the parameters of an "International Reference Building". The results determined that the Carbon Designer tool favored European data and common practices, even when changes could be made, it included components and materials specific to Europe. The author then amended the Baseline to suit the project by correcting the floor slabs and removing the EPS insulation and changing the external walls to bricks and a curtain wall assembly with aluminum frames as per the Rewardsco Building. The updated carbon footprint of the Baseline then increased to 555 Kg $\mathrm{CO_2e}$ /$\mathrm{m^2}$ and the most contributing material then became the external walls followed by the floor slabs as shown in Figure 4.7. The external walls subsequently had the highest impact due to the curtain wall and the most contributing material was the aluminium frames.

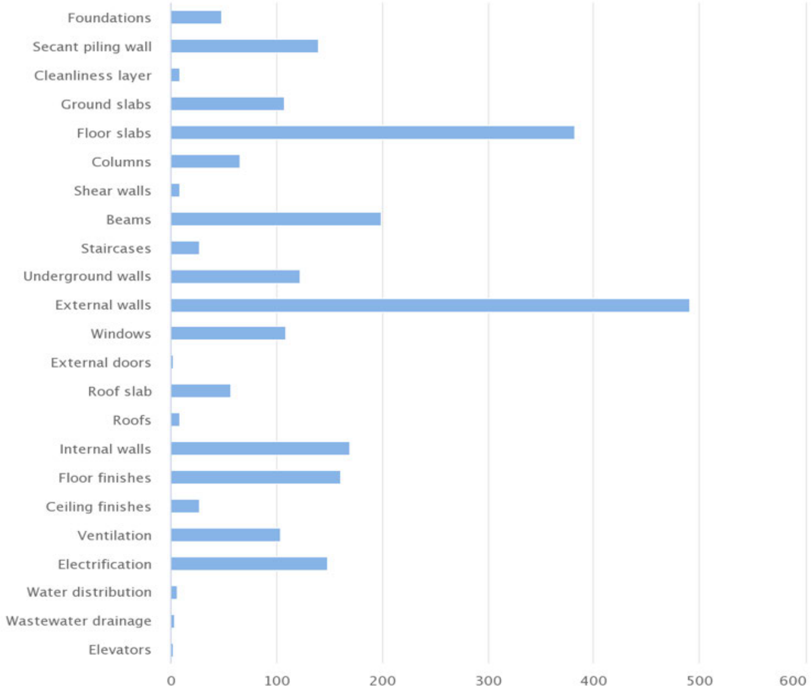


Figure 4.7. Updated Carbon Footprint of Baseline by Elements (Tonnes CO_2e) for the Rewardsco Building

Further research is needed to calculate the influence of changes in the initial design of a building and the consequences for the energy consumption of the operation stage of that building, for example, what would be the energy savings from the natural lighting as opposed to the higher emissions from using glass and aluminium in the design construction.

4.3. Green Star SA incorporation of BIM-LCA

4.3.1. Relationship between LOD and validity of LCA results

The author has found that the lifecycle results associated with the conceptual phase and baseline produce higher estimates of GWP and as the project progresses, the GWP decreases. This realization was substantiated by Habert et al. (2020), whereby the embodied GWP was examined for 34 BIM states of a model, the study revealed that the embodied GWP decreased as the project advanced due to changes in materials or material quantities. It is, therefore, important to account for uncertainties during the initial stages of design.

Based on the results presented, Figure 4.8 shows the relationship between the Level of Development (LOD) of the BIM model and the validity of LCA results. The early design phase whereby the LOD is 100 and only the Gross Floor Area (GFA) are known can use the Carbon Design Tool of the OCLCA software which determines the Baseline. The results of the Baseline indicate an over-estimated Carbon Footprint for South Africa and do not include other environmental impacts. Although this phase is over-estimated, it can highlight the potential element hotspots for carbon reductions, for example, the external walls or floor slabs.

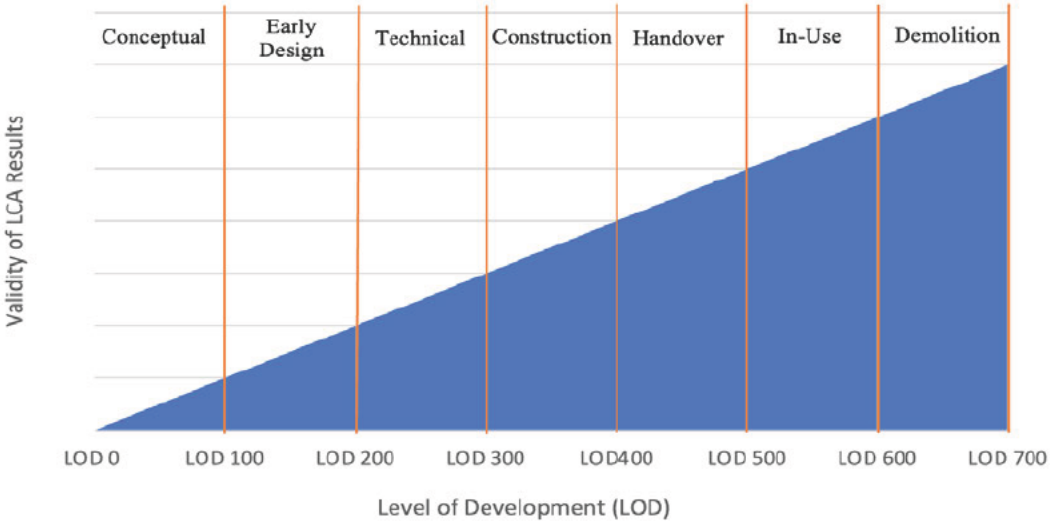


Figure 4.8. Relationship between LOD and Validity of LCA Results

The early design phase, with an LOD of 200 contains a limited amount of material information and quantities on the BIM model and the Gross Internal Floor Area (GIFA). The Rewardsco Building had an LOD of 200 whereby the concrete elements were known, GIFA and the energy consumption data was simulated using Building Energy Modelling (BEM) software. The quality of LCA results in this phase is considered low due to missing material information, it therefore presents as an under-estimate of LCA results.

The construction design phase, with an LOD of 400 has 95% of the material information contained in the BIM model. For the Udemy Building, the majority of the material data was included, the energy consumption data was determined using SANS codes and the GIFA was known. This phase presented a higher level of reliability in terms of LCA results. There is, however, a contradiction to this rule when using the OCLCA software. The software does not recognize composite materials, that is, when modelling elements such as the internal wall, it is recommended to model them solely using one material and thereafter mapping them accurately in accordance with all the materials used. For example, the internal wall may include metal studs, however, the metal studs are not required to be modelled on Revit, the OCLCA software will contain the accurate material information such as "gypsum plaster boards with metal studs and rock wool insulation" which can then be mapped to the project.

In general, when there is a lack of specific material information or EPDs, placeholder materials are used to determine the LCA results. This may present over-estimated or in some cases under-estimated LCA results. However, as building projects progress and definitive information regarding materials, energy and water consumption as well as the end-of-life phase are determined, the validity of LCA results increase. Based on the relationship of LOD and the validity of LCA results, the author recommends that the ideal LOD required for Green Star South Africa (GSSA) accreditation should be 300, which has also been recommended by Soust-Verdaguer et al. (2017). An LOD of 300 includes 90% of the materials defined and the load bearing system dimensioned, thereby increasing the reliability of LCA results. An LOD of 300 and above should be awarded one point in the GSSA accreditation for reliability of LCA results.

However, given that South Africa is in the process of BIM adoption, and that most BIM projects have an LOD of 200 (according to the limited/large companies using BIM), it is recommended that the LOD for accreditation be between 200-300 within the local context. This recommendation aligns with the MCDM principle of the experiential learning cycle proposed by Kolb and Fry (1975). The cycle begins with the introduction of a concept, followed by taking action and gaining practical experience. It emphasizes the importance of revisiting the initial concept to make improvements based on the acquired experience. Therefore, by including an LOD of 200-300 for South African accreditation, it simplifies the LCA process for consultancies, allowing for more professionals to investigate the LCA of buildings.

4.3.2. LCA Criteria for South African Green Star Rating Tool

Section 2.7 of the Literature Review presented an LCA comparison of the Green Building Rating Tools. The MCDM methodology used to compare the 3 alternatives of BREEAM, LEED and Green Star Australia was the Analytic Hierarchy Process (AHP) as illustrated in Table 4.5. This methodology ranks the alternatives in accordance with their compatibility to the local context.

Table 4.5. MCDM ranking of alternatives (GBRTs) in accordance with its compatibility to South Africa

Ranking	Alternatives - GBRTs	Compatibility with South Africa
1	Green Star Australia	- Criteria emphasizes the weighting of GWP and stipulates a benchmark (a reference building) for evaluation. - A maximum of 2 points are awarded, this is considered too little for the South African context, whereby more weighting is required to encourage LCA adoption. - There are similarities in climate between South Africa and Australia.
2	LEED	- Well defined criteria that considers GWP reductions mandatory and stipulates a benchmark - Awards a maximum of 4 points and points are easier to achieve.
3	BREEAM	- Criteria does not include a set benchmark - A maximum of 5 points may be awarded for LCA.

The LCA points for all three GBRTs are optional and not mandatory for achieving accreditation, for South Africa, the LCA points should also be optional and not mandatory. However, more points should be awarded for conducting an LCA, to encourage the acquisition of data. It is important to note that the three alternatives did not specify an LOD for BIM integrated LCA but has guidelines on how the LCA should be conducted. The South African benchmark stipulated for LCA criteria should be the notional building as per the GSSA's Office Technical Manual, and in the future, this benchmark should be improved to align with the country's NDC to reduce emissions. By improving the benchmark, the country may set Sustainable Target Values (STV) for building emissions and be able to achieve meaningful environmental impact reductions. Based on the LCA comparison and the questions posed in Section 3.8 of the methodology as part of a multi-criteria analysis, the following criteria shown in Table 4.6 is recommended by the author for the pursual of LCA accreditation:

Table 4.6. LCA Criteria for Green Star SA

Points	Criteria
3	Achieving a 50% reduction in 3 impact categories, with GWP being mandatory
2	Achieving a 10% reduction in 3 impact categories with GWP being mandatory
1	Conducting a Building LCA

A total of 3 points can be achieved for the pursual of building LCA using BIM, based on the CML method of Life Cycle Impact categories which highlights the 6 impact categories as: Global Warming, Acidification, Eutrophication, Ozone Depletion, Formation of Ozone in the Lower Atmosphere and Total Use of Primary Energy (excluding raw materials). The scope boundaries of the LCA criteria should be based on EN 15978 standards, with the following mandatory life cycle stages A1-A3 of the Construction Materials and B6 of the Use Stage of the building and an LOD of 200 - 300. Based on the criteria, the Rewardsco Building, for example, would receive 2 points for reducing the environmental impact by 10%. These points are based solely on the 10% energy reduction investigated in this study, and not based on the 51% energy reduction achieved prior from the Green Star Report (attached in Appendix 6). The Udemy Building would receive a total of 3 points for reducing the environmental impact by 50% and an additional point for conducting the LCA with an LOD of 300.

4.3. Discussion on BIM-LCA

4.3.1. Findings from interviews

The interviews were conducted on an informal basis and involved a limited sample size of 9 participants. These interviews had two primary objectives: firstly, to gain insight into the current dynamics of BIM in South Africa, including the identification of the most commonly used software; and secondly, to explore the factors contributing to the adoption of BIM and sustainable buildings in the country. The findings revealed that the limited use of BIM may be attributed to the following:

4.3.1.1. **Dependency on conventional 2D software:** Person G highlighted that international and large engineering consulting companies use BIM software, while smaller engineering firms still rely on 2D software like AutoCAD due to its familiarity. Mtya (2019) and Marsh et al. (2021) have also mentioned that the lagging progression of BIM adoption may be due to the reliance on traditional workflow and 2D software.

4.3.1.2. **Varied software preferences:** Despite Revit being a collaborative tool and the most widely used tool, the interviews indicated that there are still diverse software preferences exhibited within the industry. Different disciplines within the industry utilize software tailored to their specific tasks. For example, environmental engineers rely on DesignBuilder for energy performance, thermal performance and daylight, while structural engineers use TEKLA for analysis. This can create collaboration challenges and training challenges, resulting in workflow inefficiencies (Person A and Person I). While the use of the IFC format helps mitigate some of these challenges, it is not a perfect solution (based on the author's experience). In certain cases, the IFC format can lead to data loss, changes, or file corruption, which can impact the integrity of the transferred files.

4.3.1.3. **Lack of knowledge and expertise:** The interviews pointed out that there is a lack of knowledge and expertise in utilizing BIM effectively, especially on site (Persons A, B and H). According to Person B there are instances where contractors on site do not understand the 3D models and how to implement it, this results in further clarification and subsequently time delays. This conclusion has been substantiated by numerous researchers, highlighting it as a major barrier towards BIM implementation (Akintola et al., 2017; Mtya, 2019; Onososen and Musonda, 2022; Tabesh, 2015)

4.3.1.4. **Lack of involvement between disciplines:** Environmental design is considered the sole responsibility of environmental engineers, and civil engineers are often not involved in the environmental design process, for example, there are few structural engineers that are certified as Accredited Professionals with Green Star SA (Person E). From an interview with Person D, incentives should be offered by consulting companies to ensure that more civil engineers partake in environmental courses in a professional capacity.

4.3.1.5. **Cost and hardware requirements**: Advanced usage of BIM requires expensive hardware and substantial computer processing power, which can be a barrier for widespread adoption, especially for smaller firms (Person G and Person B)

4.3.1.6. **Client priorities and costs:** The interviews revealed that clients may be reluctant to incur additional costs associated with BIM designs, considering them expensive and not a priority within their project budgets (Person C; Mutingwende, 2019)

Apart from the limited interview participants listed in Table 3.1, the author also contacted a small sample of manufacturers in South Africa, specifically Sika Africa and Saint-Gobain Africa. The purpose was to gain insights into the factors contributing inadequate availability of EPDs in the country. The interview participants included a technical consultant from Sika Africa and the head of technical support and commercial academy at Saint-Gobain Africa. The common consensus between the participants regarding the lack of EPD data included the following factors:

- Low market demand: There is currently a relatively low demand for EPDs in the South African market, with sustainable consultants being the primary proponents of such requests. The focus in the industry is predominantly on operational carbon rather than embodied carbon, which impacts the demand for EPDs. However, it is notable that Saint-Gobain Africa has set a target of generating EPDs for 100% of their product range by the year 2030 and have partnered with the OCLCA tool to generate more EPDs.

- Absence of LCA criteria in Green Star SA: The lack of LCA criteria in the Green Star SA rating tool has an influence on market demand, as it does not explicitly promote the use of LCAs and EPDs within the certification process. Green Star SA, however, is currently working on updating the tool and including an LCA criteria. Establishing parameters as in this research is critical in this process.
- Cost and time requirements: Generating EPDs is a resource-intensive process that demands a significant amount of time and expertise. EPDs are also required to undergo third-party verification, which adds to the overall expenses associated with their development.

Based on the interview findings and communication with professionals in the field, it can be inferred that the uptake of BIM and LCA locally is slow, nevertheless, there are ongoing initiatives to address the situation. These initiatives, however, are still at the early stages. To date, the author has found no research papers investigating the integration of BIM and LCA in South Africa. At most, Onososen and Musonda (2022) explored the barriers as a whole contributing to the slow adoption rates, the study however, is general and not specific to South Africa. Table 4.7 highlights that the research focus in South Africa has predominantly been based on BIM rather than building LCA and the integration of BIM-LCA.

Table 4.7. Previous research related to BIM and Sustainable Construction in South Africa

Name	Year	Summary	Key Area
Calitz and Wium	2022	Key features for facilitation: leadership, strategy, roles and responsibility	BIM
Marsh et al.	2021	Clearly defines 10 barriers and drivers towards sustainable construction	Sustainable Construction
Knobel et al.	2021	Lack of BIM strategy with consensus on long term goals to adopt BIM but no short-term goals. Focus is primarily on profitability and productivity.	BIM
Booyens & Van Beek	2020	Research determined that most participants in the interviews perceived that only large-scale projects required BIM implementation and that one of the major inhibitors to implementation was a lack of legislation.	BIM
Mutingwende	2019	Challenges related to BIM implementation include Building economics, performance, quality and procurement.	BIM
Mtya	2019	Lack of BIM best practice and guidelines for widescale BIM implementation	BIM
Odubiyi et al.	2019	Embrace BIM requirements, encourage stakeholder collaboration and training	BIM
Akintola et al.	2017	Promotes BIM uniformity and adopting a structured approach by calling for BIM guidelines. The main driver towards implementation includes a "top-down" approach, incentives and motivations.	BIM

Goldswain et al.	2016	Identifies the benefits of BIM use in the construction industry which include increased productivity. Also identifies the risks which include human error and deem that the benefits outweigh the risks	BIM
Tabesh	2015	A proposal is made for universities to include BIM into its engineering curriculum	BIM

As observed in Table 4.7, more research is required for the BIM-LCA integration. The majority of research papers extensively discussed the drivers and barriers towards BIM implementation, however, there is a significant lack in the application of BIM-LCA using case studies in South Africa. These are important as LCA results for the case studies showed that local factors can play a significant role in the in the integration process.

4.3.2. BIM and LCA interoperability

The integration capabilities of the OCLCA tool are efficient in its compatibility with Revit, as per the author's observations, it saves time by automating the import of information, otherwise the user would have to manually input the material information on Excel and then import it to another LCA tool to run the analysis. It also saves time by serving as a web-based software. As mentioned in the interview findings, empirical BIM projects may contain a large amount of information and often require high computer processing power, by providing the tool as a web-based software, it allows the user to run the analysis outside of Revit and save time on computer processing. The time saved on the import of data and computer processing, however, may be over-shadowed by the validation checks required. Like any decision-making tool, particularly with LCA, there are inherent advantages and disadvantages, which will be discussed in the following sections. However, it should be underlined that in the local context even with incomplete data there are some advantages in integration and the quantification of environmental impacts as shown in the Rewardsco Case Study.

4.3.3. Advantages of the BIM-LCA Integration

In theory, there are numerous advantages towards adopting a BIM-LCA approach, essentially, using BIM to its full potential as an asset management tool. It saves time by providing an automated workflow and allows professionals to easily identify issues and update changes (Autodesk, 2023). However, the author observes that the computer processing power plays an important factor, although there is significant technological advancement in terms of the software used, the computer processing power or corrupt files could delay the delivery of projects. This is especially true when working with large projects under a Common Data Environment (CDE) (Person B). Furthermore, during handover and construction, contractors prefer printed copies of 2D drawings, they are however, willing to adopt digital transformation if they receive the proper guidance (Yang et al., 2021). In addition, effective and proficient project management is essential towards maximizing the benefits of BIM (Tariq and Gardezi, 2023). The Rewardsco model, for example, was fragmented and had many different users working under many different folders, thereby increasing the size of the project and increasing the computer processing power required to open the model.

Other benefits of the framework include simplifying an otherwise time-consuming task to quantify the environmental impact of buildings with the added advantage of regional customization (Grossi et al., 2023). The framework can be used on many levels, under numerous disciplines of the building process. It can be used on a small scale to determine an eco-friendly alternative to a building material, or on a larger scale to determine the entire life cycle impact of a building. With respect to its affordability, the cost of the OCLCA software is dependent on its purpose and the user, detailed LCA reports require expert licenses which can be expensive. Light versions that are more affordable exist for commercial purposes; these produce the same reliable results as the expert licenses without some of the additional features (OCLCA, 2021). Student versions are free, which is an indication of OCLCA's dedication to educational progress and instilling the principles of LCA in the upcoming generation of designers. However, the student version only lasts for one year, an extension may be granted upon request, but it does not allow the user to make any changes to the building project. Furthermore, the student version does not have access to help or training, any questions submitted to OCLCA by email or other means, are responded to with a request to acquire a light commercial version.

The advantage of incorporating BIM with LCA in general, include saving money on otherwise costly mistakes that appear as the project progresses, by having a BIM model with a high LOD and running clash detections, designers facilitate the building construction process by ensuring that there is data continuity between lifecycle phases and that construction material is not wasted. Subsequently, by conducting an LCA of the BIM model, the environmental impact of materials may be easily ascertained, and any changes may be applied through an iterative design process to reduce impact. However, the iteration process requires collaboration between all disciplines of the construction sector to select environmentally friendlier materials. It requires the knowledge of architectural components, structural integrity and environmental consequences. Furthermore, the selection of these materials, especially in developing countries such as South Africa, is heavily dependent on the associated costs.

The overall advantages of the framework may be summarized as:

- Provides designers with sustainable material alternatives – The OCLCA software shows the ranking of materials, highlighting materials that are environmentally detrimental with a red mapping and for those that are environmentally friendly with a green mapping It also determines the carbon dioxide equivalent emission reductions that can be achieved by changing materials or the design of the building. This feature however is very limited for South Africa because of the lack of construction material data.
- Promotes environmental consciousness – The use of the OCLCA software does encourage the user to prioritize environmental reductions where feasible.
- Shows precision planning for achieving sustainable building goals – OCLCA software aids in establishing sustainable building targets by having an embodied carbon benchmark feature. The benchmark however is dependent on a local sample size, and is therefore not efficient for South Africa, because of the limited use of the software.
- The LCA software is compatible and includes the integration of many other software including BEM.
- Time efficient – LCA results are obtained relatively quickly if there is consistent nomenclature when mapping.
- User-friendly interface - LCA results are visually represented in the form of graphs and can be understood by non-LCA experts.

4.3.4. Disadvantages of the BIM-LCA framework

The BIM-LCA framework is a valuable initiative to determine the GWP of buildings and other impact categories, however, it is important to note the disadvantages that may be encountered. The first disadvantage includes an inconveniency with respect to the Revit Software, as different versions of Revit cannot be used interchangeably, especially in the case of opening a newer version of a Revit model on a later version. This means that if a user is operating with Revit version 2023, the model will not open on Revit version 2021. The user can over-ride this issue by saving the model using Industry Foundation Classes (IFC), however, the IFC often degrades the quality of the model which can affect the accuracy of material quantities. Other disadvantages include data importation errors with respect to composite materials, the LCA software does not import the quantities of the composite materials proficiently, often resulting in double quantities or quantities with 0 mm thickness. The user will then be required to conduct material takeoff reports on Revit to ascertain the quantities of materials and validate them on the OCLCA tool. This increases the time consumed to conduct checks and validate the material quantities. Another drawback identified by the author is the significance of precise semantic labeling of building materials in

Revit. If the labeling is incorrect or the language too generic and not adequately specified, the LCA software will flag it with a warning or error.

Veselka et al. (2020), maintained that the two essential features of creating a BIM model for the purposes of LCA is the appropriate BIM management and Employer's Information Requirements (EIR). The Rewardsco case study had a low LOD, although it was a developed design, the structural BIM model was not created for the purpose of conducting an LCA and it was not a part of the EIR. The Revit model lacked the structural reinforcement, the architectural components and MEP components. According to the interview findings, the structural reinforcement modelling is a laborious and a time-consuming process, that would involve additional compensation from the client. It is for this reason that Revit projects in South Africa, are often modelled primarily for the purposes of 3D visualization, as opposed to a project management tool. It is, hence, considered a major drawback of the framework when a higher LOD is not requested. BIM models that lack sufficient data may be compensated for by manually adding the materials into the LCA software, this however, also becomes time consuming. Other disadvantages of the framework include a lack of standardized guidelines that govern data. There are European Standards and ISO standards that govern various aspects of data especially when it comes to EPDs. Therefore, the lack of standardization provides a variance in results and does not allow for objective comparisons of different buildings. It is, subsequently, recommended that a standardized guideline be created that takes into consideration the various climates and regions.

Lastly, a lesson learned from the application of the framework in South Africa is an unwillingness to share building data due to confidentiality issues, the reasons for which can only be assumed by the author as a lack of motivation. An unwillingness to share data compromises the reliability of LCA results. Furthermore, South Africa lacks an efficient EPD database that provides invaluable insight on construction materials and processes, insufficient data serves as one of the greatest barriers to the implementation of the BIM-LCA framework.

4.3.5. Motivations and barriers of BIM-LCA integration in South Africa

The results determined that the BIM-LCA framework is a useful tool in reducing the environmental impact of buildings and may serve as motivation to the building industry to develop more sustainable building designs. It aids in developing building improvement analyses and determining sustainable alternatives to materials. Ultimately, it provides decision-makers with the information required to reduce carbon dioxide equivalent emissions of the various lifecycle stages of a building. It also serves a motivation to reduce energy consumption and given the current energy crisis of South Africa, whereby electricity blackouts are experienced, reducing the energy consumption presents significant advantages and financial savings.

However, in South Africa's current state, the framework cannot be fully utilized to its potential due to the lack of sufficient data and the insufficient BIM-LCA competency among users. Overcoming these barriers necessitates a paradigm shift in the conventional design process of buildings, which entails the active involvement of key stakeholders. To address the challenges and successfully implement a whole-life cycle approach to building design in South Africa, the following measures should be implemented:

- BIM-LCA platform – A platform can be established to foster collaboration and knowledge sharing among material manufacturers, building industry professionals, and Green Star SA. It would serve as a hub for guidelines and best practices related to BIM-LCA implementation.
- Education and awareness – Targeted outreach programs and the introduction of BIM and LCA into tertiary institutions, may instill positive practices in the future generation of decision-makers.
- Investment – Through investments, more research may be conducted in the field which will subsequently increase data availability in South Africa.
- Incentives – Companies and Consultancies may be provided with extra Continuing Professional Development (CPD) points for undertaking environmental courses and becoming Accredited Professionals (AP) with GSSA.
- Policies – The implementation of mandatory regulations are effective towards transformation especially in developing countries (Akintola et al., 2017). However, it is considered too early to implement legislation regarding the LCA of buildings in South Africa given the inadequate EPD data of construction materials. Hence, the government may implement mandates for manufacturers to provide EPD data of construction materials.

4.4. Summary

The results of the study involved using the BIM–LCA framework for the assessment of the environmental impact of two case studies, with a specific focus on GWP. The most critical stages in the life cycle of buildings are related to the materials stage (A1-A3) and the operational use stage (B6). To achieve less carbon emissions, it is crucial to prioritize the reduction of emissions in these life cycle stages. For the improvement analyses, the operational energy reduction varied between the two case studies, with reductions of 10% and 50% respectively. This resulted in corresponding environmental impact reductions within a similar range except for the ODP impact category. Therefore, the application of the BIM-LCA framework to determine the potential environmental impacts of (concrete-dominated) office buildings has produced valid LCA results even when the LOD of the BIM model used was low and not all materials were included. The range of results for both case studies were consistent with published literature for similar buildings. The integration of BIM and LCA highlighted the importance of local data and the need to access such data.

Another aspect of the results section examined the Green Star certification process, focusing on the relationship between LOD and result reliability, and aimed to develop LCA criteria for Green Star SA. This criteria serves as a valuable starting point for promoting the adoption of BIM-LCA in South Africa. Overall, the framework proved to be effective in quantifying and mitigating the environmental impact of buildings. The advantages and disadvantages were extensively discussed, and a way forward was proposed.

Chapter 5 – Conclusion and Recommendations

5.1. Introduction

In this final chapter, the research aims, and objectives are revisited, emphasizing the steps taken to accomplish them. It presents a summary of the key findings, emphasizing the main outcomes and draws conclusions based on the findings. Recommendations for improving similar studies and for future research endeavors in the field are also included.

5.2. Summary of Results

The BIM LCA framework employed in this research has proven that it is a viable approach that can be employed in the local context to quantify and assess the environmental impact of buildings. Through its implementation, it has the potential to contribute to the environmental improvement of buildings. The study employed a local case study that represented the typical standard of BIM models utilized in South Africa, specifically a BIM model with a low LOD of 200. It included only the fundamental geometry of the building with steel and other materials missing. A theoretical building case study based on a Udemy course outline that encompassed all building materials was also investigated. The significance of utilizing a building with a low LOD provided a more accurate depiction of current BIM practices in South Africa whereby to produce a high LOD BIM model that included structural reinforcement and finishes would require additional compensation from clients. Therefore, economic restrictions and the lack of expertise inhibit the maturity of BIM models in the local context.

This study has revealed, through the LCA analysis of the two case studies, that the building's operational energy phase (B6) is the highest contributor to global warming, primarily because buildings have a long-life span. This is in line with findings from other studies included in the literature review. In addition, South Africa is heavily reliant on coal produced energy resulting in a high environmental factor and proportionally increasing the carbon dioxide equivalent emissions, ranking South Africa the 14th highest contributor of carbon dioxide emissions in the African continent. The materials phase (A1-A3) was the second highest contributor to global warming highlighting the significance of selecting sustainable materials. This conclusion is valid even for the low LOD case study where significant materials were not included. The embodied carbon dioxide equivalent emissions could be decreased through an improvement analysis whereby, recycled contents could be added to the material constituents. Concrete had the highest global warming potential for both cases followed by steel in the case study where it was included. Concrete is ubiquitous in building construction, contributing to emissions due to its vast quantity; while steel is used lower amounts than concrete, its production has a high environmental impact factor; particularly in South Africa due to the substantial amount of electricity required for the smelting process. An alternate source of electricity would be crucial to mitigate the environmental effects of the building's embodied energy (A1-A3) and energy phase (B6) in South Africa. Whereby renewable energy can be used for the operation of a building, the energy used for materials mostly depends on the national energy grid of a country.

Additionally, the study indicated that despite using a low LOD and an incomplete dataset of construction materials, the LCA results of the Rewardsco Building were consistent with the Udemy Building in its' ranking of environmental lifecycle stages. The energy consumption stage (B6) was the highest contributor to GWP followed by the construction material stage (A1-A3). This conclusion is specifically for concrete-frame buildings provided that the quantities of concrete are defined. These results serve as an incentive for the South African construction industry to delve into LCA analysis for buildings, even when faced with limitations such as a lack of EPD material data and models with a low LOD. However, to increase the reliability of LCA results, it is essential to exert pressure on manufacturers to provide EPD data and on designers to increase the LOD of BIM models.

The improvement analysis of the research was used to compare various material alternatives and determine the most sustainable option. The analysis determined that even minor improvements can have a substantial effect in the reduction of environmental impacts, notably, the ODP impact category for Case Study 2 decreased significantly. The reduction was due to the material substitution of the internal walls, changing the metal studs to timber resulted in a 92% reduction in the ODP impact category. The study showed that designers have the opportunity to incorporate various sustainable materials into their projects, such as using recycled materials in binders and recycling steel rebar. By doing so, they can effectively reduce construction and demolition waste, conserve resources, and decrease energy consumption related to the extraction of virgin materials. The BIM-LCA framework as shown in this study plays a crucial role in enabling designers to evaluate carbon savings, providing them with valuable insights into the environmental and social impact of their designs. This empowers designers to explore environmentally and socially responsible measures. However, to fully realize these benefits and to snowball the use of such tools locally, it is essential to integrate the framework into the criteria of the Green Star SA rating tool.

The Green Star Rating Tool for office buildings is not as established with respect to LCA when compared to other Green Building Rating Tools used in other countries. The GBCSA incorporates LCA thinking into its accreditation system through the materials category and greenhouse gas emissions category. However, no points are awarded for conducting an LCA. To increase the application of Building LCA in South Africa would require its introduction into the accreditation system and to accomplish this requires BIM-LCA guidelines. The author posits an LCA criteria to be introduced into the Green Star SA accreditation, which includes a total of 3 points that can be achieved.

5.3. Key Findings addressing Aims and Objectives

This section provides a comprehensive overview of how the research question, aims, and objectives of the study were addressed. The research was initiated by identifying the pressing need to address the harmful effects of climate change, which led to the formulation of research questions focused on integrating BIM and LCA to reduce carbon dioxide equivalent emissions in South African buildings and developing LCA criteria for Green Star SA. Table 5.1 provides a concise summary of the aims, objectives, and the corresponding outcomes achieved through the research.

Table 5.1. Key findings of the Aims and Objectives

	Aim / Objective	Findings
Aim 1	Evaluate a BIM-LCA integration methodology for South Africa and investigate how the tool can be used to reduce carbon dioxide emissions from office buildings	The research determined that the tool can be used by providing important information such as the environmental scores of 6 environmental impact categories, including carbon dioxide equivalent emissions in buildings. The tool can be used to develop an improvement analysis of building designs and determine sustainable material alternatives.
Objective 1	To investigate LCA and BIM as a decision-making tool for improving the environmental performance of office buildings within the local context.	The research determined that the tool, although effective, is not being used to its full potential in South Africa due to insufficient data and a lack of motivation. Despite that, even with an incomplete real life case study, improvements could be achieved.
Objective 2	To explore the interoperability and integration of BIM and LCA with regard to case studies	The interoperability of BIM and LCA saves time in computer processing and data importation, however, this may be overshadowed by validation checks and manual mapping of materials on the OCLCA tool.
Objective 3	Conduct a comparative analysis of the various International Green Building Rating Tools such as BREEAM, LEED, Green Star South Africa and Green Star Australia in relation to BIM and LCA	The comparative analysis determined that BREEAM awards 5 points for LCA based on criteria, LEED awards 4, Green Star Australia awards 2 and Green Star South Africa does not yet award any points for conducting a building LCA.
Objective 4	To provide criteria on a BIM-LCA framework for Green Star SA	The author recommends criteria based on literature and local context which suggests that 3 points be awarded for conducting building LCA.
Objective 5	To determine the motivations and barriers of the BIM-LCA adoption in South Africa	The motivations to pursue the framework included financial savings of energy consumption and reducing the environmental impacts of buildings. The barriers included insufficient data and a lack of BIM-LCA competency. Measures to overcome the barriers were recommended by the author.

5.4. Conclusion

The main aim of the research was to evaluate a BIM-LCA framework and determine its efficacy in reducing carbon dioxide equivalent emissions of a building. The research found that the framework was effective in reducing the GWP of a building and determining sustainable material alternatives. This was valid regardless of the degree of detail of the case studies investigated. This framework provided invaluable insight that would otherwise not be considered or not prioritized. It determined that the most important factors in reducing emissions was through the reduction of embodied carbon and energy consumption. The environmental impact factor associated with electricity generation in South Africa is high, therefore, energy savings in buildings are especially important with regards to reducing carbon emissions.

Ultimately, the BIM-LCA framework cannot be applied to its full potential in South Africa presently, unless the barriers are addressed. The research found that one of the biggest barriers to the framework was the lack of data for construction materials and the lack of a regional database. Currently, there are insufficient drivers in South Africa to promote the use of a BIM-LCA framework. Therefore, the onus is on key stakeholders such as the government, educational institutions, the GBCSA and forward-thinking building companies to advocate for a paradigm shift in the way buildings are designed.

5.5. Recommendations

Recommendations for similar studies include:

- User BIM competency – The user should be advanced in BIM capabilities as errors in the model will decrease the validity of results
- High Level of Development (LOD) - A higher LOD in the Revit model will result in a more detailed analysis of the LCA results.
- Naming Convention - Following a naming convention for the materials will simplify the material mapping process
- Increase in data - More data should be gathered from South African manufacturers for the purposes of Environmental Product Declarations (EPDs)

The research uptake of building LCA is increasing globally, however it remains very limited in the African continent and in South Africa. More research on the topic is imperative to develop a local database of EPDs from manufacturers. The author recommends that a BIM-LCA platform should be developed in South Africa to allow users to share knowledge and expertise on the topic and developing guidelines. Furthermore, incentives should be provided for designers to implement the framework. The GBCSA intends to include LCA into its accreditation system, once this is accomplished engineers, architects and environmental consultancies will be more motivated to apply BIM-LCA techniques into their design strategies to attain Green Star points.

5.6. Future Work

This study focused on office buildings with concrete frames, future work could analyze the effect of steel frames or wood frames. Furthermore, future studies could assess the accuracy of results using the OCLCA software by comparing the different ways to input data. A comparison could be drawn by automatically importing data from the BIM model to a manual input of data using the BOQ and mapping it accordingly. This comparison tests the robustness of results and ensures that all materials have been included with their correct quantities. In a subsequent phase, once more EPD data becomes available, studies could compare the robustness of generic data with specific EPDs to assess the uncertainty of results. There is great potential for future work in the BIM-LCA field, machine learning could be used to further automate the integration process, by identifying building materials from BIM models and providing embodied LCA results to facilitate the selection of materials for designers. Future work could also investigate trade-offs between materials in the construction life stage of a building and possible energy savings in the operation life stage. One such example is the use of glass and aluminium (in curtain walls) and the long-term savings due to less artificial lighting.

References

1. Akintola A, Root D, Venkatachalam S, 2017, Key constraints to optimal and widespread implementation of BIM in the South African Construction Industry, in: Chan, P W and Neilson, C J (Eds) Proceeding of the 33rd Annual ARCOM Conference, 4-6 September 2017, Cambridge, UK, Association of Researchers in Construction Management, 25-34.
2. Almezeraani, Y, 2021, Making Life Cycle Assessment of buildings a part of everyday building design through BIM Based Integration, Master thesis, University of Ljubljana, Ljubljana.
3. Ametepey S.O and Ansah S.K, 2015, Impacts of Construction Activities on the Environment: The Case of Ghana, Journal of Environment and Earth Science, 5 (3).
4. Anand CK and Amor B, 2017, Recent developments, Future Challenges and New Research directions in LCA of buildings: A critical review. Renewable and Sustainable Energy Reviews. 67. 408-416. DOI: 10.1016/j.rser.2016.09.058.
5. Antón L.A, Díaz J, 2014, Integration of LCA and BIM for Sustainable Construction, World Academy of Science, Engineering and Technology International Journal of Social, Education, Economics and Management Engineering. 85. 26-32. DOI: 10.1016/j.proeng.2014.10.525.
6. Asare K.A, Ruikar K, Zanni M, Soetanto R, 2020, BIM-based LCA and energy analysis for optimized sustainable building design in Ghana, SN Applied Sciences, 2 (11), DOI: 10.1007/s42452-020-03682-2
7. Autodesk, 2023, BIM benefits, Website: https://www.autodesk.com/solutions/aec/bim/benefits-of-bim#:~:text=Improved%20collaboration%3A%20BIM%20technology%20allows,reducing%20waste%20and%20increasing%20productivity Accessed on July, 2023.
8. Azhar S, Carlton W.A, Olsen D and Ahmad I. (2011), Building Information Modelling for Sustainable and LEED rating analysis. Automation in Construction. 20. 217-224. DOI: 10.1016/j.autcon.2010.09.019.
9. Baohua W, Musa N, Cheun O.C, Ramesh S, Lihua L, Wei W, 2020, Evolution of sustainability in global green building rating tools, Journal of Cleaner Production, 259. 120912. DOI: 10.1016/j.jclepro.2020.120912.
10. Bare J, Hofstetter P, Pennington D, Haes H, 2012, Midpoints Versus Endpoints: The Sacrifices and Benefits, International Journal of Life Cycle Assessment, 5, 319-326, DOI: 10.1007/BF02978665.
11. Basbagill J, Flager F, Lepech M, Fischer M, 2012, Application of Life Cycle Assessment to early-stage building design for reduced embodied environmental impacts, Building and Environment, 81-92, DOI: https://doi.org/10.1016/j.buildenv.2012.11.009

12. Bayer C, Gamble M, Gentry R and Surabhi J, 2010, AIA Guide to Building Life Cycle Assessment in Practice, Washington DC, The American Institute of Architects (AIA).
13. BCIS, Building Cost Information Service, 2006, Life expectancy of building components surveyors' experiences of buildings in use: a practical guide, London
14. Bernardi E, Carlucci S, Cornaro C, Bohne R.A, 2017, An analysis of the Most Adopted Rating Systems for Assessing the Environmental Impact of Buildings, 9. 1226. DOI: 10.3390/su9071226.
15. Bertin I, Mesnil R, Jaeger J, Feraille A, Le Roy R, 2020, A BIM-Based Framework and Databank for Reusing Load-Bearing Structural Elements, Sustainability, 12, 3147, DOI: 10.3390/su12083147.
16. Bew, M & Richards, M, 2008, BIM Maturity Model, in Paper presented at the Construct IT Autumn 2008 Members' Meeting Brighton, UK.
17. Bhagat G.V, Savoikar P.P, 2021, Auditing carbon reduction potential of green concrete using life cycle assessment methodology, IOP Conf. Seri.: Earth Environment Science, 850, DOI: doi:10.1088/1755-1315/850/1/012002
18. Boix-Cots D, Pardo-Bosch F, Blanco A, Aguado A, Pujadas P, 2022, A systematic review on MIVES: A sustainability-oriented multi-criteria decision-making method, Building and Environment, 223, DOI: https://doi.org/10.1016/j.buildenv.2022.109515.
19. Booyens D & Van Beek C 2020, Assessing BIM Application in the South African Construction Project Management Milieu, Journal of Construction, 13 (1), 5-17.
20. Borg M, 2001, Environmental Assessment of Materials Components and Buildings, Doctoral Thesis, KTH Royal Institute of Technology, Stockholm, Sweden.
21. Boshoff B, Mey C, 2020, The building emission reduction potential of South African residential building efficiency tools – A review, Acta Structilia, 27 (2), 151-185, DOI: http://dx.doi.org/10.18820/24150487/as27i2.6
22. Brander, A., 2012, Ecometrica, Greenhouse gases CO_2, CO_2e, and carbon, Website: https://ecometrica.com/assets/GHGs-CO2-CO2e-and-Carbon-What-Do-These-Mean-v2.1.pdf. Accessed on 05/03/2023
23. BRE Group, 2023, website: https://bregroup.com/buzz/all-about-breeam/ accessed on 06/03/2023.
24. BREEAM, 2021, BREEAM International New Construction, Version 6, Technical Manual – SD250, Watford, United Kingdom.
25. Bueno, C. and Fabricio, M.M., 2018, Comparative analysis between a complete LCA study and results from a BIM- LCA plug in, Automation in Construction, 90, 188-200.
26. Building Design, 2017, Website: https://www.bdonline.co.uk/cpd/cpd-5-2017-bim-levels-of-detail/5086956.article Accessed on 01/05/2023.

27. Calitz S and Wium JA, 2022, A proposal to facilitate BIM implementation across the South African construction industry, Journal of the South African Institution of Civil Engineering, 4, 29-37.
28. Calitz S, 2021, A proposal to facilitate BIM implementation across the South African construction industry, Master's thesis, Stellenbosch University, South Africa.
29. Campos-Guzmán V, García-Cáscales M.S, Espinosa N, Urbina A, 2019, Life Cycle Analysis with Multi-Criteria Decision Making: A review of approaches for the sustainability evaluation of renewable energy technologies, Renewable and Sustainable Energy Reviews, 104, 343-366, DOI: https://doi.org/10.1016/j.rser.2019.01.031.
30. Cao Z, Masanet E, Tiwari A, Akolawala S, 2021, Decarbonizing Concrete: Deep decarbonization pathways for the cement and concrete cycle in the United States, India and China, Industrial Sustainability analysis lab-Climateworks foundation, Website: https://www.climateworks.org/wp-content/uploads/2021/03/Decarbonizing_Concrete.pdf Accessed: 01/05/2023.
31. Carvalho JP, Alecrim I, Braganca L, Mateus R, 2020, Integrating BIM-Based LCA and Building Sustainability Assessment, Sustainability, 12, 7468, DOI: https://doi.org/10.3390/su12187468
32. Cavalliere, Carmine & Habert, Guillaume & Dell'Osso, Guido & Hollberg, Alexander, 2019, Continuous BIM-based assessment of embodied environmental impacts throughout the design process. Journal of Cleaner Production, 211, 941-952, DOI: 10.1016/j.jclepro.2018.11.247.
33. Cerovsek, T, 2011, A review and outlook for a "Building Information Model" (BIM): A multi-standpoint framework for technological development, Advanced Engineering Informatics, 25(2), 224–244, DOI: 10.1016/j.aei.2010.06.003.
34. Cheng S, Lin J, Xu W, Yang D, Liu J, Li H, (2020). Carbon, water, Land and Material Footprints of China's High-Speed-Railway Construction. Transportation Research Part D, 82, 102314, DOI: https://doi.org/10.1016/j.trd.2020.102314
35. Chong HY, Lee CY, Wang X, 2017, A mixed review of the adoption of Building Information Modelling (BIM) for sustainability, Journal of Cleaner Production, 142 (4), 4114-4126, DOI: 10.1016/j.jclepro.2016.09.222.
36. Ciroth A, Burhan S, 2021, Life Cycle Inventory Data and Databases, Life Cycle Inventory Analysis, In: Ciroth, A., Arvidsson, R. (eds) Life Cycle Inventory Analysis. LCA Compendium – The Complete World of Life Cycle Assessment. Springer, Cham. DOI: https://doi.org/10.1007/978-3-030-62270-1_6
37. Climate Action Tracker South Africa, 2022, Website: https://climateactiontracker.org/countries/south-africa/ Accessed on 16/05/2023

38. Crippa J, Araujo A.M.F, Bem, D, Ugaya C.M.L, Scheer S, 2020, A systematic review of BIM usage for life cycle impact assessment, Built Environment Project and Asset Management, DOI: 10.1108/BEPAM-03-2019-0028
39. CSIR, 2007, Strategic Environmental Assessment (SEA) Resource Document – Introduction to the Process, Principles and Application of SEA, CSIR Report ENV-S-C 2002-073, Version 4, Environmentek, Stellenbosch, South Africa
40. Dalla Mora T, Bolzonello E, Cavalliere C, Peron F, 2020, Key Parameters Featuring BIM-LCA Integration in Buildings: A Practical Review of the Current Trends, Sustainability, 12, 7182, DOI: 10.3390/su12177182
41. Dauletbek A, Zhou P, 2022, BIM-based LCA as a comprehensive method for the refurbishment of existing dwellings considering environmental compatibility, energy efficiency, and profitability: A case study in China, Journal of Building Engineering, 46, DOI: https://doi.org/10.1016/j.jobe.2021.103852
42. De Wolf C, Pomponi F, Moncaster A, 2017, Measuring embodied carbon dioxide equivalent of buildings: A review and critique of current industry practice, Energy and Buildings, 140, 68-80, DOI: http://dx.doi.org/10.1016/j.enbuild.2017.01.075
43. Ding, G.K.C. (2008) Sustainable Construction—The Role of Environmental Assessment Tools, Journal of Environmental Management, 86, 451-456 , DOI: https://doi.org/10.1016/j.jenvman.2006.12.025
44. Dixit M.K, Fernández-Solís J.L, Lavy S, Culp C.H, 2010, Identification of parameters for embodied energy measurement: A literature review, Energy and Buildings, 42 (8), 1238-1247, DOI: 10.1016/j.enbuild.2010.02.016.
45. Dong Y, Hossain M.U, Li H, Liu P, 2021, Developing Conversion Factors of LCIA Methods for Comparison of LCA Results in the Construction Sector. Sustainability, 13, 9016. DOI: https://doi.org/10.3390/su13169016
46. Dossche C, Boel V, De Corte W, 2017, Use of life cycle assessments in the construction sector: critical review, Procedia Engineering, 171, 302-311, DOI: 10.1016/j.proeng.2017.01.338
47. EIA – Energy Information Administration, Coal explained, coal and the environment, Website: https://www.eia.gov/energyexplained/coal/coal-and-the-environment.php#:~:text=Several%20principal%20emissions%20result%20from,respiratory%20illnesses%20and%20lung%20disease Accessed on 13/07/2023.
48. EN 15804+A2, Sustainability of construction works. Environmental product declarations. Core rules for the product category of construction products, 2019, Website: https://www.en-standard.eu/bs-en-15804-2012-a2-2019-sustainability-of-construction-works-environmental-

product-declarations-core-rules-for-the-product-category-of-construction-products/?gclid=CjwKCAjw5_GmBhBIEiwA5QSMxDHLkMb2eY43ABddUsywwk8q8tUAqdOOxTQCvnm0IJEN2cwHCyW3URoCd7QQAvD_BwE Accessed on 12/02/2023

49. EPD (Environmental Product Declaration) Saint Gobain, 2016, Gypframe metal framing components for gypsum plasterboard, website: https://oneclicklcaapp.com/app/sec/util/getEpdFile?resourceId=envdecGypframeMetalCOmp_v2&profileId=BritishGypsum2021 accessed on 11/09/2023.
50. Eskom, 2021, Eskom Fact Sheet, Website: https://www.eskom.co.za/wp-content/uploads/2022/03/GX-0001-Generation-Plant-Mix-Rev-25.docx.pdf Accessed on 03/05/2023.
51. European Commission, Energy Performance of Buildings Directive, Website: https://energy.ec.europa.eu/topics/energy-efficiency/energy-efficient-buildings/energy-performance-buildings-directive_en Accessed on 18/02/2021
52. Farinha C.B, Brito J, Veiga R, Jesus S and Pederneiras C.M, 2021, Reduction of the Cement Content by Incorporation of Fine Recycled Aggregates from Construction and Demolition Waste in Rendering Mortars, Infrastructures, 6(1), 11, DOI: https://doi.org/10.3390/infrastructures6010011
53. Fawzy S, Osman A.I, Doran J, Rooney D.W, 2020, Environmental Chemistry Letters, 18, 2069-2094, DOI: https://doi.org/10.1007/s10311-020-01059-w
54. Feng H, Zhao J, Hollberg A, Habert G, 2023, Where to focus? Developing a LCA impact category selection tool for manufacturers of building materials, Journal of Cleaner Production, 405, DOI: https://doi.org/10.1016/j.jclepro.2023.136936
55. Feng H, Zhao J, Zhang H, Zhu S, Li D, Thurairajah N, 2022, Uncertainties in whole-building life cycle assessment: A systematic review, Journal of Building Engineering, 50 DOI: https://doi.org/10.1016/j.jobe.2022.104191
56. Fenner A.E, Kibert C, Woo J, Morque S, Razkenari M & Hakim H, Lü X, 2018, The carbon footprint of buildings: A review of methodologies and applications. Renewable and Sustainable Energy Reviews. 94. 1142-1152. DOI: 10.1016/j.rser.2018.07.012.
57. Filippo R, Bursi O.S, Maggio R, 2022, Global warming and ozone depletion potentials caused by emissions from HFC and CFC banks due to structural damage, Energy and Buildings, 273, 112385, DOI: https://doi.org/10.1016/j.enbuild.2022.112385.
58. Fnais A, Rezgui Y., Petri I, Beach T, Yeung J, Ghoroghi A, Kubicki, 2022, The application of life cycle assessment in buildings: challenges, and directions for future research, International Journal of Life Cycle Assessment, 27, 627–654 , DOI: https://doi.org/10.1007/s11367-022-02058-5

59. Friedrich E, Pillay S, Buckley CA, 2007, The use of LCA in the water industry and the case for an environmental performance indicator, Water SA, 33, 4, DOI**:** 10.4314/wsa.v33i4.52938
60. Gamayunova, O. & Vatin, N, 2015, BIM-technology in architectural design, Advanced Materials Research, 1065-1069, 2611-2614, DOI: 10.4028/www.scientific.net/AMR.1065-1069.2611.
61. Gandhi S. and Jupp J, 2014, BIM and Australian Green Star Building Certification, Computing in Civil and Building Engineering, 275-282, DOI: 10.1061/9780784413616.035
62. Genova G, 2019, BIM-Based LCA throughout the design process: A dynamic approach, WIT transactions on the Built Environment, 192, DOI: 10.2495/BIM190051
63. Global Green Tag, 2023, Website: https://www.globalgreentag.co.za/products.html?search=South+Africa+building+materials Accessed on 12/01/2023
64. Goldswain C.P, 2016, BIM as a tool for quantifying the impact of change on labour productivity, Master’s thesis, Stellenbosch University, South Africa.
65. Green Building Council South Africa (GBCSA), 2017, https://gbcsa.org.za/certify/green-star-sa/net-zero/ Accessed on 17/05/2022
66. Green Star Buildings, 2021, Submission Guidelines, Version 1: Revision B, Green Building Council Australia, Australia.
67. Grossi F, Ge H & Zmeureanu R, 2023, Life Cycle Assessment of the Environmental Benefits of Using Wood Products and Planting Trees at an All-Electric University Laboratory, Buildings, 13(7), 1584, DOI: https://doi.org/10.3390/buildings13071584
68. GSSA, Green Star South Africa Office Technical Manual v1.1, 2014, Website: https://gbcsa.org.za/office-v1-v1-1/ Accessed on 07/02/2023.
69. Gu, N. and London, K., 2010, Understanding and facilitating BIM adoption in the AEC industry, Automation in Construction, 19(8), 988-999, DOI: https://doi.org/10.1016/j.autcon.2010.09.002.
70. Guinée, Jeroen & Heijungs, Reinout & Huppes, Gjalt & Zamagni, Alessandra & Masoni, Paolo & Buonamici, Roberto & Ekvall, Tomas & Rydberg, Tomas, 2011, Life Cycle Assessment: Past, Present, and Future, Environmental science & technology, 45, 90-6, DOI: 10.1021/es101316v.
71. Gutiérrez P.F, Cely-García M.F, Larrahondo J.M, 2023, Environmental management criteria, aimed at public policymaking, for the removal and disposal of asbestos-containing building materials in Colombia, Integrated Environmental Assessment and Management, 19, 1079-1088 DOI: https://doi.org/10.1002/ieam.4736
72. Haddad A.N, Silva A.B, Hammad A.W.A, Najjar M.K, Vazquez E.G, Tam V.W.Y, 2023, An integrated approach of building information modelling and life cycle assessment (BIM-LCA) for

gas and solar water heating systems, International Journal of Construction Management, 23:14, 2452-2468, DOI: 10.1080/15623599.2022.2068179

73. Hoffman C., Hoey M.V., Zeumer B, 2020, Decarbonization challenge for Steel, McKinsey and Company, Website: https://www.mckinsey.com/industries/metals-and-mining/our-insights/decarbonization-challenge-for-steel , Accessed on 03/04/2023
74. Hoffman D, Huang L, Rensburg JV, Yorke-Hart A, 2020, Trends in Application of Green Star SA credits in South African Green Building, Acta Structilia, 27(2), 1-29, DOI: 10.18820/24150487/as27i2.1.
75. IEA, The International Energy Agency, 2021, The World Energy Outlook, https://iea.blob.core.windows.net/assets/4ed140c1-c3f3-4fd9-acae-789a4e14a23c/WorldEnergyOutlook2021.pdf Accessed on 19/02/2021
76. IEA, The International Energy Agency, 2023, Buildings, Website: https://www.iea.org/energy-system/buildings Accessed 07/08/2023.
77. Ijigah E.A, Jimoh R.A, Aruleba B.O, Ade A.B, 2013 An Assessment of Environmental Impacts of Building Construction Projects, Civil and Environmental Research, 3, 1, https://core.ac.uk/download/pdf/234677538.pdf
78. Illankoon, I. M.C.S, Tam V.W.Y, Le K, Tran C and Mingxue M, 2019, Review on green building rating tools worldwide: recommendations for Australia, Journal of Civil Engineering and Management, 25, 831-847, DOI: 10.3846/jcem.2019.10928.
79. IMF, International Monetary Fund African Department, 2023, Website: https://www.elibrary.imf.org/view/journals/002/2023/195/article-A003-en.xml#:~:text=The%20official%20carbon%20tax%20rate,–22%20(Figure%203). Accessed on 16/05/2023
80. IOL, Independent Online, 2023, South Africa accelerates gas-fired power plans to address energy deficit, Website: https://www.iol.co.za/news/energy/south-africa-accelerates-gas-fired-power-plans-to-address-energy-deficit-d4689665-27cc-44b5-8dd0-3ec06c824810 Accessed on 07/11/2023.
81. IPCC, Intergovernmental Panel on Climate Change, 2018: Global Warming of 1.5°C, An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development,and efforts to eradicate poverty [Masson-Delmotte,V.,P.Zhai,H.-O.Pörtner,D.Roberts,J.Skea,P.R.Shukla,A.Pirani, W. Moufouma-Okia, C. Péan, R. Pidcock, S. Connors, J.B.R. Matthews, Y. Chen, X. Zhou, M.I. Gomis, E. Lonnoy, T.

Maycock, M. Tignor, and T. Waterfield (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, 616 pp. https://doi.org/ 10.1017/9781009157940.

82. IPCC, Intergovernmental Panel on Climate Change, 2022, Climate Change 2022: Mitigation of Climate Change, Working Group III contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change, ISBN 978-92-9169-160-9
83. Ismail, M. 2019. BIM implementation: theory and practices, in BIM Talk BIM Africa, Website: https://bimafrica.org/bimtalk/bim-implementation-theory-and-practises/ Accessed on 03/04/2023.
84. ISO, 2006, International Organization for Standardization, Website: https://www.iso.org/standard/37456.html Accessed on 02/01/2023.
85. Izaola B, Akizu-Gardoki O, Oregi X, 2023, Setting baselines of the embodied, operational and whole life carbon emissions of the average Spanish residential building, Sustainable Production and Consumption, 40, 48-50, DOI: 10.1016/j.spc.2023.07.001
86. Jalaei F, Nassiri M, Jrade A, 2015 Integrating decision support system (DSS) and building information modelling (BIM) to optimize the selection of sustainable building components, Journal of Information Technology in Construction, 20, 399-420.
87. Jo Anderson, Green Building Council of South Africa, email correspondence dated 01/07/2022.
88. Kiamili C., Hollberg A., Habert G., 2020, Detailed Assessment of Embodied Carbon of HVAC Systems for a New Office Building Based on BIM, Sustainability, 12(8):3372, DOI: 10.3390/su12083372
89. Knobel M, Ahmed V, Saboor S, Gledson B, Kassem M, 2021, A socio-cultural perspective to BIM adoption: A case study in South Africa, DOI: 10.1007/978-3-030-48465-1_68
90. Kobeticova K, and Černý R, 2019, Terrestrial eutrophication of building materials and buildings: An emerging topic in environmental studies, Science of The Total Environment, 689, DOI: 10.1016/j.scitotenv.2019.06.423.
91. Koch D, Friedl A & Mihalyi B, 2023, Influence of different LCIA methods on an exemplary scenario analysis from a process development LCA case study, Environment, Development and Sustainability, 25, 6269–6293, DOI: https://doi.org/10.1007/s10668-022-02302-w
92. Lasvaux S, Habert G, Peuportier B, Chevalier J, 2015, Comparison of generic and product-specific Life Cycle Assessment databases: application to construction materials used in building LCA studies, The International Journal of Life Cycle Assessment, **20**, 1473–1490 DOI: https://doi.org/10.1007/s11367-015-0938-z
93. LEED v4, Owens B, Macken C, Rohloff A, Rosenberg H., 2013, Impact category and point allocation development process, US Green Building Council, USA.

94. Liu T, Chen L, Yang M, Sandanayake M, Miao P, Shi Y, Yap P-S., 2022, Sustainability Considerations of Green Buildings: A Detailed Overview on Current Advancements and Future Considerations. *Sustainability*; 14(21):14393. DOI: https://doi.org/10.3390/su142114393

95. Lotteau M, Loubet P, Pousse M., Dufrasnes E., Sonnemann G., 2015, Critical review of LCA for the built environment at the neighbourhood scale, Building and Environment, 93, 165-178, DOI: 10.1016/j.buildenv.2015.06.029.

96. Maçka Kalfa, Sibel, 2018, Building information modeling (BIM) systems and their applications in Turkey, Journal of Construction Engineering, Management & Innovation, 1, 55-66, DOI: 10.31462/jcemi.2018.01055066.

97. Mao I, Lu H, Li Q, 2009, A comparison study of main-stream sustainable green/building rating tools in the world, Proceeding of international conference on management and service science, Institute of Electrical and Electronics Engineers (IEEE), Wuhan.

98. Marsh R.J, Brent A.C, De Kock I.H, Understanding the barriers and drivers of sustainable construction adoption and implementation in South Africa: A quantitative study using Theoretical Domains Framework and COM-B model, Journal of the South African Institution of Civil Engineering, 63, 11-23, DOI: http://dx.doi.org/10.17159/2309-8775/2021/v63n4a2

99. Martínez-Rocamora, A., Solís-Guzmán, J., Marrero, M. (2016). LCA databases focused on construction materials: A review. Renewable and Sustainable Energy Reviews, 58, 565–573, DOI:10.1016/j.rser.2015.12.243

100. Mathews M, 2015, BIM: postgraduate multidisciplinary collaborative education, Building Information Modelling (BIM) in Design, Construction and Operations, WIT Transactions on the Built Environment, 149, 133-143, DOI: 10.2495/BIM150121

101. Miller S, Horvath A, Monteiro P.J.M, 2018, Impacts of booming concrete production on water resources worldwide, Nature Sustainability 1, 69-76, DOI: 10.1038/s41893-017-0009-5

102. Miller SA, Horvath A, Monteiro P.J.M 2016 Readily implementable techniques can cut annual CO2 emissions from the production of concrete by over 20%, Environmental Research Letters, 11(7), DOI: 10.1088/1748-9326/11/7/074029

103. Mirabella N, Karen A & Serenella S, 2019, Current trends and limitations of life cycle assessment applied to the urban scale: critical analysis and review of selected literature, The International Journal of Life Cycle Assessment, 24, DOI: 10.1007/s11367-018-1467-3.

104. Mtya A, 2019, Evaluation of Building Information Modelling (BIM) adoption, capability and maturity within South African consulting and construction firms, Master thesis, University of Cape Town, South Africa.

105. Mutingwende E, 2019, Assessment of risks associated with implementation of BIM in maintenance of commercial buildings in Gauteng, Master's thesis, University of Witwatersrand, Johannesburg, South Africa.

106. Najjar M, Figueiredo K, Palumbo M, Haddad A, 2017, Integration of BIM and LCA: evaluating the environmental impacts of building materials at an early stage of designing a typical office building, Journal of Building Engineering, 14, 115-126, DOI: https://doi.org/10.1016/j.jobe.2017.10.005.

107. National Research Fund (NRF) – South African Radio Astronomy Observatory (SARAO), 2022, https://www.sarao.ac.za/about/strategic-environmental-assessment/difference-between-a-sea-and-an-eia/ Accessed on 29/07/2022.

108. Obrecht T.P, Rock M, Hoxha E, Passer A, 2020, BIM and LCA integration: A systematic literature review, Sustainability 12, DOI: https://doi.org/10.3390/su12145534

109. OCLCA, One Click LCA, 2021, Life Cycle Assessment for buildings, why it matters and how to use it, ebook, Website: https://www.oneclicklca.com/wp-content/uploads/2021/10/Life-Cycle-Assessment-for-Buildings-2021.pdf?vgo_ee=fehcXac1DsDegY7uj7CtfN26ziIX4g3Pmjy%2FVP4pVbs%3D#:~:text=of%20a%20building-,Building%20LCA%20is%20a%20science%2Dbased%20methodology%20for%20quantifying%20the,environmental%20impacts%20of%20a%20building.&text=LCA%20assesses%20several%20environmental%20impact,known%20as%20a%20carbon%20footprint. Accessed on 29/07/2022.

110. Odubiyi B, Aigbavboa C, Thwala W, Netshidane N, 2019, Strategies for BIM adoption in the South African Construction Industry, Modular and Offsite Construction (MOC) Summit Proceedings, Banff, Canada, DOI: 10.29173/mocs133

111. Oke A.E, Aigbavboa C, Looyen D.E, 2016, Influences of Sustainable Construction Practices in South Africa, Hanyang University, South Korea.

112. Pannier M, Schalbart P, Peuportier B, 2018, Comprehensive assessment of sensitivity analysis methods for the identification of influential factors in building life cycle assessment, Journal of Cleaner Production, 199, 466-480, DOI: https://doi.org/10.1016/j.jclepro.2018.07.070.

113. Pauer E, Wohner B, Tacker M, The Influence of Database Selection on Environmental Impact Results. Life Cycle Assessment of Packaging Using GaBi, Ecoinvent 3.6, and the Environmental Footprint Database, Sustainability, 12, DOI: 10.3390/su12239948

114. Pawłowski L, 1997, Acidification: its impact on the environment and mitigation strategies, Ecological Engineering, 8 (4), 271-288, DOI: https://doi.org/10.1016/S0925-8574(97)00023-2.

115. Petrov B.Y and Zaharieva R.A, 2020 IOP. Conference Series: Materials Science and Engineering, 951, 012008, DOI: 10.1088/1757-899X/951/1/012008

116. PRB – Population Reference Bureau, 2023, Website: https://www.prb.org/resources/urbanization-an-environmental-force-to-be-reckoned-with/ Accessed on 29 June 2023.

117. Pré, ReCiPe, 2023, Website: https://pre-sustainability.com/articles/recipe/ Accessed on 06/05/2023.

118. Reap J, Roman F, Duncan S, Bras B, 2008, A survey of unresolved problems in Life Cycle Assessment - Part 2: impact assessment and interpretation, The International Journal of Life Cycle Assessment, 13, 374-388, DOI: 10.1007/s11367-008-0009-9.

119. Reed R, Wilkinson S, Bilos A, Schulte K-W., 2011, A comparison of International Sustainable Building Tools – An Update, The 17th Annual Pacific Rim Real Estate Society Conference, 16-19.

120. Rezai F, Bulle C, Lesage P, 2019, Integrating building information modeling and life cycle assessment in the early and detailed building design stages. Building and Environment, 153, DOI: 10.1016/j.buildenv.2019.01.034.

121. Röck M, Hollberg A, Habert, G, Passer A, 2018, LCA and BIM: Visualization of environmental potentials in building construction at early design stages, Building and Environment, 140, DOI: 10.1016/j.buildenv.2018.05.006.

122. Rucińska J, Komerska A, Kwiatkowski J, 2020, Preliminary Study on the GWP Benchmark of Office Buildings in Poland Using the LCA Approach. Energies, 13, 3298, DOI: https://doi.org/10.3390/en13133298

123. Russell-Smith SV, Lepech MD, Fruchter R, Littman A, 2014, Impact of progressive sustainable target value assessment on building design decisions, Building and Environment, 85, 52-60, DOI: 10.1016/j.buildenv.2014.11.011.

124. Safari K and AzariJafari H, 2021, Challenges and Opportunities for integrating BIM and LCA: methodological choices and framework development, Sustainable Cities and Society, 67, 102728, DOI: https://doi.org/10.1016/j.scs.2021.102728

125. Sánchez-Garrido A.J, Navarro I.J, Yepes V, 2022, Multi-criteria decision-making applied to the sustainability of building structures based on Modern Methods of Construction, Journal of Cleaner Production, 330, DOI: https://doi.org/10.1016/j.jclepro.2021.129724.

126. SANEDI, South African National Energy Development Institute, Website: https://sanedi.org.za/wp-content/uploads/2022/05/EPC-Guideline-_-FINAL-_-May2022.pdf Accessed on 15/05/2023

127. Santos R, Costa A, Silvestre J, & Pyl L, 2018, A validation of study of a semi-automatic BIM-LCA tool, Conf.: 2º Congresso Português de Building Information Modelling, Lisboa, Portugal.

128. Santos R, Costa A.A, Silvestre J, Pyl L, 2019, Integration of LCA and LCC analysis within a BIM-based environment, Automation in Construction, 103, 127-149, DOI: https://doi.org/10.1016/j.autcon.2019.02.011.

129. Seppala, J, Hamalainen R.P, 2001, On the Meaning of the Distance-to-Target Weighting Method and Normalisation in Life Cycle Impact Assessment, International Journal of Life Cycle Assessment, 6(4), 211–218, DOI: https://doi.org/10.1007/BF02979376

130. Shirazi A and Ashuri B, 2020, Embodied Life Cycle Assessment (LCA) comparison of residential building retrofit measures in Atlanta, Building and Environment, 171, DOI: https://doi.org/10.1016/j.buildenv.2020.106644

131. Si J, Marjanovic-Halbard L, Nasiri F, Bell S, 2018, Assessment of building integrated green technologies: A review and case study on applications of Multi-Criteria Decision Making (MCDM) method, Sustainable Cities and Society 27, 106–115, DOI: 10.1016/j.scs.2016.06.013

132. Silveira S.S, Alves T.C.L, 2018, Target Value Design Inspired Practices to Deliver Sustainable Buildings, Buildings, 8, DOI: https://doi.org/10.3390/buildings8090116

133. Silveira SS, Alves TDCL, 2018, Target Value Design Inspired Practices to Deliver Sustainable Buildings, Buildings, 8 (9), DOI: https://doi.org/10.3390/buildings8090116

134. Simapro, 2016, Introduction to LCA with SimaPro, Website: https://pre-sustainability.com/legacy/download/SimaPro8IntroductionToLCA.pdf Accessed on 06/05/2022

135. Soust-Verdaguer B, & Llatas C, García-Martínez A, 2017, Critical review of BIM-based LCA method to buildings, Energy and Buildings,136, DOI: 10.1016/j.enbuild.2016.12.009.

136. South Africa's Intended Nationally Determined Contributions Website: https://unfccc.int/sites/default/files/NDC/2022-06/South%20Africa.pdf Accessed on 10/04/2023

137. Stanford News, 2021, Stanford Explainer: Social Cost of Carbon, Website: https://news.stanford.edu/2021/06/07/professors-explain-social-cost-carbon/ Accessed on 10/07/2023.

138. Statista, 2022, Carbon dioxide emissions from fossil fuel and industrial purposes in South Africa from 1970 to 2021, Website: https://www.statista.com/statistics/486073/co2-emissions-south-africa-fossil-fuel-and-industrial-purposes/#:~:text=South%20Africa%20was%20the%20fourteenth,carbon%20dioxide%20worldwide%20in%202021. Accessed on 29/06/2023.

139. Tabesh M, 2015, An investigation to introduce BIM in undergraduate civil engineering teaching to improve construction processes, Master's thesis, Stellenbosch University, South Africa.

140. Taherdoost H and Madanchian M, 2023, A Comprehensive Overview of the ELECTRE Method in Multi Criteria Decision-Making, Journal of Management Science & Engineering Research, 6, DOI: 10.30564/jmser.v6i2.5637.

141. Tan T, Mills G, Papadonikolaki E, Liu Z, 2021, Combining Multi-Criteria Decision Making (MCDM) Methods with Building Information Modelling: A review, Automation in Construction, 121, DOI: 10.1016/j.autcon.2020.103451

142. Tariq J & Gardezi S.S, 2023, Study the delays and conflicts for construction projects and their mutual relationship: A review, Ain Shams Engineering Journal, 14, 1, DOI: https://doi.org/10.1016/j.asej.2022.101815.

143. Theodosiou G, 2010, Cement and Concrete Institute, Concrete Industry, Greenhouse Gas Emissions, Website: https://cemcon-sa.org.za/wp-content/uploads/2021/03/Cement-and-Concrete-Institute-Concrete-Industry-Greenhouse-Gas-Emissions.pdf Accessed on 13/07/2023.

144. Torkayesh A.E, Rajaeifar M.A, Rostom M, Malmir B, Yazdani M, Suh S, Heidrich O, 2022, Integrating life cycle assessment and multi criteria decision making for sustainable waste management: Key issues and recommendations for future studies, Renewable and Sustainable Energy Reviews, 168, DOI: https://doi.org/10.1016/j.rser.2022.112819.

145. Tozan B, Stapel E, Sørensen C, Birgisdóttir H, 2022, The influence of EPD data on LCA results, IOP conference series: Earth and Environmental Science, Berlin, DOI: 10.1088/1755-1315/1078/1/012105

146. Tushar Q, Bhuiyan M, Sandanayake M, Zhang G, 2019, Optimizing the energy consumption in a residential building at different climate zones: Towards sustainable decision making, Journal of Cleaner Production, 233, 634-649, DOI: https://doi.org/10.1016/j.jclepro.2019.06.093.

147. UNEP, 2021 Global Status Report for Building and Construction, https://globalabc.org/sites/default/files/2021-10/GABC_Buildings-GSR-2021_BOOK.pdf Accessed on 19/02/2021

148. United Nations Environment Programme, (2022), 2022 Global Status Report for Buildings and Construction: Towards a Zero-emission, Efficient and Resilient Buildings and Construction Sector, Nairobi.

149. Universiteit of Leiden, 2016, Website: https://www.universiteitleiden.nl/en/research/research-output/science/cml-ia-characterisation-factors Accessed on 11/07/2023.

150. USGBC, United States Green Building Council, 2023, Life Cycle Assessment, website: https://www.usgbc.org/education/sessions/life-cycle-assessment-12855603 Accessed on 05/03/2023.

151. Usman A.M, and Abdullah K, 2018, Comparative Study on the Malaysian Sustainable Building Rating Systems. International Journal of Integrated Engineering. 10.

152. Vosloo P, Harris H, Holm D, Rooyen NV, Rice G, 2016, Life cycle assessment of clay brick walling in South Africa, The Clay Brick Association of South Africa: Technical Report 7A, University of Pretoria.

153. Wang F, Harindintwali J.D, Yuan Z, Wang M, Wang F, Li S, Yin Z, Huang L, Fu Y, Li L, Chang SX, Zhang L, Rinklebe J, Yuan Z, Zhu Q, Xiang L, Tsang D.C.W, Xu L, Jiang X, Liu J, Wei N, Kästner M, Zou Y, Ok Y.S, Shen J, Peng D, Zhang W, Barceló D, Zhou Y, Bai Z, Li B, Zhang B, Wei K, Cao H, Tan Z, Zhao L, He X, Zheng J, Bolan N, Liu X, Huang C, Dietmann S, Luo M, Sun N, Gong J, Gong Y, Brahushi F, Zhang T, Xiao C, Li X, Chen W, Jiao N, Lehmann J, Zhu Y.G, Jin H, Schäffer A, Tiedje J.M, Chen J.M, 2021, Technologies and perspectives for achieving carbon neutrality, The innovation, 2 (4), DOI: https://doi.org/10.1016/j.xinn.2021.100180

154. Wang, X. and Chong, H.-Y. (2015), "Setting new trends of integrated Building Information Modelling (BIM) for construction industry", Construction Innovation, 15 (1), 2-6, DOI: https://doi.org/10.1108/CI-10-2014-0049

155. Wastiels L, Decuypere R, 2019, Identification and comparison of LCA-BIM integration of strategies, IOP Conference Series: Earth and Environmental Science, 323, 012101, DOI: 10.1088/1755-1315/323/1/012101.

156. Weidema B.P, 2014, Has ISO 14040/44 Failed Its Role as a Standard for Life Cycle Assessment? Journal of Industrial Ecology, 18 (3), DOI: 10.1111/jiec.12139

157. Western Cape Government Environmental Affairs and Development Planning, 2015, https://www.westerncape.gov.za/eadp/files/atoms/files/EIA_2015.pdf , Accessed on 05/07/2022

158. WGBC - World Green Building Council, 2023, Bringing embodied carbon upfront, Website: https://worldgbc.org/advancing-net-zero/embodied-carbon/#:~:text=Buildings%20are%20currently%20responsible%20for,11%25%20from%20materials%20and%20construction. Accessed on 29/06/2023.

159. world. Proceeding of international conference on man-

160. world. Proceeding of international conference on man-

161. Worldometer website, population of South Africa, 2023, https://www.worldometers.info/world-population/south-africa-population/ Accessed on 01/03/2023.

162. Xue K, Hossain M.U, Liu M, Ma M, Zhang Y, Hu M, Chen X, Cao G, 2021, BIM Integrated LCA for Promoting Circular Economy towards Sustainable Construction: An Analytical Review, Sustainability, 13, 1310, DOI: https://doi.org/10.3390/su13031310

163. Yang D, de Vries B & van der Schaft L, 2021, The construction workers' preference and acceptance of innovations in data provision: A stated choice experiment study in the Netherlands, Journal of Building Engineering, 35, 101970, DOI: https://doi.org/10.1016/j.jobe.2020.101970.

164. Zimmerman R.K, Bruhn S, Birgisdóttir H, 2021, BIM-Based LCA of Buildings – An Investigation of Industry Practices and Needs, Sustainability, 13, 5455, DOI: https://doi.org/10.3390/su13105455

Appendices

Appendix 1 - Layout of Rewardsco Case Study

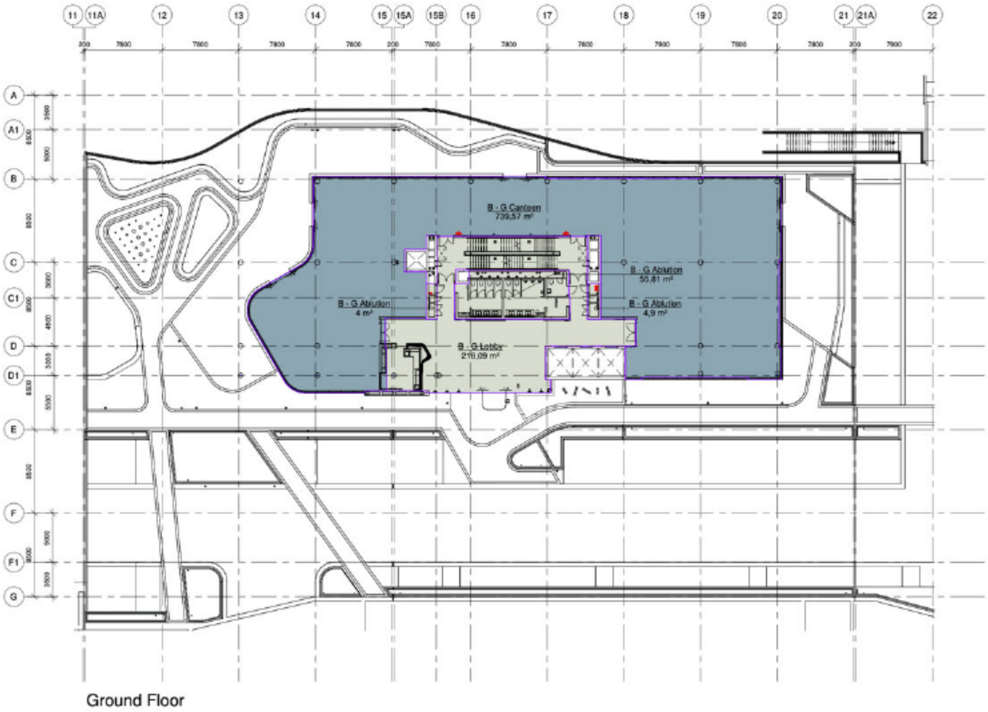


Figure A1: Ground Floor As-Built Layout

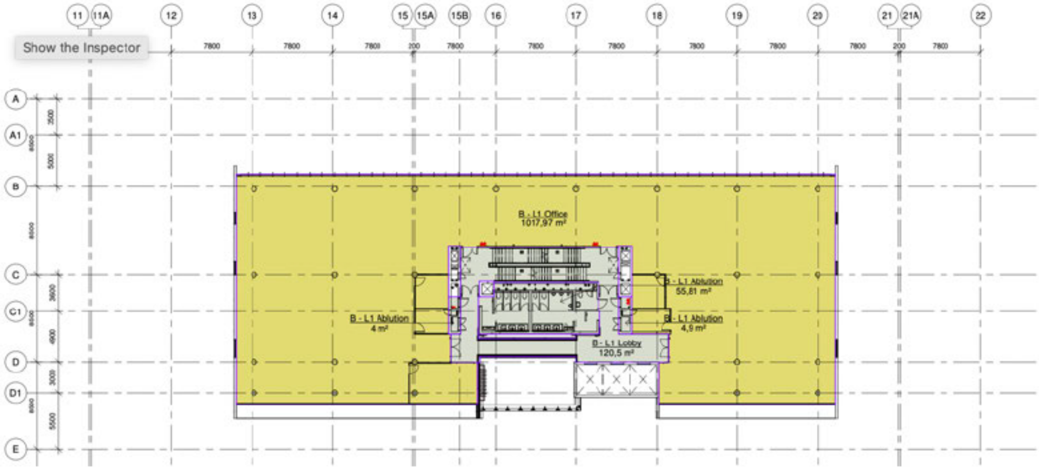


Figure A2: First Floor As-Built Layout

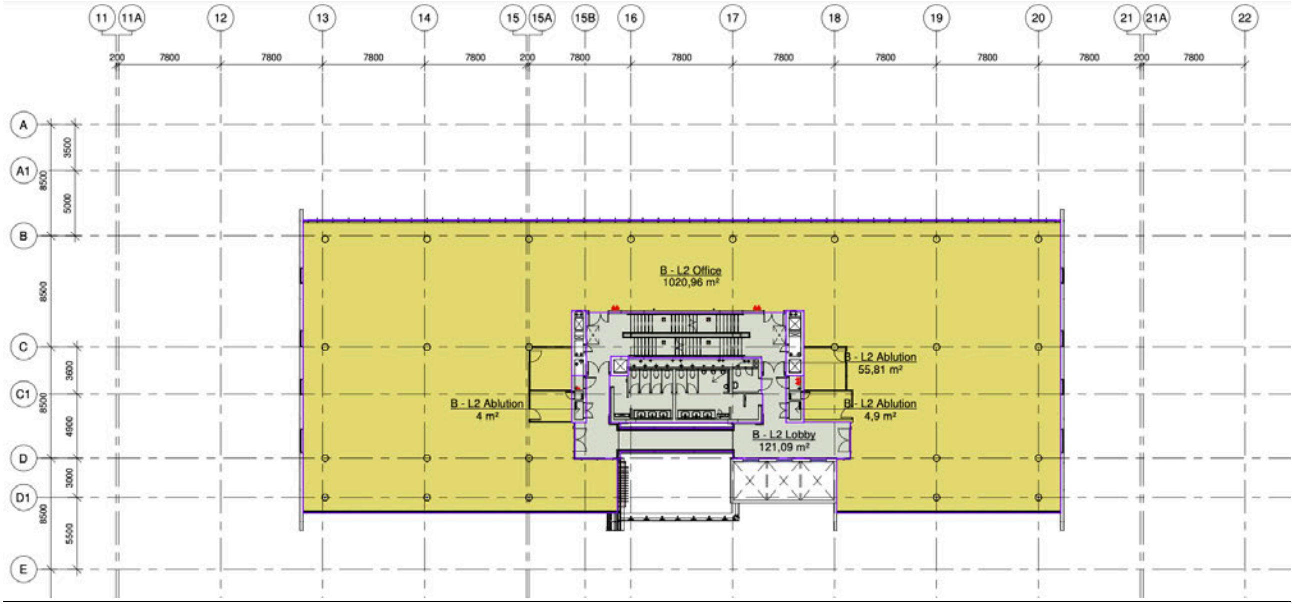


Figure A3: Second Floor As-Built Layout

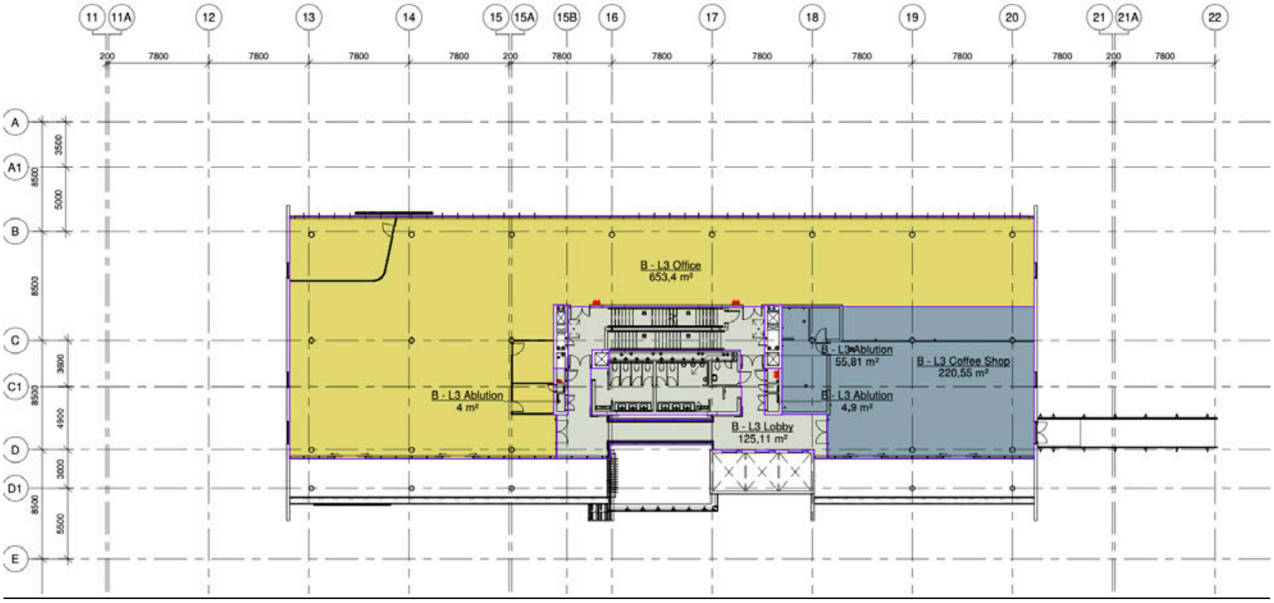


Figure A4: Third Floor As-Built Layout

Appendix 2: Step by step guidance for creating a baseline:

- The initial step is to create a building project and label it, in this instance, the project was labelled 212500019 MSc Building Project.
- Under the design phase, click on +Add a design and enter the project information:
  - Name: Rewardsco Baseline
  - Description: Block B Building
  - Stage of construction process: Concept Design/ Schematic Design
  - Project type: new construction, whole building
  - Included parts: Structure and enclosure
- Click on input data and select the carbon designer: Create baseline
- This opens the carbon designer feature and allows the user to optimize materials and to input the details of the project materials scope and building dimensions.
  - Building Parameters: Structure and enclosure
  - Building Type: International reference building v2019.1; Office Buildings
  - Total Gross Floor Area (m^2): 4 329.33
  - Number of above ground floors: 4
  - Calculation period: 50 years
  - Baseline Scenario: Concrete in situ
  - Comparison Scenario: Concrete pre-cast
  - Select more options and fill in the number of underground unheated floors: 3
  - Required foundation type and depth: Rammed concrete piling foundation for soft soils for m2 GFA, model: P270, pile length 15m (50ft) depth to bedrock.
  - Baseline Scenario: Concrete In-Situ
  - Comparison Scenario: Concrete Precast
- Click on Calculate Areas: This leads to more area details regarding the building dimensions and building structures, that should be specified, the dimensions are generated automatically by the OCLCA tool, or they can be edited by the user. In this instance, the dimensions have been edited:
- Click on Create Baseline: This presents the baseline scenarios which may be edited to show results for concrete precast, concrete in-situ, wood, or steel.
- The building elements and material choices under the components may be adjusted to the project specifications. This presents the user with comparison scenarios to determine how best to reduce carbon emissions during the conceptual stages.

- Once the baseline is saved, the user may optimize the design as required throughout the project timeline.

Appendix 3: General Workflow for OCLCA

The OCLCA website provides guidance and a general workflow that may be followed to obtain results (One Click LCA, 2022):

1. Verify your LCA parameters
2. Set your building area
3. Set your calculation period (Service life of building)
4. Input materials to your design manually or,
5. Input materials through data import
6. Include material transportation distances
7. Verify material service lives
8. Input energy consumption data
9. Input water consumption data
10. Input construction site impacts
11. Save your design and view results
12. Copy your design to compare options
13. Modify your copied design
14. Compare your building designs
15. Download your results

Appendix 4: Step by Step Guidance for Importing Data to OCLCA from Revit

1. The One Click LCA add-in must be downloaded, which will open with Revit.
2. Open the Revit model and click on the One Click LCA tab. There is an option to import the data and conduct the full analysis on Revit or to conduct the analysis on the One Click LCA cloud. Select the cloud as it is available on the student version. This option leads to the website.
3. The OCLCA tool has picked up 209 rows to import. There is an option to review the steps manually which is recommended to improve accuracy.
4. Under the settings, section includes providing details such as:
    - The project or entity: 212500019 MSc Building Project
    - Type of design: New Design

- Type of tool: Life Cycle Assessment, EN15978
- Filter settings: Building without external areas
- Data preservation: Replace existing data with imported data

At this stage it is important to define the stage of the construction process, which ranges from 0-7, the strategic definition – a building in use.

5. The next step is to select continue and move on to the next tab, classify. The class is displayed here such as beam, slab, foundation and the target location is set automatically.
6. The next step is to filter the datapoints which have been reduced to 186. The classification is based on IFC classes. There is an option to download the excel spreadsheet which shows more information regarding the materials, building elements and dimensions. Furthermore, any redundant data may be omitted in this section.
7. The tool then moves on to combine the datapoints. Individual data rows are combined to one data row if they consist of the same value in all chosen grouping criteria columns. The grouping criteria may be adjusted; it is applied according to class, material, composite, type and material group.
8. The user may then continue to Review:

   There is a list of issues that can be downloaded and further reviewed on excel. The explanation of the issues is that there are multi-constituent materials with no layer structure and there is no automatic mapping identified for majority of the data. The recommended action is to either rectify the data on the excel spreadsheet by adding information and update it accordingly or updating the information directly on the OCLCA website. Furthermore, the materials will have to be mapped in the next step.
9. The Mapping section shows that there is a total 92.23% of problematic data; that is 172 rows are required to be mapped once and the tool will thereafter remember the choice. Mapping involves associating the material named in the Revit model to a specific material, for example, concrete in-situ is mapped to 'Ready-mix concrete, normal strength, generic C30/37 (4400/5400 PSI), 10% recycled binders in cement (300 kg/m3)". There is an option to decide later if there is uncertainty regarding mapping a particular material. Once completed, save the new mappings.
10. The transportation of materials has been estimated by the software to be 60kms, this figure if known may be amended, however in the case of Rewardsco, this figure had not been determined, due to the lack of actual Bill of Quantities (BOQs).
11. The next section is the annual energy consumption. Select the type of electricity which is localized to electricity use in South Africa. According to the Energy Calculator on the Green Report, the energy usage of the actual building is 636 717 kWh/yr.

12. Optional sections include the annual water consumption and construction site operations which have been excluded from the study.
13. The building area is the next step: Information such as the gross internal floor area which is 3 652 m^2, the number of days the building is used throughout the week and the number of hours per day if known should all be entered.
14. The final step of inputting data includes the calculation period. The service life of the building is 50 years. Mandatory data includes the energy consumption of the building and the assessment period.

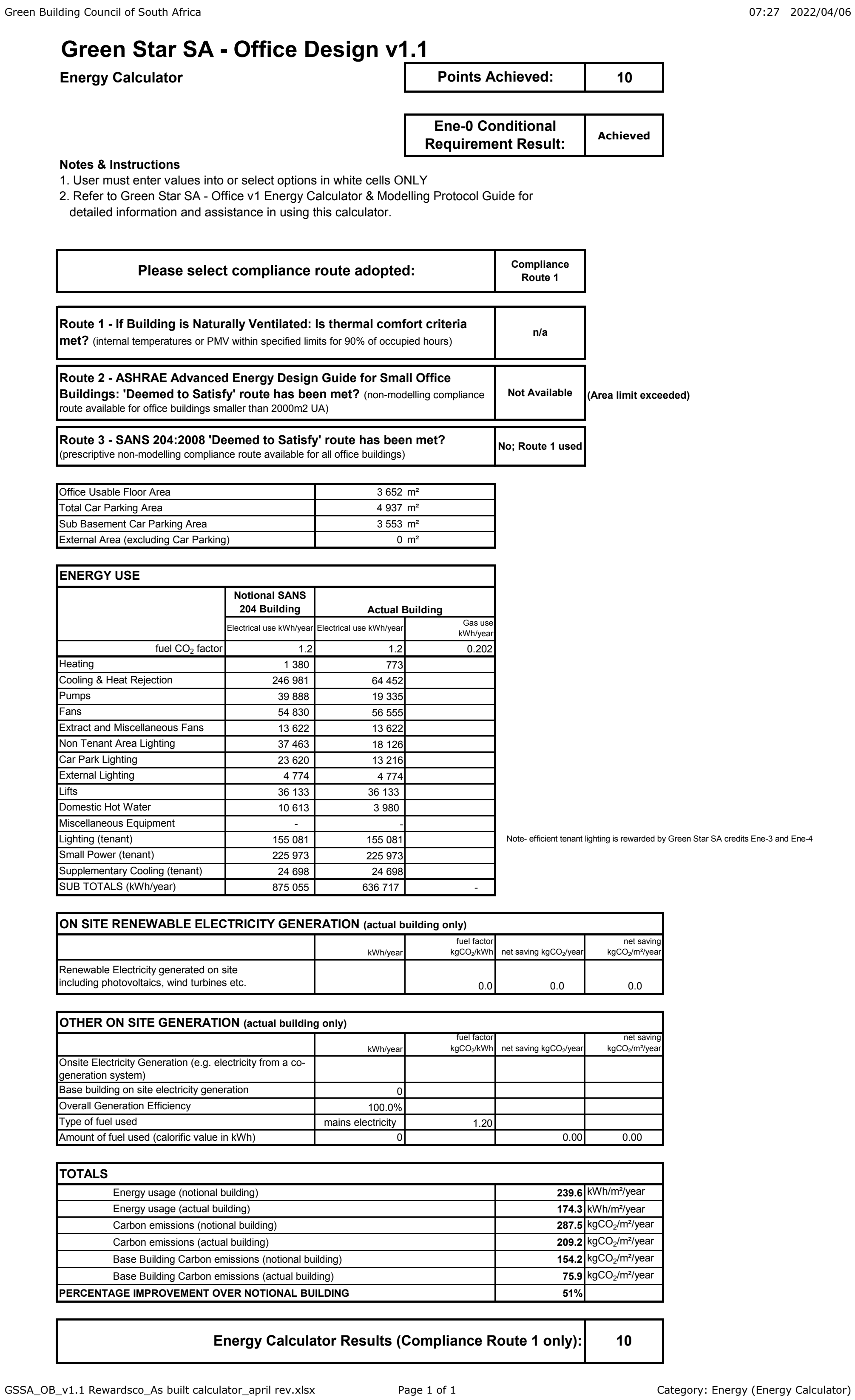
Appendix 5: Udemy Building Materials

Table A1: Udemy Building Materials

No.	Most Contributing Materials	Cradle to gate impacts (A1-A3) Tonnes (CO_2e)	Percentage
1.	Ready-mix concrete, normal-strength, generic, C30/37 (4400/5400 PSI), 10% (typical) recycled binders in cement (300 kg/m3)	210	33.0 %
2.	Reinforcement steel (rebar), generic, 0% recycled content	181	28.5 %
3.	Aluminium frame curtain wall, 38.84 kg/m2	86	13.5 %
4.	Precast concrete wall elements (solid, uninsulated), generic, C30/37 (4400/5400 PSI), 0% recycled binders in cement (300 kg/m3)	27	4.3 %
5.	Steel ceiling baffle system with acoustic inserts, 52.5mm, 7.93 kg/m2, 151.05 kg/m3	20	3.2 %
6.	Red brick, average production, UK, 215 mm x 102.5 mm x 65 mm, 2.13 kg/unit, 1485 kg/m3	18	2.9 %
7.	Metal framing components for gypsum plasterboard, 0.4-1.0 mm, 7750 kg/m3	16	2.5 %
8.	Extruded aluminium profiles for window and door frames, generic, 10% recycled content, average world aluminium manufacturing technology	10	1.9 %
9.	Gypsum plaster board, regular, generic, 6.5-25 mm (0.25-0.98 in), 10.725 kg/m2 (2.20 lbs/ft2) (for 12.5 mm/0.49 in), 858 kg/m3	7.5	1.6 %
10.	Modular carpet sheets, 4.3 mm, 1.815 kg/m2	6	1.0%
11.	Low voltage cable, Section conductrice de 5 mm2 à 120 mm2	5.8	1.0 %
12.	Dispersion-based facade paints, 1000-1700 kg/m3	5.5	0.9 %
13.	Porcelain glazed tile, 22 kg/m2	4.4	0.7%
14.	Reinforcement steel (rebar), generic, 90% recycled content, A615	4	0.7%
15.	Aluminium handrails, 7.38 kg/m	3.1	0.5%
16.	Float glass, single pane, generic, 3-12 mm (0.12-0.47 in), 10 kg/m2 (2.05 lbs/ft2) (for 4 mm/0.16 in), 2500 kg/m3 (156 lbs/ft3)	2.2	0.4%
17.	Doors with wooden frame, interior	2.4	0.4%
18.	Electric elevator elements dependent of the number of floors, 422 kg/unit, max load: 1600 kg	2.7	0.4%
19.	EPS insulation panels, white, L= 0.037 W/mK, R= 2.7 m2K/W, 100 mm, 1.5 kg/m2, 15 kg/m3, compressive strength 85kPa, 10% recycled polystyrene, Lambda=0.037 W/(m.K)	1.6	0.3 %
20.	Plaster mortar, normal plaster, 1300 - 1800 kg/m3	2	0.3 %

21.	Ceramic tiles for floors and walls, 30.426 kg/m2	1.5	0.3 %
22.	Rock wool insulation panels, unfaced, generic, L = 0.035 W/mK, R = 2.89 m2K/W (16 ft2°Fh/BTU), 50 kg/m3 (3.12 lbs/ft3) (applicable for densities: 25-50 kg/m3 (1.56-3.12 lbs/ft3)), Lambda=0.0346 W/(m.K)	0.99	0.2 %
23.	Extruded aluminium profiles for window and door frames, generic, 0% recycled content, average world aluminium manufacturing technology	1.4	0.2 %
24.	Bituminous waterproofing membrane, vapor barrier, 1.6-2.6 mm, 3.01 kg/m2	1.4	0.2 %
25.	Steel fire protection door, manual, 1.5 m x 2.8 m. 50.96 kg/m2	0.81	0.1 %

Appendix 6: Green Star Report of Rewardsco Building



Green Building Council of South Africa 07:27 2022/04/06

Green Star SA - Office Design v1.1

Energy Calculator

Points Achieved:	**10**
Ene-0 Conditional Requirement Result:	**Achieved**

Notes & Instructions

1. User must enter values into or select options in white cells ONLY
2. Refer to Green Star SA - Office v1 Energy Calculator & Modelling Protocol Guide for detailed information and assistance in using this calculator.

Please select compliance route adopted:	**Compliance Route 1**	
Route 1 - If Building is Naturally Ventilated: Is thermal comfort criteria met? (internal temperatures or PMV within specified limits for 90% of occupied hours)	**n/a**	
Route 2 - ASHRAE Advanced Energy Design Guide for Small Office Buildings: 'Deemed to Satisfy' route has been met? (non-modelling compliance route available for office buildings smaller than 2000m2 UA)	**Not Available**	**(Area limit exceeded)**
Route 3 - SANS 204:2008 'Deemed to Satisfy' route has been met? (prescriptive non-modelling compliance route available for all office buildings)	**No; Route 1 used**	

Office Usable Floor Area	3 652 m^2
Total Car Parking Area	4 937 m^2
Sub Basement Car Parking Area	3 553 m^2
External Area (excluding Car Parking)	0 m^2

ENERGY USE

	Notional SANS 204 Building	**Actual Building**	
	Electrical use kWh/year	Electrical use kWh/year	Gas use kWh/year
fuel CO$_2$ factor	1.2	1.2	0.202
Heating	1 380	773	
Cooling & Heat Rejection	246 981	64 452	
Pumps	39 888	19 335	
Fans	54 830	56 555	
Extract and Miscellaneous Fans	13 622	13 622	
Non Tenant Area Lighting	37 463	18 126	
Car Park Lighting	23 620	13 216	
External Lighting	4 774	4 774	
Lifts	36 133	36 133	
Domestic Hot Water	10 613	3 980	
Miscellaneous Equipment	-	-	
Lighting (tenant)	155 081	155 081	
Small Power (tenant)	225 973	225 973	
Supplementary Cooling (tenant)	24 698	24 698	
SUB TOTALS (kWh/year)	875 055	636 717	-

Note- efficient tenant lighting is rewarded by Green Star SA credits Ene-3 and Ene-4

ON SITE RENEWABLE ELECTRICITY GENERATION **(actual building only)**

	kWh/year	fuel factor kgCO$_2$/kWh	net saving kgCO$_2$/year	net saving kgCO$_2$/m^2/year
Renewable Electricity generated on site including photovoltaics, wind turbines etc.		0.0	0.0	0.0

OTHER ON SITE GENERATION **(actual building only)**

	kWh/year	fuel factor kgCO$_2$/kWh	net saving kgCO$_2$/year	net saving kgCO$_2$/m^2/year
Onsite Electricity Generation (e.g. electricity from a co-generation system)				
Base building on site electricity generation	0			
Overall Generation Efficiency	100.0%			
Type of fuel used	mains electricity	1.20		
Amount of fuel used (calorific value in kWh)	0		0.00	0.00

TOTALS

Energy usage (notional building)	**239.6**	kWh/m^2/year
Energy usage (actual building)	**174.3**	kWh/m^2/year
Carbon emissions (notional building)	**287.5**	kgCO$_2$/m^2/year
Carbon emissions (actual building)	**209.2**	kgCO$_2$/m^2/year
Base Building Carbon emissions (notional building)	**154.2**	kgCO$_2$/m^2/year
Base Building Carbon emissions (actual building)	**75.9**	kgCO$_2$/m^2/year
PERCENTAGE IMPROVEMENT OVER NOTIONAL BUILDING	**51%**	

Energy Calculator Results (Compliance Route 1 only):	**10**

GSSA_OB_v1.1 Rewardsco_As built calculator_april rev.xlsx Page 1 of 1 Category: Energy (Energy Calculator)

Appendix 7: Environmental Impact Categories from GSSA Office manual

Environmental Impact Categories (GSSA, 2014):

The technical manual addresses concerns related to 9 environmental impact categories:

1. Management – To reward and promote management systems that effectively apply environmental principles throughout the lifecycle of a building. A total of 14 points are assigned to this category.
2. Indoor Environment Quality (IEQ) – To promote efficient building systems that ensure successful cohesion of environmental consciousness and the well-being of occupants. A total of 24 points are assigned to this category.
3. Energy – The energy category is an essential conditional requirement towards certification, with the highest points assigned equating to 30. It aims to reduce the overall energy consumption to subsequently reduce environmental impact. It particularly focuses on reducing Greenhouse Gas Emissions, this sub-category is awarded 20 points.
4. Transport – To encourage sustainable means of transport and reduce emissions incurred by the automotive industry, this includes cyclist facilities, local connectivity and commuting mass transport. This category is assigned a total of 14 points.
5. Water – This category seeks to encourage the reduction of potable water consumption through efficient building designs that utilize recycled stormwater and grey water, it is assigned 15 points.
6. Materials – To safeguard natural resources by promoting recycling and reuse of materials as well as rewarding designs that effectively reduce the number of materials used. Materials rewarded under this category are: “sustainable timber, the reuse of building façade and structure; and recycled content of concrete and steel.” It is assigned a total of 21 points.
7. Land Use and Ecology – This category focuses on safeguarding the ecological environment and biodiversity affected by buildings. It promotes the minimization of environmental harm caused to the surroundings and is assigned 9 points.
8. Emissions – To objectively decrease the environmental impact of buildings, it awards points for selecting insulation materials that decrease damage to the ozone layer and refrigerants that decrease Global Warming Potential (GWP) among other responsible choices that seek to decrease harmful emissions. It is awarded a total of 17 points.
9. Innovation – To reward remarkable environmental initiatives that go over and beyond the scope of the rating tool which is assigned 5 points

Appendix 8: Green Building Rating Tools

GBRTs and LCA accreditation systems

BREEAM

BREEAM has included Whole Building Life Cycle Assessment (WBLCA) in its International New Construction v2.0 manual released in 2016, i.e., it includes all the building phases. The provision of a WBLCA comprises of a maximum of 5 points. It is, however, an optional requirement, one may still attain certification without it. BREEAM utilizes the MAT 01 calculator to award life cycle impacts based on the quality of the LCA tool, the method, the data, and the scope (Veselka et al., 2020). The service life of the building is required to be 60 years and there are specifications regarding which LCA tool is permissible. LCA may also be assessed in an indirect manner by observing the emissions. The carbon emissions are divided into operational and embodied emissions (Abdelaal, 2021). The energy use and carbon emissions are necessary to achieve certification, however there is no set benchmark for evaluation. Table A2 represents the LCA credits for BREEAM awarded under the embodied and operating emissions category.

Table A2: BREEAM carbon emissions (Abdelaal, 2021)

Emission	Category	Number	Credit	Carbon Reporting	Points
Embodied Emission	Materials	Mat 01 Mat 03 Mat 06	Life Cycle Impacts (EPDs) Responsible sourcing of construction products Materials efficiency	Partly	6
	Waste	WST 01 WST 02	Construction waste management Recycled aggregates	No	4
Operating Emissions	Energy	ENE 01 ENE 04 ENE 05	Energy use and carbon emissions Low carbon design Energy-efficient equipment	Yes	23
	Water	WAT 01 WAT 04	Water consumption Water efficient equipment	No	6

LEED

LCA has been introduced into the LEED certification scheme under the credit of Building Life Cycle Impact Reduction, it is worth a maximum of 3 points with an opportunity to gain one extra point. There are 6 environmental impact categories that are measured: GWP, depletion of stratospheric ozone layer, acidification of land and water sources, eutrophication, formation of tropospheric ozone and depletion of nonrenewable energy sources. The GWP must exhibit a 10% reduction when compared to a baseline along with two other categories. The remaining 3 categories cannot exceed 5% of the impact when compared to the baseline. The extra point is reserved for projects that accomplish a 10% reduction across all impact categories. The scope of the credit includes all phases and follows ISO 14040 standards, and where applicable for European projects, follows EN 15978. Table A3 highlights the points awarded for incorporating LCA in LEED.

Table A3: Points awarded for LCA incorporation in LEED (Abdelaal, 2021)

Emission	Category	No.	Credit	Carbon Reporting	Points
Embodied Emissions	Material and Resources	MR MR MR MR	Building Lifecycle Impact Reduction Environmental Product Declarations Sourcing of raw materials Construction and Demolition Waste	Partly	11
Operating Emissions	Energy and Atmosphere	EA EA EA EA	Optimize Energy Performance Renewable Energy Production Enhanced Refrigerant Management Green Power and Carbon Offsets	Yes	24
	Water Efficiency	WE WE	Outdoor Water Use Reduction Indoor Water Use Reduction	No	8

Green Star Australia

A new version of the Australian GBRT was released in October of 2020 followed by maintenance and corrections in 2021. The new version includes a life cycle impact calculator, whereby life cycle data is captured and compared to a baseline building. There are 2 points awarded for life cycle impacts under the positive category that is an optional criterion. However, the minimum requirements, under the positive category, for certification include (Green Star Australia, 2020):

- Determining the upfront carbon emissions (emissions associated with the pre-building phase i.e., the production of materials before commencing construction) and ensuring that it has 10% less emissions when compared to a standard building
- Determining the energy use and ensuring that it has 10% less consumption than a standard building
- Providing a Zero Carbon Action Plan
- Decreasing the potable water use by 10-15% when compared to a baseline building or installing efficient water fixtures.

The Australian GBRT includes a section under each credit that highlights its interrelation to other credits. For example, the following credits are related to life cycle impacts: responsible structure, responsible envelope, responsible systems, and responsible finishes, i.e., all those components are required to be sourced from responsibly manufactured products. The energy use and carbon emissions are also related to life cycle impacts. The Australian GBRT highlights the importance of understanding and reducing life cycle impacts which result in better designs. The Life Cycle Impact outcome to achieve the 2 points necessitates that a 30% reduction of life cycle impacts is required in comparison to standard practice for the 8 impact categories displayed in Table A4. The results of the WBLCA must be entered into the Australian Life Cycle calculator such that the normalization and weighting factors may be applied.

Table A4: Impact categories and the respective normalization and weighting factors (Green Star Australia, 2020)

No.	**Impact Category**	**Unit**	**Normalisation Factor**	**Weighting Factor**
1	Climate Change	Kg CO_2 equivalents (GWP 100)	6.96E+03	25.0%
2	Net use of fresh water	m^3	2.67E+02	25.0%
3	Stratospheric ozone depletion potential	Kg CFC 11 equivalents	4.75E-02	0%
4	Acidification potential of land and water	Kg SO_2 equivalents	3.87E+01	10%
5	Eutrophication potential	Kg PO_4 equivalents	1.37E+01	10%
6	Photochemical Ozone Creation Potential	Kg C_2H_4 equivalents	3.44E+00	10%
7	Mineral depletion (Abiotic Depleting Potential)	Kg Sb equivalents	6.27E-02	10%
8	Fossil Fuel Depletion	MJ net calorific value	1.47E+06	10%

The credit will not be awarded if the life cycle impact in a category is less than -10% after applying the normalization and weighting factor. The following requirements are also required of the LCA:

- Scope must be in accordance with EN 15978
- The system boundary must include all phases in accordance with EN 15978
- The functional unit is per square meter (m^2) of Gross Floor Area (GFA)
- The service life if not determined, is required to be 60 years.
- Specific Environmental Product Declarations (EPDs compliant with EN 15804) are preferred, where EPDs are not available or for imported products, generic data may be used.

Applicants can benefit from the optional criterion of the LCA as it may also be used for the upfront carbon emissions credit. The LCA is required to have quality assurance by either being conducted by an LCA certified practitioner or an experienced individual and thereafter reviewed by a qualified person.

Appendix 9 – Interview Questions

1. What design process does your company follow when designing for an office building? What steps are undertaken?
2. Does your company have a sustainability procedure or tools that it uses during the during the design stage?
3. Which BIM software does your company predominantly use and why?
4. In your experience, how does South Africa compare to other countries in terms of BIM and sustainable building designs?
5. What improvements can be made for BIM and sustainable building design in South Africa?
6. Why is there a general lack of EPD data in South Africa?
7. Are you familiar with the OCLCA tool?