SUSTAINABLE DESIGN OF BUILT INFRASTRUCTURE AND ENGINEERING SERVICES FOR SOUTH AFRICAN UNIVERSITIES

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DECLARATION OF ORIGINAL AUTHORSHIP

This thesis is submitted under the regulations of the Central University of Technology Free State for the award of a Doctoral degree by research. I, Stephen Oamen Eromobor hereby declare that this thesis is original and that no portion of it has been submitted in support of any application for another degree to any other university or institute of learning.

Signed:...

Date:..

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DEDICATION

This research is dedicated to my parents, late Ambassador PSO Eromobor, Mrs. Mary Eromobor and my brother Anslem Eromobor

ABSTRACT

Universities have made great strides in research and the development of new knowledge. They are known as centres of enlightenment. However, there is a need for universities to lead by example in other respects, in particular in limiting the environmental impact on cities. This is in respect of the sustainability of built infrastructure and the services provided on campuses, in the wake of challenges of climate change. Practical applications of research in the areas of high-performance buildings, can impact a city positively. Evidences from literature indicate that most of the South African cities were poorly designed from an ecological perspective and have large environmental impacts. New building standards have been recommended but are not comprehensive enough to address problems related to the performance of university buildings and infrastructure. Therefore, the aim of this research was to develop an appropriate model for building performance evaluation in higher education institutions based on assessment of parameters for achieving Energy Efficiency (EE), Indoor Environmental Quality (IEQ) and Water Use Efficiency (WUE). The study was executed by multiple case study approach because it permitted case studies of three university campuses in South Africa. The target universities constituted the units of analysis and therefore provided opportunity for in-depth assessment of building parameters of size, orientation, fenestrations, building materials, type of ventilation, building function, type of lighting, and behaviour of occupants to determine their effects on the categories of EE, IEQ and WUE. Data collection included both qualitative and quantitative approaches, which were used to establish relationships between the various parameters and how they affect EE, which in turn is influenced by WUE which affects IEQ. A system dynamic model was used to determine causal relations of the building parameters EE, IEQ and WUE. This approach constitutes an innovative and pioneering contribution to building performance evaluation. The study has established a basic level of awareness and understanding among design- and construction practitioners of the importance of the use of System Dynamics in building performance evaluation, which can be used as a tool for delivering strategic objectives in the preliminary designs of educational buildings and infrastructure. The results of the study contribute to building guidelines for sustainable design of educational neighbourhoods for the transformation of campuses, which in turn can motivate beneficial changes for more sustainable performance of the built facilities.

Keywords: Built infrastructure; Energy efficiency; Indoor Environmental Quality; Sustainable Development; System Dynamics Modelling; Water use efficiency

Central University of Technology, Free State

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DEFINITIONS OF TERMS

Air-conditioning system: A system of mechanical ventilation where air that has been filtered is supplied to a building under conditions of controlled temperature, humidity, distribution and movement (SABS 2011).

Artificial ventilation system: A system in which air is caused to circulate through a room by means of a mechanical apparatus which forces air into or extracts air from such room (SABS 2011).

Building Envelope: In this thesis the building envelope refers to the exterior surface of a building's construction: the walls, windows, roof and floor; also referred to as 'building shell' (GBCSA 2014).

Building Information Modelling (BIM): BIM refers to a modeling method that allows for multi-disciplinary information to be superimposed within one model. It creates an opportunity for sustainability measures and performance analysis to be performed throughout the design process (Autodesk, Inc., 2008). In this thesis, Building Information Modeling represents the building as an integrated database of coordinated information. The building is considered as a system with geometric and non-geometric interdependencies. It can aide designers to have more comprehensive assessment of design strategies in the initial stages of the design (Eromobor, Das & Emuze 2014).

C-Value: In this thesis C-Value refers to the thermal capacity (kJ/m2·K) of a material, which is the ability to store heat energy, and is the arithmetical product of specific heat capacity (kJ/kg·K), density (kg/m3) and thickness (m) (SABS, 2011).

CR-Value: In this thesis, CR-Value refers to the time constant (hours) of a composite element, such as a wall, and is the arithmetical product of total C-value and the total R-value (SABS, 2011).

Energy Efficiency: In this thesis Energy Efficiency refers to efficient use of energy for provision of good indoor environmental quality, water, and other essential services in buildings. A system is thought of as energy-efficient if its requirements are low in relation to the results produced and if energy is not wasted" (ECE 1991). Siemon (2009) notes that for something to be considered energy efficient, the absolute minimum of input and wastage of energy in relation to the results produced must be utilized.

Energy simulation: In this study, it refers to the use of design models such as system dynamic models to predict the energy use/consumption of a building**.**

Façade: In this thesis façade refers to the external wall of the building as noted by Aksamija (2013), façades perform two functions: firstly they are the barriers that separate a building's interior from the external environment and secondly – more than any other component – they create the image of the building. (Aksamija 2013).

Integrated Project Delivery: In this thesis, Integrated Project Delivery refers to a project delivery approach that integrates people, systems, business structures, and practices into a process that collaboratively harnesses the talents and insights of all project participants to optimize project results, increase value to the owner, reduce waste, and maximize efficiency through all phases of design, fabrication and construction (AIA 2007).

Indoor Environmental Quality (IEQ): In this thesis IEQ refers to healthy and good indoor environment with regards to indoor lighting, heating cooling and general healthy indoor environment, while also concentrating on reducing energy and water usage. The GBCSA (2014) indicated that poor IEQ is considered to be the principal cause of Sick Building Syndrome (SBS) which, according to scientific research, has a substantial price tag in loss of productivity and even more in health sector costs.

Mixed-Mode Ventilation: A ventilation strategy that combines natural ventilation and mechanical ventilation, allowing the building to be ventilated either naturally or mechanically according to the season or ambient temperatures (GBCSA 2014).

Natural Ventilation: The process of supplying and removing air in building spaces by natural means, by using openings in the façade (e.g. windows), non-powered ventilators, solar chimneys and infiltration processes. A building can still be termed 'naturally ventilated' if it contains propeller type ceiling fans – provided they only recirculate air and their energy use is included in the energy modelling (GBCSA 2014).

Re-engineered: In this thesis it refers to redesign of buildings and services to achieve high performance for efficiency in energy, indoor environmental quality and water use. Beck (2011) wanted to know how the built infrastructure of the city can be re-engineered to restore the natural capital and ecosystem services of the nature that inhabited the land before the city arrived there in 'geological time'

R-Value: In this thesis refers to the measurement of the thermal resistance of a material which is the effectiveness of the material to resist the flow of heat, i.e. the thermal resistance (m2·K/W) of a component calculated by dividing its thickness by its thermal conductivity, (SABS 2011).

Water Use Efficiency (WUE): In thesis WUE refers to savings reducing water consumption and wastewater. Chebaane & Hoffman, (2011), noted that WUE also means reducing energy use because less water will be pumped or heated, and there will be more water recycling for heating. Water savings will lower treatment costs and capital costs by scaling down pumps and water heaters.

ABBREVIATIONS

AL	Artificial Lighting
AEDG-SO	Advanced Energy Design Guide for Small Office Buildings
ACUPCC	American College and University Presidents' Climate Commitment
AIA	American Institute of Architects
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
ASHRAE (DTS)	ASHRAE (Deemed to Satisfy)
AAC	Autoclaved aerated concrete
BIM	Building Information Modelling
BREEAM	Building Research Establishment Environmental Assessment Method
CFG	City as a Force for Good
CSIR	Council for Scientific and Industrial Research
CUT	Central University of Technology
DEO	Department of Energy (United States)
DUT	Durban University of Technology
EC	Energy Consumption
EE	Energy Efficiency
EUI	Energy Use Intensity
GB	Green Building
GBCSA	Green Building Council of South Africa
HVAC	Heating, Ventilation and Air Conditioning.
IEQ	Indoor Environmental Quality
IESNA	Illuminating Engineering Society of North America
IPD	Integrated Project Delivery
LEED	Leadership in Energy and Environmental Design
LWC	Lightweight concrete walls
MV	Mechanical ventilation
NL	Natural lighting
NV	Natural ventilation
OA	Outdoor Air
OECD	Organization for Economic Co-operation and Development
OPR	Owner's Project Requirements

PSV	Passive Stack Ventilation
SABS	South African Building Standards
SANS 10400-XA: 2011	South African National Standards 10400-XA: 2011
SANS 204:2011	South African National Standards 204:2011
SHGC	Solar heat gain coefficient
TUT	Tshwane University of Technology
USGBC	US Green Building Council
UNESCO	United Nations Educational, Scientific and Cultural Organization
USGBC	US Green Building Council
WSSD	World Summit on Sustainable Development
WUE	Water Use Efficiency
WWR	Window-to-wall ratio
VLT	Visible light transmittance

CHAPTER 1: RESEARCH ORIENTATION

1.1 Introduction

Sustainable infrastructure and buildings have become cornerstones for developing sustainable cities. Increasingly efforts are being made to make the buildings and related infrastructure and services more efficient and sustainable. Consequently, concepts of green buildings, energy efficient buildings, low carbon emission buildings have emerged. Simultaneously, various approaches have evolved to evaluate the performance of buildings in order to design and build green, efficient and sustainable buildings. Programmes such as Leadership in Energy and Environmental Design (LEED) and organisations such as Green Building Councils have emerged for this purpose. Also, arguments have emerged to retrofit or re-engineer buildings, infrastructure and services so as to make them use less resources and become more efficient and contribute to their sustainability. Various concepts and approaches have been followed while designing and constructing buildings and associate infrastructure. For example, the 11-storey headquarters building of the San Francisco Public Utilities Commission (SFPUC) has a wetland ecosystem in its atrium as a live, full-scale demonstration of how the “wastewater” of the building’s occupants is being recycled (Harrington, 2012) to make it sustainable from a water use point of view. Equally, the 38-storey “Walkie-Talkie” office block in the City of London features a green roof garden[1] and it was stipulated as a condition for approval of the building’s planning application that the garden be open to the public (to be visited by appointment). Therefore, it is apparent that single buildings, as well as clusters of buildings, can be created as beacons of sustainability in the urban environment and there is an occurrence of many such examples.

Universities can emulate this model for development of such buildings and infrastructure and communicate and educate by practical example. Their educational complexes being subsets of the city, universities can lead in the efforts of achieving sustainability by research and applied action. They can become examples to cities by designing, constructing or re-engineering their buildings, related infrastructure and services to make them sustainable, which would contribute to the sustainability of cities. As both outer environment and microclimate environment for apposite indoor air quality can lead to sustainable solutions for buildings, infrastructure and services, the following three aspects are vital to sustainability when considering buildings and

[1] See“First view of Europe’s highest roof garden — an oasis on top of the Walkie Talkie tower”; *Evening Standard*, posted 6 June, 2013, www.standard.co.uk.

associated infrastructure: energy efficiency, water use efficiency and indoor environmental quality. Thus, for the purpose of improving performance in energy efficiency (EE), indoor environmental quality (IEQ), and water use efficiency (WUE) of buildings, it is essential to explore the linkage among the various building parameters such as appropriate building orientation, building form, thermal mass, insulation, electrical and lighting devices, natural lighting, water recycling and water harvesting. Therefore, this research explored how sustainable buildings and infrastructures should evolve at universities.

1.1.1 University neighbourhoods for sustainability of cities

As mentioned in the previous section, this study is concerned with design of sustainable built infrastructure (buildings and associate infrastructure and services such as energy and water) for South African universities, which forms part of the need for universities to aid cities in becoming sustainable. This study is also concerned with the design or re-engineering of infrastructure so that it can add value as agent to sustainability rather than being hazardous to the environment. In this regard, to make cities 'forces of good' or sustainable, the question arises how the built infrastructure of the city can be built or re-engineered to restore the natural capital and ecosystem services of the environment in 'geological time' to what it used to be before development of the city (Beck, 2011). One could also ask if university buildings and infrastructure can be designed or re-engineered to become 'forces of good' or sustainable within their academic neighbourhoods and thus positively influence transformation of cities to become sustainable.

Universities are centres of knowledge generation through research and academic activities; however, universities have also become centres of applied action, particularly in the areas of sustainability. Many universities – especially in industrialized countries – have promoted and adopted various measures aimed at promoting sustainability on campuses in order to spread these ideals across to the society. As seen in Figure 1.1, research, academic learning and applied action at universities are interrelated, indicating that through a combined effort, a university can positively affect its surrounding city and enhance efforts to address the challenges of sustainability in the wake of resource constraints and far greater dangers of climate change.

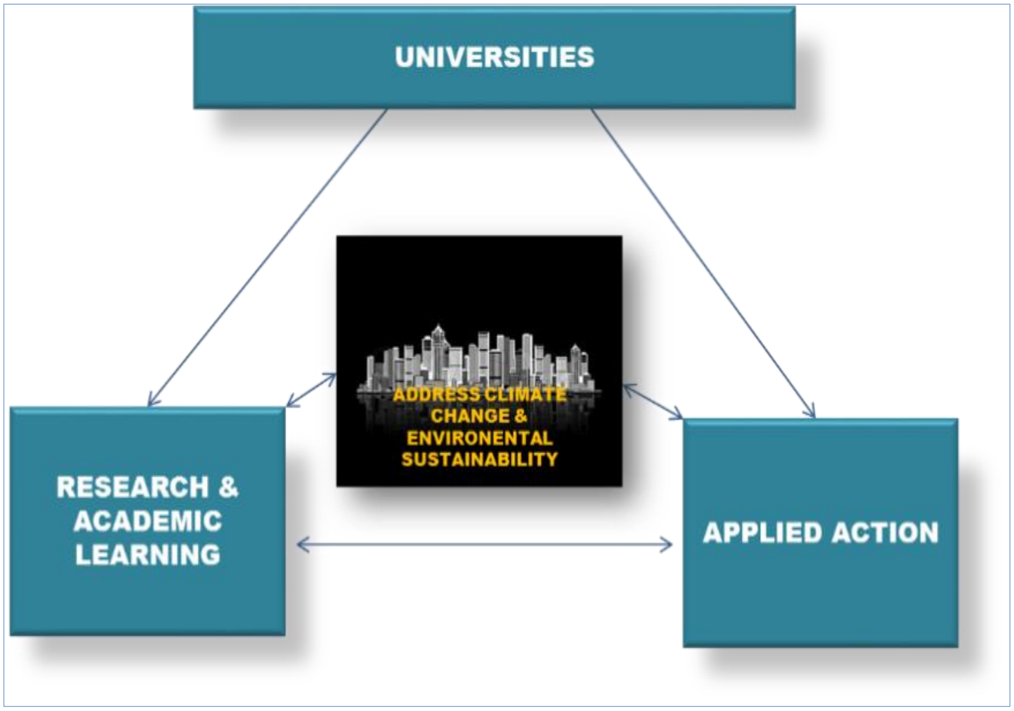

Figure 1.1 Relations of universities with research, academic learning and applied action

In this context, Van Weenen (2000) observed that universities have come to the forefront of sustainable development. They are dealing with the challenge of sustainable development in many different ways and the approaches vary from aiming to function as an environmentally friendly company to formulating principles and signing declarations, establishing totally new institutions, or focusing the mission and management of an existing university on the quest for sustainability (Van Weenen, 2000). Similarly, the Princeton review (2012) noted that the American College and University Presidents' Climate Commitment (ACUPCC) is an important effort undertaken by a network of colleges and universities to incorporate sustainable practices into their operations and curriculum. Officially launched in June 2007, the ACUPCC's mission is to "educate students, create solutions, and provide leadership by example for the rest of society." The Princeton Review also reported that ACUPCC signatory institutions commit to meeting a series of benchmarks that will significantly reduce their greenhouse emissions, including completing an emissions inventory, incorporating sustainability into the curriculum, and making progress reports on their climate action plans publicly available. The implications of going green have meant changes in the way these institutions of higher learning transport students to campus, maintain their grounds, provide food services, construct and operate their buildings, dispose of waste, perform their research, and instruct students, among other things (The Princeton Review, 2012). Therefore, it is apparent that sustainable university neighbourhoods engendered by sustainable built infrastructure can contribute to the sustainability of cities and that universities remain at the forefront of contributing to the sustainability agenda.

1.1.2 Significance of sustainable building infrastructure

It has been established that the built environment has a significant impact on the natural environment. The built environment is the world's largest user of energy, emitter of greenhouse gases (GHG) and has the largest potential for achieving efficiency in energy conservation, and water services (UNEP, 2009). According to the United States Green Building Council (USGBC), buildings annually consume more than 30% of the total energy and more than 60% of the electricity, and use billions of litres of water while leaving behind huge quantities of wastes. Public buildings, including buildings used for various functions on university campuses, are inclusive in this phenomenon. Therefore, sustainability in built infrastructure and services of university buildings are significant because higher education institutions are in a unique position to lead and benefit from campus-wide sustainability initiatives. As driving forces behind innovation and progress, universities face a singular opportunity to lead in addressing the challenges of climate change and environmental sustainability, not only through research and academic learning, but also through applied action. For instance, Van Weenen, 2000 noted that at the University of Waterloo, Canada, a vision for a Sustainable University of Waterloo has been articulated. It states that by embodying a set of desired characteristics, which includes the use of alternative energy systems and reduction in energy consumption, the university can lead the greater community in becoming a model for sustainability. (Van Weenen, 2000).

According to Harvey (2009), provision of a high-performance envelope is the single most important factor in the design of low energy buildings, which entails a reduction in energy consumption through alternative (and low-energy) systems. A high performance building also includes improving IEQ, which is considered in the context of its effect on occupants' productivity and health. Improving the IEQ includes better interior lighting and thermal comfort. Improved building envelopes and upgraded building systems reduce the need for mechanical heating and cooling equipment. For instance, buildings with dramatically lower energy use (50–75% savings) often entail no greater construction cost than conventional design while yielding significant reduction in annual energy-cost (Harvey, 2009). Also, a sustainable building need to be efficient in water use as well as have water harvesting facilities.

Currently, most of the existing buildings and infrastructure on South African campuses have been planned and designed based on the prevailing building codes and design guidelines. However, apparently, they are found to be inadequate to meet the green building standards for efficiency in energy and resource use such as water use in terms of making them sustainable. Therefore, this investigation intends to explore how built infrastructures and services on South African campuses can either be planned and designed or renovated so as to improve their performances by applying green building principles to achieve sustainability.

1.2 Research aim

The broad research aim was to develop design guidelines and performance options in order to improve existing buildings. The focus was on energy use reduction, efficient water harvesting and use, indoor environment improvement, and appropriate material usage.

1.3 Scope of the study

The scope of the research was to develop planning guidelines for the design and retrofitting of built infrastructure and services on South African campuses. The investigation included only functional buildings in the form of academic buildings. The context of the research is specific to South Africa.

1.4 Problem statement

A common theme in institutional policies as well as in national and international declarations is the importance of sustainable and green campus physical operations (Wright, 2002). Kosnik (2007) categorized various initiatives of sustainable campus operations into building construction and renovation, energy management, transportation, and water usage. Implementing Green Building (GB) practices on university campuses have resulted in conservation of energy and water, reduced operating costs, and added educational benefits (McIntosh et al., 2008). However, currently, codes for construction of built immovable assets, including buildings and associated infrastructure and services on South African campuses, do not address the need for high performance GBs. Although South Africa has adopted many international protocols and frameworks on environmental conservation and sustainable development (Hill et al., 1994a; Irurah and Boshoff, 2003), this has not been followed through in implementation in various sectors of the economy, (Ross, Bowenand Lincoln, 2010). As an illustration, most of the existing built infrastructure in the university system of South Africa were built using conventional building codes, and therefore do not adequately address the importance of design for efficiency in energy use, materials use and efficiency in water services. DEAT (2008) noted that most South African cities were poorly designed from an ecological perspective and have large environmental impacts (DEAT 2008). Hill et al (2002) describe South African settlements and cities as inefficient and spatially distorted, with low density urban sprawl, mono-functional areas and trapping the poor and newly urban in large dysfunctional townships on the outskirts of the city, therefore rendering them unsustainable. This land pattern results in inefficient, energy consuming and costly transport measures, expensive city administration, the exclusion of people from easy access to economic opportunities and facilities, and the destruction of valuable ecological and agricultural land (Hill et al., 2002). This developmental issue is exacerbated by ever-increasing urbanization, resulting in rapid growth of slums and unauthorized settlements, overcrowding, and neglect of the environment (du Plessis et al., 2002).

Thus, most of the existing built infrastructure and services on South African university campuses are not found to be sustainable, as far as energy, daylight, air and water based perspectives are concerned. In this context, some of the prominent problems encountered include:

- Inappropriate design of building envelopes;
- Inefficient use of daylight and poor quality of indoor environment, and
- Users are exposed to health and safety challenges that are not limited to sick building syndrome alone.

The key issues in built infrastructure performance evaluation are efficiency and productivity. Although the most important indicators in this regard are environmental performance in terms of energy use and water efficiency, and whether the building adds value or makes economic sense (Okolie 2011), there is a need for sustainability in the planning and design of buildings (either new construction or renovations). In the context of evolving a comprehensive approach to design and planning, this study explored how built infrastructure and services on selected South African university campuses can be sustainably planned and designed.

1.5 Hypotheses

Hypothesis 1: *Improved design by using green building principles with optimal use of daylight (measurements through observations and survey of perception of occupants) will reduce electrical energy consumption and improve the indoor quality of a building*.

Hypothesis 2: *The use of appropriate building materials for new construction and renovations or retrofits will improve quality of indoor environment and energy efficiency in buildings.*

1.6 Specific objectives

In order to achieve the research aim and test the aforesaid hypotheses, the specific objectives of the study include:

1. Assessing the energy efficiency in existing buildings on South African campuses based on green building principles.
2. Assessing the indoor environmental quality of existing buildings on South African campuses based on green building principles.
3. Evaluating the performance of the existing buildings with respect to water usage.
4. Establishing theoretical models for improving energy efficiency, water use efficiency, and indoor environmental quality.
5. Evolving plausible guidelines for designing sustainability compliant buildings, infrastructure and services on South African campuses.

1.7 Methodology

According to Geyer (2012), designers often develop conceptual designs, including building shape and appearance, without considering energy and resource consumption. This results in probable neglect of interdependency and insufficient exploitation of energy and resource efficiency potential (Geyer 2012). Based on this premise, it is construed that in planning for sustainability of buildings, the design should present a holistic model to determine how parameters such as building form, building materials, insulation and climatic conditions influence the buildings and their infrastructure in achieving higher efficiency related to energy consumption, indoor environment and water use efficiency.

In this context, the methodology of this investigation was set in the context of sustainable design of built infrastructure and services on South African campuses. For this purpose, an inductive research method was followed. In this regard, a multiple case study approach was used to assess existing buildings for their sustainability performance. Data collection included observation, retrieval of archival resources, and survey of the perception of building users. Triangulation of data was included in the analysis and comparisons of performances with respect to the standards expected of high performance green buildings were indicated. Subsequently, relevant statistical analysis and development of conceptual models were conducted by using system dynamics model principles to establish the linkages among various variables that form design guidelines for sustainable development of built infrastructure and services. The detailed methodology and research design are presented in Chapter 3.

1.7.1 Study area

Universities in three provinces of South Africa, namely the Free State, Gauteng and Kwazulu Natal were considered for the case studies. The universities include the Central University of Technology (CUT), Free State in Bloemfontein, the Tshwane University of Technology (TUT) in Pretoria (Gauteng) and the Durban University of Technology (DUT) in Durban (KwaZulu-Natal). These locations are shown in Figure 1.2. The details about the case studies are presented in Chapter 4.

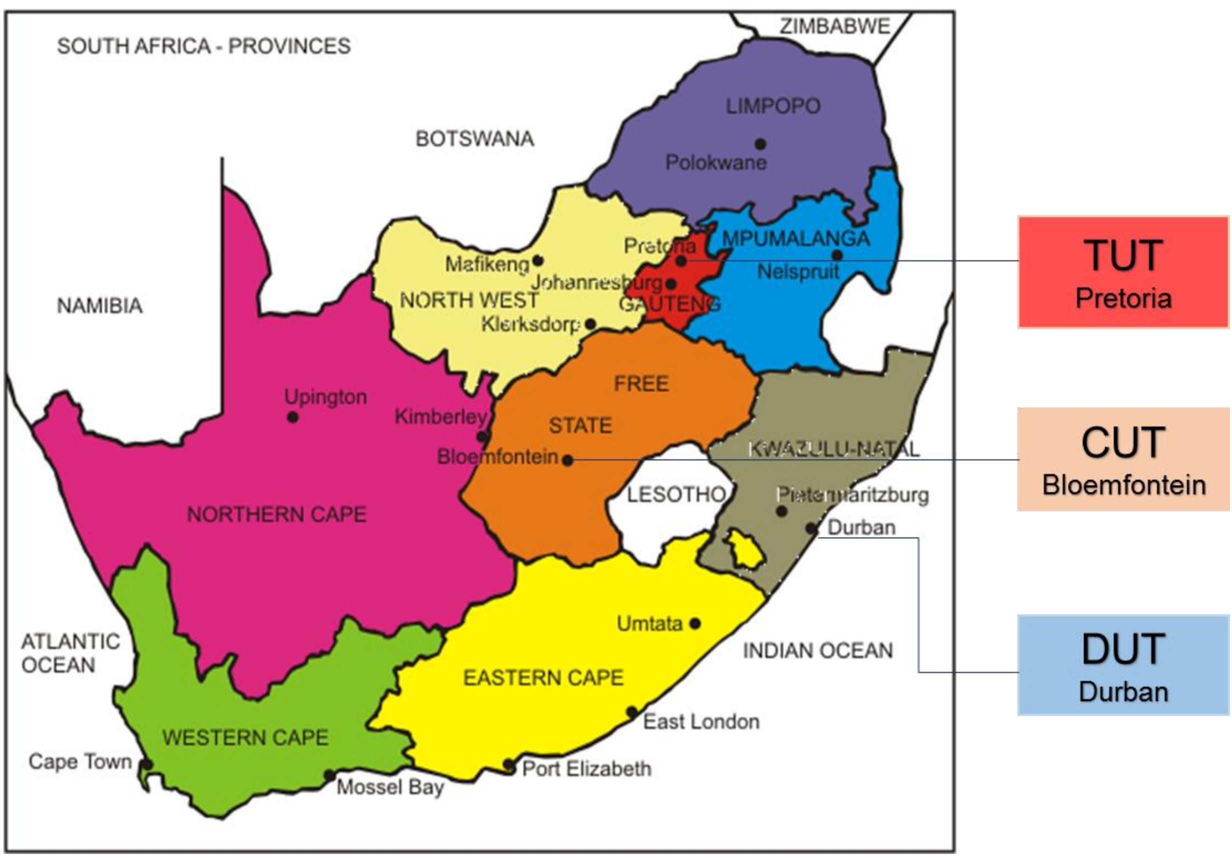

Figure 1.2 Map of Case study provinces in South Africa,
source http://www.sataxguide.co.za

System dynamics modelling principles based on the Applied Systems Analysis (ASA) approach were employed to develop theoretical models in this investigation. System dynamics is a theory of structure and behaviour of systems (Forrester, 1968; 1969). It is characterised by the concepts of causal feedback loops and time delays, which represent the dynamic complexity of a system (Sterman, 2000). Causal loop maps are usually employed to describe the elements of the system (Montibeller & Belton, 2006). The interdependencies of elements that have causal feedback relationships create specific conditions within the building and related built infrastructures. According to Harvey (2009), the ASA approach requires an Integrated Design Process (IDP), in which the building performance is optimized through an iterative process.

Following this modelling approach, this study established three interdependent models and one integrated model for the built infrastructure in the following categories:

- Energy Efficiency (EE);
- Water Use Efficiency (WUE)
- Indoor Environmental Quality (IEQ);
- Integrated built infrastructure and services model.

The detailed theoretical models are presented in chapter 6. Figure 1.3 presents the sequential steps used for conducting the investigation.

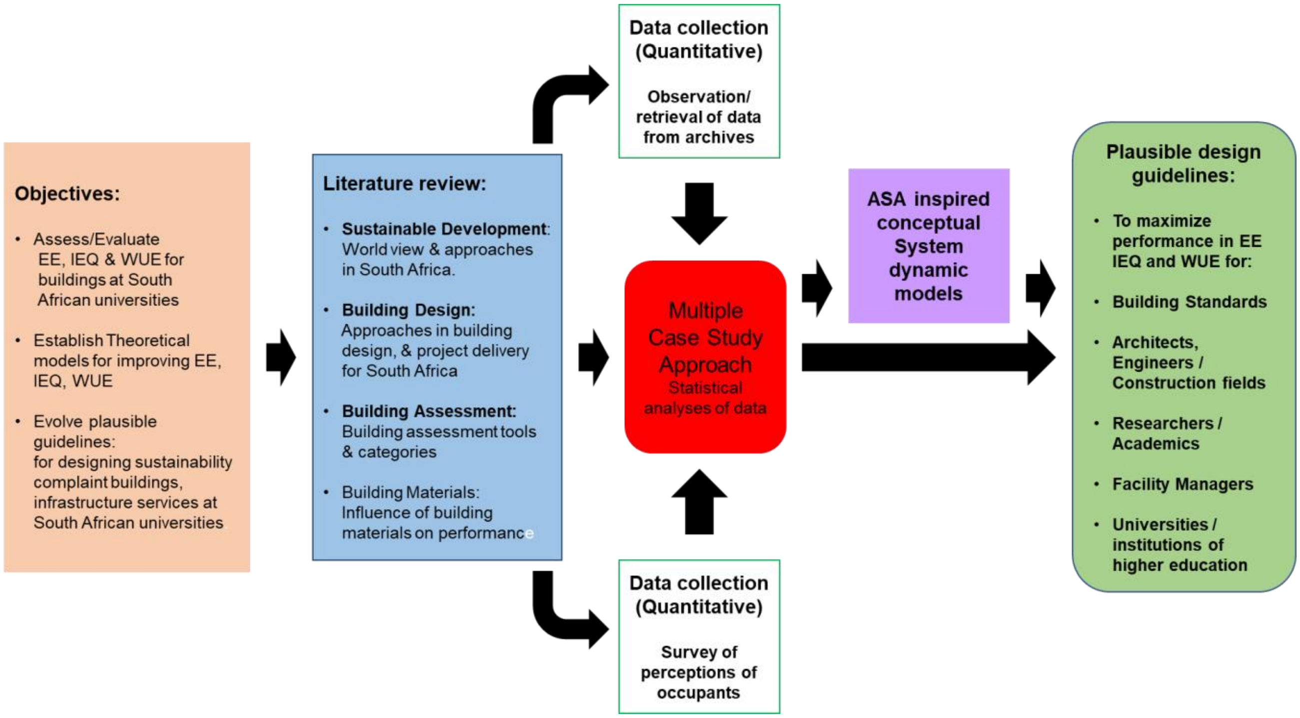

Figure 1.3 Methodology flow chart

1.8 Chapters and thesis organisation

The chapter organisation of the thesis is presented in Figure 1.4. where:

- Chapter 1 comprises of the introduction, problem statement, hypothesis, specific objectives and the introduction to methodology.
- Chapter 2 constitutes review of literature.
- Chapter 3 discusses the research methodology used in the study.
- Chapter 4 includes a case study and presentation of data.
- Chapter 5 presents the results of the data analysis.
- Chapter 6 presents theoretical system dynamics models based on the ASA paradigm.
- Chapter 7 constitutes findings, results, design guidelines, the conclusion and recommendations.

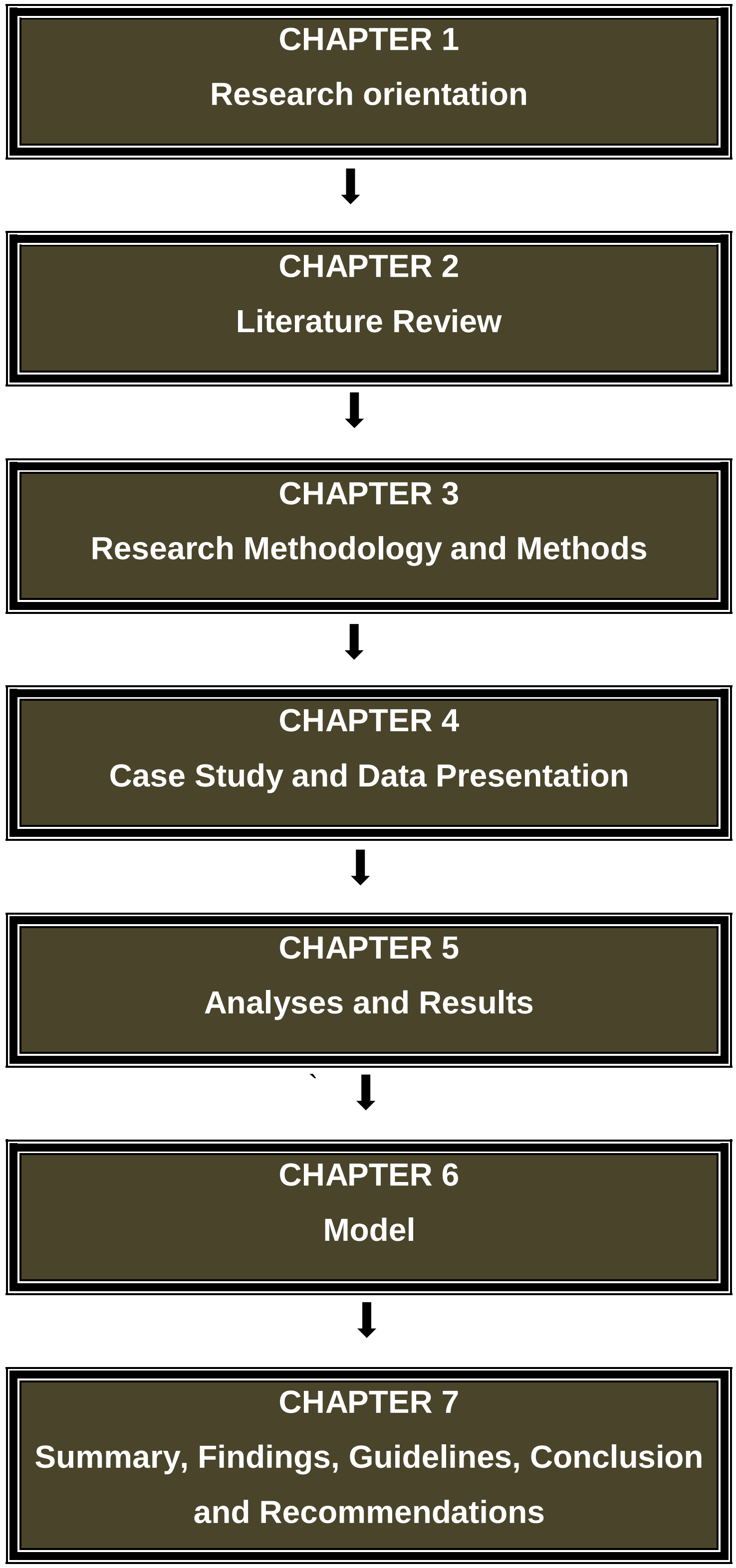

Figure 1.4 Graphical Representation of Thesis Structure

CHAPTER 2: LITERATURE REVIEW

2.1 Introduction

Sustainable built infrastructure remains as one of the vital elements of sustainable neighbourhoods and cities at large. As a consequence, systemic and focused investigations have been conducted relating to the challenges and issues of sustainable built infrastructure as seen both at global and local level. However, since sustainability of buildings and associated infrastructure and services is an important component of sustainability of universities and their neighbourhoods as well as the cities at large, an investigation of such a challenge is warranted. However, such a study requires a theatrical base. Therefore, this chapter pertains to the development of discourse on the various challenges and issues for sustainable buildings and infrastructure based on existing research and the perspective developed from theoretical and applied principles. For this purpose, a thorough literature review was conducted by drawing upon classical and current research works as well as practical applied principles. In this regard research works and case studies both at local and global level were reviewed. The various parameters analysed include orientation of buildings, energy efficiency, indoor air quality, use of building materials and water use efficiency.

2.2 Sustainability in university built infrastructure: A Global perspective

As much as concerns about climate change, energy consumption patterns and the increasing incidence of threats to the natural resource base are growing internationally, there is a growing desire to address these concerns. Accordingly, a number of international and national conferences were conveyed to address such issues, including the World Summit on Sustainable Development (WSSD) and the United Nations Framework Convention on Climate Change. All convey one central message, namely that the time has arrived to reassess the way in which human beings interact with- and use natural resources of water, air, soil and biodiversity (Van der Bank, 2012). One of the most compelling internal drivers for integrating sustainability into universities, is the ethical obligation to address this significant global challenge. Given their collective knowledge and research capacity, there is a moral responsibility for universities to educate future leaders and to advance knowledge that can lead to the creation of a sustainable environment (Moore 2005; Nicolaides 2006).

In recent years, it has been observed that universities have come to the forefront of sustainable development. They are dealing with the challenge of sustainable development in many different ways. The approaches range from aiming to function as an environmentally friendly company to formulating principles and signing declarations, establishing totally new institutions, or focusing the mission and management of an existing university on the quest for sustainability (Van Weenen, 2000). According to the United Nations Educational and Cultural Organization (UNESCO) (1997), education and higher educational institutions are humanity's best hope and most effective means in the quest to achieve sustainable development. It is evident from various examples and practices that universities all over the world are gearing themselves towards achieving sustainability on their campuses through various initiatives pertaining to energy management, waste management, and use of low cost and appropriate materials, among others.

Higher education has the unique academic freedom and the sheer exposure to critical thinking to comment on society and its challenges, and to engage in bold experimentation in environmental sustainability (Cortese, 2003). Developing a sustainable campus infrastructure would only be feasible if the entire campus inculcated a culture of sustainability (Cortese, 2003).
Accordingly, Shriberg (2002) noted that higher education institutions must go beyond adding classes on environmental issues and move toward a fundamental reorganization of how these institutions educate students, conduct research, interact with local communities and ecosystems, operate their campuses, and provide an ideal for other social establishments. Consequently, a common theme that emanates from institutional policies as well as national and international declarations, is the importance of development of green campuses and their physical operations (Wright, 2002). As a result, various sustainable built infrastructure development and operation initiatives have been developed and categorised. The various initiatives of sustainable campus development and operations include building construction and renovation, energy management, transportation, and water use (Kosnik, 2007). In this regard, the examples which include implementing GB practices on university campuses have resulted in conservation of energy and water, reduced operating costs, and added educational benefits. Similarly, the greening of campus day-to-day operations as a part of sustainable built infrastructure at universities has been cited as the most successful aspect addressed by higher education institutions (McIntosh et al., 2008).

2.3 Sustainable development principles in South Africa

Van de Bank (2012), noted that The South African Government does not stand oblivious to these international developments, especially when a very prominent role in protecting the environment is carved out for local government. Government: Municipal Systems Act 32 of 2007 (hereafter the Systems Act) states that municipalities are to strive to ensure that municipal services are provided in a financially and environmentally sustainable manner (Van de Bank 2012), However, it is observed that apparently explicit research on this aspect of development of sustainable built infrastructure and services at South African universities is meagre. As indicated in section 1.4, DEAT (2008) noted that most South African cities were poorly designed from an ecological perspective and have large environmental impacts.

2.4 Planning and municipal authorities in South Africa

According to Section 40(1) of the South African Constitution, a common constitutional objective and duty of the three spheres of government (national, provincial and local spheres) is environmental protection and the securing of an environment that is not detrimental to the health or well-being of people, both the present and future generations.

In a 2011 South African government publication, the Department of Trade and Industry announced that country-wide regulations for the sustainable development of buildings in South Africa were put in place. These included regulations towards the construction of more energy-efficient buildings.

Additionally, in 2011 the South African government published South African National Standards: SANS 10400-XA: 2011. The Application of the National Building Regulations — PART X: Environmental Sustainability — Part XA: Energy Usage in Buildings (for promotion of efficient energy usage in buildings). This standard specifies the design requirements for new energy efficient buildings and services with natural environmental control and artificial ventilation or air conditioning systems. Its objective is to provide guidelines for the design of new energy efficient buildings and services, in order to reduce operational energy usage in new buildings without compromising comfort and amenity (Tramontin, Loggia, and Trois, 2012).

2.5 Codes, building standards and guidelines in South Africa

It is important to note that the South African environmental law makes provision for municipalities to actively pursue environmentally sustainable management. For purposes of attaining South African government objectives of sustainable development, the department of environment and tourism in a 2008 publication noted five strategic priority areas for action and intervention that are necessary to reach the desired state of sustainable development (DEAT, 2008).

These priority areas include:

- Enhancing systems for integrated planning and implementation of economic development
- Sustaining our ecosystems and using natural resources efficiently
- Economic development via investing in sustainable infrastructure
- Creating sustainable human settlements
- Responding appropriately to emerging human development, economic and environmental challenges (DEAT, 2008).

SANS 10400-XA: 2011, has been developed according to the South African Buildings Standards (SABS), to promote energy efficiency in buildings (Van der Bank, 2012). The new regulation came into effect in November 2011. This standard specifies the design requirements for new energy efficient buildings and services with natural environmental control and artificial ventilation or air conditioning systems. In terms of this standard, buildings must be designed and constructed so that the building is capable of using energy efficient methods, while it fulfils the needs of the user in relation to vertical transport degradation and pollution or technological advancement (Van der Bank, 2012). SANS 10400-XA: 2011 is a revision of the SANS 204 and it provides higher standards for energy efficiency. These standards are designed to correspond with international best practices yet be appropriate to local conditions.

The new regulation requires, for instance, that new buildings have solar water heaters, heat pumps or similar technologies, which use renewable energy sources. Walls, windows, roofs and floors have to meet minimum thermal requirements for preventing heat loss (in winter) or gain (in summer) in order to meet the energy efficient targets (Tramontin, Loggia, and Trois, 2012). The standards provide that external walls comply with thermal inertia and resistance requirements and that glazing systems satisfy both aggregate conductance and solar heat gain requirements. These standards have been set to comply with the climatic conditions in South Africa.

However, in the study by Tramontin, Loggia, and Trois, (2012) the following flaws were noted in the SANS 10400-XA: 2011 building standard:

- This new legislation does not provide specific prescriptions for the sustainable retrofit of existing buildings, but implies that prescriptions for new buildings could also be applied to existing buildings.
- The new legislation does not make provision for the conservation and re-use of water, which should be taken into consideration by the future SANS 10400-XA. Since water is a scarce commodity in South Africa, the re-use of rain-, grey- and black water is one of the key components to sustainable design and building.

The Green Building Council SA is an independent, non-profit company that was formed in 2007 to lead the greening of South Africa's commercial property sector (GBCSA, 2014). In 2009 South Africa's first green certification was awarded by the GBCSA. (GBCSA, 2014). Aurecon (2011) noted that Aurecon's office building in Century City, Cape Town was the first building in South Africa to be awarded a 5 Star Green Star SA Office Design v1 rating by the Green Building Council of South Africa (Aurecon 2011; GBCSA).

2.6 Integrated project delivery for sustainable building design

In order to realize the objectives of this study it is essential to understand the methods of project delivery and methods for achieving sustainable, high performance building projects. American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) et al. (2011), noted that terms surrounding project delivery methods can be confusing and that experienced professionals often misuse them. A project delivery method is the comprehensive process by which designers, constructors, and various consultants provide services for design and construction to deliver a complete project to the owner. The three main delivery methods are design-bid-build (DBB), construction manager at risk (CMR), and design-build (DB) (ASHRAE et al., 2011). According to the latter publishers, projects start with initial project meetings including a project Kick-off meeting which is the most important meeting of the entire project with regards to establishing the Owner's Project Requirements (OPR). This exercise is usually led by the commissioning authority, and allows the owner's personnel and stakeholders to define what a successful project means for them (ASHRAE et al., 2011).

In this study, reduction of energy consumption – together with provision of appropriate IEQ and efficient use of water – are the main concerns in achieving sustainable design. It is important to note that sustainable design of buildings requires a different approach to design and construction other than the traditional approach.

In recent years Integrated Project Delivery (IPD) has become a common approach towards the achievement of the design and construction of sustainable buildings. The American Institute of Architects (AIA, 2007) defines IPD as a project delivery approach that integrates people, systems, business structures, and practices into a process that collaboratively harnesses the talents and insights of all project participants to optimize project results, increase value to the owner, reduce waste, and maximize efficiency through all phases of design, fabrication and construction.

Integrated projects often rely on cutting edge technologies. Technologies are specified at project initiation to maximise functionality, generality and interoperability. Open and interoperable data exchange based on disciplined and transparent data structures are essential to support IPD. Because open standards best enable communications among all participants, technology that is compliant with open standards is used whenever available (AIA, 2007). The IPD process is illustrated in the figure below.

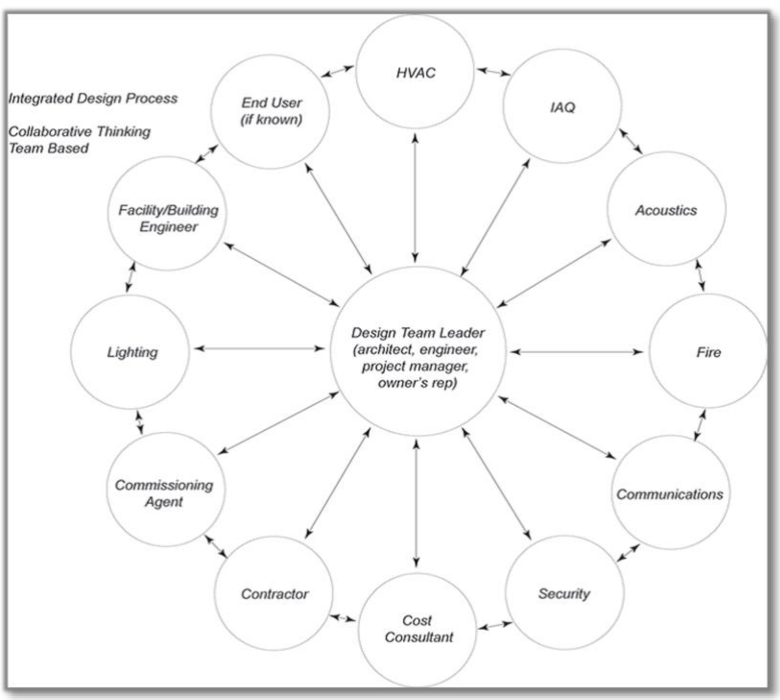

Figure 2.1: Integrated Project team Design: (ASHREA 2009).

The IPD delivery method as illustrated above, allows participants to be involved even in early stages of the design. This is a significant difference from the traditional method of project delivery in which participants work on a fragmented approach, with less collaboration in the initial- and other stages of the design.

2.6.1 Developing a design concept using integrated project delivery

For the purpose of designing for sustainability – especially if energy efficiency is an important part of design objectives – understanding the status of site conditions is an important part of developing the design concept of buildings, in addition to conforming to the clients' requirements. For instance, the design would consider pre-existing shading or wind-shadows caused from adjacent buildings; landscaping; outdoor air quality; and outdoor ambient noise environment among the important considerations. ASHREA et al. (2011) noted the following factors as significant to design of buildings:

- Availability of natural resources (sun, wind, geothermal energy, climate, bodies of water)
- Local material availability or re-use
- Site documentation with regard to storm water run-off schemes and utilities available
- Status of surrounding buildings and review of code/planning regulations that may create obstructions to natural resources in the future or otherwise limit the design (such as the effects of the proposed building on its neighbours or other city planning concerns)

ASHREA et al. (2011) further noted that it would be important for all participants to consider the following particularly to achieve energy efficiency and sustainable design:

- Daylighting potential versus glare versus solar heat gain
- Reflectivity of other surfaces
- Natural ventilation potential for cooling
- Glazing types, shading devices, and fenestration size
- Operable window sizes (if allowed)
- Perimeter occupant comfort
- Daylight harvesting and impact on potential energy savings
- Landscaping potential for natural shading
- Selection of structural material and its relative use as thermal mass or thermal insulation
- Selection of internal wall finish type and its potential to absorb internal heat gains

- Selection of floor material type and finish and its potential use as an air-distribution-, heating-, or cooling device
- Selection of façade type; orientation and relative proportion of each face; and performance of glazing and opaque wall insulation
- Selection of glazing visible transmittance (VT) versus solar heat gain coefficient to allow daylighting without overheating
- Configuration of roofing shape/slope/direction and applicability of cool-roofing materials, clerestory skylights, and/or installation of photovoltaic or solar hot water panels
- Selection of electric lighting approach and zoning compatibility to accommodate ambient versus task lighting, occupancy sensors, daylight harvesting, and time-of-day controls
- Commitment to ENERGYSTAR equipment for plug-load usage reduction
- Review of plug-load use intensity by the owner's personnel
- Review of alternative HVAC and comfort cooling systems
  (ASHREA et al., 2011).

These parameters are significant in design for EE and IEQ. For instance, daylighting potential is significant for both EE and IEQ.

2.6.2 IPD design approach and building envelope components

It is significant to note the role of IPD in providing a platform for early consideration of very important design factors that impact the sustainability of a building. According to Azhar, Brown, & Sattineni (2010) the early design and preconstruction phases of a building are the most critical times to make decisions on its sustainability features. The International Energy Agency (2013) noted that the energy performance of building envelope components – including external walls, floors, roofs, ceilings, windows and doors – are critical in determining how much energy is required for heating and cooling.

According to the International Energy Agency (2013) energy loss through the building envelope is highly variable and depends on numerous factors such as building age and type, climate, construction technique, orientation, geographical location and occupant behaviour (They further indicated that there are two predominant perspectives on the relative importance of the building envelope and heating- and cooling equipment. The passive design approach supports high levels of energy efficiency in building envelope components, with any remaining need for heating or cooling met by basic and efficient mechanical equipment. The smart technology approach promotes high energy efficiency in mechanical equipment because it is routinely replaced and installing it is easier than retrofitting old, and inefficient building envelopes. Either approach can be appropriate. The balance between advanced envelopes and advanced equipment needs to be established at regional or local level, while considering product availability, cost, climatic conditions and energy prices (International Energy Agency, 2013).

2.6.3 IPD aided by Building Information Modelling (BIM)

The purpose of Building Information Modelling (BIM) is to foster IPD in order to have a holistic approach to design. To achieve this, it is important to think not only in geometric terms but also in regard to considering the entire building as a system with geometric and non-geometric interdependencies. It can aide designers in more comprehensive assessment of design strategies in the initial stages of the design (Eromobor, Das & Emuze, 2014; Krygiel & Nies, 2008). BIM represents the building as an integrated database of coordinated information. Beyond graphically depicting the design, much of the data needed for supporting sustainable design is captured naturally as design of the project proceeds. In addition, the integration of a building information model with performance analysis tools greatly simplifies the often cumbersome and difficult analysis. This approach gives architects easy access to tools that provide immediate feedback on design alternatives early on in the design process. Krygiel & Nies (2008) indicated that BIM can aid in the following aspects of sustainable design:

- Building orientation (to select the best building orientation that results in minimum energy costs)
- Building massing (to analyse building form and optimize the building envelope)
- Daylighting analysis
- Water harvesting (to reduce water needs in a building)
- Energy modelling (to reduce energy needs and analyse renewable energy options such as solar energy)
- Sustainable materials (to reduce material needs and to use recycled materials)

BIM represents the process of development and use of a computer-generated model to simulate the planning, design, construction and operation of a building facility. The resulting model, a BIM, is a data-rich, object-oriented, intelligent and parametric digital representation of the building facility, from which views and data appropriate to various users' needs can be extracted and analysed to generate information that can be used to make decisions and improve the process of delivering the facility (The Associated General Contractors of America 2005; Azhar, Khalfan, and Maqsood 2015). The BIM technology hailed from the object-oriented parametric modeling technique (Azhar et al., 2008).

Due to the fact that BIM allows for multi-disciplinary information to be superimposed within one model, it creates an opportunity for sustainability measures and performance analysis to be performed throughout the design process (Autodesk, Inc., 2008).
BIM use needs to be assessable if the productivity improvements that result from its implementation are to be made apparent. Without such metrics, teams and organizations are unable to consistently measure their own successes and/or failures. Performance metrics enable teams and organizations to assess their own competencies in using BIM and, potentially, to benchmark their progress against that of other practitioners. Furthermore, robust sets of BIM metrics lay the foundations for formal certification systems, which could be used by those procuring construction projects to pre-select BIM service providers. Assessment of building parameters for performance can be achieved using Green Building rating tools (Succar, Sher & Williams, 2012).

2.7 Performance assessment of a building using green building rating tools

As this study is concerned with the assessment of existing buildings and infrastructure, it is important to understand how buildings are assessed using existing rating tools. Considerable work has gone into developing systems to measure a building's environmental performance over its life. These systems have been developed to evaluate how successful any development is with regards to balancing energy, environment and ecology, taking into account both the social and technological aspects of projects (Clements-Croome, 2004). According to Ding (2008) separate indicators, or benchmarks based on a single criterion, have been developed to monitor specific aspects of environmental building performance such as air quality and indoor comfort. However, these benchmarks serve to emphasize the need for a comprehensive assessment tool to provide a thorough evaluation of building performance against a broad spectrum of environmental criteria. Ding (2008) also noted that the Building Research Establishment Environmental Assessment Method (BREEAM) in 1990 was the first such comprehensive building performance assessment method. Green Building rating tools are currently used in a range of countries, after the development of BREEAM in the UK in 1990. The Leadership in Energy and Environmental Design (LEED) was established in the United States of America (USA) followed by Green Star in Australia in 2003. The Green Building Council of South Africa GBCSA (2008) established the Green Star, SA system which is based on existing systems and tools in overseas markets – most notably the Green Star system developed by the Green Building Council of Australia (GBCSA, 2008).

These rating tools provide a more holistic approach to assessment of buildings which reflects the concept of sustainability in building design and construction. The purpose of this system is to set a list of environmental criteria against which building performances are checked and evaluated. There are basically two categories of tools, namely assessment tools which provide quantitative performance indicators for design alternatives, and rating tools which determine the performance level of a building in stars (Ding, 2008).

2.7.1 BREEAM rating system

BREEAM, the first rating system established, is the most widely used environmental rating scheme of buildings in the United Kingdom (UK) and has been adopted by numerous countries worldwide. Even though it is a voluntary standard, the energy performance assessment adopts the UK Building Regulation as a benchmark to rate the level of performance improvement. The latest version for non-domestic buildings is BREEAM UK New Construction: Non-Domestic Buildings. Similar to the credit rating system in LEED, BREEAM (2014) defines categories of credits according to the impact of the building on the environment, which include management, health & well-being, energy, transport, water, materials, waste, land use & ecology, pollution and innovation.

The total score is calculated based on the credits available, the number of credits achieved for each category and a weighting factor. The overall performance of the building can be categorised as Unclassified (<30), Pass (>30), Good (>45), Very Good (>55), Excellent (>70) and Outstanding (>85). For each category, there are a minimum number of credits that must be achieved. The energy assessment in BREEAM is referred to as Credit Ene 1-Reduction of CO2 emissions. It allows up to 15 credits to be achieved when the assessed building demonstrates an improvement in the energy efficiency of the building fabric and building services. The energy performance of the building is shown as a CO_2 based index (Roderick, et al., 2009).

According to BREEAM (2014), to be able to set up the asset rating, two building models need to be created, which are the actual building and the reference building. The asset rating is then calculated as the ratio of the CO_2 emissions from the actual building to the Standard Emission R, which is determined by applying a fixed improvement factor to the CO_2 emissions from the reference building (BREEAM, 2014).

2.7.2 LEED rating system

LEED is the most recognized environmental assessment scheme of buildings. It is widely used in the USA and several other countries. The current version is LEED v4, an improvement on LEED 2009. Roderick et al. (2009) indicated that LEED is based on a set of prerequisites and credits. Each credit refers to one of the following aspects: sustainable sites, water efficiency, energy and atmosphere, materials and resources, indoor environmental quality, and innovation & design process. One point will be awarded to each credit when the requirement is met, except for the energy performance credit and the renewable energy credit, in which a number of points will be awarded to each credit depending on the level of performance improvement being achieved (Roderick et al., 2009).

According to USGBC (2014) there are up to 80 points that can be achieved. Based on the awarded points, a building is certified on one of the following four levels: Certified (40-49 points), Silver (50-59 points), Gold (60-79 points) and Platinum (80 points and above) (USGBC 2014). There are two approaches to assess building energy performance (also known as Credit EA1-Optimize Energy Performance). The first is the Prescriptive Compliance Path, which allows certain projects to achieve up to 4 points when they meet the prescriptive measures of the ASHRAE Advanced Energy Design Guide (AEDG) for small office buildings. The other approach is the Whole Building Energy Simulation, which allows up to 10 points when the building demonstrates improvement on energy cost against a normalised building (Roderick et al., 2009). Roderick et al. (2009) further indicates that for both approaches, the assessed building needs to meet a minimum performance level of 2 points. The Whole Building Energy Simulation requires the use of a simulation program that can perform thermal analysis to the specifications laid down by ASHRAE Standard 90.1-2004 appendix G (also known as the Performance Rating Method (PRM)). The method specifies that two types of building models be created, the first being the proposed building model and the second being the baseline building model.

2.7.3 Green Star SA system for rating green buildings

Green Star is the most followed voluntary environmental assessment scheme for buildings in Australia. It was developed to accommodate the need of green buildings in hot climates where cooling systems and solar shading are of major importance. It has also been adopted in New Zealand and South Africa (GBCA, 2008; Roderick et al., 2009). Similar to LEED and BREEAM, Green Star uses the credit rating system based on the number of points allocated to the credits in order to determine the total scoring and hence the level of certification. The score is determined for each category based on the percentage of points achieved versus the points available for that category (Roderick, et al., 2009).

This study carefully considers the quantitative performance indicators for design to assess buildings for their performance used by the Green Star SA system for rating green buildings. The Green Star SA rating tool rates 9 categories to determine the extent of Green building objectives being met by the building. These Categories include:

- Management;
- Indoor Environment Quality;
- Energy;
- Transport;
- Water;
- Materials;
- Land Use and Ecology;
- Emissions; and
- Innovation.

Green Star SA establishes a number of categories under which specific key criteria are grouped and assessed. The categories are divided into credits, each of which addresses an initiative that improves or has the potential to improve a project or building's environmental performance. Points are awarded in each credit for actions that demonstrate that the project has met the overall objectives of Green Star SA and the specific aims of the Green Star SA rating tool (GBCSA, 2014).

The energy credit in Green Star, known as Credit Ene-1 of Greenhouse Gas Emissions, allows up to 20 points to be awarded based on the greenhouse performance of the rated space, which counts for around 14.5% of the total score of the scheme. There are three methods to calculate the predicted greenhouse emissions. The first is to use the Green Star Energy Calculator and modeling protocol. This tool is used to determine if gas emissions are less than or equal to the predicted gas emissions of a reference building within the same location. The other method is to use a software program to perform an energy modelling calculation that determines if the building complies with the requirements and verifications detailed in the ASHREA AEDG. For small office buildings, this method is referred to as ASHREA Deemed-To-Satisfy (DTS). This method is similar to the path used by LEED. The third method is to determine if the building complies with SANS 204:2011 Energy Efficiency in Buildings 'Deemed to Comply' (DTC) clauses regarding building fabric and building services (GBCSA, 2014).

2.7.4 Application of ASHRAE standard 90.1-2004 in Green Star

LEED and Green Star both have a 'Compliance Paths for Energy Efficiency' clause which requires conformity with relevant clauses in the AHSRAE AEDG for small office buildings. The GBCSA (2014), noted that in choosing this option, designers should abide by recommendations outlined by the AEDG. These include recommendations for building envelope, lighting and heating, ventilation and air-conditioning (HVAC), (GBCSA, 2014). These recommendations are significant in their effect on energy consumption. For instance, the AEDG contains recommendations for walls, roofs and window construction to ensure they meet the thermal insulation and solar performance described in the guide. In this regard, an energy calculator is used to aide in a Building Energy Simulation. This simulation program performs thermal analysis to the specifications laid down by the ASHRAE AEDG for small office buildings. The method specifies that two types of building models should be created. The first is the proposed building model and the second is the baseline building model (GBCSA, 2014).

2.7.5 SANS 204:2011 route for Green Star SA.

The GBCSA (2014) indicates that the design requires compliance with the SANS 204:2011 Energy Efficiency in buildings 'Deemed-to-Comply' clause regarding building fabric and building services. Green Star SA has rating tools for different phases of the building lifecycle (design, construction, operations, refurbishment or fit-out) and for different building classes, (e.g. office, retail, public & education, multi-unit residential, etc.) (GBCSA, 2014).

According to Tramontin et al. (2012), the revised SANS 204 provides guidelines to reach international best practice applicable to South Africa and – although it is not directly a part of the National Building Regulations– it may be used to comply with the requirements of SANS 10400-XA and to achieve a higher standard of energy efficiency than the minimum performance set out in this one. The new regulation requires, for instance, that new buildings have solar water heaters, heat pumps or similar technologies, which use renewable energy sources. Walls, windows, roofs and floors have to meet minimum thermal requirements for preventing heat loss (in winter) or heat gain (in summer) in order to meet the energy efficient targets. External walls, in particular, are required to comply with thermal inertia and resistance requirements, through the arithmetical product of total thermal capacity (C-value) and the total thermal resistance of a material (R-value). The product parameter (the minimum products of the CR-values are based on occupancy and climatic zone and vary, for instance for residential buildings, between 60h and 100h (6)), while roof assemblies require only a thermal resistance level, but with much more stringent values (minimum R-value, based on climatic zone and with a range from 2.7 m^2K/W to 3.7 m^2K/W (8)). Glazing systems have to satisfy both aggregate conductance (which derives from thermal transmittance U-value of glazing) and solar heat gain requirements (related to the solar heat gain coefficient SHGC of glazing), which include the effect of external and integral shading devices. Buildings also have to be fitted with energy efficient heating, air conditioning and mechanical ventilation systems (Tramontin et al., 2012).

In the Green Star tool, the reference building and actual buildings are both assumed to be air-conditioned and the HVAC energy consumption of both buildings is assumed to be the same. In this route glazing levels, insulation levels and applicable services should satisfy minimum requirements of SANS 204:2011.

The Green Star rating tools evaluated in this study include the public and education tools and existing building performance tools. A summary of the categories and their constituents for Energy, IEQ, Water and Materials within the Green Star SA Public and Education rating tool are indicated in Table 2.1 below.

Table 2.1: Selected categories from Technical Manual, Public & Education Building v1

Category title	Credit no.	Points available
Energy		
Conditional Requirement	Ene - 0	0
Greenhouse Gas Emissions – Heating & Cooling	Ene - 1	20
Energy Sub-Metering	Ene - 2	3
Lighting Zoning	Ene - 4	2
Maximum Electrical Demand Production	Ene - 5	3
Unoccupied Spaces	Ene - 11	2
Total		**30**
Indoor Environment Quality		
Ventilation	IEQ - 1	2
Carbon Dioxide Monitoring	IEQ –3	1
Daylight	IEQ - 4	3
Daylight Glare Control	IEQ –5	1
Electric Lighting Levels	IEQ –7	1
External Views	IEQ - 8	2
Thermal Comfort	IEQ - 9	2
Hazardous Materials	IEQ - 11	1
Internal Noise Levels	IEQ - 12	3
Volatile Organic Compounds	IEQ - 13	3
Formaldehyde Minimisation	IEQ - 14	1
Mould Prevention	IEQ –15	1
Dedicated Exhaust Riser	IEQ - 26	1
Stairs	IEQ – 23	1
Total		**23**
Water		
Potable Water	Wat - 1	12
Water Sub-Metering	Wat - 2	3
Total		**15**
Materials		
Recycling Waste Storage	Mat - 1	2
Building Reuse	Mat - 2	5
Recycled Content & Re-used Materials	Mat - 3	3
Concrete	Mat - 5	3
Steel	Mat - 6	3
Sustainable Timber	Mat - 8	2
Design for Disassembly	Mat – 9	1
Dematerialisation	Mat - 10	1
Local Sourcing	Mat - 11	2
Masonry	Mat - 13	2
Total		**24**

Source: GBCSA 2014

Although the Green Star scheme does not give a clear indication of the weighting of the categories, importance is given to energy which is allocated the highest weight. For the purpose of evaluating energy efficiency (EE), the energy category uses sub- metering to check for the amount of energy used. However, there is no way of assessing how other factors such as heating or cooling affect energy consumption. There is no link between IEQ and its effect on energy use, neither is there an indication of how materials used effect energy consumption of the building. For the purpose of obtaining a comprehensive assessment of energy efficiency (EE), the rating system can be improved by understanding how these categories and their constituents interrelate (GBCSA, 2014).

2.7.6 Constraints of using green building rating tools

Zimmerman and Kibert noted that assessment systems are increasingly criticised for being market driven, one-size-fits-all approaches that fail to adequately address underlying environmental sustainability issues (Zimmerman and Kibert 2007). It is becoming increasingly evident that focusing on 'getting more points' for 'doing less harm' as encouraged by current green building tools, will not necessarily produce design solutions that support and strengthen the human-nature system, (Gou and Xie 2017).
The review of measurement and benchmark of these green building concepts and practices pointed to the deficiency of measurement of environmental performance. The measurement and benchmark green building which lays the foundation for the common attributes of different green building tools is based on, reducing negative impacts such as, reducing resource use and reducing energy consumptions. It has been used consistently to describe buildings that have a less negative environmental impact compared with that of typical buildings. The current green building design and assessment tools needs to compose a more comprehensive set of indicators and more flexible framework to be adapted to different contexts. (Gou and Xie 2017).

2.7.7 Categories of assessment and constituent elements

In this study EE, IEQ and WUE are the main categories of focus, with energy being the focal point. The influence of materials was examined with regards to its impact on energy efficiency. The purpose of the assessment of these main categories was to have a comprehensive quantitative performance indication for the category of energy efficiency and how it was influenced by the other categories. Such a preliminary assessment was performed to determine the performance of these categories and how they affect the consumption of energy on the campus. Sadineni, Madala & Boehm (2011), noted that building energy efficiency can be improved by implementing either active or passive energy efficient strategies. Improvements to heating, ventilation and air conditioning (HVAC) systems and electrical lighting can be categorized as active strategies, whereas improvements to building envelope elements can be classified under passive strategies. (Sadineni, Madala & Boehm, 2011).

2.8 Energy in the built environment

Over the past 30 years the consumption of energy has become a global concern. Despite this growing alarm, non-renewable energy sources are being depleted at a remarkable rate. Studies have suggested that if the trend of consumption of the natural resources does not change, many of these resources will be depleted within the lifetime of the current generation. (Siemon, 2009). However, in order to understand the implications of energy use, it is necessary to clearly understand the definition of energy and energy efficiency.

The Organization for Standardization (ISO) has defined efficiency in the ISO 9000 standard as "the relationship between the result obtained and the means used" (Hegger et al., 2008). According to the Economic Commission for Europe (ECE), energy efficiency can be defined as "the capacity to produce results with a minimum expenditure of energy inputs. A system is thought of as energy-efficient if its requirements are low in relation to the results produced and if energy is not wasted" (ECE, 1991). According to Siemon (2000) there are four determining factors of efficiency that include capital, materials, human efforts, and energy. Each of the factors requires the minimum expenditure of resources in order to contribute towards efficiency. He also noted that for something to be considered energy efficient, the absolute minimum of input and wastage of energy in relation to the results produced must be utilized. In other words, if very little energy is used, wasted and produced, the results are not very energy efficient. On the other hand, if very little energy goes in and a lot comes out without great amounts of waste, the results can be considered energy efficient (Siemon, 2009).

2.8.1 Energy efficiency in buildings

Building shell performance has a large impact on the heating, cooling and illumination requirements of commercial buildings (GBCSA, 2008). This is also the case for certain types of office- and educational buildings. Improvements in thermal daylight and natural ventilation performance of these buildings will indirectly reduce energy consumption and greenhouse gas emission. Office buildings consume a high amount of energy in the form of space cooling/heating and lighting, equipment, water heating, ventilation and other applications (Hens, 2009). Bastide et al. (2006) note that the massive magnitude of energy consumption in buildings for cooling and heating by heaters and air-conditioner systems, portrays a huge problem in the system. Available statistics states that the heating, ventilation and air conditioning (HVAC) systems in standard buildings account for more than 50% of annual energy consumption globally (Bastide et al., 2006).

According to Harvey (2009) the energy use of buildings depends to a significant extent on how the various energy-using devices (pumps, motors, fans, heaters, chillers, and so on) are put together as systems, rather than depending on the efficiencies of the individual devices. The integrated approach to design produces buildings that represent better value for the owner and more efficient operation. In addition, the systems approach requires an Integrated Design Process (IDP) in which the building performance is optimized through an iterative process that involves all members of the design team from the beginning (Harvey, 2009). Harvey summarizes the steps in the most basic IDP as follows:

- To consider building orientation, form, and thermal mass.
- To specify a high-performance building envelope to maximize passive heating, cooling, ventilation and daylighting.
- To install efficient systems to meet remaining loads.
- To ensure that individual energy-using devices are as efficient as possible and properly sized.
- To ensure the systems and devices are properly commissioned.

Furthermore, it is also argued that building form and a high-performance envelope can minimize heating- and cooling loads, maximize daylighting opportunities, and downsize mechanical systems (Harvey, 2009). All these aspects result in reduction of energy input within the building system and more efficient use of energy.

2.8.2 Effects of envelope design approach and services on energy efficiency

It is observed that the approach to the design of the building envelope and type of services incorporated significantly affects the consumption of energy in the building. Other factors such as function, size, and behaviour of occupants also have a very significant effect on energy consumption (EC) and on IEQ and WUE of buildings. Bastide et al. (2006) note that the massive magnitude of EC in buildings for cooling and heating by heaters and air-conditioner systems portrays a huge problem for energy use in buildings. Available statistics state that the Heating, Ventilation and Air Conditioning (HVAC) systems in standard buildings account for more than 50% of annual energy consumption globally (Bastide et al., 2006). This indicates that there is a need for proper envelope design that maximizes passive systems for heating /cooling and lighting in order to reduce the energy demand required by mechanical systems and services. In order to minimize the demand for energy use, priority should be given to proper building design in the initial stages. In this regard, the following 3 stages – in order of priority – can be considered: basic building design, passive systems and mechanical systems., The three stages are illustrated in figure 2.2 below.

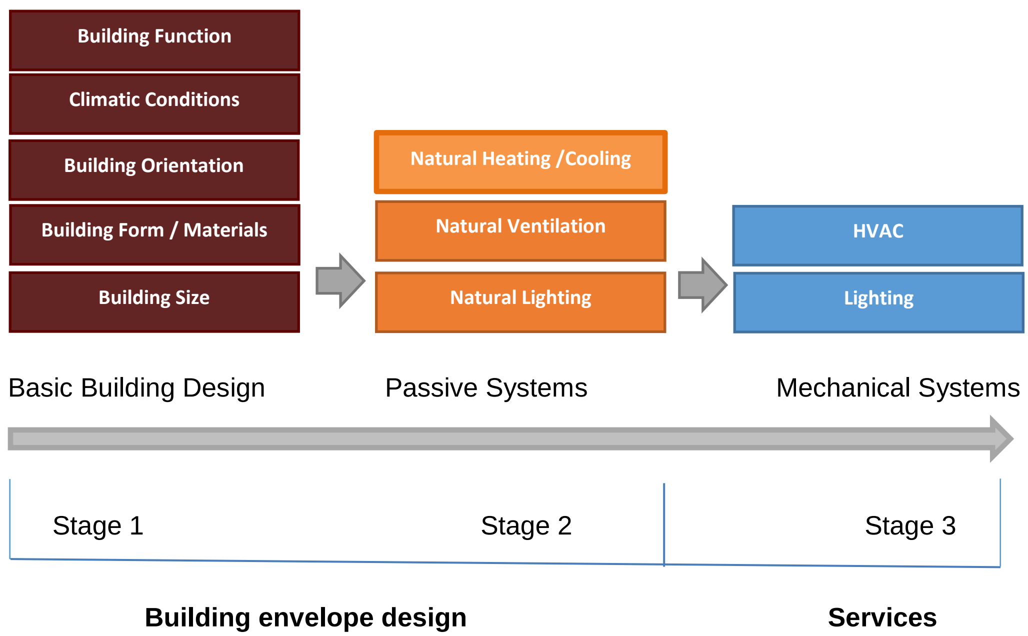

Figure 2.2: Indication of priority of design for minimizing Energy Consumption

Stage One: This is the basic design of the building itself, depending on the function of the building while considering climatic conditions and using the form and structure of the building to minimize heat loss in winter and heat gain in summer. This stage is achieved through the architectural design of the building and the appropriate decisions made here can greatly reduce the building's energy loads and increase thermal comfort. For instance, The National Institute of Building Sciences (2015) indicated that a building's size, shape, and orientation, which would greatly impact any form of passive means for cooling or heating of the building, are all considered at the initial stages as it is best to incorporate passive solar heating into a building during the initial design.

Stage Two: This stage involves harnessing natural energies through the use of passive systems or systems which do not require additional energy to operate. At this stage architectural design is used to maximise natural heating, cooling, ventilation and lighting. The main focus is use of the building envelope to harness natural elements to achieve comfort in the building. According to Ralegaonkar & Gupta (2010), the function of building envelope is to physically separate the interior of the building from the exterior environments, therefore it serves as an external protection to the indoor environment while facilitating climate control at the same time. Climatic thermal design of the building envelope affects thermal performance which also affects EC. Kubota & Ahmad (2006) noted that adopting the natural ventilation system in a building environment lowers EC and green gas emissions.

Stage Three: This is the design of the mechanical systems that are used to compensate for the remaining loads on the building. The use of efficient heating, cooling and ventilation systems can further reduce energy use, but it is more advantageous to reduce loads through the first two stages before relying on mechanical equipment. The argument here is that energy required to provide comfort in the building can be reduced by first adopting proper architectural design, followed by using passive means to achieve comfort, mechanical means can then be utilized to offset any additional requirements to achieve comfort.

2.8.3 Building envelope components and effects on energy efficiency

Generally, there are two main building envelope systems, namely the opaque and the transparent system. Opaque envelope systems include walls, roofs, floors and insulation, while transparent envelope systems include windows, skylights, and glass doors (Ralegaonkar & Gupta, 2010). It is important to indicate that transparent components such as windows are also referred to as fenestrations. Sadineni et al. (2011) noted that because building envelopes separate the indoor from outdoor environments, they are exposed to temperature fluctuations of humidity, air movement, rain, solar radiation and other natural factors. Climatic thermal design of the building envelope affects thermal performance which also affects energy consumption (Al-Saadi & Budaiwi, 2007). DoE, U.S. (2011), indicated that 73% of the total heat gain/loss is contributed by the building envelope. The choice of construction materials is dependent on the thermal, moisture and sound considerations. Walls, doors, windows, ventilators and roofs are components which are directly exposed to the sun.

According to Sabouri (2012) there are five methods for heat and mass transfer in the buildings:

- Conduction through opaque elements including external walls, ceiling, floor slabs, roofs and partitions.
- Solar radiation and conduction through window glazing.
- Infiltration of outdoor air and air from adjacent rooms.
- Heat and moisture dissipation from the lighting, equipment, occupants and other materials inside the room.
- Heating or cooling and humidification or dehumidification provided by the HVAC system.

Studies have also shown that a strong relation exists between various building components such as shading devices, external wall, external roof, external glazing, insulation and the reduction of energy consumption as well as cooling in buildings. Furthermore, Parasonis and Keizikas (2010), note that energy usage is also significantly affected by the shape – such as length, width and height – of buildings. The interlinkage among the EC and the influence of building envelope components on EC are presented in Figure 2.3 below.

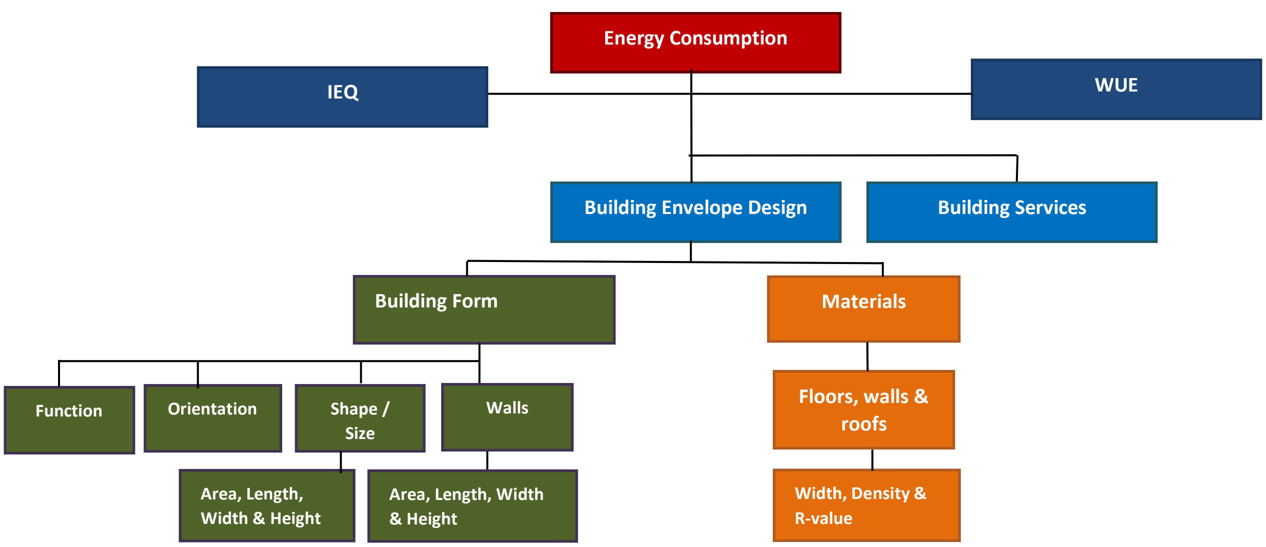

Fig: 2.3: Relation of building envelope components to energy consumption.

2.8.4 Effects of orientation, form and size on energy consumption

Orientation

Building designers can develop the basic plan, design the shape and choose materials of the building without considering the climatic influence. However, due to the building orientation on site and its exposure to solar radiation, its shape can influence the EC of building (Mirrahimi et al., 2016). A study by Al-Tamimi (2011) in Malaysia suggested that in day-to-day comparisons of thermal performance, building orientation has a significant impact amid the presence or absence of natural ventilation. Daylight and air movement through the building are affected by the shape of the building which is subsequently affected by its orientation. Eromobor and Das (2013) noted that with appropriate design interventions, proper orientation, geometry, location and size of openings, access to natural light can lead to reduction of energy consumption. According to Kannan (1991), buildings lined longitudinally along north and south had 10% less energy consumption than buildings arranged longitudinally along east to west, regardless of building form. Thus, orientation of building plays a vital role in reduction in energy consumption in a building.

Building size and form

Parasonis and Keizikas (2010) observed that changes in the shape of the building caused changes in energy losses, although the physical characteristics of the building remained the same. In volumetric design of buildings, it is important to rely on the use of architectural solutions for obtaining higher energy efficiency and lower consumption of other resources (Parasonis, Keizikas and Kalibatiene, 2012).

Parasonis, Keizikas and Kalibatiene (2012) also determined that the geometric efficiency of a building depends on both its size and proportions. Each building with a particular heated area has its standard geometric efficiency. The results from the evaluation of energy losses indicated that the larger the building, the weaker the effect of its proportions on both geometric and energy efficiency. This study determined that in the context of the total energy consumption, heat losses through the envelope elements constitute a large part of the total amount of the consumed energy (including ventilation, external air infiltration, linear thermal bridges, hot water preparation, maintaining the operation of the ventilation system and other services). The strongest effect of size on the demand for energy and other resources was determined for buildings enclosing up to 3,000 m^2 of heated area. In a study by Ratti, Raydan & Steemers, (2003), 24 building forms and 5 settlement texture alternatives were analysed and several simulations were conducted using

Design Builder software. The results indicated that building form and settlement texture are influential in heating and cooling loads for a hot-dry climate zone in order to provide optimum conditions. (Ratti, Raydan & Steemers, 2003). Furthermore, in another study by Yaşa & Ok (2014), a Computational Fluid Dynamics program was used to analyse the thermal comfort statuses and energy performances of 7 different courtyard shapes in inter-courtyard and building volumes in hot-dry and hot-humid climates. It was determined that they required annual energy demand increased in parallel with the increase in courtyard length (Yaşa & Ok, 2014).

2.8.5 Building materials

Life cycle

The manufacture, transport and installation in a building made of materials such as steel, concrete and glass require a large quantity of energy, despite them representing a minimal part of the ultimate cost in the building as a whole (Bribián, Capilla & Usón, 2010). Before buildings are constructed, the raw materials required to build them are extracted and then manufacturing and transportation take place. All these activities require energy and can be hazardous to the environment, especially with regards to environmental pollution emitted during the manufacturing process. The extraction of minerals causes a significant reduction in the energy of our planet's natural stock, which is mainly concentrated in iron ore (63% of the total minerals), followed by aluminium (24%), and copper (6%) (Valero, Valero & Mudd, 2009).

The life cycle focus must help decision-making when selecting the best technology available and minimising the environmental impact of the buildings through their design or refurbishing. Often products that are presented as cheap in the medium term can have high maintenance or waste management costs, and highly technological products can have very high production costs that are never recouped (Bribián, Capilla & Usón, 2010). This can vary depending on the location. In a study by Sartori & Hestnes (2007) on different buildings located in 9 countries (including Sweden, Germany, Australia, Canada and Japan), it was found that the proportion of embodied energy in materials used and life cycle assessed varied between 9% and 46% of the overall energy used over the building's lifetime when dealing with low energy consumption buildings (with good insulation, adequate orientation, passive conditioning, etc.) and between 2% and 38% in conventional buildings. In these studies, the lifetime variations presented significant differences in each country. Variations ranged from 30 years to 100 years depending on the country and type of building. It was noted that the wide range in results was due to the variety of buildings, materials, the lifetime considered and the geographic and climatic conditions.

It is also found that in South Africa the production of cement is responsible for approximately 90% of the greenhouse gas emissions associated with concrete production (GBCSA, 2014). The Green Star SA rating tools give credits towards the use of renewable building materials such as timber. Credits are also awarded towards use of materials that have been manufactured by constituents whose manufacturing processes have limited hazardous impact on the environment. The aim of the rating tool is to limit the environmental impact of building materials by reducing the quantities of virgin building materials and choosing the least harmful when selecting virgin building materials. Preference in the tool is given to re-used materials and it encourages designs that prolong the useful life of existing products and materials. However, as indicated in the GBCSA (2008), the Green Star SA tool does not emphasize the performance of the materials with regards to energy efficiency.

2.8.6 Building materials used for building envelope components: Properties and performance

The building envelope is characterized by the opaque components, and transparent components / fenestrations. If the provision of high-performance envelope and the reduction of energy used for services are significant factors in the design of low energy buildings, then understanding properties of constituent parts that make-up of the building, is vital in the design of these buildings types. Type of materials used for building components can affect the buildings thermal transmittance (U-factors), which is the use of thermal mass and control of solar heat gains. ASHREA, et al (2011) note that the term thermal mass refers to the building's thermal capacitance- the amount of heat that is required to raise or lower the building temperature by a fixed amount. Greater thermal mass tends to reduce building peak conditioning loads by spreading these loads over an extended time span. Building thermal mass can reduce total conditioning loads if, across the daily cycle, exterior temperature conditions are both above and below the desired interior temperatures (ASHREA, AIA, IESNA, USGBC & DOE 2011).

2.8.7 Envelope components: Façade (walls and windows)

2.8.7.1 Walls

Yu et al (2013), explain how the building envelopes are the interface between indoor and outdoor environment which affect the indoor heat gain and heat loss in the design of sustainable buildings. Walls are a predominant fraction of building envelope and are expected to provide thermal and acoustic comfort within a building, without compromising the aesthetics of the building (Yu et al., 2013). When considering construction materials, there are two main categories, namely high thermal mass and low thermal mass. The first category of materials with high thermal mass are cement blocks, bricks and other solid masonry materials. These materials absorb heat from solar radiation at a slower rate and are very effective in countering rapid heat transfer. For example, Aldous (2013) indicated that even though the Department of Environmental Affairs (DEA) building in Pretoria used the HVAC system, the building structure was comprised of high thermal mass to assist the HVAC system by reducing its morning cooling loads. This is made possible by the ability of the building to utilize the thermal mass of its concrete structure to store the rapid heat gains, thus limiting the energy requirement of the mechanical cooling system (Aldous, 2013). The second category includes materials of low thermal mass such as timber and steel. These materials not only absorb heat quickly but also release it quickly (Mirrahimi et al., 2016). Thus, mass of materials are important parameters that affect heat flow in construction materials. Asdrubali et al. (2014) note that the growing attention to energy savings in the building sector has led to higher performance walls characterized by very low values of thermal transmittance. This parameter describes the insulating capacity of a wall (Asdrubali et al, 2014).

To obtain the best results, low energy buildings or passive houses have to have high insulation levels (Baglivo et al., 2014). The thermal transmittance of opaque walls is the main parameter to assess building efficiency during the heating season, while during the warm period other parameters (above all mass and heat capacity) have to be taken into account because of the dynamic behaviour of the structure (Asdrubali et al., 2014). Low thermal transmittance (U-value) indicates a high thermal resistance, therefore Sadineni, Madala & Boehm (2011) note that the thermal resistance (R-value) of the wall is crucial as it influences the energy consumption of the building heavily, especially in high-rise buildings where the ratio between wall and total envelope area is high (Sadineni, Madala & Boehm, 2011).

Al-Sanea et al. (2016) who was engaged in the determination of optimum R-values for building walls under different climatic conditions, noted that high energy efficiency buildings in North Europe adopt the technology of multi – layered walls. Structural materials of low density and thermal isolation are used to achieve very low and steady thermal transmittance. The study also determined that in hot and dry conditions thickness of insulation materials are significant in obtaining optimum R-value. Asdrubali et al. (2014) studied the actual performance of a theoretical calculated U-value with in situ thermal transmittance measurements. The results of the investigation indicated that the in situ thermal transmittance measurements and the theoretical calculated U-value are not in perfect agreement. Wong and Baldwin (2016) determined that the application of a double-skin green façade to high-rise residential buildings in Hong Kong was significant in creating a comfortable indoor environment and reducing energy consumption of air-conditioning and reducing carbon dioxide emissions.

The use of common walls and other types of advanced building wall designs can be applied to improve the energy efficiency and comfort levels in buildings. The following are examples:

Ventilated or double skin walls

An air gap between two layers of masonry walls braced with metal ties constitutes a ventilated or double skin wall. They are also called cavity walls. A typical summer cooling energy saving of 40% can be achieved with a carefully designed ventilated wall (Sadineni, Madala & Boehm, 2011).

Lightweight concrete (LWC) walls

Lightweight concrete (LWC) refers to any concrete produced with a density of less than 2000 kg/m³. The thermal resistance of lightweight concrete can be improved by mixing with lightweight aggregates from natural materials such as pumice, diatomite, expanded clay or expanded shale. Autoclaved aerated concrete (AAC) is a type of LWC produced by introducing aluminium powder to generate miniscule air bubbles. It has superior thermal resistance than other types of LWC. AAC was first introduced in the early 20th century in Europe and it is gaining popularity as exterior and interior wall material as an alternative to clay bricks in recent years in developing countries (Sadineni, Madala & Boehm, 2011).

2.8.7.2 Windows

Windows are regarded as one of the most important building components, and are acknowledged for their positive influence on the health and well-being of building occupants (Mangkuto et al, 2016). Mangkuto et al. (2016) also noted that in the design phase, contradictions often occur when trying to maximise daylight penetration and view, which usually translates to applying large windows, while trying to minimise energy consumption, which usually translates to applying small windows. The International Energy Agency (2013) has indicated that in a typical office building, artificial lighting consumes the bulk of energy, followed by cooling- and heating operation. Fenestrations play vital roles in providing thermal comfort and optimum illumination levels in a building. They are also important from an architectural standpoint in adding aesthetics to the building design. In recent years, there have been significant advances in glazing technologies. Ke, Yeh and Jian (2013) noted that window glazing plays an important role in energy performance and has a significant effect on the overall building energy consumption. Heat flow through a glazed window contributes to the heat gain due to incident solar radiation, which eventually increases the cooling load (Ke, Yeh & Jian, 2013). Krarti, Erickson and Hillman (2005) noted that transmittance of the glass profoundly affects the efficiency of daylight which induces energy savings. When glazing transmittance is reduced, lighting energy savings is also reduced. Tinted windows help in energy savings and are linearly dependent on window area, which is dissimilar to the diminishing returns behaviour of higher transmittance glazing (Krarti, Erickson and Hillman, 2005).

Thermal performance of windows fundamentally hinges on its U-value which represents the heat loss coefficient. In other words, the thermal performance improves when the U-value becomes lower, and this can be achieved in different climate conditions through different means such as adding more glazing layers, applying special coatings to control solar radiation, and avoiding gaps between two layers with low thermal conductive gases such as argon or krypton (Arasteh et al. 2004; Al-Saadi, 2006). In a simulation study by Singh and Garg (2009), carried out on 10 different glazing types applied to five different climatic zones in India, it was observed that the annual energy savings by a window is dependent on not just the thermal conductivity (U-value) and the solar heat gain coefficient (SHGC or g-value) of the window, but also on its orientation, climatic conditions and building parameters such as insulation level and floor area.

Glazing

Glazing can be considered as the most important part of fenestration products and it plays an important role in energy use in buildings. This is especially true when calculating the U-value of a window, as the glazing which nearly always covers the largest area of the constituent parts, greatly affects the overall U-value (Gustavsen et al., 2008). The type of glazing also influences the U value. In this context the types of glazing, glazing materials and glazing technologies used in buildings are discussed below.

Multilayer Glazing

The most common glazing that gives a low U-value is triple glazing. Typically, this is with a gas fill of either argon or krypton, with krypton producing lower U-values with less cavity or fill thickness and volume (Jelle et al., 2012).

Suspended Films

There are some products on the market that offer a variation on the more common multilayer glass with gas fill method. These incorporate 'suspended coated films' (SCF) or only 'suspended films' in-between the outer and inner panes, which act as a third or fourth 'glass pane'. These films can reduce the weight of the window and may also allow for a larger gas cavity thickness in the same window cavity than ordinary multilayer glazing, due to the films being thinner than a glass pane (Jelle et al., 2012).

Aerogel glazing

This type of glazing can be formed from a variety of materials, including silica, alumina, lanthanide and transition metal oxides, metal chalcogenides, organic and inorganic polymers and carbon. Aerogel glazing entered the contemporary glazing market in the year 2006 and is, essentially, a granular aerogel encapsulated between polycarbonate construction panels that weigh less than 20% of the equivalent glass unit and have 200 times more impact strength. Light transmission and U-value of aerogel panels are a function of panel thickness. Their high performance, low density and outstanding light diffusing properties make them an appropriate choice for roof-light applications (Baha, James & Jentsch 2008).

Vacuum glazing

Vacuum space is created between two glass panes to eliminate the conductive and convective heat transfers between the glass panes, reducing the center-of-glass U-value to as low as 1W/m2 K. Most often, low-e coating is applied on one or both of the glass panes to reduce the re-radiation into the indoor space (Baha, James & Jentsch, 2008). According to Sadineni, Madala & Boehm (2011), though the technology faces some challenges in maintaining vacuum for longer periods, it is still a widely used energy efficient glazing option.

Low-emissivity coatings

Low-emissivity (low-e) coatings are typically metals or metallic oxides and can be categorised into hard and soft coatings. Hard coatings such as pyrolytic deposited doped metal oxides, are on-line coatings, i.e. they are applied as part of the float line production. They are more durable than soft coatings and can be toughened. Soft coatings usually consist of dielectric-metal-dielectric layers and are most often off-line coatings, i.e. they are applied to individual glass panes after manufacturing. The best process of applying soft coatings is magnetron sputtering. Soft coatings have higher infrared reflection and are more transparent than hard coatings, but require extra protective layers due to their lack of durability (Hammarberg & Roos, 2003; Del Re et al., 2004; Chiba et al., 2005; Reidinger et al., 2009; Jelle et al., 2012).

Smart windows

Smart windows have already been researched for some decades and today the first commercial products are emerging onto the market. The windows can change solar factor (SF) and transmittance properties to adjust to outside and indoor conditions, thus reducing energy costs related to heating and cooling. Smart windows can be divided into three different categories: (thermo-, photo- and electro-) chromic materials, liquid crystals and suspended particle devices (Baetens et al., 2010; Jelle et al., 2012).

Solar cell glazing

Recent developments in technology have enabled solar energy collection from transparent glass. The technology involves spraying a coating of silicon nanoparticles onto the window which work as solar cells (Sherer, 2008; Lewis and Jiang, 2009; Jelle et al, 2012). Windows with the capability to produce electricity highlight the alternative uses of windows and have as such a lot of potential in the building industry (Jelle et al, 2012).

Glazing cavity gas fills

According to Jelle et al. (2012), between the extremities of vacuum and aerogels, there is normally a gas between the glass panes in a window. Naturally, the traditional and also cheapest gas has been common air. As air has a rather high thermal conductivity of about 26 mW/(mK) at room temperature and atmospheric pressure, the noble gas argon (Ar) with a thermal conductivity around 18 mW/(mK) is commonly used as a gas fill in the present day fenestration products. The noble gases krypton (Kr) and xenon (Xe) offer considerably lower thermal conductivities, i.e. about 9.5 mW/(mK) and 5.5 mW/(mK) respectively, offering even lower U-values and thinner glazing units than with argon. However, as the costs of krypton and especially xenon are very high, these gases are not generally used these days. Optimum glazing cavity thicknesses with respect to the different gases, their costs and the number of panes may be found, where thickness restrictions or limitations of the glazing unit may also play a role (Jelle et al., 2012).

Walls and windows form part of the building façade. Jelle et al. (2012) indicated that façade factors related to energy performance are thermal quantities (e.g., U-value) and solar heat gain quantities (e.g., solar heat gain coefficient (SHGC). These are important façade – or wall and window quantities to consider in the reduction of energy consumption in buildings. According to Lomas (1992), the heat flux coefficient, which is defined as the product of the density, thermal conductivity and specific heat capacity, quantifies the ability of the material to absorb heat. It has been found to reflect the influence on thermal comfort of different surfaces and is therefore used as the basic thermo-physical property for defining the materials.

2.8.8 Envelope components: Roofs

Roofs account for large amounts of heat gain / loss, especially in buildings with large roof areas such as auditoriums, lecture theatres, exhibition halls, etc. Roof shading is one way of reducing the impact of solar radiation on the roof surface. Economical roof shading is usually achieved with local material such as terracotta tiles, hay, date palm branches, inverted earthen pots, etc., which can usually contribute to a 6^0C drop in the indoor temperature (Sanjay & Prabha, 2008). The use of roof coatings is another way to mitigate the impact of solar radiation on the roof surface. High solar reflectance and high emissivity are the respective daytime and night-time factors that govern the selection of a roof coating. A cool coating can reduce the surface temperature of a white concrete roof by 4^0C during a hot summer day and by 2^0C during night (Sanjay & Prabha, 2008). Roofing systems in South Africa include the use of clay or concrete tile roofing, reinforced concrete slabs, or lightweight aluminium – and their usage depends on function. In more recent years, thermal roof insulation systems, Photovoltaic roofs, Green roofs and other more advanced roofing systems have become more significant.

2.8.8.1 Thermal roof insulation systems

Sabouri (2012) noted that there are many types of roof insulation materials like the reflective (such as aluminium foil) types which have low thermal emittance; and the resistive (poly- urethane) types. An average of as much as 60% of the thermal energy leakage occurs through the roofs. Thus, roof insulation has the potential of saving both cooling and heating loads. Polystyrene or polyurethane insulation layers have the capability of reducing the load by more than 50% when compared to an identical roof without insulation (Sanjay & Prabha, 2008).

2.8.8.2 Photovoltaic roofs

Building integrated PV (BIPV) offer an effective solution by the use of building surface area while facilitating energy production and building envelope weather protection. PV roof tiles replace roofing material and are installed directly onto the roof structure. Ceramic tiles or fibre-cement roof slates have crystalline silicon solar cells glued directly on them. Another type of roof-integrated system has a PV element (glass/glass laminate) positioned in a plastic supporting tray anchored to the roof (Sadineni, Madala & Boehm, 2011). In South Africa, the use of PV – particularly for hot water heating – has become more common in recent years. For example, the DEA building incorporated the largest roof top mounted PV systems in South Africa on a commercial building. It utilizes both high efficiency solar-thermal systems for hot water and photovoltaic for direct electrical energy production (Aldous, 2013).

2.8.8.3 Green roofs

A roof of a building that is either fully or partly covered with a layer of vegetation is called a green roof. It is a layered composite system consisting of a waterproofing membrane, growing medium and the vegetation layer itself. The green roofs not only reflect the solar radiation, but also act as an extra thermal insulation layer (Sadineni, Madala & Boehm, 2011). Green roofs shade the underlying building. This benefit applies primarily to the summer season, when energy is needed to cool the building. The foliage absorbs radiant energy from the sun and prevents that energy from reaching the roof surface. Green roofs also reduce heat transfer through advection. Advection occurs when air movement causes thermal transfer. The higher the velocity of air movement, the greater the thermal transfer. This phenomenon is often attributed to wind chill during the winter months. However, advection can occur during the summer months as well, having warm air continuously introduced to the building (Roofscapes, 2006). Green roofs provide some benefit as simple insulators when the growing medium is dry. It is important to note that green roofs are not good insulators and the real thermal benefit of green roofs comes from their ability to act as heat capacitors, absorbing and releasing energy, and to act as latent heat managers (Roofscapes, 2006). For instance, the V&A WATERFRONT project in Cape Town utilizes a green roof that contributes to thermal roof insulation and storm water retention (GBCSA, 2015)

2.8.9 Envelope components: Insulation

Thermal insulation is a material or combination of materials, that, when properly applied, retard the rate of heat flow by conduction, convection and radiation. Appropriate application of thermal insulation in the building envelope is the most effective method to reduce the rate of heat transmission and energy consumption for the cooling and heating of the internal space (Thani, Mohamad & Idilfitri, 2012). Thus, insulation reduces heat loss through a wall by reducing the thermal transmittance (U-value). When buildings are properly thermally insulated, the annual cooling load and peak cooling demands for buildings in hot dry and hot humid regions can be significantly reduced (Wagner & Zalewski, 2009).

Al-Homoud (2005) noted that the amount of heat loss through walls is frequently speculated and figures ranging between 10% and 45% are commonly quoted. There is no average value and actual heat loss depends on countless variables including wall surface area, age, composition, condition and construction technology. However, the application of insulation to walls and the resulting reduction in thermal conductivity should significantly contribute to an overall improvement in the energy performance of a building. The magnitude will depend on several variables such as building type, climatic conditions and performance of insulation materials. Thani, Mohamad and Idilfitri (2012) additionally noted that the thickness of insulation material used is one of the most important aspects in building design because thick insulation material means less internal space.

The thermal conductivity and thermal inertia are practically the most important factors that affect the selection. The increase in temperature and moisture content of the thermal insulation increases its thermal conductivity, thereby degrading its performance. According to Sadineni, Madala & Boehm (2011), the thermal insulation is available in different physical forms such as:

- Mineral fibre blankets: batts and rolls (fiberglass and rock wool).
- Loose fill that can be blown in (fiberglass, rock wool).
- Poured in or mixed with concrete (cellulose, perlite, vermiculite).
- Rigid boards (polystyrene, polyurethane, polyisocyanurate and fiberglass).
- Foamed or sprayed in place (polyurethane and polyisocyanurate).
- Boards or blocks (perlite and vermiculite).
- Insulated concrete blocks and insulated concrete form.
- Reflective materials (aluminium foil, ceramic coatings).

2.8.10 Selection of building materials to improve performance

According to Thornton et al. (2009), energy conservation measures (ECMs) that might be applied during the schematic design phase, include the selection of materials. It was noted that typical exploratory interdisciplinary discussions during this phase include the following:

- Selection of structural material and its relative use as thermal mass or thermal insulation.
- Selection of internal wall finish type and its potential to absorb internal heat gains.
- Selection of floor material type and finish and its potential use as an air-distribution, heating or cooling device.
- Selection of façade type, orientation, relative proportion of each face and performance of glazing and opaque wall insulation.
- Selection of glazing visible transmittance (VT) versus solar heat gain coefficient to allow daylighting without overheating.
- Configuration of roofing shape/slope/direction and applicability of cool-roofing materials, clerestory skylights, and/or installation of photovoltaic or solar hot water panels.
- Selection of electric lighting approach and zoning compatibility to accommodate ambient versus task lighting, occupancy sensors, daylight harvesting, and time-of-day controls.
- Commitment to ENERGYSTAR equipment for plug-load usage reduction.
- Review of plug-load use intensity by the owner's personnel.
- Review of alternative HVAC and comfort cooling systems.

As a conclusion to the discussions, the design team usually identifies a certain number of ECMs that they wish to pursue as optimizations imposed on the base case. (Thornton et al., 2009).

2.9 Effects of indoor environmental quality (IEQ) on energy efficiency

As indicated in the Green Star SA Public and Education rating tool (Table 1.1), there are many sub-categories associated with IEQ. They include – but are not limited to – ventilation, carbon dioxide levels, external views, thermal comfort, daylight, and hazardous materials (GBCSA,2014). As previously discussed in section 2.5.1, architects make many crucial decisions that can affect the energy use of proposed buildings. Important decisions regarding daylighting, reflectivity of other surfaces, natural ventilation potential for cooling, glazing types, shading devices, fenestration size, operable window sizes, daylight harvesting and other important decisions that affect building envelope design, have significant impact on the IEQ (ASHREA et al., 2011). As indicated in Figure 2.2, building envelope design is affected by building form, size and materials used, which determines the IEQ conditions.

TC, ventilation and daylight (sub-categories of IEQ) can affect the overall influence of IEQ on the occupants of a building and how much energy the building consumes. Maximizing the provision of adequate IEQ whilst minimizing energy consumption is important to achieve a sustainable building. There are several studies that have contributed to research on IEQ, particularly concerned with relation of TC and Indoor Air quality (IAQ) to Energy Efficiency (EE). These studies include Davanagere et al. (1997), who studied the effect of the new ASHRAE-62 IAQ requirements for school buildings on life cycle costs when using different HVAC systems. But, this study did not address the architectural or construction features of the building. Dorer and Weber (1999) noted the significance of an integrated evaluation of the energy and IAQ response of a multi-storey school building, but addressed only two specific features: natural night, which was achieved by natural stack airflow; and ventilation, provided by naturally driven shaft ventilation through the façade spaces. Becker and Paciuk (2003) observed the improved effect on total energy loads of various IAQ, ventilation and night ventilation schemes, enabled by utilizing the buffering effect of an existing central atrium, but did not address their impact on electricity consumption. According to the GBCSA (2015), comfort in the DEA building was addressed through inclusion of high performance double glazing – improving the thermal performance of the space as well as providing significant improvement in the reduction of indoor noise levels and acoustic disruptions. Becker, Goldberger and Paciuk (2007) addressed the effects of thermal comfort and indoor air quality on energy efficiency in school buildings, but did not address lighting or building materials.

2.9.1 IEQ: Thermal comfort

Mirrahimi et al. (2016), indicated that the range of thermal comfort with regards to outside climate conditions, ethnic factors and adaptive behaviour of occupants can be determined. These factors have been thoroughly described in different building standards. The American Society of Heating Refrigerating and Air Conditioning Engineers (ASHRAE) Standard 55 and the ISO Standard 7730 define thermal comfort as the condition of mind which expresses satisfaction with the thermal environment. The American ASHRAE Comfort Standard 55 and the International ISO Standard 7730 are considered as standard tools for the evaluation of thermal comfort levels by means of the thermal predicted mean vote (PMV) and the predicted percentage of thermally satisfied (PPS) occupants in the vicinity of neutral thermal sensation; and for different combinations of hygro-thermal conditions and personal factors (Becker & Paciuk, 2003). The Green Star SA manual notes that the sensation of comfort is based on a wide range of parameters which include air temperature, humidity, air movement, clothing levels and metabolic rates.

Using natural ventilated spaces to achieve thermal comfort, the Green Star SA rating tool awards points to designs that comply with internal temperatures within the ASHRAE standard 55-200. Maximum points are awarded for acceptability limits of at least 98% of occupied hours during the year.

In mechanically ventilated spaces maximum points are awarded if predicted mean vote (PMV) levels – calculated in accordance with ISO7730 using standard clothing and metabolic rate values – are within the following limits for at least 98%:

- PMV levels of between -1 and +1
- PMV levels of between -0.5 and +0.5 (maximum points awarded)
- In mechanical ventilated spaces the following criteria are vital to achieve standards:
- Dry bulb temperature ranges of 20 to 24 degrees
- Mean radiant temperatures within the range of 20 to 27 degrees or shading is provided to meet credit criteria
- IEQ glare control
- Relative humidity within the range 40% to 60%
- Air velocity of not more than 0.2m/s (GBCSA, 2008)

In its Adaptive Comfort Temperature (ASHRAE 55-2004), ASHRAE defines a range of temperatures which are deemed to be comfortable for a naturally ventilated space where occupants have control over openings. These depend on outside air temperature based on the fact that people living in warmer areas can tolerate higher internal temperatures than those in colder areas. In the range of temperatures, a mean outdoor temperature is indicated, which determines the range of the minimum and maximum indoor temperature. Table 2.2 presents an example where the outdoor temperature is 10 degrees centigrade, the standard temperature for indoor comfort ranges between 10-24.5 degree centigrade (GBCSA, 2008).

Table 2.2 Outdoor temperature and recommended indoor temperature by ASHREA

Mean monthly outdoor temp ºC	Min internal (80% acceptability) ºC	Min internal (90% acceptability) ºC	Max internal (90% acceptability) ºC	Max internal (80% acceptability) ºC
10	17.5	18.5	23.5	24.5
15	19	20	25	26
20	20.5	21.5	26.5	27.5
25	22	23	28	29
30	23.5	24.5	29.5	30.5

(Source: GBCSA, 2008)

According to Harvey (2009) the thermal envelope refers to the shell of the building as a barrier to the transfer of heat between the inside and outside of the building. The effectiveness of the thermal envelope depends on (1) the insulation levels in the walls, ceiling and other building parts; (2) the thermal properties of windows and doors; and (3) the rate of uncontrolled exchange of inside and outside air which, in turn, depends in part on the air tightness of the envelope (Harvey 2009).

2.9.2 IEQ: Ventilation

The energy used by natural ventilation is minimal. Passive ventilation strategies for natural heating/cooling in building design is one of the most economical yet effective ways to minimize the need for mechanical heating/cooling systems. These strategies include:

- Proper window placement (also doors as they comprise a large part of the exterior building envelope and have a major impact on the human activities inside the building and on energy use)
- Daylighting design
- Selection of appropriate glazing for windows and skylights
- Proper shading of glass when heat gains are not desired
- Use of light-coloured materials for the building envelope and roof
- Orientation decisions, etc.

  By integrating these principles into building design, demand for energy may be reduced significantly (Lun and Ohba, 2012).

The GBCSA (2008) indicated that reductions in energy consumption can easily be achieved by reducing the amount of fresh air delivered to occupants, but this would be at the expense of the occupant's comfort and wellbeing (GBCSA, 2008). The best overall Green Star rating is obtained by balancing the requirements for achieving good IEQ while also concentrating on reducing energy usage. LEED and Green Star SA have adopted IEQ standards from the American Society of Heating, Refrigeration and Air-conditioning Engineers (ASHRAE); these are used extensively in the determining standards for good IEQ. IEQ is also a critical element of healthy buildings. Poor IEQ is considered to be the principal cause of sick building syndrome, which according to scientific research has a substantial price tag in lost productivity and even more in health sector costs (GBSA, 2008).

Becker, Goldberger & Paciuk (2007) noted that in warm and moderate climates during summer, whenever external temperatures are lower than the required indoor temperature, ventilation can remove the excessive heat load produced by both incident solar radiation and internal sources, thus allowing the achievement of comfortable indoor temperatures. However, whenever external temperatures exceed the required comfort level temperature, active mechanical cooling must be provided. The GBSA technical manual (2008) indicates minimum permissible rates for ventilation. The minimum ventilation rates are specified to cater for general contaminants such as body odours, volatile organic compounds, etc. They are expected to be contained at concentrations below levels that have potential to cause adverse health effects to a substantial majority of occupants (GBSA, 2008).

Minimum standards are set in accordance with SANS10400-O, where points are awarded for naturally ventilated spaces. In such spaces, it is demonstrated that 95% of usable area are naturally ventilated and buildings provide a minimum of 5% open able area (GBCSA, 2014). In mechanically ventilated spaces Green Star encourages the use of outside air rates that surpass available standards in SANS 10400-O, and use of HVAC systems that are clearly sized to accommodate the increased outside air rates. In spaces where both natural and mechanical means are used (mixed-mode), buildings should satisfy criteria for both naturally ventilated and mechanically ventilated spaces (GBCSA, 2014). Thus, there is a need to strike a balance between providing adequate outside air in recirculation systems to dilute contaminants and the loss/gain of heat with the resulting increased energy consumption needed to maintain comfort levels.

2.9.3 IEQ: Lighting in buildings

Use of fossil fuel for lighting, cooling and heating buildings produce CO_2, which consequently causes environmental degradation. Buildings consume a large amount of energy for lighting and consequent space cooling (Ochoa & Capeluto, 2006). Heschong (1999) noted that economic potential of daylight is achieved not only by saving energy, but also by increasing workers' productivity in offices, factories, schools and retail premises. Ochoa, & Capeluto (2006) indicated that artificial lighting is the main light source, leading to greater use of air conditioning and ventilation systems in order to remove the associated heat. Energy used for lighting accounted for up to a third of electricity consumed in office buildings. This is a contrasting situation because favourable natural lighting conditions are present during working hours and throughout the year (Ochoa & Capeluto, 2006).

Over the last three decades, several measures have been considered to reduce electricity use associated with artificial lighting. The use of compact fluorescent lamps, installation of occupancy sensors, and better design strategies to minimize the number of fixtures are commonly utilized energy efficiency measures. These measures can achieve substantial energy and cost savings for both new and retrofitted buildings. Though beneficial, these measures require the continuous use of artificial lighting to illuminate buildings (Krarti, Erickson & Hillman, 2005). For example, the GBCSA (2015) noted that energy saving measures utilized in the design of the DEA building in Pretoria, included optimization of orientation to maximise daylight in the building.

According to Edmonds and Greenup (2002), problems associated with using daylight in hot climate regions are that daylighting is not the main concern in building design as the main concerns are to reduce heat gain, glare and direct light inside a building. Therefore, in order to reduce heat gain and glare, shading devices and small openings are considered to be the main features of buildings designed to control the excessive penetration of directional sunlight. For example, the principal objective of subtropical window design is thermal comfort in summer, generally requiring the exclusion of sunlight from interior spaces (Edmonds & Greenup, 2002). Hence, the objective of an appropriate daylighting system in tropical and subtropical areas, is not only to provide the building with ambient daylight, but also to do so without the associated problems of glare or undesirable heating of the building (Edmonds & Greenup, 2002).

2.9.4 Effect of daylight on IEQ

The exploitation of daylight is recognised as an effective means to reduce the artificial lighting requirements of nondomestic buildings. In practice, however, daylight is a greatly under-exploited natural resource (Nabil & Mardaljevic, 2006). As an alternative to artificial lighting, daylighting offers a lighting source that most closely matches human visual response and provides a more pleasant and attractive indoor environment. It is reported that daylighting improves student performance and health in schools (Plympton, Conway & Epstein, 2000). On the other hand, according to Nabil & Mardaljevic (2006), real daylight illuminances across the workplace exhibit cause large variations both spatially and temporally. For example, daylight illuminances typically diminish rapidly with increasing distance from windows. Equally, daylight illuminances at a point can vary greatly from one moment to the next due to changing sun position and/or sky conditions. If the daylight illuminance is too small (i.e., below a minimum), it may not contribute in any useful manner to either the perception of the visual environment or in the carrying out of visual tasks. Conversely, if the daylight illuminance is too great (i.e., above a maximum), it may generate visual or thermal discomfort, or both. Nabil & Mardaljevic (2006) call illuminances that fall within the bounds of minimum and maximum, useful daylight illuminances. This is important in understanding the use of daylight, particularly in how to maximise the use of daylight in a way that is comfortable for users.

It is acknowledged that there is a large range of lighting conditions over which the human eye performs satisfactorily, and that there is a large range of variation among individuals as to what comprises satisfactory visual conditions (Vine et al, 1998; Selkowitz, 1999). Useful daylight illuminances are defined as those illuminances that fall within the range of 100–2000 lux. The range used to define the limits of useful daylight illuminance is based on a comprehensive review of the latest data from field studies of occupant behaviour under daylight conditions (Nabil & Mardaljevic, 2006).

The UK Chartered Institution of Building Services Engineers (CIBSE) Code for Interior Lighting recommends that offices should have a design illuminance level of 500 lux. A design illuminance of 500 lux is, in fact, commonplace throughout much of the developed world. Consequently, electric lighting is usually designed to deliver 500 lux of (artificial) illuminance evenly across the workplace. When sufficient daylight is available, electric lighting may be reduced, or switched off

altogether by either the occupants themselves or some control mechanism (Nabil & Mardaljevic, 2006).
The GBCSA (2008), notes that international researchers have found that students studying in environments with natural light have better attention rates, are less prone to being distracted or disruptive and enjoy better health than fellow students in artificially lit rooms (GBCSA, 2014). Daylight is also accepted as beneficial because of improvement in the internal environment and saving on energy used for artificial lighting. However, there are problems that occur with natural light, which include glare, thus the GBCSA requires that buildings should be designed to eliminate all direct sun penetration.

The guidelines provided by the GBCSA (2014) to improve the daylight illumination include points awarded any of the following:

- Percentage of a usable area (UA) that has a measured daylight factor of at least 2% at desk-height level under a uniform design sky,
- The percentage of UA that has daylight luminance of (DI) at least 250 lux as measured at finished floor level (FFL) under a uniform design sky
- The percentage of UA that has a Daylight Illuminance (DI) of at 300 lux, based on an annual dynamic simulation model, for 50% of the standard occupied hours (Daylight Autonomy incremental method)

The GBCSA (2014) provides points for increase in daylight illumination. The higher the amount of illumination provided for usable areas, the more the points obtained. Minimum points are given for 30% illumination and maximum points are given for 90% illumination. These percentages reflect the importance of increasing the natural illumination in buildings which fosters use of lower levels of artificial lighting, thus reducing energy use particularly during the daytime periods (GBCSA, 2014).
The GBSA (2008) also noted that in order to improve illumination, reflectance of light within the internal environment is vital. The methods prescribed by the GBSA to improve reflectance, include that the reflectance values in the interiors of buildings be indicated. Standard minimum values range from 0.3 for floors (assumes a light coloured carpet) to 0.8 ceilings (assumes a white paint).

2.9.5 Effect of daylight on energy consumption

Utilizing daylight is another way of improving indoor environment quality and reducing building energy consumption. Daylight devices such as light wells, light shelves and different types of windows were investigated with numerical modelling and experimental measurement (Wong et al., 2008). Daylight is used not only for energy saving and protecting the environment, but also for its positive effect on the health and psychology of occupants. It has the potential to improve human health, mood, performance and productivity (Freewan, Shao & Riffat, 2009).

Energy consumption can be reduced with regards to the natural lighting methods used in the Green Star rating tool, depending on the function of the building. Maximising the use of natural light can reduce consumption of electricity with regards to reduction in the use of artificial lighting within the building. In addition, Green Star gives credits for the use of energy saving lighting appliances such as the use of high frequency ballasts. The Green Star rating tool demonstrates that the various parameters including building form, size of openings, materials and air conditioning systems can influence the energy use in a building. Okba (2005) noted that the building façade – such as walls, roof as well as all openings like windows – play an important role in controlling air flow and they help to maintain the indoor air via a combination of fresh outdoor air with indoor air. The proper façade design can definitely reduce the overall cooling load and decrease the use of air-conditioning (Okba, 2005). An important metric of the characteristics of a façade is the window-to-wall ratio (WWR) which is the proportion of glazed to opaque façade area. This ratio is a significant contributor to the solar heat gain and energy consumption of a facade (Aksamija, 2013). The methodology of determining the most appropriate input for any of the specific parameters can be demonstrated using modelling (GBCSA, 2014). Control measures are important in ensuring adequate interior lighting. For instance, Aldous (2013) noted that the DEA building incorporated extensive lighting controls that featured occupancy sensing, continuous dimming and addressed lighting components. Photometric based control was achieved by integration with a building management system.

2.10 Building services

As indicated in Figure 2.2, basic building envelope design and use of passive strategies for heating and cooling can affect the type of services a building is used for. The energy loads a building uses for mechanical means to compensate for heating or cooling can be reduced if passive means are maximized. However, the specific building function may require mechanical means for cooling or heating. Mirrahimi et al. (2016) noted that using a poorly designed building envelope will cause higher consumption besides relinquishing thermal comfort. Simply stated, the design of the building envelope affects energy consumption. Building envelopes reduce energy consumption by protecting the interior from direct solar radiation penetration while reducing glare, minimizing water penetration, providing natural ventilation, and reducing external reflection (Mirrahimi et al. 2016).

2.11 Water Use Efficiency (WUE)

Urban infrastructure – particularly water supply, sanitation, drainage and solid-waste management – is essential if improvement is to be made to the urban environment (Choguill, 1996). The relationship between the urban area and hinterland involves the flow of resources – including water – into and out of the city. In his book '*Cities as Forces for Good in the Environment*', Beck (2011) notes that the city, like a large grazing animal, takes in its daily grass and daily water – but unlike the animal and for unsustainable reasons – we have engineered the return of the residuals of this metabolism to the air, water, and land environments surrounding the city. Beck also notes that most cities in industrialized countries were designed with urban water infrastructure for the purpose of delivering healthy drinking water and to prevent the spread of disease; where residuals are treated as waste to be disposed of and are not considered as resources to be used to replenish the environment. He therefore argues that cities can be re-engineered to both maintain a healthy supply of drinking water whilst replenishing the surrounding environment with their residuals which contain important nutrients of carbon, nitrogen and phosphorus (Beck, 2011; Beck et al., 2012). Thus, in order to improve performance of the city infrastructure, there is a need of maximizing the use of resources that flow through the city, the efficiency of city infrastructure. This includes efficiency of buildings in the use and consumption of water and the appropriate engineering for the supply of potable water and re-use of its residuals in the surrounding hinterland.

2.11.1 Water efficiency in design of sustainable building infrastructure

In South Africa, water has long been considered a precious high-demand resource that is essential for living things. South Africa falls in a region with low unreliable rainfall and therefore potable water sources do not get adequate annual replenishment from rainwater (GBCSA, 2008).

In design of high-performance buildings, achieving water efficiency is particularly important in countries that have unreliable rainfall or problems with limited availability of water. The Green Star SA rating tool encourages and recognizes designs that reduce water consumption by building occupants and credits are given for the following factors, which enhance water service efficiencies:

- Fixtures that minimize water usage
- Use of rain water systems
- Re-use of grey water
- Black water treatment and re-use
- Installation of water meters for all major water usage
- Reduction of potable water for landscape irrigation
- Reduction of potable water used in heat rejection systems in air-conditioned spaces (GBCSA, 2014).

In addition to reducing the water demand, the Green Star SA rating tool aims to reduce operating costs of water usage in the building. Thus, the objectives are the simultaneous reduction of the impact of the use of water on the environment and the reduction of water consumption by buildings. The Green Star rating tool awards credits towards the minimization of the use of PVC pipes for plumbing within the building. Alternative materials such as Vitrified clay pipes suitable for underground sewage are recommended. Other recommended alternative materials include zinc, cast iron, copper and galvanised steel (GBCSA, 2014). In the DEA building in Pretoria, a rain water harvesting system, indigenous plants and efficient irrigation systems are utilized to reduce water consumption (GBCSA, 2015).

2.11.2 Efficiency of water usage and services

Lowering the overall urban water demand has recently become an important issue for water utilities and regulatory bodies. This could be achieved by a combination of different measures such as increasing the efficiency of water supply systems (lowering real losses), installation of water-efficient appliances, raising public awareness to water saving, and re-using water as a “new” alternative resource (Friedler and Hadari, 2006). When considering urban water re-use, on-site grey water re-use has the potential of playing a significant role. Many works have greatly contributed to knowledge by estimating the potential for potable water savings in buildings by using different strategies such as rainwater, greywater and water-efficient appliances, or combinations of these. Water services efficiency is considered in categories of water usage, water pipe length, plumbing and related accessories. The approach also considers sourcing of water beyond municipal supplies, this would include secondary non-potable water such as water from rainfall. Agudelo-vera et al (2012) refer to this as multi sourcing of water.

Besides, Liu & Ping (2012) note that water-saving retrofitting measures of existing buildings mainly include the following three aspects: the application of water-saving appliances and equipment, the treatment and re-use of recycled water. The collection and use of rainwater also enhance water use and services efficiency of both new and existing buildings (Liu & Ping, 2012).

Furthermore, Agudelo et al. (2009) noted that harvesting local resources that includes water also assist in enhancing water use efficiency. Local resources can be harvested in four ways, namely multi-sourcing, cascading, quality upgrading and recycling, and quality upgrading and closing loops (Agudelo et al., 2009). Multi-sourcing refers to harvesting primary and secondary resources that are locally available and renewable, e.g. harvesting of rainwater or solar energy. Though not a new technology, harvesting of rainwater has become an important means of preventing water wastage whilst adopting the use of a naturally available source of water. Cascading refers to harvesting remaining qualities of flows and re-using them for lower quality demanding purposes (Sirkin et al., 1994; Van den Dobbelsteen et al., 2007). Within this system cascading aims to reduce waste inputs and outputs. Cascading further aims to match qualities in demand of supply, by using low quality flows for low quality demand activities, e.g. using wastewater from the shower (grey water) to flush the toilets. Quality upgrading and recycling refers to on-site treatment for further re-use, e.g. grey water reclamation or using a heat pump to increase the temperature. Quality upgrading and closing loops refer to on-site treatment of a system which does not have inputs or outputs. However, quality upgrading implies resources and energy inputs and those should be powered by local non-fossil energy and sustainable materials.

Fixtures that minimize water usage

In a study by Liu & Ping (2012) it was noted that taps are the most widely used water appliances and that use of water saving taps can save about 20% -30% of the water consumed. The same study stated that whilst water consumption of toilets accounts for 30%-40% of the total daily water consumption, the use of water saving flushing devices can save about 25% of the water used for flushing toilets. Other affirmations made by the study are that the water consumption of a shower accounts for 20%-35% of the total water consumption of which savings of up to 30% can be attained depending on the type of water saving devices used for the showers

Harvesting of rainwater

Though not a new technology, harvesting of rainwater has become an important means of preventing water wastage whilst adopting the use of a naturally available source of water. According to Li et al. (2010) harvested rainwater and treated ground water can play a major role in substituting and/or supplementing water supply from the centralized water supply facilities. The potential of potable water savings can be substantial by using these water systems either separately or together. Rainwater harvesting would require more plumbing accessories and piping; however, it would reduce dependence on municipal supply of water (Li et al. 2010).

Treatment and use of grey water

Grey water is defined as the urban wastewater that includes water from baths, showers, hand basins, washing machines, dishwashers and kitchen sinks, but excludes streams from toilets (Ottoson and Stenström, 2003). Grey water treatment and re-use schemes have already been piloted in many countries around the world and are becoming increasingly commonplace in water stressed areas such as Australia and Mediterranean countries (Friedler and Gilboa, 2010; Masi et al., 2010; Pinto & Maheswari, 2010). The recycled water is usually used for flushing toilets, irrigating landscape and spraying roads. Liu & Ping (2012) noted that the amount of recycled water accounts for 60% -70% of the total amount of municipal wastewater. The treatment and re-use of recycled water is an effective way to increase the use efficiency of wastewater (Liu & Ping 2012).

Re-use of resources in black water

According to Agudelo-vera et al. (2012), secondary resources are important flows to consider because of increasing urbanization. Secondary resources are outputs from human activities that can be used as an input to other human activities. Examples of secondary resources are grey water or residual heat. Therefore, cities can be seen as producers of secondary resources (Agudelo-vera et al, 2012). One can also argue that other secondary resources are the residues from the human body deposited in the water as a result of the use of toilets in buildings. The materials that are needed in food for sustaining ourselves – nitrogen (N), phosphorus (P), carbon (C) and so on – pass through our bodies to the toilet and are then headed to some form of aquatic environment. Prior to comprehensive installation of toilets and sewerage, this was not naturally the case (Beck, Walker & Thompson, 2013). Thus should human excretion being transported in the sewerage system (previously regarded as pollutants to be disposed of at a cost), now be viewed as resources of carbon, nitrogen, phosphorus and other materials to be recovered it is necessary to view the carbon, nitrogen, phosphorus and other materials entrained into the water metabolism of the city (or buildings) (as a result of the WC) as pollutants to be rid of, at a cost, as resources to be recovered – with profit' (Beck et al., 2012).

Smarter water usage and energy efficiency

The provision of important means to maximize water usage could affect energy demand, because energy is required for pumping and treating water. Chueng, Mui & Wong (2013) presented an energy efficiency evaluation measure for water supply system designs and a mathematical model. The model was demonstrated to be useful for establishing optimal design solutions that integrate energy consumption into urban water planning processes, which cater to various building demands and usage patterns (Chueng, Mui & Wong, 2013). In this particular research, water supply is linked with energy efficiency and provision of IEQ.

2.12 Challenges of sustainable design for South African university neighbourhoods

As indicated in section 1.11, city infrastructure can become forces for good so that engineering infrastructure can add value as agents to repair, rather than being hazardous to the environment (Beck 2011). This indicates a link between the sustainability of cities and university neighbourhoods within these cities. From literature review it is noted that historically, the management of South African cities has been driven by the ideology of 'separate development' rather than by a concern to create a healthy, viable urban environment (Ramphele, 1991).

2.12.1 Historical challenges

According to Patel (2000) the stark juxtaposition of First- and Third World conditions in close proximity within the urban environment presents a range of environment and development challenges. The complexity and diversity of the urban milieu provide the full spectrum of environmental challenges, ranging from issues of production and consumption to industrial pollution and its effects on global systems, and to concerns of the brown agenda in areas that lack infrastructure and services (Patel, 2000). DEAT (2008) noted that South African cities are vital in efforts to curb the use of non-renewable resources, to reduce pollution and other forms of environmental degradation and to promote climate mitigation and adaptation because most were poorly designed from an ecological perspective and have large environmental impacts.

2.12.2 Challenges in new standards and financial constraints

As indicated in section 2.4, the study by Tramontin, Loggia and Trois (2012) noted certain flaws in the SANS 10400-XA: 2011 building standard, one of them being the new legislation not providing specific prescriptions for the sustainable retrofit of existing buildings, but implying that prescriptions for new buildings could also be applied to existing buildings. In addition, the new legislation does not make provision for the conservation and re-use of water, which should be taken into consideration by the future SANS 10400-XB since water is a scarce commodity in South Africa.

Other challenges facing universities include financial constraints. According to Wright (2010), financial constraints can limit the implementation of sustainability initiatives at universities due to competing priorities for limited resources and the long-term savings of these projects are not being accounted for in budget modelling.

It is only in recent years that South Africa has taken important steps to transform the impact of cities on the environment and climate change by establishing the GBCSA and adopting new building codes such as SAN204XA.The Green Building Council SA is an independent, non-profit company that was formed in 2007 to lead the greening of South Africa’s commercial property sector (GBCSA, 2014). All three of the assessed universities were established before this period. For instance, the Central University of Technology was established in 1981 as "Technikon Free State" or “Polythecnic of the Free State”.

2.13 Summary of findings from literature:

- Most South African cities were poorly designed from an ecological perspective and have large environmental impacts (DEAT, 2008; Martine et al., 2008).

- Financial constraints can limit the implementation of sustainability initiatives at universities due to competing priorities for limited resources and the long-term savings of these projects not being accounted for in budget modelling (Wright, 2010).

- The project delivery method is very significant in the development of sustainable buildings and infrastructure. The methodology of delivery and the final product are all significant in achieving sustainable high-performance buildings.

- An integrated project delivery is recommended to achieve sustainable design because this approach integrates people, systems, business structures and practices into a process that collaboratively harnesses the talents and insights of all project participants to optimize project results, increase value to the owner, reduce waste, and maximize efficiency through all phases of design, fabrication and construction (AIA 2007).

- Integrated projects often rely on cutting edge technologies. Technologies are specified at project initiation to maximise functionality, generality and interoperability.

- Open and interoperable data exchange based on disciplined and transparent data structures is essential to support IPD. Because open standards best enable communication among all participants, technology that is compliant with open standards is used whenever available (AIA, 2007).

- The use of Building Information Modelling (BIM) to foster IPD for a holistic approach to design. It can aide designers in a more comprehensive assessment of design strategies in the initial stages of the design (Eromobor, Das & Emuze, 2014; Krygiel & Nies, 2008)

- Understanding and identifying building parameters is very significant for attaining Energy Efficiency, IEQ and WUE in design. Parameters are interconnected (e.g. adequate daylight is important for both EE and IEQ, whereas landscaping affects EE and WUE).

- In EE and IEQ, daylight harvesting has an impact on the potential of energy saving, natural ventilation, glazing types, shading devices, fenestration size, operable window sizes, occupant comfort, landscaping for natural shading, and the selection of building material and its relative use as thermal mass or thermal insulation.

- In WUE, methods should include fixtures that minimize water usage, use of rainwater systems, re-use of grey water, black water treatment and re-use, installation of water meters for all major water usage, reduction of potable water for landscape irrigation, and reduction of the use of potable water in heat rejection systems in air-conditioned spaces.

2.14 Chapter summary

From the literature review, the indication is that South Africa as a country has taken important steps in establishing a policy to facilitate the movement of South Africa to a green economy. Universities contain substantial amounts of buildings and infrastructure which leave significant carbon footprints within the cities they exist. The focus has been on 3 main categories: EE, IEQ and WUE. It is clear from literature that EE is profoundly affected by the provision of appropriate building envelope. A strategy for design was discussed, indicating the necessity to establish appropriate building envelope design that provides passive means for heating and cooling prior to providing designs for services. For IEQ it was revealed that IEQ standards should meet standards for thermal comfort as established by ASHRAE. It was also revealed that reliance on artificial lighting as the main source of lighting leads to greater use of air conditioning and ventilation systems in order to remove the associated heat. Review of literature revealed that improvement in water use efficiency can be attained by including the use of water efficient fixtures, water harvesting systems and installation of water meters to monitor water usage. An integrated method of design was discussed that noted the significance of understanding how building parameters affect each other, which affect optimization of building envelope design. This is important for maximizing passive systems for heating or cooling and lighting that can reduce the energy demand required by mechanical systems and services.

CHAPTER 3: RESEARCH METHODOLOGY

3.1 Introduction

This chapter presents the research philosophy and methodological arguments behind the conduct of this research. It examines the methods and techniques for this study. As indicated in the introduction of this thesis, the research problems, research aims and objectives were discussed as the main point of the inquiry that forms the basis of the study. The research problem notes that currently codes for construction of built immovable assets such as buildings and infrastructure services on South African campuses do not address the need for high performance GBs, and most of the existing built environment infrastructure in the university system of South Africa have been built using conventional building codes. Thus, the broad research aim was to develop design guidelines and performance options in order to improve existing building codes that are relevant for the planning and design of university buildings. The focus was on the reduction of energy use, improvement of indoor environment, increase in water usage efficiency and appropriate material usage. However, examination of such aspects and development of appropriate design guidelines require an opposite research method and to follow a proper research design. It is therefore necessary to further explain and clarify the methodology used in the study with regards to the aim and objectives of this study.

3.2 Research Philosophy

The science of research has its roots in philosophy. The philosophy of research can therefore be viewed as a way of describing how research can be conducted and how the real world, empirical data, models and theories relate to each other. A research methodology is driven by certain ontological and epistemological assumptions, (Okolie, 2011). Ontology explains the nature of knowledge and assumptions about reality (Pathirage, Amaratunga and Haigh, 2008). It discusses the claims and assumptions that are made about the nature of reality. This view is consistent with the proposition of Gill and Johnson (2002) that research methods can be positioned by taking nomothetic (realist) and ideographic ontologies into account. Nomothetic approaches emphasize the importance of basing research upon systematic techniques as well as methods employed in the natural sciences which focus on the process of testing hypothesis (Okolie 2011). It also emphasizes the explanation of laws and deductions using quantified operational concepts.

Ideographic approaches on the other hand, emphasize the analysis of subjective accounts that is generated by getting inside situations. (Pathirage et al., 2008). For this study the researcher assumes the nomothetic (realist) view, therefore based on this ontological position, the epistemological beliefs of this research represent the positivist stance. Easterby-Smith et al (2008), in their review of research philosophies refer to the two ends of epistemological undertakings as positivism and constructionism. The positivists believe that the social world exists externally and that its properties should be measured through objective measures where the observer must be independent of what is being observed. Social constructivism on the other hand stems from the view that reality is not objective and exterior; it is socially constructed and given meaning by people who are conscious, purposive actors with ideas about their world and attaching meanings to what is going on around them (Robson,2002).

3.3 Research methods

The advancement of knowledge is the purpose of a research. It involves the detection and gathering of data and information, which are subsequently analysed to arrive at important findings. A research methodology refers to the principles and procedures of logical thought processes, which are applied to a scientific investigation (Sutrisna, 2009; Fellows and Liu, 2015). This is significant in understanding how the researcher approaches the study. The research methodology entails the overall strategy designed to achieve the aim and objectives of the research. It includes the procedures and techniques of investigation for effective and reliable representation of the research. Research methods on the other hand are simply tools used in gathering and analysing data for the research. It can also be described as a subset of the research methodology. Thus, within a research methodology, different research methods or tools may be used to achieve the aim and objectives of the research (Sutrisna, 2009). These assumptions or paradigms are essential for the research because the researcher's chosen methods must reflect the context of the underlying assumptions. This study followed a case study analyses to effectively assess the existing buildings on South African campuses. The data collection was followed by a conceptual system dynamics modelling approach, used to develop different policy options and solutions based on the interlinkage and causal feedback relations among different control variables.

3.3.1 Research design: Multiple case study approach

In this research, a multiple case study approach was used because it permitted various methods of obtaining quantitative data from both observation, and survey of perception retrieved from data in archives. This multiple case study approach follows from the research context (performance evaluation of existing buildings on South African campuses) and the complexity of information required in shedding light on the performance of academic buildings. This particular field of research falls within Architecture, Engineering and Construction management. As these fields of study fall within the paradigms of design, natural and social sciences, the multi case study approach was considered suitable for the research. Within the multiple case study approach, alternative methods can be incorporated for gathering data. As indicated in Figure 2.1, the establishment of conceptual system dynamic models also forms a significant part of the research in which interlinkage and causal feedback relations among various control variables – which assist in developing policy options or solutions – have been established. The reason for this approach is that causality and logic are important for determining the best possible standards for establishing plausible design guidelines.

3.3.2 Population and sampling

The nature of the research and the study population largely determine the sample to be selected. In this research, the population were existing academic buildings on South African campuses. A sample is that element (or set of elements) considered for selection in a study (Babbie, 2008). According to Yin (2003), four main factors relate to the selection of case-study organisations. They are:

- Relevance – which refers to the extent to which the selected organisation suits the purpose of the study;
- Feasibility – which refers to the practicability of the research being conducted. In the study it is important to conceptualise, plan, execute and report back on the research project. The case organisation should be within reasonable reach of the researcher in terms of distance and the researcher should have the appropriate managerial and operational support to ensure successful completion of the project;
- Access – which requires that the full co-operation of the organisation should be secured for the duration of the research. Accessibility also requires that the nature of business of

the case-study organisation should be non-security sensitive and they should be willing to participate in the research at both executive and operational level; and

- Applicability – which refers to the extent to which the case-study method can be applied in a particular situation.

In terms of relevance to this study, the targeted universities are academic institutions. These are universities of technology with curricula focused on Science, Technology, Engineering and Mathematics (STEM) programmes. Concerning feasibility, ties with the universities have been developed in the capacity of lecturer at CUT and TUT, while DUT remained an unfamiliar environment. In relation to accessibility, all relevant procedures and regulations were observed. Prior to case study visits, co-operation was sought from the institutions. All necessary permits were secured where applicable (see Appendix 1-2) and access was granted by relevant authorities at the universities. In relation to the applicability of the research and the extent to which the empirical data collection can be applied, variation in size of buildings, building forms, and differences due to region and location were considered in the exercise.

Physical structures were assessed and the users of these structures were questioned with regards to the performance of the buildings. For the purpose of this study a total sample of 16 academic buildings at three universities of technology was selected for assessment. These universities include (1) the Central University of Technology, Free State (CUT); (2) the Durban University of Technology, KwaZulu-Natal (DUT); and (3) the Tshwane University of Technology, Gauteng (TUT). Since the research is a multiple case-study, an appropriate sampling technique was required to realise the objectives and data requirements of the study, therefore a purposive sampling technique was used to collect data. Purposive sampling is a non-probability technique that selects informative subjects or units of observation as a representation of the wider phenomenon under investigation (Okolie, 2011). The primary criterion for the selection of the buildings was their function for academic purposes (teaching / learning / staff offices). Physical assessment of the buildings selected for the study, which is crucial for observation and recording of data, was conducted in 2016. The physical observation data were further enhanced with a user perception survey conducted among the students and academic staffs. A total of one hundred and sixty (160) questionnaires were distributed to users of these buildings by using the purposive sampling technique. The survey was conducted in person where all unclear issues were clarified with the respondents during the survey.

3.3.3 Data collection

The survey incorporated a multiple case-study approach for collection of data. Data collection instruments include observations, walkthroughs, measurements of interior building conditions, photographs, assessment of building plans, archival records (for various services including electricity & water usage data), and questionnaires. Relevant instruments such as geometrical measuring instruments (measuring tapes), and portable weather stations (thermometer, hygrometer- humidity sensor, light meter, etc.) were used to measure building size, temperature, humidity, and illumination of existing buildings at the target universities. These tools were concerned with issues relating to the building performance indicators as identified in the literature. The use of semi-structured questionnaires was deployed to obtain the perceptions of the users (staff & students) with regards to the performance of the academic buildings.

Thus the two data sets include quantitative data from physical observation of the buildings and the completion of user survey questionnaires. The initial set of quantitative data was obtained from measuring building size, use of materials, internal conditions of temperature humidity, illumination and evaluation of water efficiency. As indicated in Table 3.1, these data were collected from 16 buildings which include six buildings each at CUT and DUT and four buildings at TUT. In addition, 60 users from CUT and 50 users each from DUT and TUT were surveyed. The total number of survey participants is recorded as 95 users of the buildings.

Table 3.1 Location and number of buildings assessed

University	Location	Buildings	User Response	Sample size
CUT	Bloemfontein	6	40	60
DUT	Durban	6	30	50
TUT	Pretoria	4	25	50
Total		16	95	160

3.3.4 Data from physical observations

In this research, quantitative methods were utilized for gathering and measuring cardinal data. Quantities that represent values of categories and sub-categories were further analysed to determine causal relationships in order to determine the influences of the different variables on energy efficiency and other relevant aspects of buildings and infrastructure on South African campuses. Quantitative research utilizes quantitative methods for data collection and analysis. This research approach emphasizes the importance of basing research on systematic techniques and methods employed in the natural sciences. Thus, the approach focuses on the process of testing hypotheses (Pathirage et al., 2008). Nahiduzzaman (2006) indicated that researchers who use logical positivism, employ experimental methods and quantitative measures to test hypothetical generalization. Quantitative researchers emphasize the measurement and analysis of causal relationships between variables.

In the reviewed literature, it emerged that the building envelope design and services have significant effects on energy use and IEQ. Building parameters assessed include building form, size and orientation – all of which feature in building envelope design and services in the provision of appropriate IEQ, energy consumption and water usage. Data with regards to building form, building size and materials were gathered through observation of the buildings, studying of relevant building plans and physical measurements. In addition, technical documents available from relevant asset and maintenance departments of the universities were obtained and studied.

Energy and water usage data were procured from relevant departments of the universities and analysed. The physical measurements of relevant parameters related to indoor environment were taken by use of various measuring instruments. Figure 3.1, 3.2 and 3.3 illustrate the instruments used for this purpose. The instruments used for measuring the indoor/outdoor temperature, humidity and lighting conditions include a mobile weather station, indoor temperature/humidity sensors and a light meter.

Fig 3.1 Mobile weather station

Fig 3.2 Temperature and humidity sensor

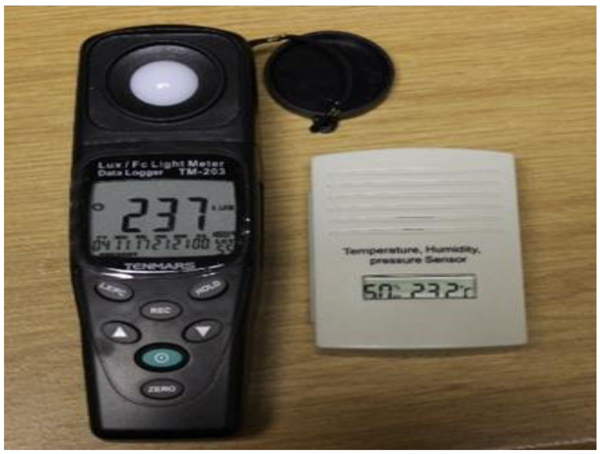

Fig 3.3 Light meter

3.3.5 Data from user survey

As mentioned earlier, data were collected through user surveys. Appendices 3-4 represent the questionnaires and cover letters used in the survey research. The design of the questionnaire was intended to obtain representative perceptions of the users concerning the levels of IEQ performance of the assessed buildings. The Likert scale was used on a rating continuum of one to five to measure the varying degrees of respondents' perceptions about IEQ conditions. The Likert scale was used as it is found suitable to measure perceptions, opinions and beliefs (Agresti and Franklin, 2007). The questionnaires were divided into two sections. The first section requested data on location and demographic issues such as experience, position/status and gender, and number of employees. The second section sought responses on perceptions of the users with regards to building performance. These include the perceptions of the users on IEQ of buildings.

The respondents selected for the questionnaire (see Chapter 4) were full time students and academic staff who have spent at least three years at the universities.

Table 3.2 Profile of respondents

University	Respondent Type	Numbers	Percentage (%)
CUT	Staff	8	8.4
	Student	32	33.7
DUT	Staff	5	5.3
	Student	25	26.3
TUT	Staff	4	4.2
	Student	21	22.1
Total		95	100.0

A total number of 160 questionnaires were distributed to users of buildings at all three target universities. Out of this number, 95 questionnaires were completed and returned, which corresponds to a response rate of about 59%. The response of building users to questionnaires about their perceptions of the buildings reflects the perception of the sample of buildings selected. Some of the questionnaires were returned uncompleted and were therefore disregarded because they were unusable. Table 3.3 shows the population distribution of the respondents and the percentage response to the questionnaires.

Table 3.3 Population distribution of questionnaires and percentage response

Case university	Number of questionnaires distributed	Number of questionnaires received & response	Percentage contribution to total response
CUT	60	40	42
DUT	50	30	32
TUT	50	25	26
Total	**160**	**95**	**100**

3.3.6 Data modelling

Statistical quantitative analyses were followed by developing conceptual models using System Dynamics (SD) principles in order to develop policy options and solutions that could aid in developing design guidelines. A system constitutes a set of components which are interlinked and interdependent on each other to perform a function as a whole (Von Bertalanffy, 1974; Forrester, 1968). In a system, if a sub-system performs at a higher efficiency than others or becomes defunct, then the effect is felt on the whole system. In order for the system to perform at a higher efficiency, the sub-systems of the system are to work in a co-ordinated manner.

System Dynamics (SD) is designed for complex systems to understand how and why the dynamics of concern are generated and to search for policies to improve the situation. It amalgamates ideas developed in various system theories and is a result of cross-fertilisation of ideas from traditional management, cybernetics, and computer simulation (Shen et al., 2009). It is a theory of structure and behaviour system (Forrester, 1969, 1968) and blends the art of traditional management with the science of feedback control. It is a theory of structure and behaviour of systems (Forrester, 1968, 1969) and is characterised by the concepts of causal feedback loops and time delays, which represent the dynamic complexity of a system (Sterman, 2000). According to Montibeller and Belton (2006) causal loop maps are usually employed to describe the elements of the system.

The SD model is generally developed by using three kinds of variables (stock, rate and auxiliary); two kinds of flows (physical/material and information, only through which variables could interact and respond to others); feedbacks; and delays. There is always a stock in a system that accumulates the difference between input and output. Rates/decision rules or policies represent the criteria used to regulate flows in attempts to drive the system to a desired state, whereas flows are the movement of contents throughout the system. Feedback loops – which represent a chain of causality – are responses created by the system that will change the current pattern. Delays are sources of dynamics that create instability and oscillations (Sterman, 2000). Variables, together with flows, consist of the basic structure of one dynamic system – called stock-flow diagram – in which feedback loops, the foremost concept in simulation of the model, could be observed. The simulation is entirely governed by the passage of time, known as 'time-step simulation' (Coyle, 1996).

SD has two forms of modelling, which include the conceptual and mathematical (computational) models. The conceptual model is based on the causal feedback relations among the various variables to understand the interaction through cause and effect among various variables. The development of the mathematical model is based on the causal feedback relations developed by conceptual models to understand the behaviour of the system and generate policy options through generating simulated scenarios. In this particular study, the scope of modelling is limited to conceptual models, which were used to understand the causal feedback relations among the variables. The conceptual modelling approach aligns with known SD methodologies.

The use of SD in solving real world problems is now prevalent in urban development, building, construction management, water systems, environmental systems, supply chain management and many more. Scholars such as Robinson (2008) outlined a conceptual model as a consistent and unifying theory of behaviour taken from bits of information about the real world. It provides a framework for clear understanding of the problem before any attempts of mathematical modelling and simulation. Particularly in social complex systems such as a building, it could elicit intended and unintended consequences of the different policy interventions through the causal relations among different factors influencing the performance of the system. It is therefore paramount to understand the problem first through conceptual modelling and the causal relations it offers. Conceptual models based on the causal relations among the various parameters influencing different characteristics of the buildings were developed by using SD modelling principles. Before developing the models, discussions with the experts, consultants and professionals, municipal authorities and university authorities were conducted by use of a semi structured interview process. The causal relations in the models and consequent interventions were also validated through consultations with experts and users.

To be succinct, in this research, each building was treated as a system and its different components such as energy, circulation, water, environments, etc., were considered as the sub-systems. While developing the causal relations, variables such as information, decision, action and environment (system) were identified. These variables were connected with simple one-way causality in terms of one-way linkages of: information – decisions – actions – impact on the environment (i.e., information assisting in evolving decisions (policy interventions) – decisions leading to appropriate actions – and actions influencing the environment (system)) (El Halabi, Doolan, Cardew-Hall, 2012).

While developing causal feedback relations, all four variables were not necessarily part of every loop; however, decisions and environment needed to be interlinked. Once the one-way causality was established, the feedback relations were checked. Having identified the variables and causal relations, causal feedback diagrams were compiled for each major factor influencing the measured variables. The diagrams were then discussed with professional and experts in the field to check their veracity, and relevant modifications were made thereafter. The various experts and professionals include Professional Architects, Engineers, Planners and Designers. The validation was based on the experience and expertise and the best practices that are used by the professionals while designing built infrastructures. The valid causal feedback diagrams (causal loop diagrams) were then employed to develop the conceptual SD models. The validated conceptual models were then used to generate policy options and design guidelines for developing sustainable buildings and infrastructures on South African campuses.

3.4 Chapter summary

This chapter presented the methodology adopted in this research. It provided the justifications for the methods of data collection. The research design described in this chapter has linked important elements of the research methodology, namely the research methods/approach, data collection- and modelling techniques. The use of SD modelling in this study has also been highlighted. The next chapter presents the analysis of research results.

CHAPTER 4: DESCRIPTIVE NARRATION OF STUDY SITES

4.1 Introduction

In this chapter, the case studies and relevant data obtained from measurements, archival records and results of questionnaire surveys administered to respondents are presented. The first section introduced the case campuses being assessed. Technical documentation consisting of building plans, energy consumption data and archival records were obtained from physical planning units in the various universities. Weather data was obtained from the South African weather service.

Two of the sixteen assessed university buildings were determined to be the benchmark buildings because they stood out in terms of appropriate envelope design.

In the second section, a green building rated by the Green Building Council of South Africa (GBCSA) is presented for the purpose of comparison between the required standards and performance of different attributes for the existing buildings on the case study campuses. Photographs and diagrams were used extensively in presentation of the buildings.

In the third section, data from observation and surveys of the three campuses are evaluated.

4.1.1 Location and Climatic Conditions

The Council for Scientific and Industrial Research (CSIR) created a new Köppen-Geiger climatic map to accurately classify the climatic regions of South Africa to support passive design and improve the performance of different building technologies. Conradie & Kumarai (2012) indicated that in order to design energy-efficient buildings using an optimal combination of passive design strategies such as passive solar heating, thermal mass, direct evaporative cooling, indirect evaporative cooling and natural ventilation, it is necessary to understand the particular climate of the location of the proposed building. Figure 4.1 displays the Koppen-Geiger climatic map that illustrates the categories for the different climatic regions in South Africa. Table 4.1 indicates the climatic characteristics and passive design strategies for the climate zones. ASHRAE and SANS 204: 2011 have compiled design standards for climatic zones which give design application suitable for buildings located in these climatic zones, this is indicated in table 4.2.

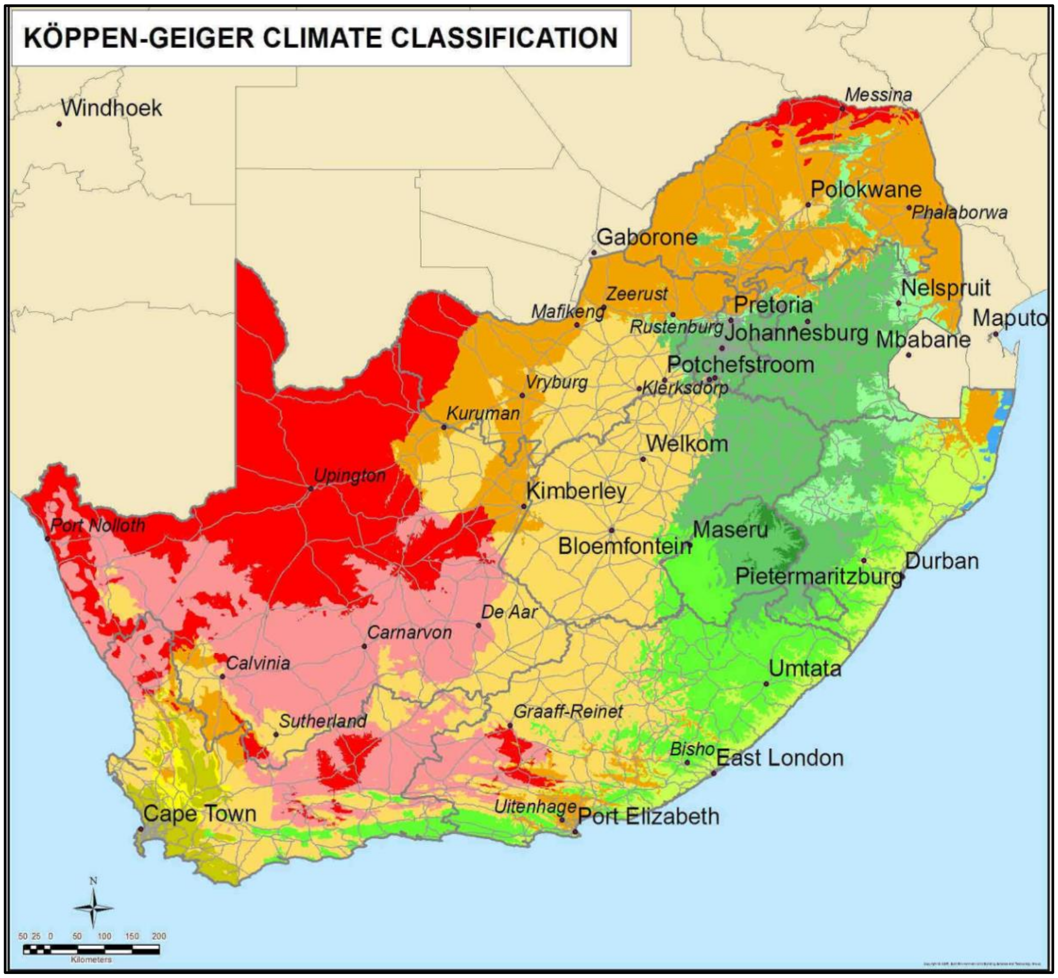

Figure 4.1: Koppen-Geiger map (Conradie, 2012) modified by author

Table 4.1: Köppen-Geiger categories

Climatic characteristics				Passive design strategy					
Description	Köppen-Geiger class.	Area in km²	Percent (%)	Passive solar-heating	Thermal mass	Exposed mass and night purge ventilation	Natural ventilation	Direct evaporative cooling	Indirect evaporative cooling
Equatorial climates (0.2%)	Aw	2296	0.20	■			■		
Arid climates (70.89%)	Bsh	192 269	16.59						
	Bsk	275 927	23.81	■	■	■	■	■	■
	Bwh	188 784	16.29						
	Bwk	164 629	14.20	■	■	■	■	■	■
Warm temperate climates (28.91%)	Cfa	42 918	3.70	■			■		
	Cfb	93 405	8.06	■	■		■		■
	Cfc	84	0.01	■	■		■		
	Csa	5 120	0.44						
	Csb	18 395	1.59	■	■		■		
	Cwa	31 162	2.69	■	■	■	■		
	Cwb	140 405	12.11	■	■		■		
	Cwc	3 564	0.31	■	■		■		
	Total	1 158 958	100.00						

Conradie & Kumarai 2012, modified by author

As indicated in table 4.2, the cities presented are classified according to Koppen-Geiger categories and zone classifications for SANS 204: 2011, and ASHREA. The table summarizes the buildings and design recommendations by SANS and ASHRAE for the climatic conditions of each of the three locations of the case study. This information was important for comparing the performance standards to building performance data of the assessed buildings.

Table 4.2: Case study location, classification and SANS and ASHRAE zones

Location	Type	Description	SANS 204:2011 Classification	ASHRAE Classification
Bloemfontein	Bsk	Arid, Steppe, Cold arid	Zone 1	Zone 3B
Durban	Cfa	Warm temperate, Fully Humid, Hot summer	Zone 5	Zone 2A
Pretoria	Cwb	Warm temperate, Dry winter, Warm summer	Zone 2	Zone 2B

Conradie & Kumarai 2012, SANS 204: 2011, modified by author

4.2 Profile of the universities

In this research, three (3) Universities (case studies) are explained in terms of location, nature and type of building facilities and services provided by the institutions. This was followed by the research process and presentation of results. As previously noted, the institutions referred to are CUT, Free State; TUT, Pretoria; and DUT, Durban. The schedule of data collection is indicated in Table 4.3 below.

Table 4.3: Schedule of data collection for case study

Method /Instrument	Buildings / Users	Date/ Duration	University Site
Building Assessment	Academic Buildings	25/01/2016 - 29/01/2016	CUT
Survey administration	Building Users: Students / Staff	25/01/2016 - 05/02/2016	CUT
Building Assessment	Academic Buildings	02/02/2016 - 05/02/2016	DUT
Survey administration	Building Users: Students / Staff	02/02/2016 - 05/02/2016	DUT
Building Assessment	Academic Buildings	08/02/2016 - 12/02/2016	TUT
Survey administration	Building Users: Students / Staff	08/02/2016 - 12/02/2016	TUT

4.2.1 Central University of Technology, Free State

CUT is a University of Technology located in Bloemfontein, the capital city of the Free State Province of South Africa. It was established in 1981 as "Technikon Free State" or Polytechnic of the Free State. It was promoted to University of Technology status as part of the South African government's restructuring of tertiary education for the new millennium. The university is located in the heart of the city close to the provincial administrative nerve centre.

There are three campuses. The main campus is situated in the city centre of Bloemfontein city. The other two campuses have been established in Welkom (famous for its gold mines) and Kimberley (known for its diamond mine) – two important mining cities of South Africa that are respectively within a distance of about 170 km from Bloemfontein. However, the buildings of the main campus were considered in the study. The access approach, main campus and aerial views of the main campus of CUT, are shown in Figures 4.2, 4.3 and 4.4 respectively.

Figure 4.2: Entrance of the Bloemfontein campus, CUT

Figure 4.3: Views of the library and engineering buildings at Bloemfontein campus, CUT

Figure 4.4: Aerial view of Bloemfontein campus, CUT **Photo: Google earth**

4.2.1.1 University profile and services provided

The statement of vision indicates that by 2020, CUT shall be an engaged university that focuses on producing quality social and technological innovations for socio-economic development, primarily in the Central Region of South Africa. In other words, by 2020, CUT will be a centre of knowledge, innovation and excellence producing a critical mass of innovators that directly contributes to prosperity-creation. The mission of the University is to use teaching, and research to nurture innovation.

The University has four academic units (known as faculties), constituting of a number of academic departments. The various faculties of the university and academic departments under them are:

- **Faculty of Engineering and Information Technology**
  - Department of Built Environment
  - Department of Civil Engineering
  - Department of Electrical, Electronics and Computer Engineering
  - Department of Information Technology
  - Department of Mechanical and Mechatronics Engineering

    - Department of Mathematical and Physical Science
- **Faculty of Health and Environmental Sciences**
    - Department of Agriculture
    - Department of Clinical Sciences
    - Department of Health Sciences
    - Department of Life Sciences
- **Faculty of Humanities**
    - Department of Communication Science
    - Department of Design and Studio Art
    - Department of Language and Social Science Education
    - Department of Mathematics Science and Technology Education
    - Department of Post Graduate Studies
- **Faculty of Management Sciences**
    - Department of Accounting
    - Department of Business Management
    - Department of Business Support Studies
    - Department of Government Management
    - Department of Hospitality Management
    - Department of Tourism and Event Management

There are several other departments and units at the University, offering academic, administrative, co-curricular and extracurricular activities and support. The various support units are as follows:

Academic Administration

- Academic Development and Support (ADS)
- Academic Planning
- Schools Advancement Academy
- Student Services

Other support departments

- Communications and Marketing
- Finance
- Human Resources (HR)
- IT and Logistics

- International Office
- Strategy Execution Unit (SEU)

Facilities and maintenance unit

The facilities and maintenance unit falls under the Information Technology and Logistics division of the administrative department of the university. The facilities and maintenance unit is responsible for the design and management of the university buildings. It also provides a wide range of services that are essential to the development, operation, maintenance and care of university buildings and engineering services. The Bloemfontein campus of the university has large built-up spaces within the city of Bloemfontein which are intersected by a major street. The buildings and infrastructure include academic (instructional) spaces (buildings), office buildings for academic staff, laboratory buildings, buildings for administrative and management functions, library, student centre, community buildings, meeting halls, examination halls, internal circulation (transportation areas), off-street parking area, entertainment arenas, sporting arena, restaurants and cafe, etc. Reasonable residential accommodation for the students is also located on the campus, although most of the student accommodation is off- campus. From a sustainability point of view, the efficient operation and management of buildings constitute a challenge because many of the buildings are old and were built according to building codes that are not sustainability compliant, although certain buildings are observed to be retrofitted. However, compliance to sustainability standards in the retrofitted buildings could not be ascertained. A sustainability office that has been established by the university, that monitors the present stock of buildings/infrastructure and promotes awareness of sustainability matters at the university.

4.2.1.2 Evaluation of CUT buildings

As indicated in Figure 4.5, six buildings, namely BHP1, BHP2, BHP admin, ETB-Engineering, Library and Hotel School, were assessed at CUT. These buildings – excluding the library – are located at the Faculties of Engineering and Health Sciences respectively. The buildings differed in size and form as well as design approaches with regards to orientation and size of fenestrations. Figure 4.5 presents the location and orientation of the assessed buildings. The differences in design approach, form and orientation resulted in differences in indoor environment and energy consumption.

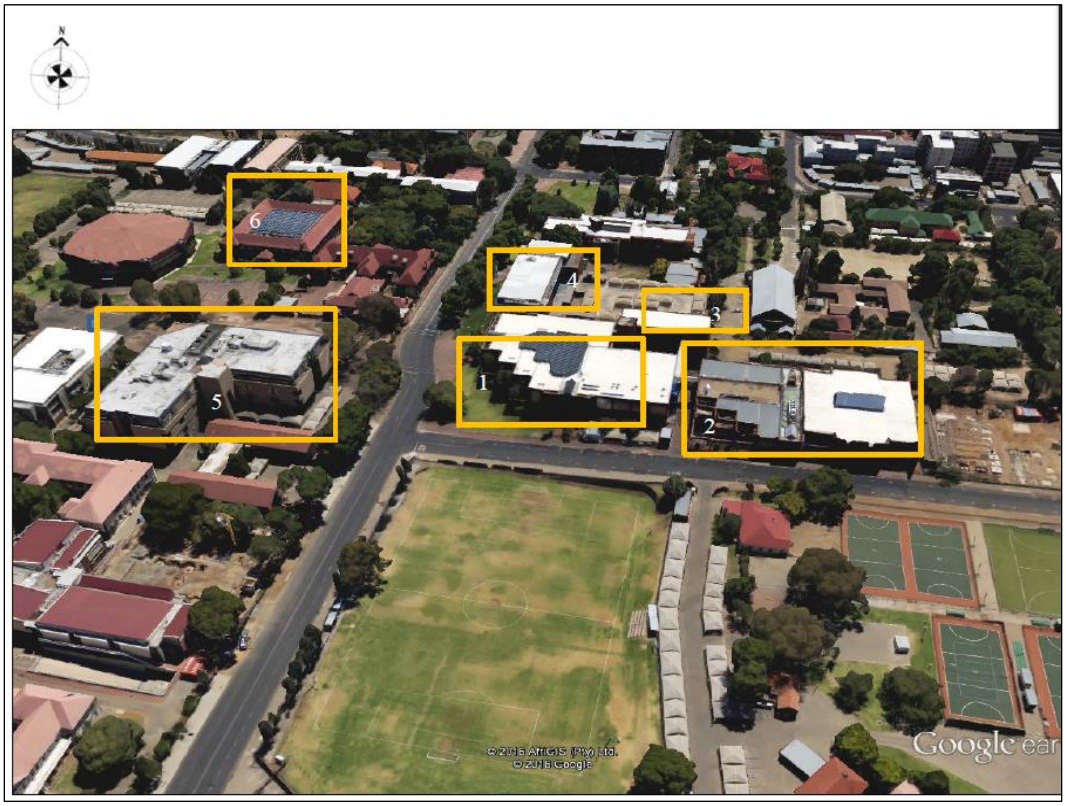

Figure 4.5: Orientation, form and location of buildings assessed at Bloemfontein campus, CUT Photo: Google earth
1: BHP1, 2: BHP2, 3: BHP Admin, 4: ETB Engineering Building, 5: Library 6: Hotel School

4.2.1.3 BHP1: Faculty of Engineering

BHP 1 is a lecture block at the Faculty of Engineering consisting of lecture rooms, laboratories, computer rooms, and offices. The orientation of the building is such that it is aligned longitudinally along North and South. The building has 4 storeys and consists of large atriums located at the centre. The lecture rooms have large windows that remain closed for most of the year. Although the windows give access to daylight, they provide limited ventilation due to limited openings in the internal walls of the lecture rooms. A combination of daylight and artificial light is used for illumination of the lecture rooms. In the one-sided corridor configuration, sufficient daylight from the atrium is provided for the corridors, but not to the classrooms because adjacent walls between classrooms and corridors do not have sufficient glazing or openings. The lecture rooms depend mainly on natural ventilation, whereas room air conditioners (mechanical ventilation) is used for heating and cooling of the offices. Figure 4.6 illustrates the floor plan, façade views and building envelope features of a typical lecture room of BHP 1. The total building area is 8,810.7 m^2 and the external window-to-wall ratio 0.29. The building operates for 13 hours a day and consumes 675,238 kwh/annum at a rate of 74.3 kwh/m^2/annum. A summary of key features of the building is presented in Table 4.4.

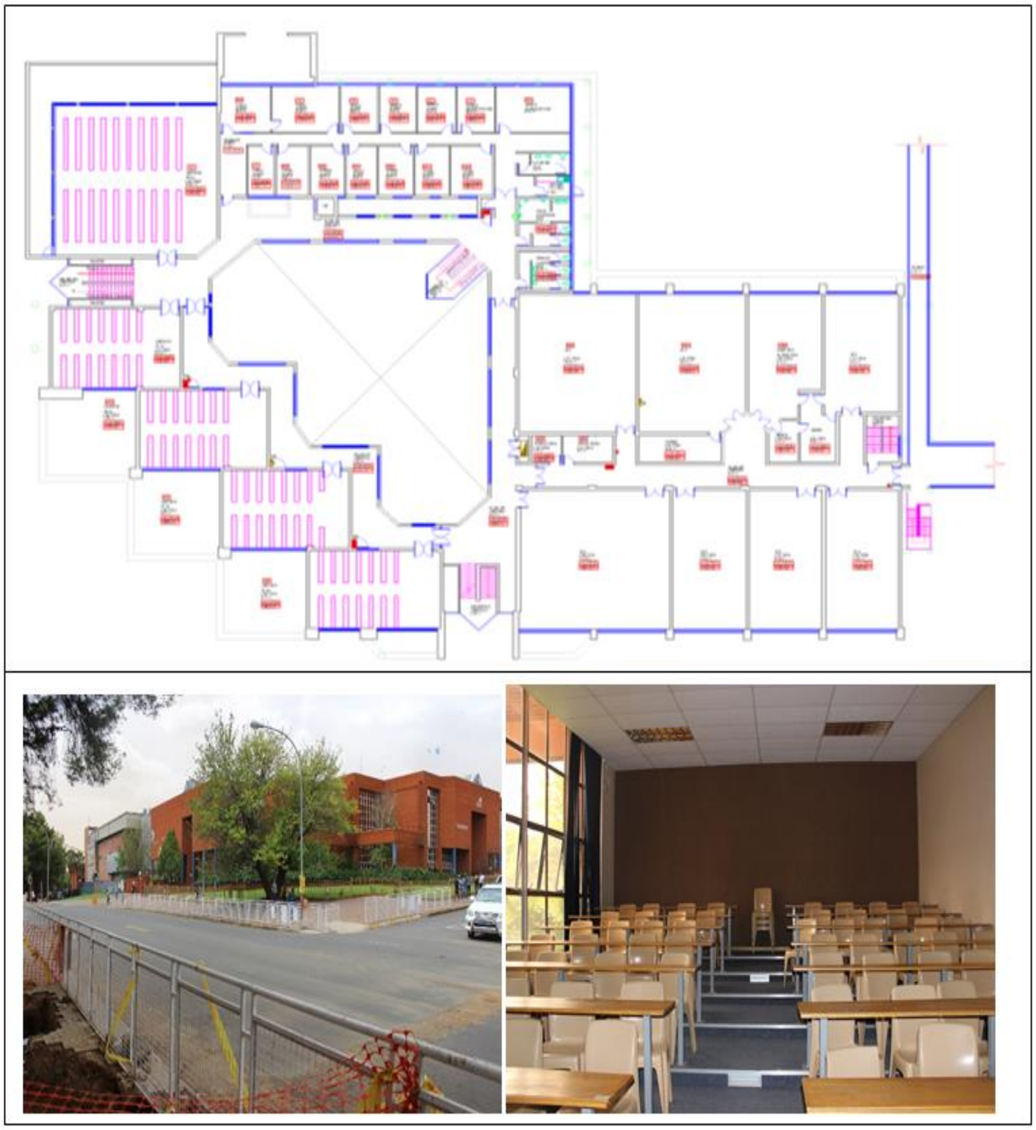

Figure 4.6: Floor plan, façade views, and interior of a typical lecture room of BHP 1
Floor plan: CUT facilities and maintenance unit

Table 4.4: Summary of key features of the BHP 1 building (CUT)

Building Location	Central University of Technology (CUT)
Building Function	Teaching & Learning
Orientation	North & South
Total Area of Building (m^2)	9088
Number of floors	4
External Window – Wall Ratio (WWR)	0.29
Services Type: Heating, Cooling & Ventilation	Mixed: Natural & Mechanical (MN)
Number of Occupants	1,280
Hours of Operation	13
Energy Consumption per square meter (Kwh/m^2/annum)	74.3
Total Energy Consumption (Kwh/ annum)	675,238

Source: Facilities and maintenance unit at CUT

4.2.1.4 BHP 2: Faculty of Engineering (CUT)

BHP 2 contains lecture- and computer rooms, laboratories and offices. The orientation of the building is such that the longitudinal facades predominantly face North and South and it has a less complex geometric configuration in comparison to BHP 1. There are very few fenestrations or transparent portions in the building façade. The lecture rooms and theatres have no access to natural light or natural ventilation and are completely dependent on mechanical means for lighting and ventilation. Figure 4.7 presents the building plan and images of the right side of the building with mainly lecture rooms and limited windows/no access to natural light. The left side of the building has mainly offices with reasonable access to natural light. In comparison to the external window-to-wall ratio of all the other buildings at CUT, BHP 2 has the lowest value of 0.09. Due to the limited number of windows, it is apparent that a comparatively high amount of energy is required to provide adequate indoor environmental conditions for the function of teaching and learning. The building consumes 1,145,040 kwh/annum electricity, with comparatively high values for energy consumption per square meter (165 Kwh/m^2/annum). Table 4.5 presents a summary of key features of the building.

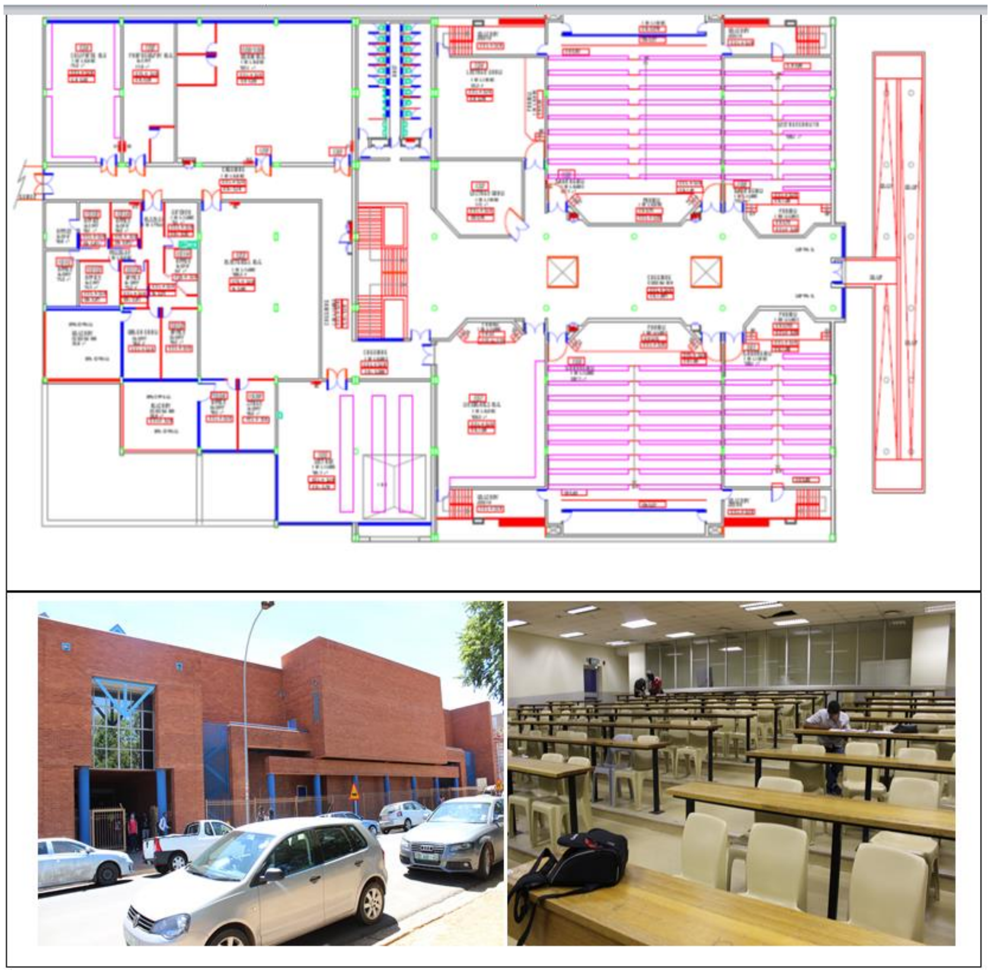

Figure 4.7: **Floor plan, façade view and typical lecture room of BHP 2**

Floor plan: CUT facilities and maintenance unit

Table 4.5: Summary of key features of the BHP2 building (CUT)

Building Location	**Central University of Technology (CUT)**
Building Function	Teaching & Learning
Orientation	North & South
Total Area of Building (m^2)	8810.7
Number of Floors	3
External Window – Wall ratio (WWR)	0.09
Services Type: Heating, Cooling & Ventilation	Mechanical (M)
Number of Occupants	1978
Hours of Operation	13
Energy Consumption per square meter (Kwh/m^2/annum)	165
Total Energy Consumption (Kwh/ annum)	1,145,040

Source: Facilities and maintenance unit at CUT

4.2.1.5 BHP Admin: Faculty of Engineering (CUT)

The building is mainly an administrative building that forms part of the BHP lecture block. The building uses mechanical ventilation systems (central air conditioning and room air conditioning) for heating, cooling and ventilation. It is oriented in such a way that the longitudinal facades face North and South. As illustrated in figure 4.8, the floor plan has offices aligned along a single corridor (double bunked) and building orientation and window arrangement indicate good access to daylight for offices. The double bunked corridor is illuminated by a combination of daylight from internal office walls and artificial lighting. The total building area is 1,755.6 m^2 and the external window-to-wall ratio is 0.35. The building operates for 13 hours a day and consumes 251,108 kwh/annum electricity at a rate of 143 kwh/m^2/annum. The summary of key features of the building is presented in Table 4.6

Figure 4.8: Floor plan, façade views and typical office of BHP Admin

Floor plan: CUT facilities and maintenance unit

Table 4.6: Summary of key features of the BHP Admin building (CUT)

Building Location	**Central University of Technology (CUT)**
Building Function	Teaching & Learning
Orientation	North & South
Total Area of Building (m^2)	1,755.6
Number of Floors	4
External Window – Wall ratio (WWR)	0.35
Services Type: Heating, Cooling & Ventilation	Mechanical (M)
Number of Occupants	988
Hours of Operation	13
Energy Consumption per square meter (Kwh/m^2/annum)	143
Total Energy Consumption (Kwh/ annum)	251,108

Source: Facilities and maintenance unit at CUT

4.2.1.6 ETB: Faculty of Engineering (CUT)

ETB functions mainly as an academic building, which uses a central air conditioning system for heating, cooling and ventilation. The building contains mainly computer and engineering laboratories, a few lecture rooms and office spaces. The building is oriented in such a way that the longitudinal facades face East and West and the typical floor plan has offices at the side of the building. The offices therefore have access to natural light, but the lecture rooms have less access to natural light due to fewer and smaller sizes of windows as illustrated in figure 4.9. The plan indicates the limited access of the lecture rooms to natural light due to poor orientation (longitudinal façades on the East and West is not appropriate for daylight optimization). Though the building has a WWR ratio of 0.36, the effect of poor orientation results in inappropriate glazing. The total building area is 3,798.8 m^2 window-to-wall ratio and the building operates for 13 hours a day, consuming 1,037,202 kwh/annum electricity at a rate of 216 kwh/m^2/annum. The summary of key features of ETB is presented in Table 4.7.

Figure 4.9: Floor plan, facade views and typical computer room of ETB

Floor plan: CUT facilities and maintenance unit; Photos: Author

Table 4.7: Summary of key features of the ETB building (CUT)

Building Location	**Central University of Technology (CUT)**
Building Function	Teaching & Learning
Orientation	East & West
Total Area of Building (m^2)	3798.8
Number of Floors	4
External Window – Wall ratio (WWR)	0.36
Services Type: Heating, Cooling & Ventilation	Mechanical (M)
Number of Occupants	930
Hours of Operation	13
Energy Consumption per square meter (Kwh/m^2/annum)	216
Total Energy Consumption (Kwh/ annum)	1,037,202

Source: Facilities and maintenance unit at CUT

4.2.1.7 Library building (CUT)

The library is an academic building that serves all the faculties. It typically contains lending areas, areas for book stacks, reading rooms, computer rooms and offices. The shape and orientation of the building is such that the longitudinal views face both North- South and East-West. It has 4 storeys and consists of a large atrium located at the centre. The envelope design plan indicates use of large windows predominantly on the north and west façades of the building. Though the windows give access to daylight, they do not allow any natural ventilation since they remain closed throughout the year to prevent damage to books. The building depends on a central HVAC system for heating, cooling and ventilation. Figure 4.10 also presents the plan and views/perspectives of the library. The summary of key features of the building indicates a total building area of 8,055.6 m^2 and an external window-to-wall ratio of 0.32. The building operates for 13 hours a day and consumes 756,104 kwh/annum at a rate of 107 kwh/m^2/annum (Table 4.8).

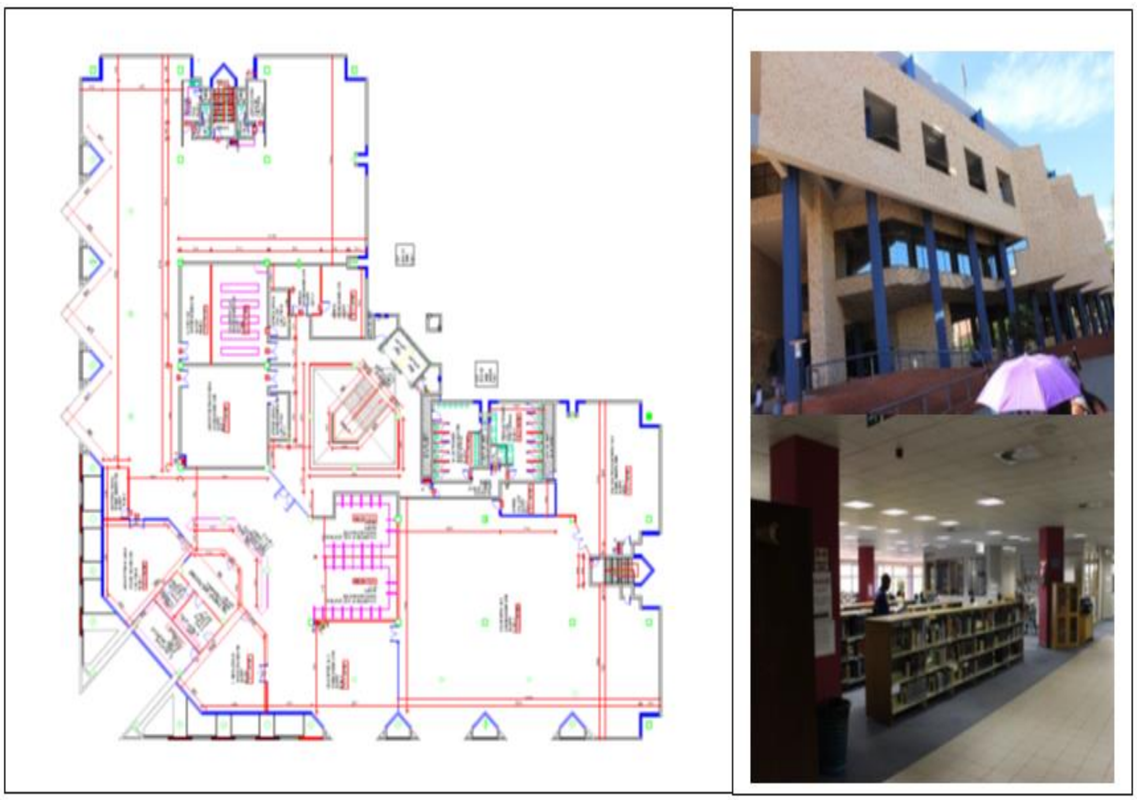

Figure 4.10: Floor plan and facade views of the library

Floor plan: CUT facilities and maintenance unit

Table 4.8: Summary of key features of the library building (CUT)

Building Location	**Central University of Technology (CUT)**
Building Function	Teaching & Learning
Orientation	North &South
Total Area of Building (m^2)	8,055.6
Number of Floors	4
External Window / Window ratio	0.32
Services Type: Heating, Cooling & Ventilation	Mechanical (M)
Number of Occupants	905
Hours of Operation	13
Energy Consumption per square meter (Kwh/m^2/annum)	107
Total Energy Consumption (Kwh/ annum)	756,104

Source: Facilities and maintenance unit at CUT

4.2.1.8 Hotel School (CUT)

The hotel school is an academic building that contains lecture rooms, kitchens, laboratories, computer rooms and offices. It is functionally different from the other buildings because it contains kitchens that use heavy-duty cooking appliances. The plan and façade properties of the hotel school is presented in Figure 4.11. The building is square- shaped with orientation such that all façades face North & South and East & West. The hotel school is of 2 floors and consists of a large atrium located at the centre. The plan (figure 4.11) indicates the arrangement of windows on external and internal façades. The building has relatively small windows which remain closed throughout the year and there is reasonable access to natural light. The windows at the internal facades provide access to light from the centrally located atrium. The building depends on both mechanical- and natural ventilation for heating and cooling. The summary of key features presented in table 4.9 indicates that energy consumption in this building is 627,598 kwh /annum or 216 Kwh/m^2/annum, the external window-to-wall ratio is 0.30 and the building operates for 13 hours a day. The hotel school and the ETB building both use 216 Kwh/m^2/annum, which is the highest amount of energy consumption per square meter observed.

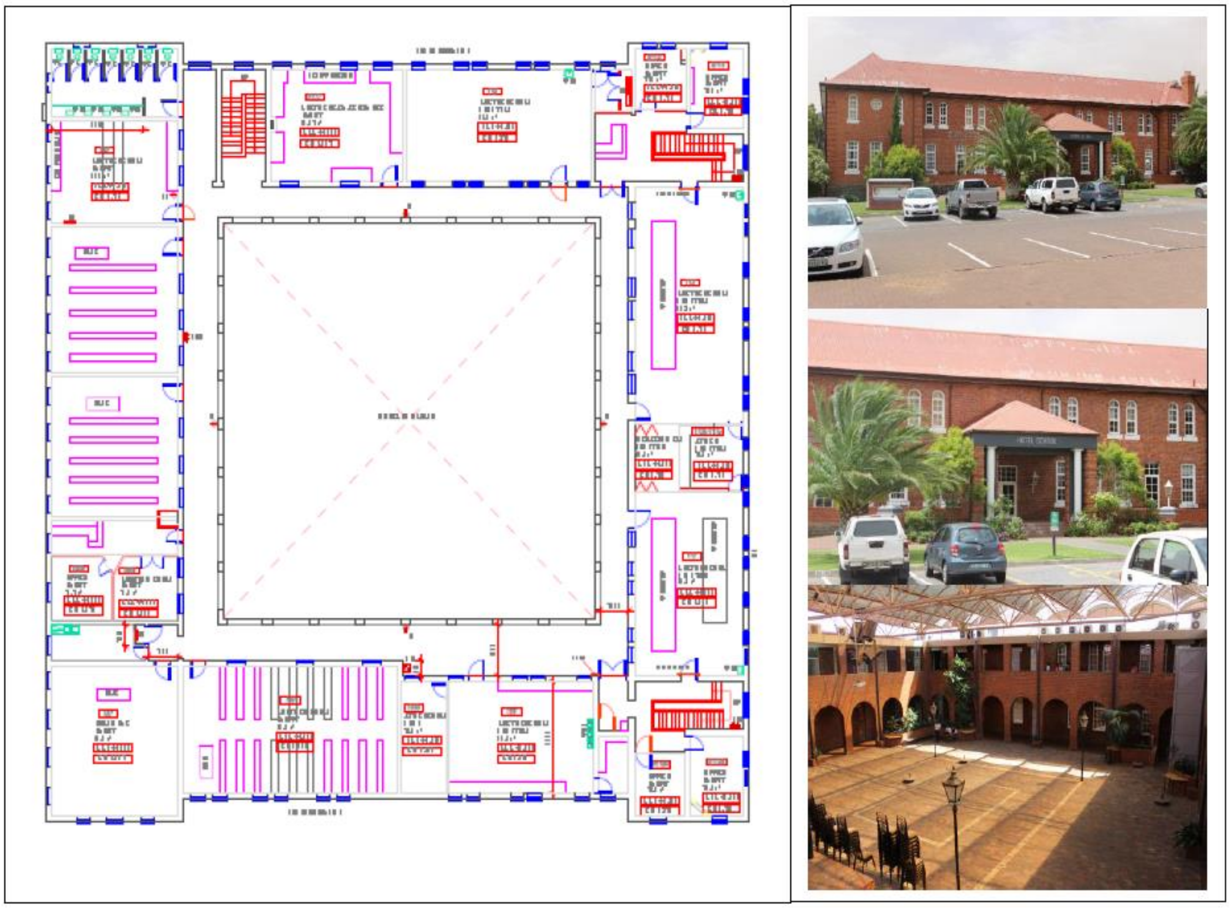

Figure 4.11: Floor plan and facade views of the hotel school

Floor plan: CUT facilities and maintenance unit

Table 4.9: Summary of key features of the Hotel School building (CUT)

Building Location	**Durban University of Technology (DUT)**
Building Function	Teaching & Learning
Orientation	North & South
Total Area of Building (m^2)	4000.4
Number of Floors	2
External Window – Wall ratio (WWR)	0.30
Services Type: Heating, Cooling & Ventilation	Mechanical (M)
Number of Occupants	488
Hours of Operation	13
Energy Consumption per square meter (Kwh/m^2/annum)	216
Total Energy Consumption (Kwh/ annum)	627,598

Source: Facilities and maintenance unit management at CUT

4.2.1.9 User Survey Data

There were 3 sections in the questionnaires that covered demographic questions (section one); and student and staff perceptions of IEQ in lecture and office venues (sections two and three). Parameters evaluated by the questionnaire included perception of temperature, humidity (stuffiness of the air), ventilation, lighting and overall comfort. The respondents were asked to rate the IEQ perceptions of lecture venues in the assessed buildings of all three universities on a scale of 1 (very dissatisfied) to 5 (very satisfied). The responses to this section of the questionnaire are presented in appendix (6), and analyzed in section 5.4.

4.2.1.10 User Survey Data: Responses to the demographics section for CUT

The responses to the gender distribution inquiry for CUT (table 4.10) indicate that 62.5% were male respondents while 37.5% were female. The age structure of respondents for CUT is presented in table 4.11 and the responses to occupation/position profile are indicated in table 4.12

Table 4.10: Gender Distribution of respondents at CUT

CUT: Gender Distribution		
	Number	**Percentage**
Male	25	62.5
Female	15	37.5
Total	40	100

Source: Response to questionnaire

Table 4.11: Age Structure of respondents at CUT

Age	Number	Percentage
Below 20	3	7.5
20-24	22	55
25-39	10	25
40-49	3	7.5
50-59	1	2.5
60+	1	2.5

Source: Response to questionnaire

Table 4.12: Responses to occupation/position profile for CUT

Occupation	Number	Percentage
Student	32	80
Technical Assistant	0	0
Junior Lecturer	0	0
Lecturing Assistant	1	2.5
Lecturer	4	10
Senior Lecturer	2	5
Associate professor	1	2.5

Source: Response to questionnaire

4.2.2 Durban University of Technology, Durban

DUT is a University of Technology located in Durban, a major coastal city in KwaZulu-Natal Province of South Africa. It was formed in 2002 by the merger of two technikons, Technikon Natal and ML Sultan Technikon. It was previously known as the Durban Institute of Technology. It has five campuses in Durban and two in Pietermaritzburg. However, buildings at two campuses, the Steve Biko campus and ML Sultan campus – both located in Durban – were assessed for this study. The aerial views of Steve Biko and ML Sultan campuses are shown in Figure 4.12 and Figure4.13 respectively.

Figure 4.12: Aerial view of Steve Biko campus, DUT **Photo**: **Google earth**

Figure 4.13: Aerial view of ML Sultan campus, DUT **Photo: Google earth**

4.2.2.1 University profile and services provided

DUT's vision is to be a preferred university for developing leadership in technology and productive citizenship. It has a mission is to excel through:

- A teaching and learning environment that values and supports the university community;
- Promoting excellence in learning and teaching, technology transfer and applied research; and
- External engagement that promotes innovation and entrepreneurship through collaboration and partnership.

Academic activities at DUT are managed by 6 faculties such as:

- Faculty of Accounting and Informatics
    - Department of Auditing and Taxation
    - Department of Finance and Information Management
    - Department of Financial Accounting
    - Department of Information and Corporate Management
    - Department of Information Technology
    - Department of Management Accounting
- Faculty of Applied Sciences
    - Department of Biotechnology and Food Technology
    - Department of Clothing and Textile Studies
    - Department of Food and Nutrition Consumer Sciences
    - Department of Horticulture
    - Department of Maritime Studies
    - Department of Mathematics, Statistics and Physics
    - Department of Sports Studies

- Faculty of Arts and Design
    - Department of Drama & Production Studies
    - Department of Fashion and Textiles
    - Department of Fine Art and Jewellery Design
    - Department of Media, Language and Communication
    - Department of School of Education
    - Department of Video Technology
    - Visual Communication

- Faculty of Engineering and the Built Environment
    - Department of Architectural Technology
    - Department of Chemical Engineering
    - Department of Civil Engineering and Surveying
    - Department of Construction Management and Quantity Surveying
    - Department of Electrical Power Engineering
    - Department of Electronic Engineering
    - Department of Industrial Engineering
    - Department of Mechanical Engineering
    - Department of Town and Regional Planning
    - Department of Urban Futures Centre

- Faculty of Health Sciences
    - Department of Basic Medical Sciences
    - Department of Biomedical and Clinical Technology
    - Department of Chiropractic and Somatology
    - Department of Community Health Studies
    - Department of Dental Sciences
    - Department of Emergency Medical Care and Rescue
    - Department of Homoeopathy
    - Department of Medical Orthotics and Prosthetics
    - Department of Nursing
    - Department of Radiography
    - Department of Short Courses

- Faculty of Management Sciences
    - Department of Applied Law
    - Department of Business Studies
    - Department of Ecotourism
    - Department of Entrepreneurial Studies and Management
    - Department of Hospitality and Tourism
    - Department of Human Resources Management
    - Department of Marketing and Retail
    - Department of Operations and Quality Management

- Department of Public Management and Economics
- Department of Public Relations Management

Various other departments and units exist at the university to provide institutional support and administrative functions. They include:

Academic Administration

- Institutional Support
- Human Resources
- Institutional Planning

Management Information Systems

- Physical Planning
- Projects and Services / Maintenance and Facilities Management
- Protection Services / Health and Safety
- Transport

Student Services and Development

- Financial Aid Services
- Sports Centre
- Student Counselling and Health Centre
- Student Affairs
- Student Housing

Physical Planning

The purpose of physical planning is to support the Deputy Vice Chancellor (DVC), Institutional Support, by directing and co-ordinating the overall planning of facilities within the DUT. It aims at providing cost effective advice and support to optimize utilization of existing space and facilities and plan the university's future spatial- and facilities requirements in alignment with the objectives and vision of the DUT.

In accordance with policy recommendations from the university, the physical planning unit also contributes to the research, design and development of relevant facilities, planning related policies, procedures, plans and systems on an on-going basis in line with relevant legislation and national standards.

The various specific responsibilities of the Physical Planning Unit include:

- Management of Campus Planning Function
- Records and Documentation Control
- Moves and Relocations
- Planning
- Project Management
- Advice and Liaison
- Customer Advice and Support
- Systems Management
- Resources Management
- Representation

The built-up area of the university continues to increase with new construction. Over years several new projects have been built and many buildings have been renovated. With regards to the sustainability of the buildings and infrastructure, there are similarities with buildings at CUT. The buildings and infrastructure include academic (instructional) spaces (buildings), office buildings for academic staff, laboratory buildings, buildings for administrative and management functions, library, student centre, community buildings, meeting halls, examination halls, internal circulation (transportation areas), off-street parking area, entertainment arenas, sporting arena, restaurants and cafe, etc. However, most of the buildings were designed and built according to codes that are not compliant to sustainability concerns.

4.2.2.2 Evaluation of Buildings (DUT)

Six buildings from both the Steve Biko- and ML Sultan campus of DUT were assessed. The buildings evaluated at Steve Biko campus were S3 and S8 from of the Faculty of Engineering. At the ML Sultan campus, the buildings assessed include Block D, E, G (Library) and J, which belong to the Faculty of Management Sciences. An aerial view of the buildings is presented in Figure 4.14 and Figure 4.15.

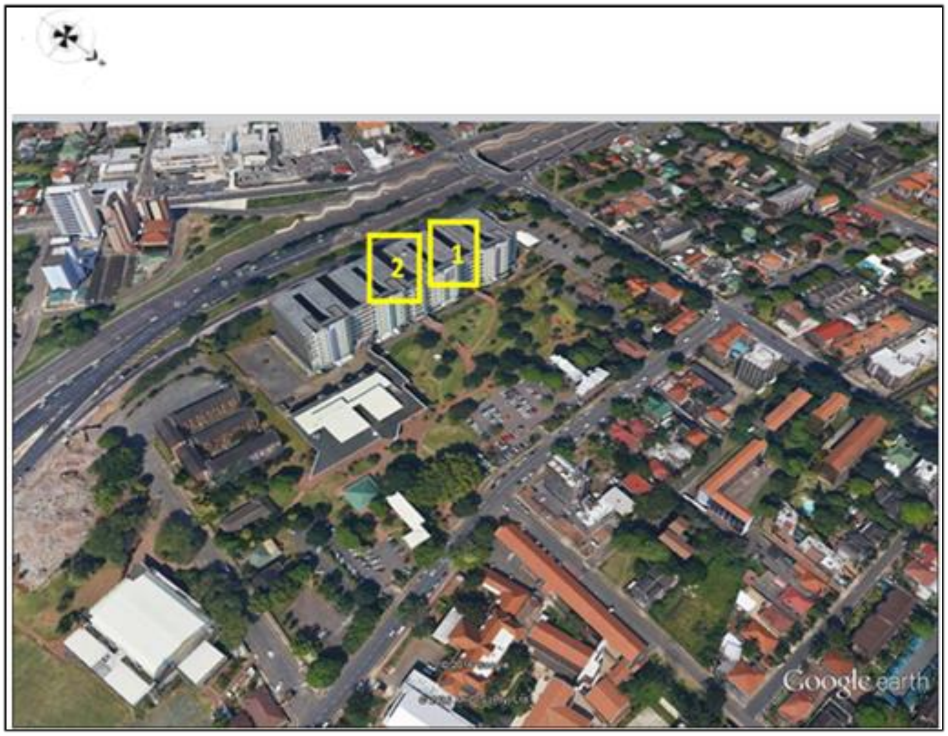

Figure 4.14: Building location and orientation of assessed buildings at Steve Biko campus. 1: S3, 2:S8 Photo: Google earth

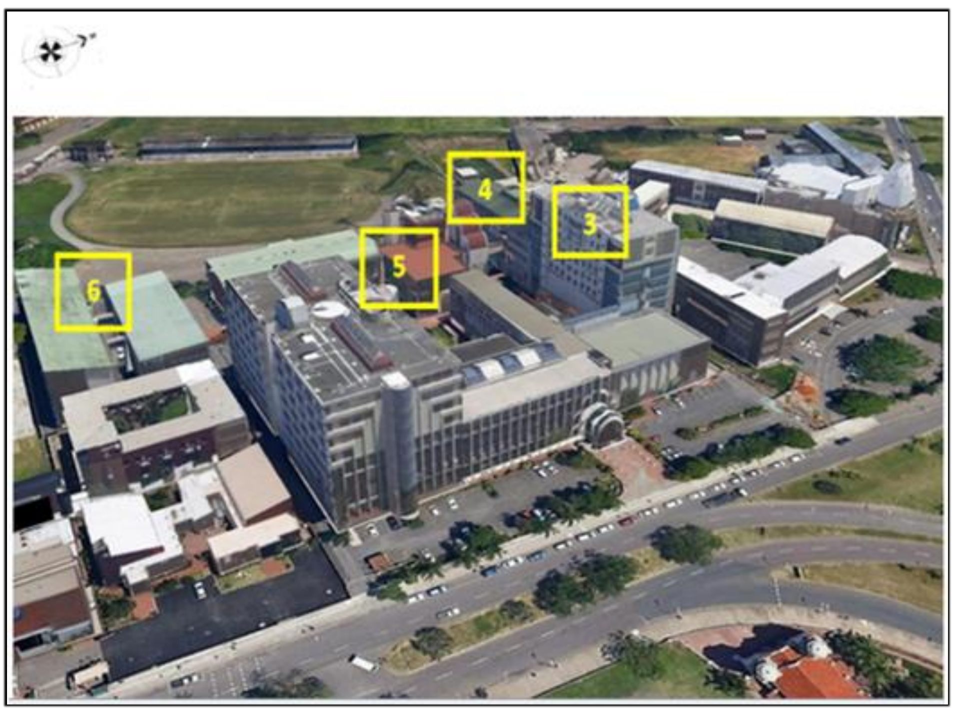

Figure 4.15: Building location and orientation of assessed buildings at ML Sultan campus, DUT. 3: Building D, 4: Building E, 5: Building G, 6: Building J; Photo: Google earth

4.2.2.3 Building S3 (DUT)

Building S3 is within the S-Block set of buildings which consists of 8 buildings connected by bridges. They are all academic buildings in the Faculty of Engineering. S3 contains lecture rooms, laboratories, computer rooms and offices. The orientation of the building is such that the longitudinal facades face East and West (figure 4.16). The building has 8 storeys and consists of large courtyards that separate the buildings. The lecture rooms have large windows that give access to daylight and ventilation. The lecture rooms use a combination of daylight and artificial light for lighting purposes. The building consists of a courtyard surrounded by one-sided corridor configurations, which gives access to natural light and ventilation from the courtyard. The lecture rooms depend mainly on natural ventilation; however, fans are available in some venues to improve ventilation. The offices use room air conditioning (mechanical ventilation) for heating, cooling and ventilation. Figure 4.16 presents the plan and views/perspectives of building S3. The envelope design plan indicates use of large windows predominantly on the east and west facades of the building. The summary of key features of the building (table 4.13) indicates that energy consumption in this building is 342,176 kwh/m^2/annum or 90kwh/m^2/annum and the total building area 3435.3 m^2. The external window-to-wall ratio is 0.24 and the building operates for 13 hours a day.

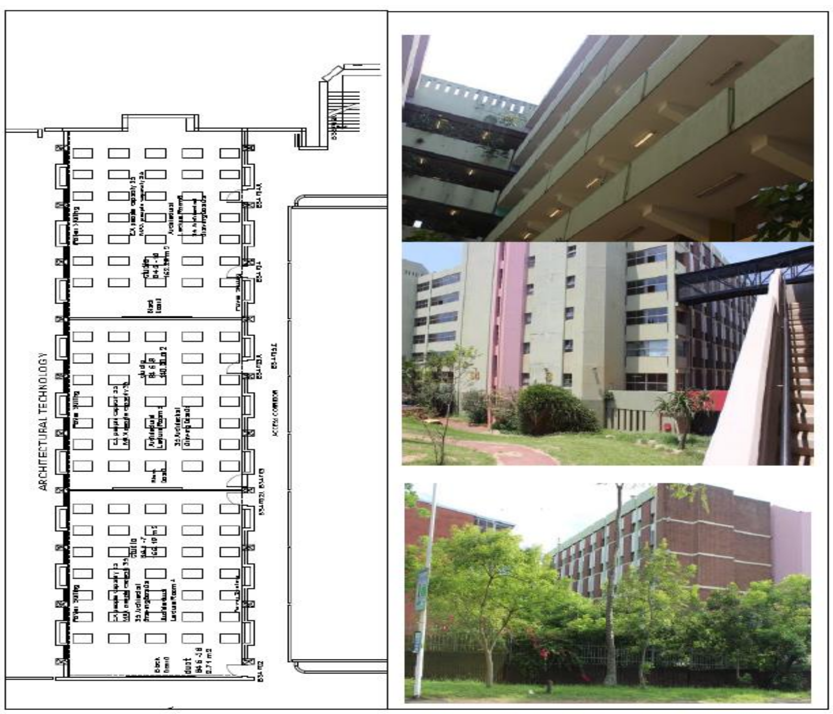

Figure 4.16: Building plan and façade features of building S3
Floor plan: DUT Physical Planning unit

Table 4.13: Summary of key features of building S3 (DUT)

Building Location	**Durban University of Technology (DUT)**
Building Function	Teaching & Learning
Orientation	East & West
Total Area of Building (m^2)	3435.3
Number of Floors	8
External Window – Wall ratio (WWR)	0.24
Services Type: Heating, Cooling & Ventilation	Mixed: Natural & Mechanical (MN)
Number of Occupants	561
Hours of Operation	13
Energy Consumption per square meter (Kwh/m^2/annum)	90
Total Energy Consumption (Kwh/ annum)	342,176

Source: Physical Planning unit at DUT

4.2.2.4 Building S8 (DUT)

Building S8 is within the S-Block set of buildings which consists of 8 buildings connected by bridges. They are all academic buildings at the faculty of Engineering. S8 is exactly the same in size and shape as S3, the difference being that S8 is surrounded by two similar buildings on both sides as indicated in figure 4.17. The building also contains lecture rooms, laboratories, computer rooms and offices. The orientation of the building is such that the longitudinal facades face East and West. The building also has 8 storeys and consists of large courtyards that separate the buildings. The large windows of lecture rooms give access to daylight and ventilation. The lecture rooms use a combination of daylight and artificial light for lighting purposes and they depend mainly on natural ventilation. The offices use room air conditioning (mechanical ventilation) for heating, cooling and ventilation and fans are available in some venues to improve ventilation. Figure 4.17 presents the plan and views/perspectives of building S8. The envelope design plan indicates use of large windows predominantly on the east and west façades of the building. The summary of key features is similar to building S3 as indicated in table 4.14. The energy consumption in this building is 342,176 kwh/m^2/annum or 90kwh/m^2/annum, the external window-to-wall ratio is 0.24, and it operates for 13 hours a day.

Figure 4.17: Building plan and façade features of building S8

Floor plan: DUT Physical Planning unit

Table 4.14: Summary of key features of building S8 (DUT)

Building Location	**Tshwane University of Technology (DUT)**
Building Function	Teaching & Learning
Orientation	East & West
Total Area of Building (m^2)	3435.3
Number of Floors	8
External Window – Wall ratio (WWR)	0.24
Services Type: Heating, Cooling & Ventilation	Mixed: Natural & Mechanical (MN)
Number of Occupants	561
Hours of Operation	13
Energy Consumption per square meter ($Kwh/m^2/annum$)	90
Total Energy Consumption (Kwh/ annum)	342,176

Source: Physical Planning unit at DUT

4.2.2.5 Building D (DUT)

Building D, a 7 storey academic building located at the ML Sultan campus contains lecture rooms, lectures theatres, laboratories, computer rooms and offices. As shown in figure 4.18, the orientation of the building is such that the longitudinal facades face North and South. The large windows of the lecture rooms give access to daylight and ventilation. The first two floors have no windows for the lecture theatres. In subsequent upper floors the lecture rooms use a combination of daylight and artificial light for lighting purposes. The lecture rooms also depend on both natural and mechanical means for ventilation. Offices use room air conditioning (mechanical ventilation) for heating and cooling. Figure 4.18 presents the plan and views/perspectives of building D. The envelope design plan indicates use of large windows predominantly on the north and south façades of the building. The energy consumption in this building is 785,000 kwh/m^2/annum or 92 kwh/m^2/annum (table 4.15). The external window-to-wall ratio is 0.12 and the building operates for 13 hours a day.

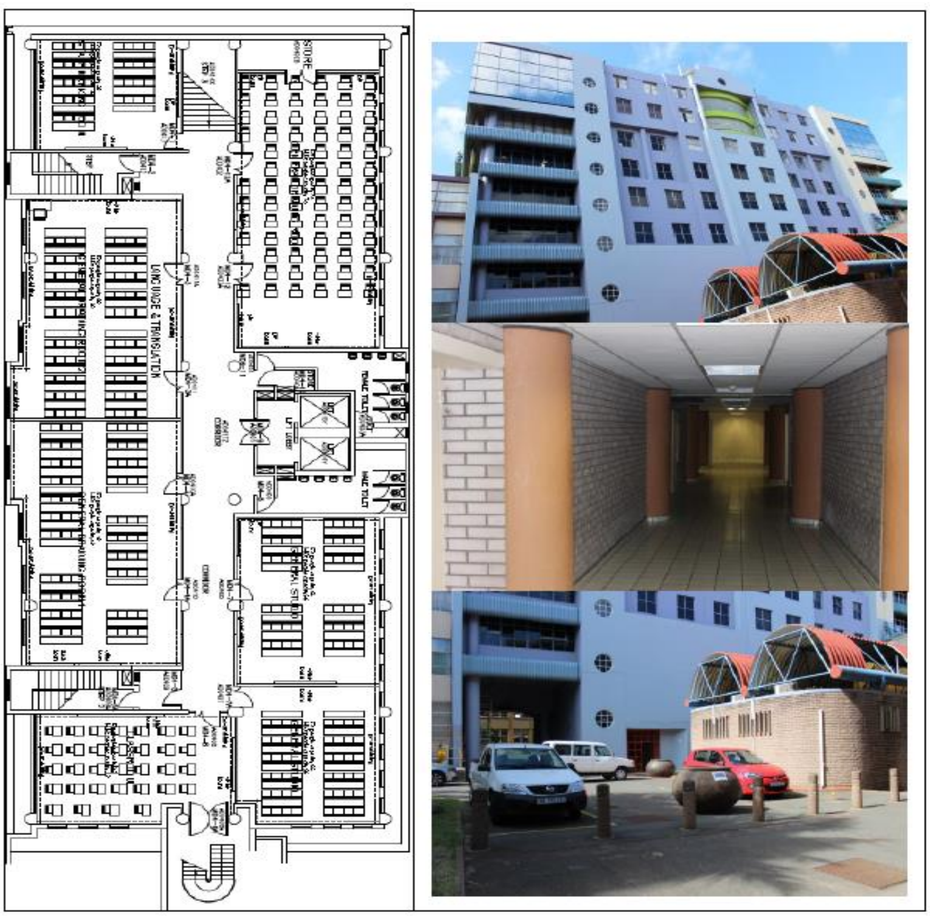

Figure 4.18: Building plan and façade features of building D

Floor plan: DUT Physical Planning unit

Table 4.15: Summary of key features of building D (DUT)

Building Location	**Durban University of Technology (DUT)**
Building Function	Teaching & Learning
Orientation	North & South
Total Area of Building (m^2)	8,750
Number of Floors	7
External Façade / Window ratio	0.12
Services Type: Heating, Cooling & Ventilation	Mixed: Natural & Mechanical (MN)
Number of Occupants	1879
Hours of Operation	13
Energy Consumption per square meter (Kwh/m^2/annum)	92
Total Energy Consumption (Kwh/ annum)	785,000

Source: Physical Planning unit at DUT

4.2.2.6 Building E (DUT)

Building E, a 3 storey academic building, is also located at ML Sultan campus. Like most other academic buildings, it contains lecture rooms, laboratories, computer rooms and offices. The orientation of building E is such that the longitudinal façades face North and South (figure 4.19). The lecture rooms have large windows that give access to daylight and ventilation. Whereas the first two floors have no windows for the lecture theatres, the lecture rooms on subsequent upper floors use a combination of daylight and artificial light for illumination and also depend on both natural and mechanical means for ventilation. Offices use room air conditioning (mechanical ventilation) for heating, cooling and ventilation. Figure 4.19 presents the plan and views/perspectives of building E. The summary of key features of this building is indicated in Table 4.16. The envelope design plan indicates use of large windows predominantly on the North and South façades of the building. The energy consumption of this building is 432,416 Kwh/annum or 170 Kwh/m^2/annum, the external window-to-wall ratio is 0.29, and it operates for 10 hours a day.

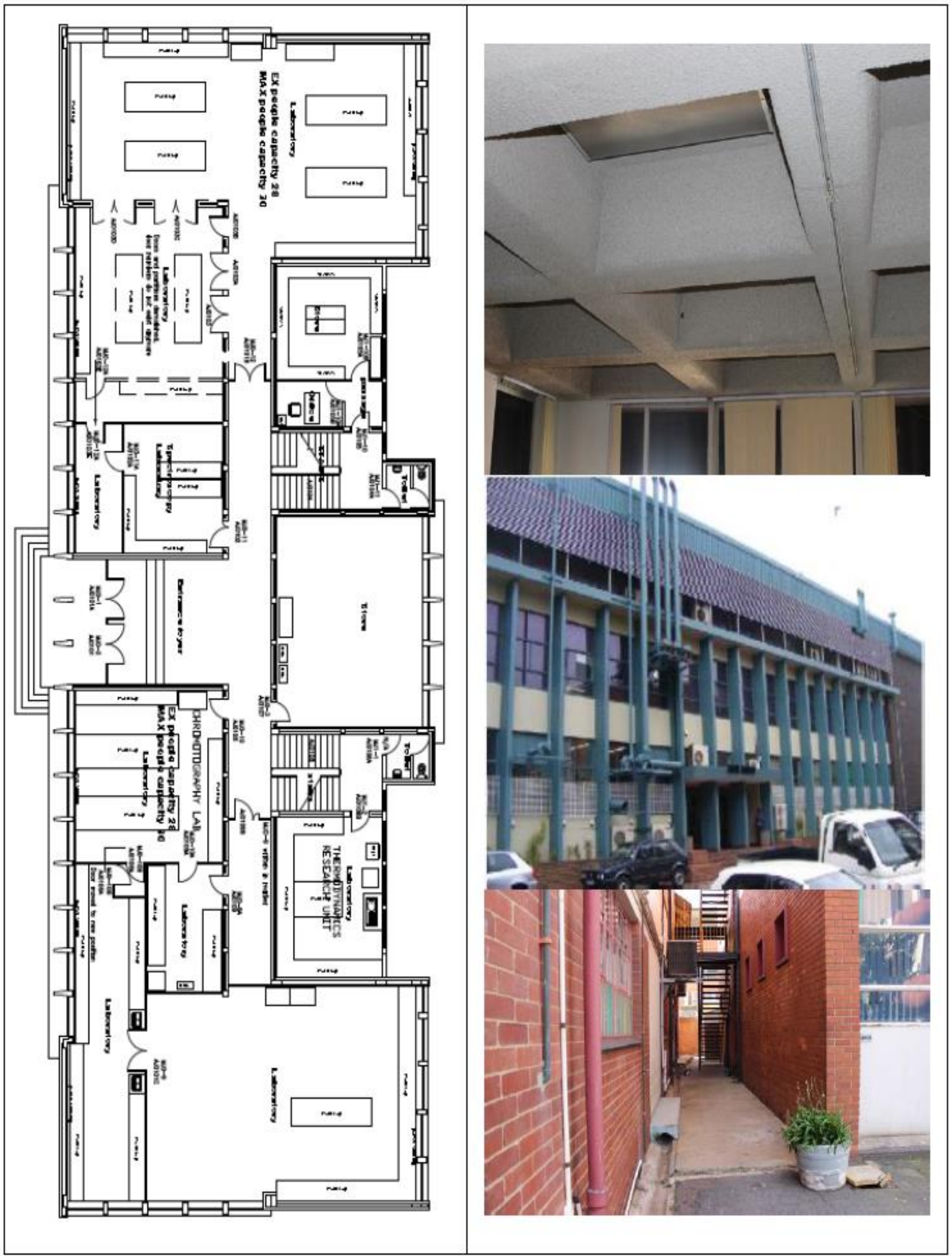

Figure 4.19: Building plan and façade features of building E

Floor plan: DUT Physical Planning unit

Table 4.16: Summary of key features of building E (DUT)

Building Location	**Durban University of Technology (DUT)**
Building Function	Teaching & Learning
Orientation	North & South
Total Area of Building (m^2)	2,640
Number of Floors	3
External Window – Wall ratio (WWR)	0.29
Services Type: Heating, Cooling & Ventilation	Mixed: Natural & Mechanical (MN)
Number of Occupants	422
Hours of Operation	10
Energy Consumption per square meter (Kwh/m^2/annum)	170
Total Energy Consumption (Kwh/ annum)	432,416

Source: Physical Planning unit at DUT

4.2.2.7 Building G (DUT)

The 3 storey library (building G) at ML Sultan campus contains lending rooms, reading rooms, computer rooms and offices. Similar to buildings D and E, its orientation is such that the longitudinal façades face North and South, (figure 4.20). Although the large windows of the lecture rooms give access to daylight, they remain closed. The lending rooms, reading rooms as well as other rooms depend on mechanical means for heating, cooling and ventilation. Figure 4.20 presents the plan and views / perspectives of building G. The envelope design plan indicates large windows predominantly on the north and south façades of the building whereas glass curtain walls are used on the South elevation. The summary of key features of building G is indicated in table 4.17. The energy consumption of this building is 289,480 Kwh/annum or 119 Kwh/m^2/annum, the external window-to-wall ratio is 0.19, and it operates for 13 hours a day.

Though both the library at CUT and the library at DUT operate for 13 hours a day, the energy consumption in the DUT library (building G) is higher than the 107 Kwh/m^2/annum consumed in the library building at CUT. It is important to note that the library at CUT has a window-to-wall ratio of 0.32, whereas building G at DUT has a window-to-wall ratio of 0.19. This means the CUT library has more access to natural light.

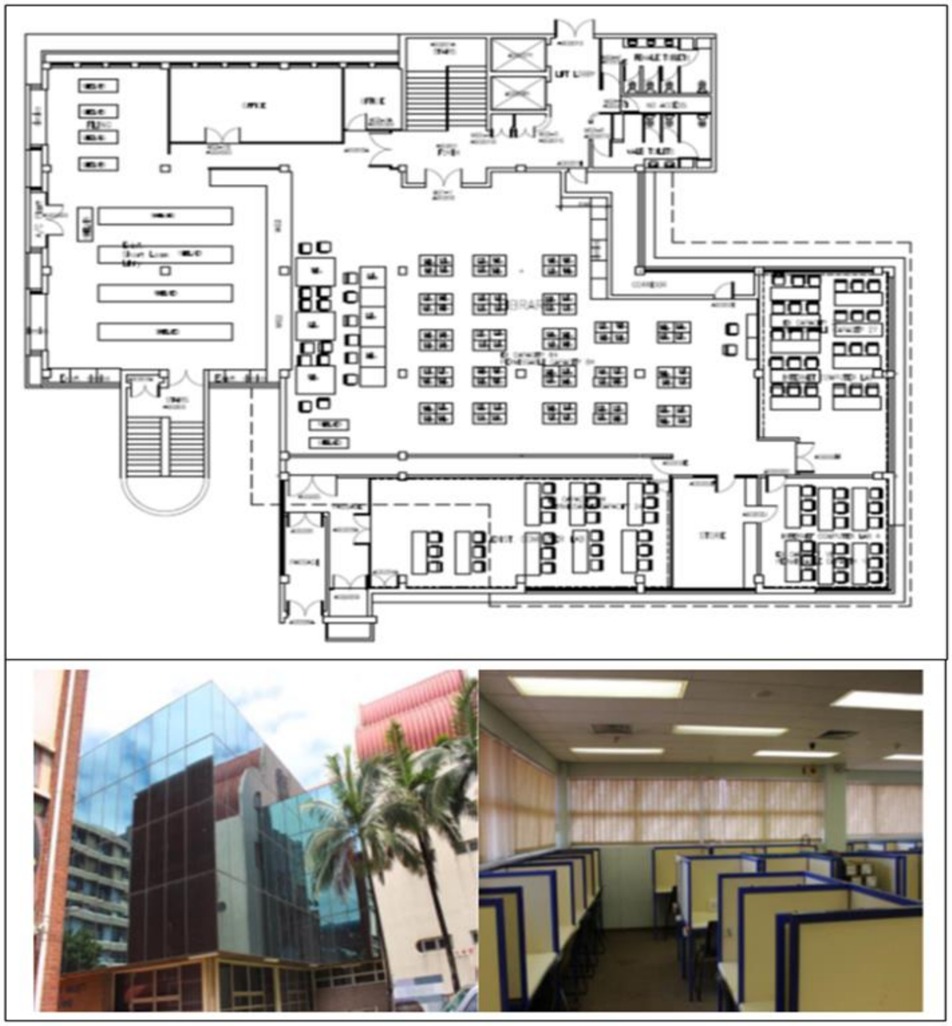

Figure 4.20: Building plan and façade features of building G

Floor plan: DUT Physical Planning unit

Table 4.17: Summary of key features of building G (DUT)

Building Location	**Durban University of Technology (DUT)**
Building Function	Teaching & Learning
Orientation	North & South
Total Area of Building (m^2)	2700
Number of Floors	4
External Façade – Window ratio	0.19
Services Type: Heating, Cooling & Ventilation	Mechanical (M)
Number of Occupants	370
Hours of Operation	13
Energy Consumption per square meter (Kwh/m^2/annum)	119
Total Energy Consumption (Kwh/ annum)	289,480

Source: Physical Planning unit at DUT

4.2.2.8 Building J (DUT)

Building J at the ML Sultan campus is a 4 storey academic building that typically contains lecture rooms, laboratories, computer rooms and offices. The orientation of the building – similar to building D – is such that the longitudinal view faces North and South, (figure 4.21). The lecture rooms have large windows that give access to daylight and ventilation, but the first two floors have no windows for the lecture theatres. In subsequent upper floors the lecture rooms use a combination of daylight and artificial light for lighting purposes. The lecture rooms also depend on both natural and mechanical means for ventilation whereas offices use room air conditioning (mechanical ventilation) for heating and cooling. Figure 4.21 presents the plan and views / perspectives of building J. The envelope design plan indicates use of large windows predominantly on the north and south façades of the building. The energy consumption of this building is 244,662 Kwh/annum or 116 Kwh/m^2/annum, the external window-to-wall ratio is 0.23, and the building operates for 13 hours a day. The summary of key features of building J is presented in Table 4.18.

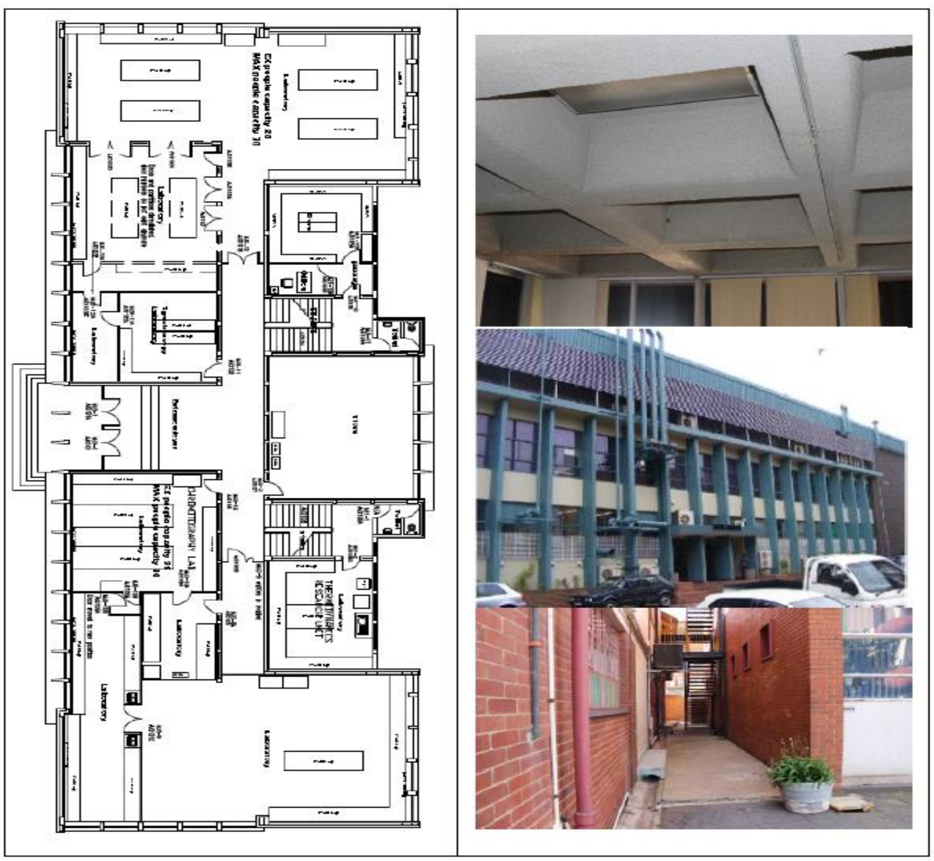

Figure 4.21: Building plan and façade features of building J
Floor plan: DUT Physical Planning unit

Table 4.18: Summary of key features of building J (DUT)

Building Location	**Durban University of Technology (DUT)**
Building Function	Teaching & Learning
Orientation	North & South
Total Area of Building (m^2)	2820
Number of Floors	4
External Façade – Window ratio	0.23
Services Type: Heating, Cooling & Ventilation	Mixed Mechanical (NM)
Number of Occupants	264
Hours of Operation	13
Energy Consumption per square meter (Kwh/m^2/annum)	116
Total Energy Consumption (Kwh/ annum)	244,662

: Physical Planning unit at DUT

4.2.2.9 User Survey Data: Responses to Demographics Section for DUT

The responses to the gender distribution inquiry at DUT are presented in table 4.19. The table shows that 67% of respondents were male while 33% were female. The age structure of respondents at DUT is presented in table 4.20 while responses to occupation/position profile are indicated in table 4.21.

Table 4.19: Gender distribution of respondents at CUT

DUT: Gender Distribution		
	Number	**Percentage**
Male	20	67
Female	10	33
Total	30	100

Source: **Response to questionnaire**

Table 4.20: Age structure of respondents at DUT

Age	**Number**	**Percentage**
Below 20	2	7
20-24	19	63
25-39	8	27
40-49	1	3
50-59	0	0
60+	0	0

Source: **Response to questionnaire**

Table 4.21: Responses to occupation/position profile of DUT

Occupation	Number	Percentage
Student	24	80
Technical Assistant	0	0
Junior Lecturer	0	0
Lecturing Assistant	0	0
Lecturer	3	10
Senior Lecturer	2	7
Associate professor	1	3

Source: **response to questionnaire**

4.2.3 Tshwane University of Technology (TUT), Pretoria campus

Tshwane University of Technology is a higher education institution (University of Technology) in South Africa that came into being on 1 January 2004, with the merging of the former Technikon Northern Gauteng, Technikon North-West and Technikon Pretoria. Its geographic footprint covers four of South Africa's provinces including Gauteng, Mpumalanga, Limpopo and the North-West Province. It is the largest of the Universities of Technology in South Africa.

The various campuses of this University of Technology are located in Tshwane (Pretoria, Soshanguve and Ga-Rankuwa), Mbombela (previously called Nelspruit), eMalahleni (previously called Witbank) and Polokwane (previously called Pietersburg). Large numbers of students are also drawn from other provinces and from neighbouring countries such as Botswana, Zimbabwe, Namibia and Swaziland. The university also encompasses a large built infrastructure, particularly on the Pretoria campus. For the purpose of this study, buildings only on Pretoria campus were assessed. Figure 4.7, 4.8 and 4.9 present the aerial and approach views of TUT's Pretoria campus respectively.

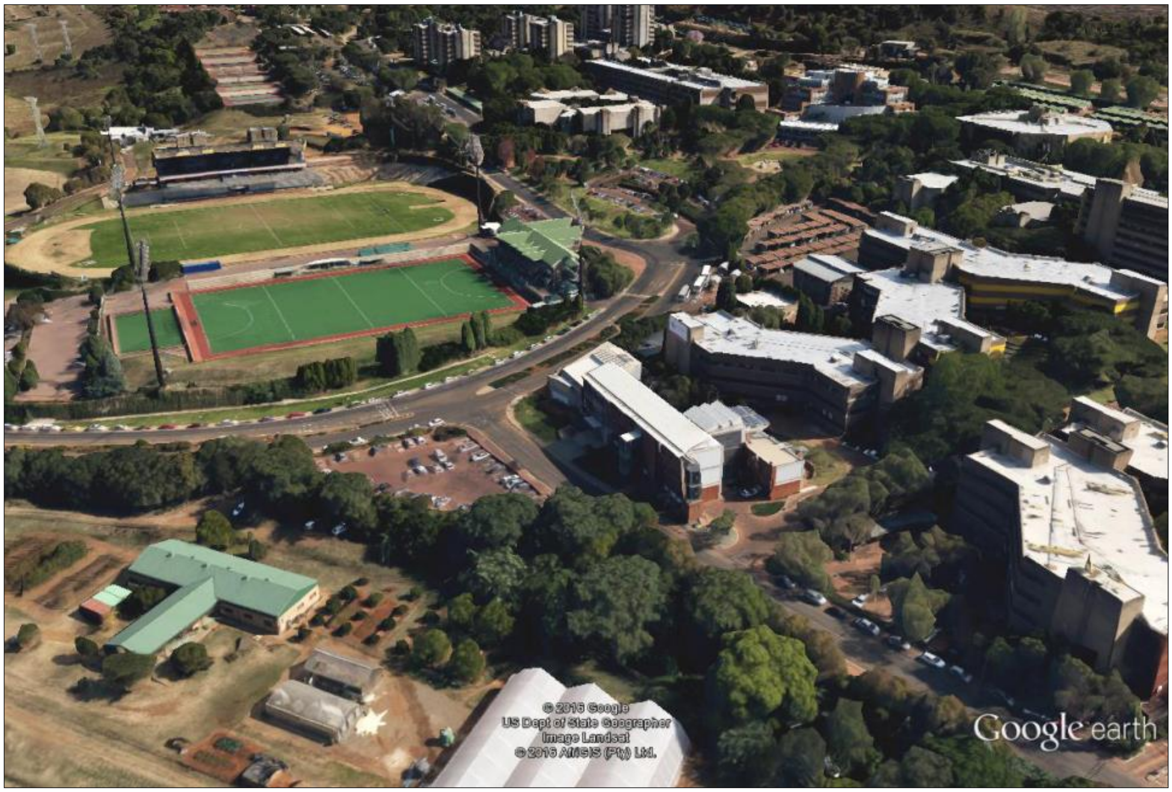

Figure 4.22: Aerial view of TUT's, Pretoria campus **Photo**: **Google earth**

Figure 4.23: Aerial view of TUT's Pretoria campus **Photo**: **Google earth**

Figure 4.24: Approach views of TUT's Pretoria campus

4.2.3.1 Organizational profile and services provided

Tshwane University of Technology (TUT) strives to be a leading institution, viewing the diversity of its staff, students and other stakeholders as a strength to be nurtured in service of the country and the African continent. The University is committed to on-going transformation to make it ever more responsive to the needs of Southern Africa and the continent as a whole.

Its vision is to pioneer an enterprising and transformative brand of twenty-first Century University of Technology scholarship. To attain its vision, the staff and students of TUT commit to

- Social accountability
- Duty of care
- Non-discrimination
- Greening the environment

The various academic activities at TUT are managed by 7 faculties:

- Faculty of Engineering and the Built Environment
    - Department of Architecture

  - Department of Building Sciences
  - Department of Chemical, Metallurgical and Materials Engineering
  - Department of Civil Engineering
  - Department of Electrical Engineering
  - Department of Geomatics
  - Department of Industrial Engineering
  - Department of Mechanical Engineering

- Faculty of Science
  - Department of Animal Sciences
  - Department of Biomedical Sciences
  - Department of Biotechnology and Food Technology
  - Department of Chemistry
  - Department of Crop Sciences
  - Department of Environmental Health
  - Department of Environmental Water and Earth Sciences
  - Department of Horticulture
  - Department of Mathematics and Statistics
  - Department of Nature Conservation
  - Department of Pharmaceutical Sciences
  - Department of Physics
  - Department of Sport, Rehabilitation and Dental Sciences
  - The Adelaide Tambo School of Nursing Science

- Faculty of Humanities
  - Department of Applied Languages
  - Department of Public Relations and Business Communication
  - Department of Law
  - Department of Safety and Security Management
  - Department of Journalism
  - Department of Educational Studies
  - Department of Educational Management (Distance Education)
  - Department of Mathematics, Science and Technology Education
  - Department of Public Management

- Department of Post Graduate Studies (Education)

- Faculty of Management Sciences
    - Department of Hospitality Management
    - Department of Management and Entrepreneurship
    - Department of Marketing, Logistics and Sport Management
    - Department of Office Management and Technology
    - Department of Operations Management
    - Department of People Management and Development
    - Department of Tourism Management

- Faculty of Information and Communication Technology
    - Department of Software Engineering
    - Department of Computer Systems Engineering
    - Department of Informatics
    - Department of Web and Multimedia Computing
    - Department of Information Technology
    - Department of Computer Science
    - Department of End User Computing

- Faculty of The Arts
    - Department of Drama and Film
    - Department of Entertainment Technology
    - Department of Fashion Design and Technology
    - Department of Fine and Applied Arts
    - Department of Performing Arts
    - Department of Visual Communication

- Faculty of Economics and Finance
    - Department of Economics
    - Department of Accounting
    - Department of Managerial Accounting and Finance
    - Department of Auditing
    - Department of Public Sector Finance

Building and Estates Unit

The Building and Estates Unit of TUT's Pretoria campus It is also concerned with the development and implementation of techniques within the engineering and built environment which relates to the designs; tender writing, construction and maintenance; long term scenario planning, impact assessment, maintenance and legal aspects related to property development and investment and disposal; as well as the development and monitoring of relevant policies.

Like the other two case study universities, TUT's Pretoria campus constitutes a number of buildings and infrastructures which include academic (instructional) spaces(buildings), office buildings for academic staff, laboratory buildings, buildings for administrative and management functions, library, student center, community buildings, meeting halls, examination halls, internal circulation (transportation areas), off-street parking area, entertainment arenas, sporting arena, restaurants and cafe, etc. However, it is observed that most of the buildings were designed and built according to codes that are not compliant to sustainability concerns.

4.2.3.2 Evaluation of Buildings (TUT)

Four buildings at TUT main campus (Pretoria) were assessed. These include buildings from the Faculty of Engineering and Built Environment and the Teaching and Learning centre, namely Building 11, Building 13, Building 2-A and Building 3. The location, form and orientation of these buildings are presented in figure 4.25. The benchmark buildings 11 and 13 have already been presented in sections 4.4.1.1 and 4.4.1.2 respectively.

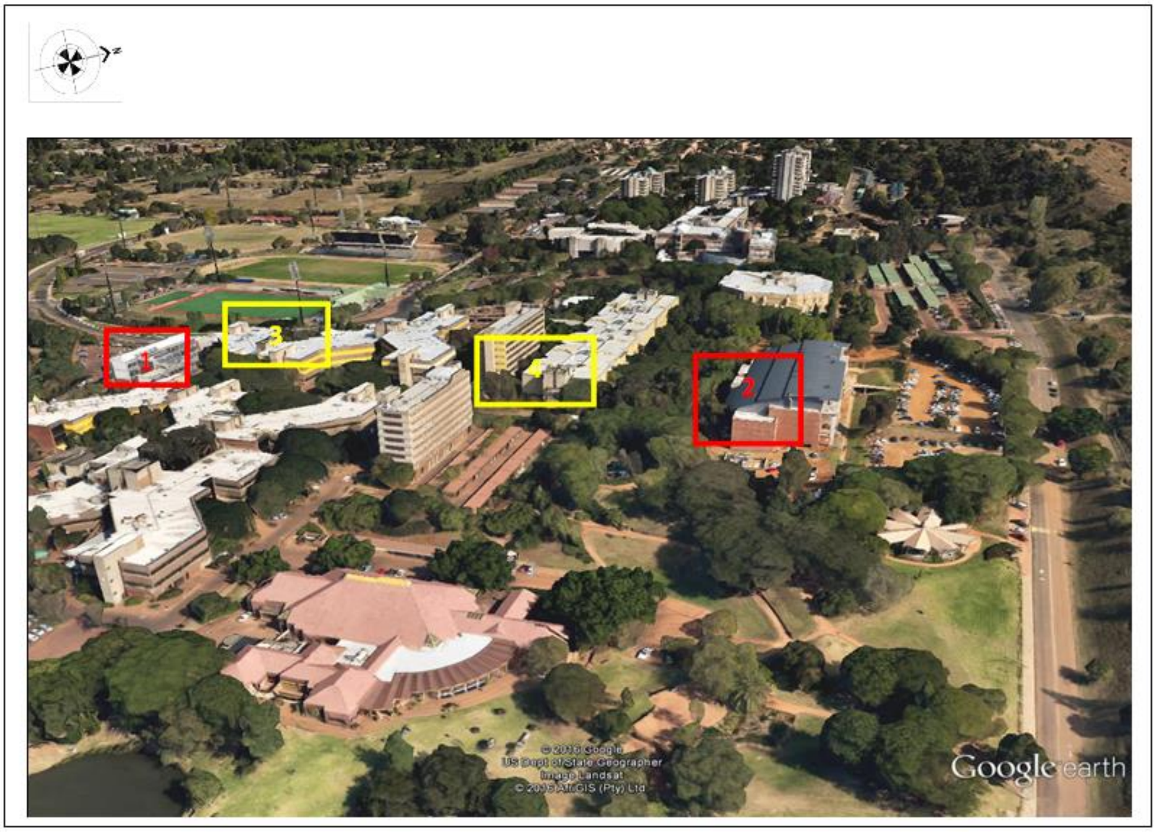

Figure 4.25: Orientation, shape and envelope features of buildings assessed at TUT's Pretoria campus **Photo: Google earth**

1: Building 11; 2: Building 13; 3: Building 2-A; 4: Building 3

4.2.3.3 Building 2-A (TUT)

Building 2-A located in the Faculty of Engineering contains lecture rooms, laboratories, computer rooms and offices. Figure 4.26 presents the orientation, plan and perspectives of the building. The orientation of the building is such that the longitudinal view is partially aligned to North & South and East & West. The building has 4 floors and is surrounded by trees and grass that separate the building from other buildings. The envelope design plan indicates use of large windows predominantly on the 45^o alignment of the buildings. The lecture rooms that have reasonably large windows giving access to daylight and ventilation, use a combination of daylight and artificial light for lighting purposes. There is a two-sided corridor configuration that has lecture rooms on both sides of the corridor. The lecture rooms and laboratories depend mainly on both natural - and mechanical ventilation for heating and cooling, depending on function while the offices use individual mechanical ventilation for heating and cooling. According to the key features of the building presented in table 4.22, the total floor area is 2,820m^2 and the external façade /

window ratio is 0.23. The energy consumption of the building is 280,371 Kwh/annum or 107 Kwh/m^2/annum.

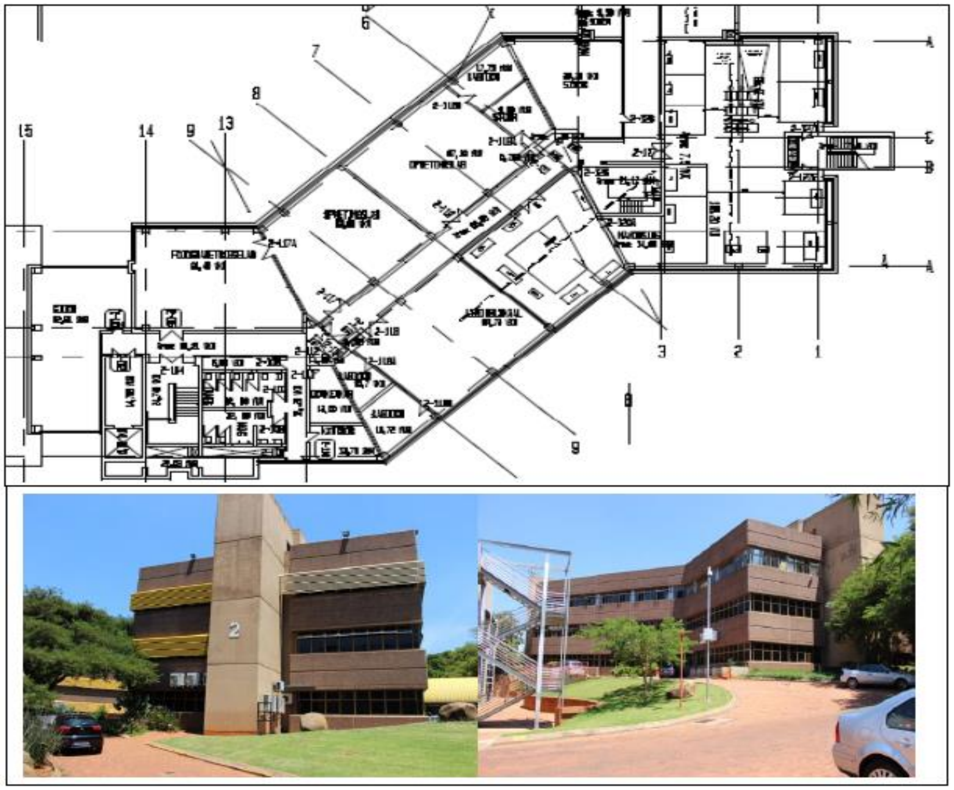

Figure 4.26: Building plan and façade features of building 2-A

Floor plan: TUT Building and Estates Unit

Table 4.22: Summary of key features of building 2-A (TUT)

Building Location	**Durban University of Technology (DUT)**
Building Function	Teaching & Learning
Orientation	North & South , East & West
Total Area of Building (m^2)	2820
Number of Floors	4
External Façade – Window ratio	0.23
Services Type: Heating, Cooling & Ventilation	Mixed Natural & Mechanical (NM)
Number of Occupants	422
Hours of Operation	13
Energy Consumption per square meter (Kwh/m^2/annum)	107
Total Energy Consumption (Kwh/ annum)	280,371

Source: Building and Estates Unit at TUT

4.2.3.4 Building 3 (TUT)

Building 3 within the Faculty of Engineering contains staff rooms, offices and lecture rooms. The building plan, façade and orientation are presented in figure 4.27. The orientation of the building is such that the longitudinal views face North and South. The building has 8 floors and the offices have reasonably large windows that give access to daylight and ventilation. The windows are arranged in all façade views; however, the East-West views have shading devices. The offices and staff rooms use a combination of daylight and artificial light for lighting purposes. There is a two-sided corridor configuration that has rooms on both sides of the corridor. The offices use individually controlled local air-conditioning systems for heating, cooling and ventilation. The envelope design indicates use of large windows, arranged along the North-South façades of the buildings. Table 4.23 presents the key features of the building. The energy consumption of this building is 587,676 Kwh/annum or 117 Kwh/m^2/annum.

A comparison between building 3 of TUT and BHP Admin of CUT shows that more energy is consumed by building 3 than by BHP admin (143 Kwh/m^2/annum). Although the two buildings have similar functions and similar designs, there are differences in window to façade ratios (WWR). The WWR ratio of building 3 (0.38) is higher than that of BHP admin (0.35). This indicates that building 3 had more access to daylight.

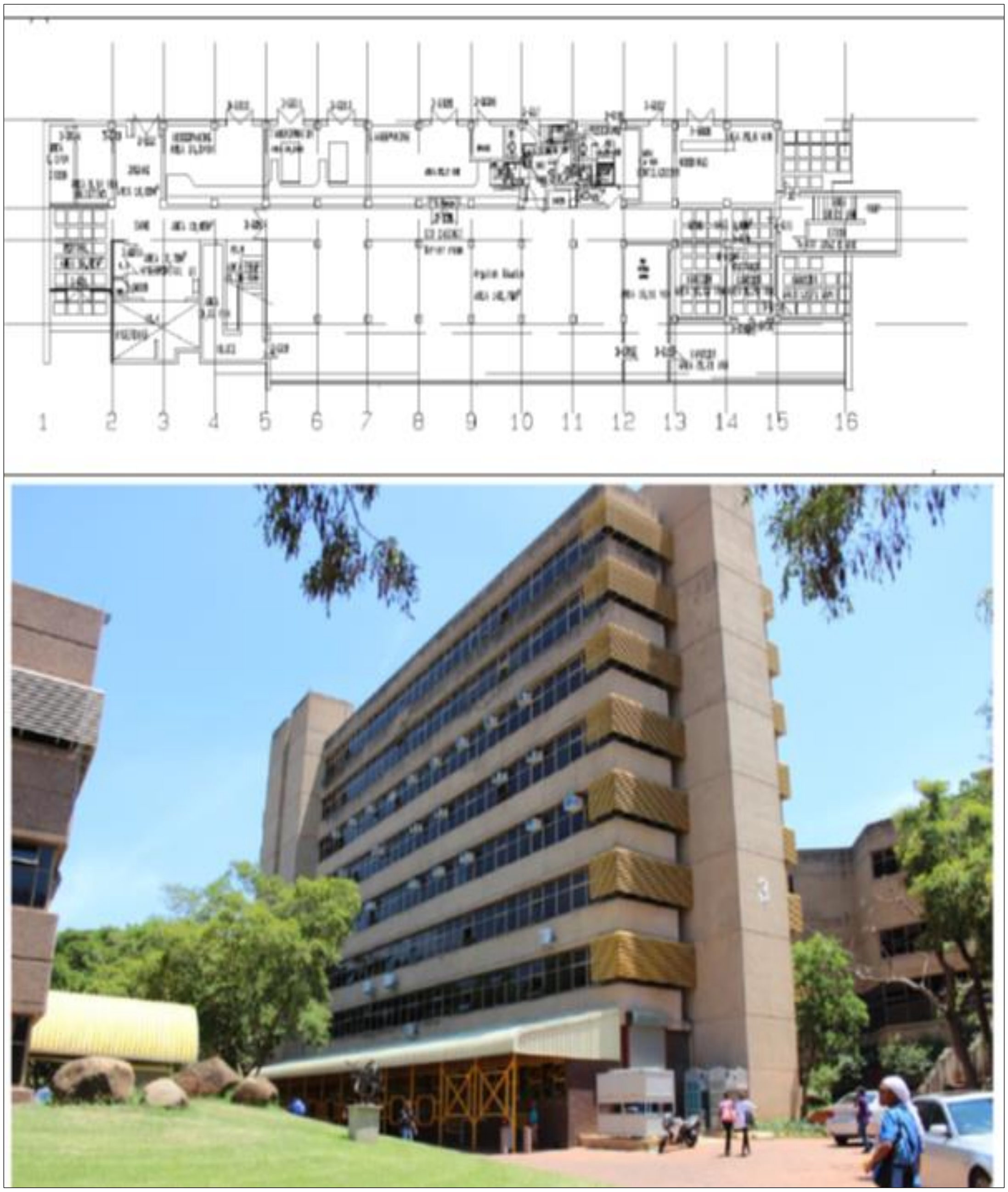

Figure 4.27: Building plan and façade of building 3

Floor plan: TUT Building and Estates Unit

Table 4.23: Summary of key features of building 3 (TUT)

Building Location	**Tshwane University of Technology (DUT)**
Building Function	Teaching & Learning
Orientation	North & South
Total Area of Building (m^2)	5760
Number of Floors	8
External Façade – Window ratio	0.38
Services Type: Heating, Cooling & Ventilation	Mechanical (M)
Number of Occupants	512
Hours of Operation	13
Energy Consumption per square meter (Kwh/m^2/annum)	117
Total Energy Consumption (Kwh/ annum)	587,676

Source: Building and Estates Unit at TUT

4.2.3.5 Building 11 (TUT): Benchmark building

Building 11 is an academic building that contains lecture rooms, architectural studios, computer laboratories and offices. It is an open plan 3 storey building with limited demarcation of spaces. The orientation of the building is such that it is aligned longitudinally along North and South (longitudinal façades face north & south) as shown in figure 4.28. All floors have large windows on almost all facades of the building, giving access to abundant daylight and ventilation. In comparison to other assessed buildings, building 11 recorded the highest value for window to wall ratio (WWR). As indicated in section 2.9.5, WWR is the proportion of glazed- to opaque façade area (i.e. ratio of the area of façade windows (exterior wall windows) versus the area of the external wall).

The use of space (open plan), also determines the flow of light and air throughout the interior of the building. The functional spaces depend on passive stack ventilation (PSV), where the air is not conditioned but vertical ducts are used to ventilate the lecture rooms. It works by combining stack effect with air movement and wind passing over the roof, which depends on wind effect of natural ventilation for heating and cooling of spaces. The offices use partially glazed partitioning, which allows flow of daylight from both the façades as well as from within the building. Figure 4. 28 presents a plan and exterior perspective/views of building 11. The envelope design plan indicates the use of large windows arranged along the north and south façades of the buildings.

There is also extensive use of insulation in ceilings and walls/floors to control flow of heat through the building. Figure 4.29 presents the exterior and interior views of building 11, indicating the exterior use of a rainwater harvesting system and. the interior use of insulation materials for walls and windows to control heat flow in the building. In comparison to all other buildings, insulation materials are used extensively in building 11. Green building principles adopted in building 11 include appropriated building orientation, extensive use of daylight and use of insulation materials. As indicated in table 4.24, the energy consumption of the building is the lowest of all assessed buildings (106,320 kwh/annum at a rate of 45 kwh/m2/annum).

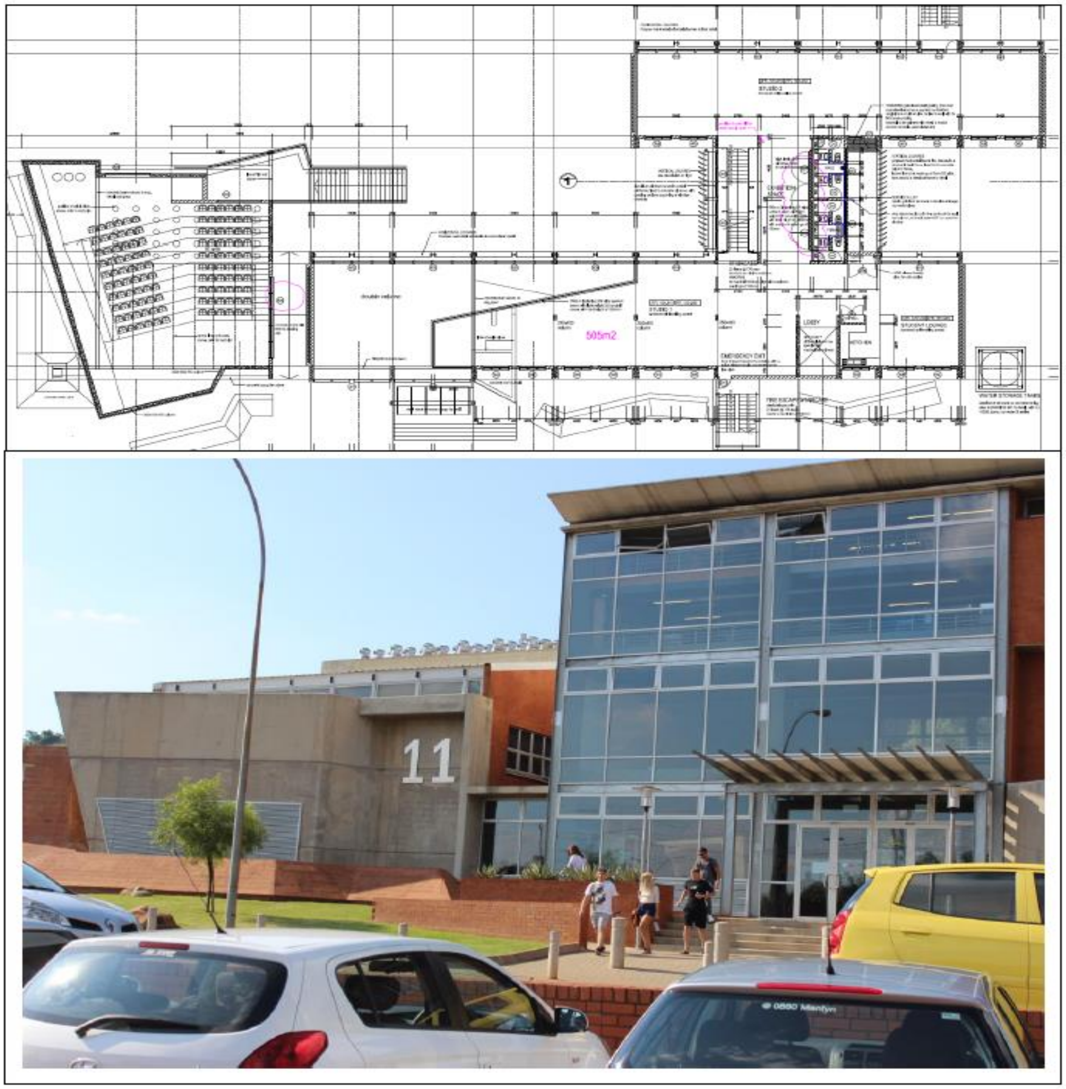

Figure 4.28: Building plan and façade features of building 11
Floor plan: TUT Building and Estates Unit

Figure 4.29: Façade features and interior view of building 11

Table 4.24: Summary of key features of building 11 (TUT)

Building Location	**Tshwane University of Technology (TUT)**
Building Function	Teaching & Learning
Orientation	North & South
Total Area of Building (m^2)	2,579.5
Number of Floors	3
External Window – Wall ratio (WWR)	0.48
Services Type: Heating, Cooling & Ventilation	Natural (N)
Number of Occupants	198
Hours of Operation	24
Energy Consumption per square meter (Kwh/m^2/annum)	45
Total Energy Consumption (Kwh/ annum)	106,320

Source: Building and Estates Unit at TUT

4.2.3.6 Building 13 (TUT): Benchmark building

Building 13 is a 3 story academic building that contains lecture theatres, computer laboratories and offices. The orientation of the building is such that the longitudinal facades face North and South (figure 4.30). There are no windows in the ground floor lecture theatres. Circulation spaces are of double volumes which facilitates vertical air movement. Glass curtain walls on the south façade provide access to abundant daylight. Heating, cooling and ventilation of the building is achieved by a similar method used by building 11, namely passive stack ventilation (PSV). Akin to building 11, the air is not conditioned but vertical ducts are used to ventilate the lecture rooms, which work by combining stack effect with air movement and wind passing over the roof, depending on the strength of the wind. Table 4.25 presents the key attributes of building 13. The total building area is 2,578.5 m^2 and the external window-to-façade ratio is 0.31. It operates for 13 hours a day and consumes 272,520 kwh/annum at a rate of 52 kwh/m^2/annum.

Figure 4.30: Building plan, façade features and interior views of building 13

Floor plan: TUT Building and Estates Unit

Table 4.25: Summary of key features of building 13 (TUT)

Building Location	**Tshwane University of Technology (TUT)**
Building Function	Teaching & Learning
Orientation	North & South
Total Area of Building (m^2)	6,814.2
Number of Floors	3
External Window / Wall ratio (WWR)	0.31
Services Type: Heating, Cooling & Ventilation	Natural (N)
Number of Occupants	283
Hours of Operation	13
Energy Consumption per square meter (Kwh/m^2/annum)	52
Total Energy Consumption (Kwh/ annum)	272,520

Source: Building and Estates Unit at TUT

4.2.3.7 User Survey Data: Responses to demographics section of TUT

The gender distribution of respondents at TUT presented in Table 4.26 shows that 68% were male respondents while 32% were female. The age structure of respondents at TUT is presented in Table 4.27 and their responses to the occupation/position profile are indicated in Table 4.28.

Table: 4.26: Gender distribution of respondents at TUT

TUT: Gender Distribution		
	Number	**Percentage**
Male	17	68
Female	8	32
Total	25	100

Source: Responses from questionnaires

Table: 4.27: Age structure of respondents at TUT

Age	Number	Percentage
Below 20	3	12
20-24	14	56
25-39	6	24
40-49	1	4
50-59	1	4
60+	0	0

Source: Responses from questionnaires

Table 4.28: Responses to occupation/position profile for TUT

Occupation	Number	Percentage
Student	22	88
Technical Assistant	0	0
Junior Lecturer	0	0
Lecturing Assistant	0	0
Lecturer	2	8
Senior Lecturer	1	4
Associate professor	0	0

Source: Responses from questionnaires

4.2.3.8 Benchmark buildings.

As indicated in sections 4.2.3.5 and 4.2.3.6, two of the assessed buildings were determined to be benchmark buildings because there was a deliberate attempt to apply green building principles in the design of these buildings. Both these buildings (11and 13) are located at Tshwane University of Technology (TUT).

4.3 Rated green building case study: Department of Environmental Affairs, Pretoria

For the purpose of comparing sustainability of buildings and infrastructures at the above mentioned universities, it was deemed necessary to relate an existing rated green building (which is considered as a sustainable building), to the assessed buildings at the universities. However, access to data on a rated educational green building in South Africa was not available, therefore the office building of the Department of Environmental Affairs (DEA) which is located in Pretoria, was selected as the benchmark building. The reason for this choice is that office buildings share similarities with educational buildings with regards to size, use of materials and in some cases type of heating cooling and air-conditioning services. The gross floor area of the selected building is 30,654 m^2 of which 27,422 m^2 is the commercial floor area. Energy consumption of the building is 115Kwh/m^2/annum (GBCSA, 2015). The building is located in zone 2, the required standard is 200 Kwh/m^2/annum. This indicates that energy use is less than or better than the required standards. However, this building presented constraints with regards to limited availability of empirical performance data that is within the context of this research. Despite these limitations, this building was highly rated within the context of the GBCSA rating system. The GBCSA (2015) indicated that the Department of Environmental Affairs (DEA) in Pretoria was the first government building in South Africa to achieve a 6 Star Green Star SA rating. The project also achieved the highest score awarded by the GBCSA to date for a commercial office space of this magnitude.

Figure 4.31: DEA building in Pretoria Photo: the GBCSA website

The key performance indicators of the building on which the assessment wasbased, are daylight, heating and cooling, IEQ, water efficiency, and renewable energy systems. These key performance indicators are discussed in the following subsections.

Table 4.29: Key performance indicators

Indicators	Description	Source
Daylight	Optimization of daylight through orientation to reduce energy consumption.	(GBCSA 2014)
	Use of lighting controls, including occupancy sensing and continuous dimming.	(Aldous 2013)
Heating and cooling	The building structure comprises of high thermal mass, which is utilized for the purpose of assisting the HVAC system by reducing morning cooling loads.	(Aldous 2013)
IEQ	Building comfort is addressed through inclusion of high performance double glazing, thus improving the thermal performance of the space as well as providing significant improvement in the reduction of indoor noise levels and acoustic disruptions.	(GBCSA 2015).
Water Efficiency	A rainwater harvesting system, indigenous plants and efficient irrigation systems are utilized to reduce water consumption	(GBCSA 2015).
Renewable Energy Systems	Using rooftop mounted PV systems, the DEA building utilizes both high efficiency solar-thermal systems for hot water and photovoltaic for direct electrical energy production	(Aldous, 2013).

4.4 Observation data

Generally, the data of the assessed buildings indicated that there is a large variety of shapes and sizes of buildings. In most cases there was inconsistency in the orientation of the buildings which affected the number of openings and the WWR ratios. The type of ventilation and window-to-wall ratio was very significant in determining the functionality of the building. In many cases not enough consideration was given to use of daylight in lecture rooms. For example, the lecture rooms in the BHP2 building at CUT neither had access to daylight nor had windows. Out of all the buildings assessed at the universities, only 2 buildings at TUT incorporated the use of insulation for energy efficiency. Similarly, none of the buildings assessed – except one building at TUT – has incorporated water efficiency measures. The TUT building has incorporated a miniature water efficiency system.

In the assessment of the 16 selected buildings, the focus was energy consumption which is influenced by IEQ, and WUE. It was noted in the problem statement (section 1.4) that most of the existing built environment infrastructure in the university system of South Africa were built using conventional building codes, and therefore do not adequately address the importance of design for efficiency in energy use, use of materials and efficiency in water services. Therefore, based on two of the objectives of this study, namely to assess the energy and water usage efficiency in existing buildings at South African universities based on green building principles; and to assess the indoor quality of existing buildings at South African universities based on green building principles, it was deemed suitable to use a green building rated by the GBCSA to compare findings. It was also important to compare observations to standards from SANS 204:2011.

4.4.1 Observation and measurements of physical structure

The data collected from the observations and measurements in the buildings are presented in the following subsections.

4.4.1.1 Functional organization of buildings assessed

Observation of the buildings revealed differences in energy consumption levels of the various assessed buildings occurred due to differences in type of heating cooling and ventilation systems used. The differences in function/use of the buildings determined the type of ventilation system used by the buildings. All library buildings assessed used mechanical heating, cooling and ventilation. Similarly, academic buildings used predominantly for staff offices were also mechanically ventilated. In addition, in one mechanically ventilated building the majority of spaces were used for computer laboratories, computer rooms and offices. Only two buildings emphasized energy efficiency during design, whereas only one building emphasized water use efficiency.

The buildings were grouped in the following types of heating, cooling and ventilation systems used by the buildings:

- Natural ventilated buildings (N)
- Mixed mode ventilated building (includes both mechanical and natural ventilated spaces) (NM)
- Mechanically ventilated building (M)

Data on each building and its site characteristics were collected to determine effects of key parameters (EE, IEQ, WUE) on other parameters of the building. For example, gross interior floor area (m^2) (i.e. the total building floor area) was used to compare with energy consumption and water consumption.

Table 4.30 presents the location, function and type of ventilation of the various buildings assessed at the three universities. It is found that majority (8) of the buildings use both natural and mechanical ventilation systems, 6 buildings use mechanical ventilation and only 2 buildings use natural ventilation stream. Thus, it indicates that majority of the buildings at the three universities use either mechanical ventilation systems or a combined system.

Table 4.30: Summary of location and function of assessed buildings

Region & University	Building Name	Building function	Type of ventilation
Zone 1 CUT	BHP1	Teaching & learning	NM
	BHP2	Teaching & learning	M
	BHP Admin	Staff Offices	M
	ETB	Teaching & learning	M
	Library	Library	M
	Hotel School	Teaching & learning	NM
Zone 5 DUT	S3	Teaching & learning	NM
	S8	Teaching & learning	NM
	Block D	Teaching & learning	NM
	Block E	Teaching & learning	NM
	Block G	Library	M
	Block J	Teaching & learning	NM
Zone 2 TUT	Building 2A	Teaching & learning	NM
	Building 3	Staff Offices	M
	Building 11	Teaching & learning	N
	Building 13	Teaching & learning	N

Table 4.31 indicates the maximum energy use standard of SANS 204, 2011 for different energy zones of the country. It is found that Bloemfontein and Pretoria which are located in zones 1 and 2 respectively, have the maximum energy use standard for office buildings (200 Kwh/m^2/annum). However, Durban which is situated in zone 5, has a slightly lower energy use standard (190 Kwh/m2/annum). This indicates that buildings at CUT in Bloemfontein and TUT's Pretoria campus consume more energy than buildings at DUT in Durban.

Table 4.31: SANS 204 2011 standards for maximum energy use for office buildings

Location	SANS 204:2011 Classification	Maximum Energy use ($Kwh/m^2/annum$) SANS 204:2011
Bloemfontein	Zone 1	200
Durban	Zone 5	190
Pretoria	Zone 2	200

SABS (2011)

4.4.1.2 Building function, energy use and interior climate at the three universities.

Building function and usage indicate the activity in each building and the usage of functional spaces with regards to time. Energy consumption can vary from building to building due to the functionality of these buildings. Key findings from data indicated that the function of spaces determined the usage of air-conditioning and artificial lighting and the amount of time these services are used. For instance, the libraries used air-conditioning not only for thermal comfort but also for protection of their books. Services of lighting and air-conditioning were required for the duration of use of the building. Table 4.32 indicates the relation between building function versus energy consumption and internal condition. The results indicated that none of the universities applied automated controls for lighting. Building 11 did not require or use any air-conditioning due to appropriate building envelope design. Of the 16 buildings assessed, only 2 buildings – namely BHP admin at CUT and building 3 at TUT – were mainly used for staff offices. . This implied that a higher percentage functional spaces were used for offices which require air-conditioning for heating and cooling. The results indicated that energy consumption increased with increase in use of building services (lighting and air-conditioning) and increase in area of laboratories, offices / functional spaces that require air-conditioning.

4.4.1.3 Temperature, humidity, average illumination and their linkage with energy consumption

As noted in section 2.8.2, there is a need for proper envelope design that maximizes passive systems for heating/cooling and lighting in order to reduce the energy demand required by mechanical systems and services. The American Society of Heating Refrigerating and Air Conditioning Engineers (ASHRAE) Standard 55 and ISO Standard 7730 define thermal comfort as the condition of mind which expresses satisfaction with the thermal environment (section 2.9.1). In its Adaptive Comfort Temperature (ASHRAE 55-2004), ASHRAE defines a range of temperatures which are deemed comfortable for a naturally ventilated space where occupants have control over openings (section 2.9.1). This depends on outside air temperature and is based on the fact that people living in warmer areas can tolerate higher internal temperatures than those in colder areas. According to Wang, Wong and Li (2007) the advantages of natural ventilation include reduction of operational costs, preparation of satisfactory thermal comfort as well as modification of indoor air quality. The use of natural ventilation as an inactive or passive cooling strategy for buildings provides a significant opportunity to address issues associated with artificial cooling of buildings (Wang, Wong and Li, 2007). Generally speaking, north and south facing facades can provide much better thermal comfort than west and east facing facades and thus should be considered as priority (Wang, Wong and Li, 2007). Mirrahimi, et al. (2016), noted that the of window-to-wall ratio determines the amount of incident solar radiation entering the interior. In order to choose the correct glazing, it is important to consider the external climate conditions and the expected internal environment of the buildings (Al-Tamimi, 2011).

In this study, it was important to assess how the design of the existing buildings linked with IEQ conditions of temperature, humidity and illumination and effects on energy consumption. It was important to understand the type of orientation, window-to-wall ratios (WWR) and type of heating, cooling and ventilation (artificial or natural). Measurements of actual internal temperature, humidity levels and illumination were vital observations. Additionally, were measurements of perceptions with regards to comfort, temperature, humidity (air stuffiness) and indoor lighting (determined through questionnaires) necessary. Comparison between measurements of actual IEQ conditions and perceptions of IEQ conditions were important to determine their correlation with building design and subsequent effects on energy consumption. Table 4.32 indicates measurements of average IEQ conditions with regards to temperature, humidity and illumination of the buildings assessed. Results of perceptions on IEQ conditions and further analyses thereof is presented in chapter 5.

Table 4.32: Building function versus energy consumption and internal condition

University Building		Function: T&L, Admin, Lib	Hours of Operation	Energy Consumption (Kwh / annum)	Average Temperature Typical Room (Summer) ºC	Average Humidity of Typical Room (Summer) %	Illumn Average Lux
CUT	BHP1 (NM)	T&L	13	675238	26	43	310
	BHP2 (M)	T&L	13	1145040	24	35	310
	BHP Amin (M)	Admin	12	251108	25	36	270
	ETB (M)	T&L	12	1037202	26	36	305
	Library (M)	Lib	13	756104	29	37	370
	Hotel School	T&L	13	627598	28	38	370
DUT	S3 (NM)	T&L	13	342176	29	56	490
	S8 (NM)	T&L	13	342176	28	58	450
	Block D (NM)	T&L	13	785000	28	49	450
	Block E (NM)	T&L	13	432416	28	48	490
	Building G (M)	Lib	13	289480	26	48	380
	Block J (NM)	T&L	13	244662	25	35	270
TUT	Building 2A (NM)	T&L	13	280371	30	39	550
	Building 3 (M)	Admin	13	587676	27	39	360
	Building 11 (N)	T&L	24	106320	27	40	600
	Building 13 (N)	T&L	13	272520	27	38	305
	Nomenclature: T&L is Teaching and Learning, Admin is Administration, Lib is Library, Illumn is Illumination						

4.4.1.4 Building Envelope design: Orientation, Size and Form

Building orientation contributes to the reduction in energy consumption. As noted in section 2.8.1, Kannan (1991) indicated that buildings lined longitudinally along North to South have 10% less energy consumption than buildings arranged longitudinally along East to West. Building size, length, width and size of windows all also affect energy consumption. Further analyses were conducted to establish relations with energy efficiency. Table 4.33 presents the building design envelope of the buildings assessed at the three universities. The table shows data obtained from observation of orientation, building size and window-to-wall ratio (WWR). Data of building design are presented in the table to determine links between design parameters and energy consumption. For instance, from the table it is noted that building 11 which depends on natural means for heating, cooling and ventilation, is oriented such that the longitudinal façades face North to South and the building has the highest WWR of 0.48. It should be noted that building 11 uses the least amount of energy. The table specifies the type of heating / cooling / ventilation used by each building. In further analyses in chapter 5, data of design parameters for orientation, building size and window-to-wall ratio are linked with energy consumption data to establish correlation or trends.

Table 4.33 Building envelope design parameters

University & Buildings		Orientation	Size of Building								Window area / WWR	
			L (m)	B (m)	H (m)	A1 (m^2)	FL	A2 (m^2)	A3 (m^2)	V (m3)	WA (m^2)	WWR
CUT	BHP1 (NM)	N&S	73	31	15	2272	4	9088	2636.8	36751	766.5	0.29
CUT	BHP2 (M)	N&S	72.8	44	12.8	2936.9	3	8810.7	2956.8	41014	274.4	0.09
CUT	BHP AD (M)	N&S	33.5	13.5	12.8	438.9	4	1755.6	1346.6	5617.3	240.1	0.35
CUT	ETB (M)	E&W	53.4	25.5	14.5	949.7	4	3798.8	2227.2	29723	800	0.36
CUT	Library (M)	N&S & E&W	61.4	33	17.0	2013.9	4	8055.6	3202.8	36236.7	1035	0.32
CUT	HS (NM)	N&S & E&W	46.3	28	9.0	2000.2	2	4000.4	1611	18001	486	0.30
DUT	S3 (NM)	E&W	42.1	12	32	429.4	8	3435.3	3392	13741.4	822	0.24
DUT	S8 (NM)	E&W	42.1	12	32	429.4	8	3435.3	3392	13741.4	822	0.24
DUT	Block D (NM)	N&S	50.0	30	34	1250	7	8750	5100	42500	621	0.12
DUT	Block E (NM)	N&S	44.0	16	12.0	660	4	2640	1516	17920	439.2	0.29
DUT	Bloch G (M)	N&S	45	15	14	675	4	2700	1470	9450	273.6	0.19
DUT	Block J (NM)	N&S	47	15	14	705	4	2820	1736	9870	413.1	0.23
TUT	Build 2A (NM)	N&S & E/S	48.5	14	14.5	705	4	2820	1928.5	12658.5	450.9	0.23
TUT	Build 3 (M)	N&S	45	12.5	28.0	720	8	5760	3416	25560	1320	0.38
TUT	Build11 (N)	N&S	89.4	11.5	14.0	886.2	3	2579.5	3141.6	10889	2176	0.48
TUT	Build13(N)	N&S	72.8	30	16.0	2271.4	3	6814.2	3328.8	36341	1059	0.31

Nomenclature:
Orientation: N/S is North / South; E&W is East & West.
Size of Building: L (m) is length in meters, B (m) is breadth in meters, H(m) is height in meters, A1 (m2) is floor area in square meters, A2 (m2) is total area in square meters, FL is number of floors, A3 (m2) is area of external wall, V (m3) is volume of building
Size of windows: WA (m^2) is area of windows in square meters, WWW is window-to-wall ratio

Research observation

4.4.1.5 Building envelope design: Building materials

It is indicated in section 2.8.7 that several studies noted that the properties of building materials, including the mass, density, thermal transmittance and width of the material, are significant parameters that affect heat flow and energy efficiency in buildings. Building materials should generally control heat flow in buildings. It was also noted in section 2.8.7 that certain studies determined that reducing the rate of heat flow in buildings – which is affected by U-value, density and width of materials –was significant in the reduction of energy consumption in buildings. Table 4.34 presents results of building materials being used in the assessed buildings.

Results indicated that majority of the assessed buildings used similar materials for floors, walls and windows; however, the benchmark buildings 11 and 13 used insulation materials. The use of insulation materials indicated a significant reduction in energy consumption of the 2 buildings.

Table 4.34: Materials used and properties of materials

University Building	Location	Material	Properties		
			U-value $Kw/m^2.K$	Density Kg/m^3	Thickness m
All buildings assessed used these materials	Floor	Concrete	1.5	2323	0.15
	Floor (Tiles)	Clay tiles	0.84	1922	0.03
	Wall	Brickwork	0.82	1826	0.220
	Wall Plaster	Cement	1.5	2323	0.02
	Windows	Glass	0.75	2483	0.05
	Ceiling	Gypsum	0.17	993	0.03
	Roof	Concrete	1.5	2323	0.15
Building 11 & 13 at TUT had insulation properties	Wall	Brickwork	0.82	1826	0.220
	Wall Insulation	Wood	0.71	512.6	0.025
	Ceiling Insulation				
	Roof	Steel	1.5	2323	0.15
	Roof Insulation				

Source: Research observation

4.4.1.6 Water use efficiency

Only one building (building 11), adopted water efficiency measures – specifically the use of rainwater collecting measures. Based on building data and number of building users, water usage data (which is presented in Chapter 5) was calculated.

4.5 User survey data

4.5.1 Responses to demographic questions of universities

Responses to the demographics section of each university were presented in sections 4.2.1.10, 4.2.2.9 and 4.2.3.7. Tables 4.35, 4.36 and 4.37 present responses to demographic questions on each of the three universities. The percentage of all students and staff questioned at each of the assessed universities is presented in Table 4.35. It is observed that at all three universities 82% of the respondents were students who had been at the university for at least 3 years.

Table 4.35: Percentage of students and staff at the three universities

Occupation	Number	Percentage
Students	78	82
Academic Staff	17	18
Total	**95**	**100**

Source: Response to questionnaire

Responses and analyses to the gender inquiry of demographic section 1 is presented in table 4.36. It shows that at all three universities 66% of the respondents were male and 34% female. This reflects the South African university education system which has a higher percentage of male students and staff. The age structure of the respondents is presented in figure 4.37. It is observed that most (58%) of the respondents were within the age bracket of 20-24, which consists mostly of students. This is followed by the age bracket of 25-39, which consists of mainly students and a few staff members.

Table 4.36: Responses to gender inquiry in the three universities

Gender	Number	Percentage
Male	63	66
Female	32	34
Total	**95**	**100**

Source: Response to questionnaire

Table 4.37: Responses to Age distribution in the three universities

Age	Number	Percentage
Below 20	8	8
20-24	55	58
25-39	24	25
40-49	5	5
50-59	2	2
60+	1	1
Total	**95**	**100**

Source: Response to questionnaire

Responses to occupation/position at the university (table 4.38) revealed that most (82%) of the respondents are students and 18% are staff members.

Table 4.38 Profile of responses to position / occupation

Category	Number	Percentage
Students	78	82
Technical Assistant	0	0
Junior Lecturer	0	0
Lecturing Assistant	1	1
Lecturer	9	9
Senior lecturer	5	5
Associate professor	2	2
Total	**95**	**100**

Source: Response to questionnaire

4.5.2 Responses to perceptions of IEQ: Sections 2 and 3

As indicated in section 4.4.1.3, parameters evaluated by the questionnaire included perception of temperature, humidity (stuffiness of the air), ventilation, lighting and overall comfort. The respondents were asked to rate the IEQ perceptions of lecture venues in the assessed buildings at each of the three universities on a scale of 1 (very dissatisfied) to 5 (very satisfied). The responses to this section of the questionnaire were presented in appendix (6) and analysed in section 5.4.

4.6 Chapter summary

Data of the 16 buildings indicated that building function was used as a means of determining building configuration, shape, size and type of heating cooling and ventilation system incorporated. This was clear from the comparison of buildings of similar functions. Two buildings were selected to be benchmark buildings because findings indicated design approaches and use of materials that were consistent with green building principles. The key features of the 16 case study buildings, data from observations and measurements of buildings, as well as demographic characteristics of the response survey sample were presented in this chapter. Detailed analyses of the data collected are presented in the next chapter.

CHAPTER 5: EMPIRICAL RESULTS AND ANALYSIS

5.1 Introduction

In this chapter, analyses of data from measurements of the physical structure and from survey questionnaires are presented. Parameters for analysis, as well as the purpose of analysis and relevance to the study are indicated.

The first section of this chapter presents analyses of energy efficiency (EE). For this purpose, values of parameters for EE were compared and evaluated to establish relationships – specifically to determine how energy consumption (EC) was affected by the associated parameters. For example, comparisons of EC to window to wall ratio (WWR) were conducted to determine association of WWR with EC in the evaluated buildings.

In the second section, values of parameters obtained from the questionnaire survey on indoor environmental quality (IEQ) of assessed buildings are analysed. The purpose of this evaluation is to determine association between IEQ and associated parameters. Values for perception of building users are compared to determine how comfort is affected by other IEQ parameters and also how IEQ parameters affect EC. Key findings from comparison are also discussed.

The third section focusses on water use efficiency (WUE), how it affects EE and is influenced by IEQ. In this section, a brief discussion on WUE is presented. A profile of water usage in the assessed buildings is presented, followed by presentation of relevant data. Values of parameters for WUE are compared and evaluated to determine relations and specifically how WUE affected EE and IEQ.

5.2 Assessment of energy efficiency and indoor environmental quality

The problem statement (section 1.4), indicates that most of the existing built environment infrastructures in the university system of South Africa were erected using conventional building codes that do not adequately address the importance of design for efficiency in energy use, the use of materials and efficiency in water services. It was important to analyse the data obtained from physical investigation and to compare results with the data from an existing GB – the Department of Environmental Affairs (DEA) building in Pretoria – in order to ascertain design and construction shortcomings of the existing university buildings. As indicated in sections 4.2.3.5 and 4.2.3.6, two of the university buildings that were designed by using green building principles, were used as benchmark buildings.

The purpose of the analysis – which includes the comparison of various parameters – was to determine the performance of the buildings due to design. As indicated in section 2.8.2, design for efficiency includes the relation of energy use to orientation, function, size and behaviour of occupants. Section 2.8.3 noted that studies have shown that a strong relation exists between various building components such as external wall, external glazing and insulation with regards to the reduction of EC as well as cooling in buildings. Additionally, energy usage is also significantly affected by the shape of the building such as length, width and height, as indicated in table 4.32 Table 4.33 presents data of building function, EC and internal conditions, while table 4.33 presented data of building envelope parameters such as orientation, size of building and size of windows. The parameters evaluated for energy efficiency were building function, building orientation, and building geometry (form and size of the building including length, breadth, height and external window-to-wall ratio). Similarly, were the parameters evaluated of building materials, the type and property of materials used for building envelope.

5.3 Energy efficiency: Effect of building envelope design (orientation, function, size and form) on energy consumption

The parameters indicated in section 4.4.1.3 and 4.4.1.4 were used for analysis of the results of EE, IEQ, and MU. As indicated in section 2.8.2, the massive amounts of energy consumed by heaters and air-conditioning used for cooling and heating in buildings, significantly increases the total energy consumption of buildings. It is also observed that the use of air-conditioning varies due to the need for comfort and functional requirements of buildings. Figure 5.1 shows the comparison between EC of the assessed buildings and EC of the DEA building (case study) in Pretoria in Kwh/m^2/annum. It illustrates that the lowest energy was consumed by building 11 (45 Kwh/m^2/annum) and the highest consumers were the Hotel school and ETB buildings which both used 216 Kwh/m^2/annum. The DEA building used 115 Kwh/m^2/annum, which is 60% more than building 11 (the lowest consumer) and 88% less than the Hotel school and ETB buildings (the highest consumers).

Section 4.2.3.5 and 4.2.3.6 indicated that buildings 11 and 13 (the lowest consumers) depend on natural ventilation for heating, cooling and air exchange. Flow of heat is also controlled by extensive use of wall and roof insulation in both buildings and the significant reduction in EC is due to the use of natural ventilation for cooling and airflow. Comparison of buildings 11 and 13 to the Hotel School and ETB building presented a contrast. The hotel school consumes significant amounts of energy for food preparation and also for air-conditioning of lecture venues. The ETB building also depends on air-conditioning for all lecture venues and offices in the building and though the building has a comparatively good WWR, it is not optimized due to inappropriate orientation as indicated in table 4.33. It was noted that neither the ETB building nor the Hotel School use insulation materials to control heat flow and that both have a lower WWR when compared to building 11. The combination of these factors indicated that more energy was used for artificial lighting.

Figure 5.2 illustrates the comparison of the DEA building to all mechanically heated, cooled and ventilated buildings considered as the case study buildings. The comparison indicates that the DEA building uses less energy than all the mechanically ventilated buildings – except for the library building of CUT, Free State which uses 107 Kwh/m^2/annum. The DEA building used 7.4% more energy than the library building. The explanation for this difference is due to difference in functionality. The library building which is an academic building, depends on mechanical ventilation which is not used throughout the year as there are holiday periods when the building is not in use, whereas the DEA building is used most of the year. The functional difference also indicates that the DEA building uses more energy to function as an office building. This means that there are more plug loads for individual offices and equipment used for offices. The library has fewer office space and larger public spaces, and therefore requires less plug loads because there are fewer offices and office equipment. As indicated in section 4.3, the DEA building uses green building features such as good insulation materials that include thermal mass which, as indicated by Mirrahimi et al. (2016) in section 2.8.7.1, absorbs heat from solar radiation at a slower rate and is very effective in countering rapid heat transfer. It also assists the HVAC system by reducing energy demand / consumption. On the other hand the library building reduces EC due to differences in functionality.

Among all the buildings, the Hotel School and ETB buildings used the largest amount of energy. The reason for this is that the Hotel School building differs from the other academic buildings in function. It functions as an academic building for lectures and it is also used for food preparation practical classes. As indicated in section 4.2.1.6 (profile of ETB building), it contains more functional spaces for computer laboratories and electrical equipment which have more plug loads than the other assessed buildings. However, the building is poorly oriented (East-West), has low WWR and no insulation materials are used to control heat flow. These design flaws contributed to increase in the use of artificial means for lighting, heating, cooling and ventilation. Therefore, the building has poor envelope features and functionally requires mechanical methods for heating and cooling, all of which accounted for the very high demand for energy.

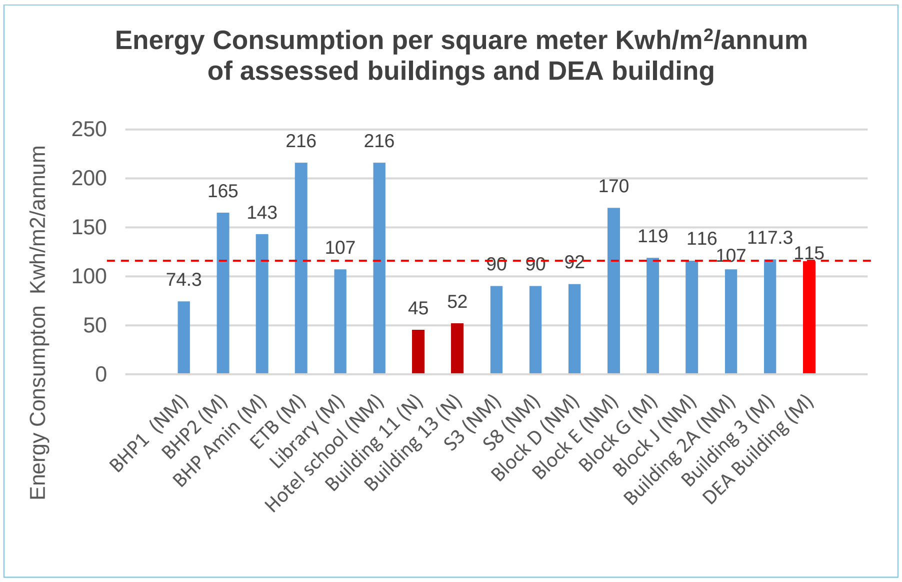

Figure 5.1 Energy consumption of assessed buildings and the DEA case study, Pretoria

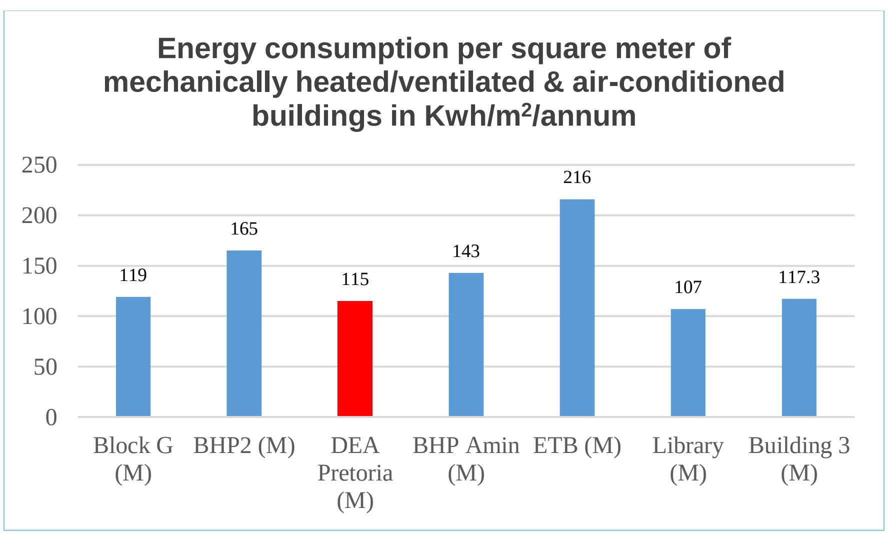

Figure 5.2 Energy consumption of all mechanically heated and ventilated and air-conditioned buildings

As indicated in Figure 5.1, buildings 11 and 13 have the lowest demand for energy use among the natural/mixed mode heated and ventilated buildings. The comparison of buildings 11 and 13 with the mixed mode buildings being assessed indicates that there are certain factors that account for this reduction. As indicated in sections 4.2.3.5, functionally building 11 consists of spaces for lecturing and drawing studios. The building also has fewer laboratories. In the envelope design the two buildings maximize daylight through good orientation and relatively high window-to-façade ratios. Building plans and interior views also indicated extensive use of insulation materials for walls, floors, ceilings and roofs. The two buildings depended on only natural ventilation for heating, cooling and ventilation. Findings show that the lowest demand for EC of both buildings 11 and 13 can be attributed to a combination of factors such as function of the buildings, good orientation, high WWR and use of insulation materials in walls and ceilings to reduce the rate of heat flow through the building. This demonstrated that the two buildings were designed with a more comprehensive design approach which resulted in reduction of energy demand.

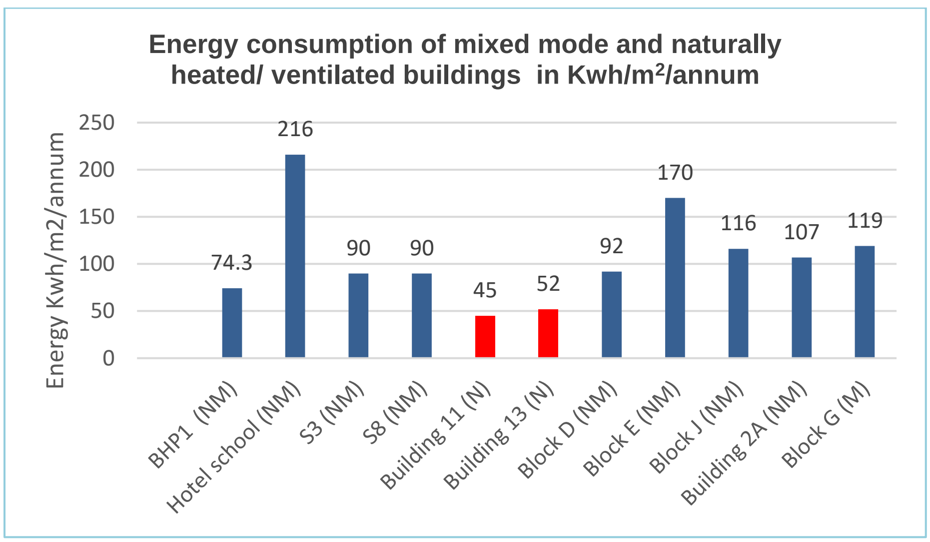

Figure 5.3 Energy consumption of mixed mode and naturally heated/ventilated buildings

5.3.1 Orientation of the university buildings

As noted above in section 5.3, orientation of the ETB building had a significant effect on other parameters (lighting, ventilation, heating and cooling) that resulted in a higher demand for energy in the building. Poor orientation – along with a smaller number of windows on the longitudinal façade that result in low window-to-wall ratios – increase EC because of the requirement of artificial lighting. Table 5.1 indicates that 62% of the buildings assessed were appropriately oriented (North-South). However, there are other buildings such as BHP 2 that did not maximise the orientation potentials due to poor WWR.

Table 5.1: Number of orientation of assessed buildings presented as a percentage.

Orientation	Number	Percentage
N&S	10	62
E&W	3	19
N&S / E&W	3	19
Total	16	100

Source: Observation of buildings

5.3.2 Function: Effect on energy consumption

Building function and usage indicate the activity each building is used for (function) and the usage of functional spaces with regards to time. EC can vary from building to building due to the functionality of these buildings. It is also argued that depending on orientation and location, the control of electrical power with regards to daylight leads to savings of 45%–60% in office buildings (Roisin et al. 2008). Similarly, Garg and Bansal also noted that smart energy occupancy sensors installed in buildings can save up to 35% of energy consumption in buildings (Garg & Bansal 2000).

In this investigation, section 4.4.1 discussed key findings from observation data which indicated that the function of spaces determines the usage of air-conditioning and artificial lighting and the length in time these services are used. For instance, the library buildings use air-conditioning not only for thermal comfort, but also for protection of their books. Services of lighting and air-conditioning are required for the full duration of use of the building. Physical investigation established that none of the buildings uses smart technologies or occupancy sensors and that none of the universities apply automated controls for lightings.

In this investigation, two buildings out of the sixteen assessed are mainly used for staff offices. These are BHP admin at CUT and building 3 at TUT. The results indicated that energy consumption increases along increase in use of building services (lighting and air-conditioning) and increase in area of laboratories or number of offices or functional spaces that require air-conditioning. Thus, an investigation was conducted to establish the relation between size of functional spaces and energy consumption. The results indicate a positive linear relation between the two variables (Figure 5.4). which is presented by the equation 1 (Eq.1). The scatter diagram also shows the association of functional spaces with EC, which indicates a fairly good correlation between the two variables (correlation coefficient of 0.821399). Regression analysis shows that $R^2 = 0.6747$, and P-value = 0.00017332 which further validates the association between the 2 variables.

$Y=91.618X_1 + 9318$ (Eq. 1)

Where Y= Energy consumption in Kwh/annum

X_1= Area of functional spaces in m^2

$R^2 = 0.6747$, P-value = 0.00017332

Thus, a correlation between size of functional space and energy consumption in a university building was established that indicates energy consumption can be optimized by optimizing the size of functional spaces.

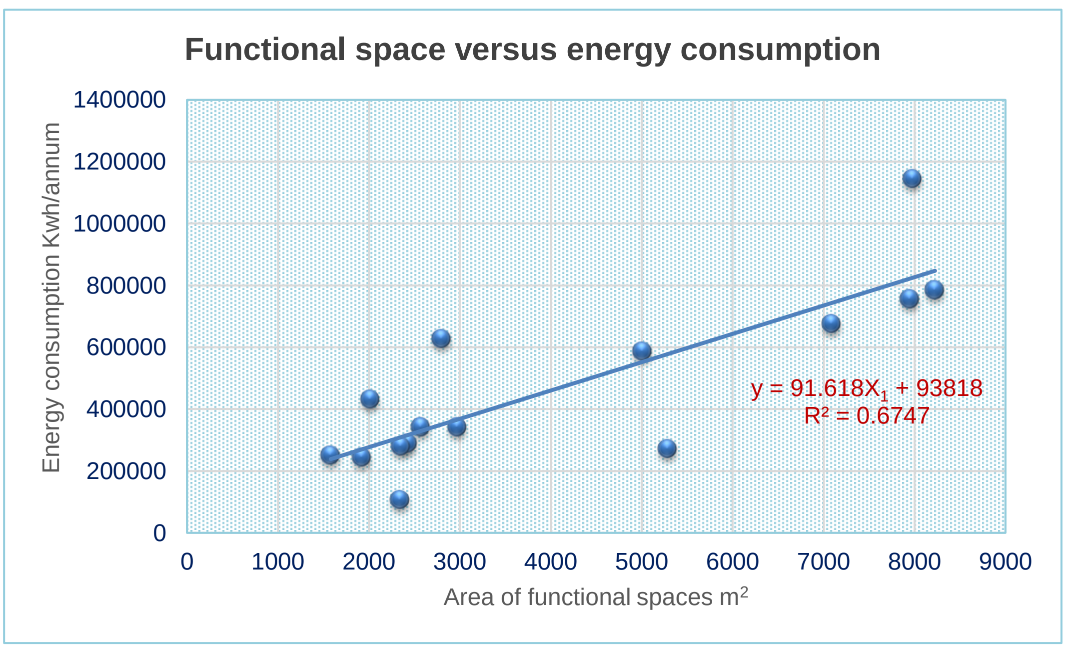

Figure 5.4 Relation between functional spaces and energy consumption

5.3.3 Building size: Volume versus energy use

All parameters for building size – including length, breadth, height and volume –define the physical characteristics of the building. As indicated in section 2.8.4, Parasonis, Keizikas and Kalibatiene (2012) asserted that geometric efficiency of a building depends on its size and proportions. Thus, the results for EC and volume of each assessed building presented in tables 4.32 and 4.33 were used to determine the relation between the volume of the buildings and EC (figure 5.5). It is noted that a linear relation exists between volume (size) of buildings and EC, which is defined by equation 2 (Eq.2) and the two variables are fairly correlated (correlation coefficient 0.88032). Regression analysis shows that $R^2 = 0.775$, and P-value = 0.0000149093 which further validates the association between the 2 variables. However, building 11 was excluded from developing the relation because the design and materials used in this building differ from those of the other assessed buildings.

$Y = 21.936X_2 + 46831$ (Eq. 2)

Where Y= Energy consumption in Kwh/annum

X_2= Volume (size) of buildings in m^3

$R^2 = 0.775$, P-value = 0.0000149093

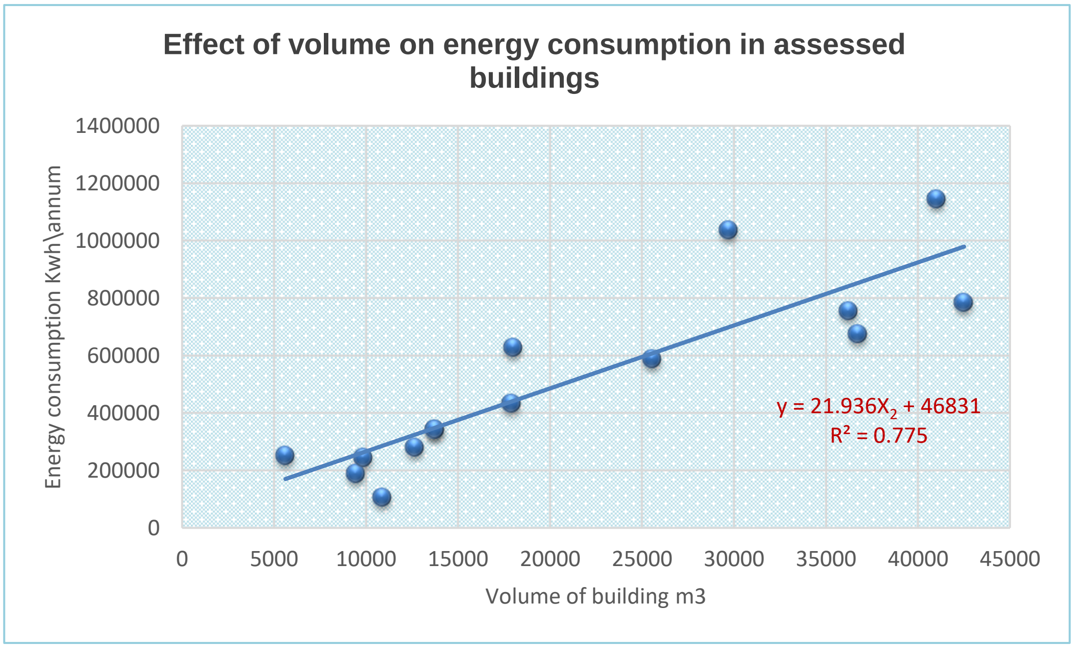

Figure 5.5Relation between electrical energy consumption and volume of buildings.

5.3.4 Building form: Breadth of building and electrical energy consumption

Length and breadth of envelope elements define the proportions of the building with regards to size and shape/form. Reducing the breadth of the building envelope redefines the building in terms of form and length-to-breadth ratios. After comparison of EC to values of the breadth of buildings, an association between energy consumption and breadth of the building was noted. Figure 5.6 shows the relation between breadth of the building and EC defined by equation 3 (Eq.3) The results show a linear relation between the breadth of the buildings and EC with a good correlation coefficient of 0.93647. Regression analysis shows that R^2 = 0.936476205, and P-value = 0.00000006303 which further validates the association between the 2 variables.

Furthermore, a reduction in breadth in proportion to the form of the building denotes an increase in length (if building shape is rectangular). In a rectangular building, increasing the length of the building in relation to the breadth could mean more access to daylight depending on orientation.; This in turn could affect energy consumption due to reduction in the use of artificial lighting. EC due to heating and cooling can also be reduced, depending on the function of the building. It is thus noted that a significant amount of energy demand on the building can be affected by building shape and orientation.

$Y= 22423X_3-15399$ (Eq. 3)

Where Y= Energy consumption in Kwh/annum

X_3= Breadth of buildings in m^3; R^2 = 0.93647, P-value = 0.00000006303

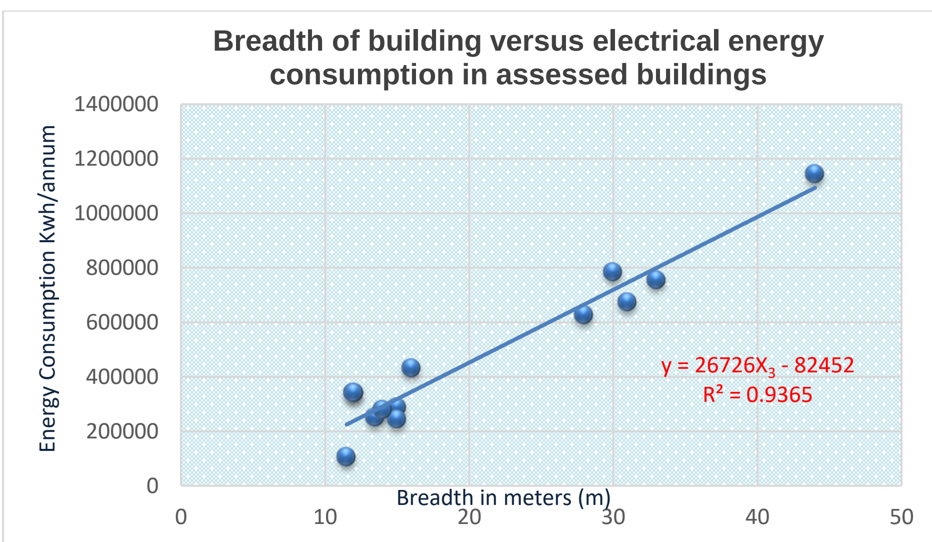

Figure 5.6 Relation between breadth of buildings and energy consumption.

The comparison of energy consumption per square meter to length and breadth (Figure 5.7) resulted in the following observations:

- Building 11 has the lowest consumption of energy per square meter (45 kwh/m^2/annum) at the lowest breadth-to-length ratio of 12.9 %.
- The ETB and Hotel School buildings have the highest consumption of energy per square meter (216 kwh/m^2/annum) at comparatively high breadth-to-length ratios of 47.8% and 60.5% respectively. (The Hotel School has the maximum length-to-breadth ratio of 60.5%)

Thus, it is evident that although there are other factors that influence energy consumption in these buildings, the breadth-to-length ratios have a significant effect on the energy consumption of the building.

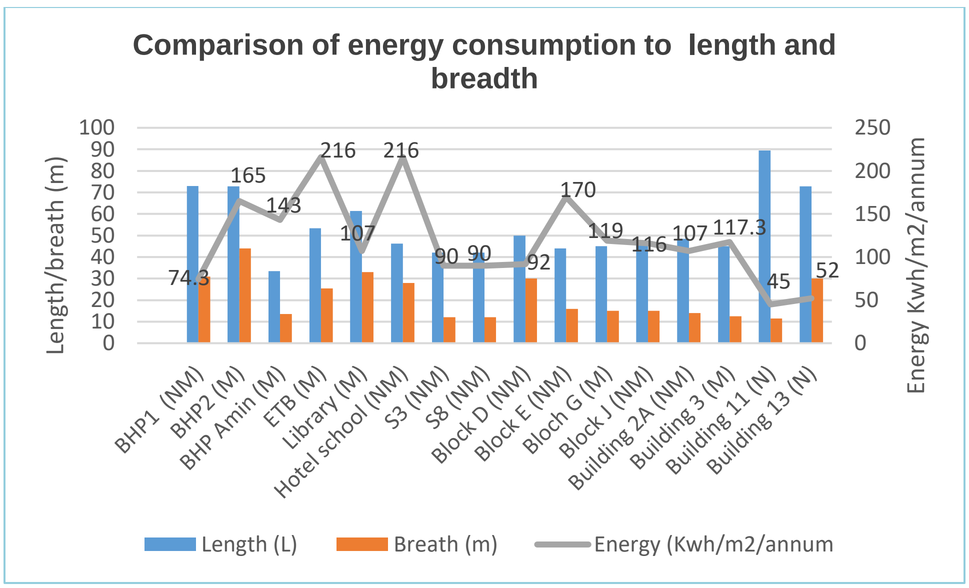

Figure 5.7 Comparison of energy consumption to breadth and length

5.3.5 Building form: Window-to-wall ratio (WWR)

As indicated above (section 5.3.4), appropriate orientation (North - South) and appropriate building form including low breadth-to-length ratios, can increase access to daylight in the building by increase in window sizes. Figure 5.7 indicates that increase in length or decrease in breadth of buildings leads to reduction in energy consumption. It should be noted that other factors such as building function and type of heating/cooling method also affect energy consumption.

Further analysis was conducted to establish the linkage between WWR and EC. This relation is presented in figure 5.8 and in equation 4 (Eq. 4). It is noted that buildings with the lowest values for WWR have the highest EC and that building 11, which consumes the least amount of energy, has the highest WWR ratio (0.48). Figure 5.8 establishes a linear relation (as given in equation 4) between WWR and EC with a correlation coefficient of 0.767. Regression analysis shows that R2 = 0.7296, and P-value = 0.0001006 which further validates the association between the 2 variables.

$Y = -(3E+06)\, X_4 + (2E+06)$ (Eq. 4)

Where Y= Energy consumption in Kwh/annum

X_4= WWR ratio

R2 = 0.7296, P-value = 0.0001006

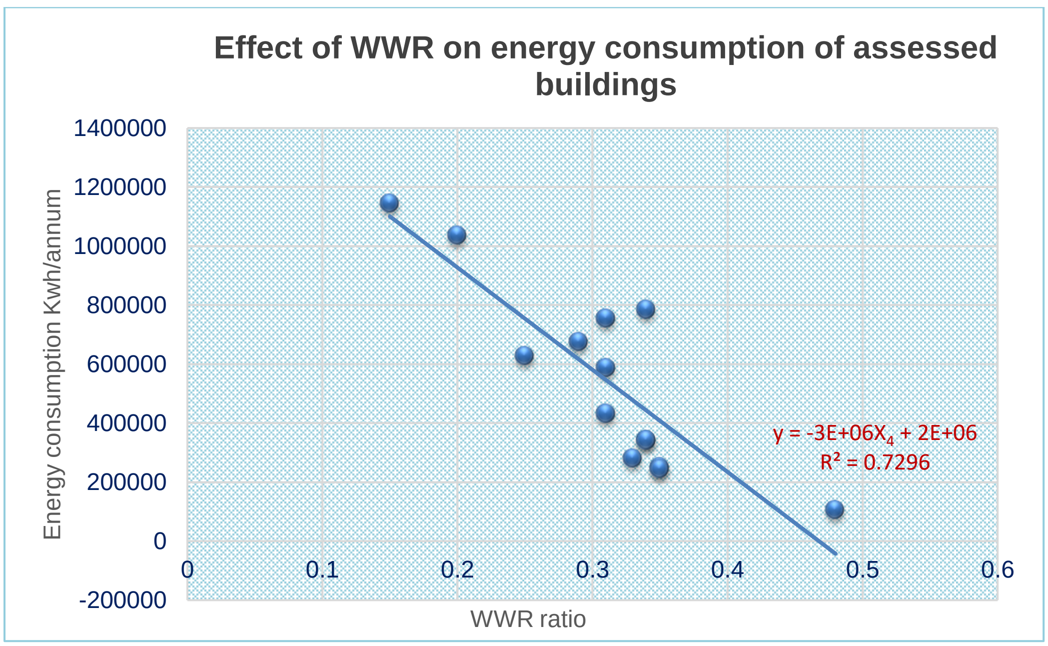

Figure 5.8 Relation between energy consumption and WWR.

Furthermore, Figure 5.9 shows the relation between WWR and EC in individual buildings. It shows that building 11, which has the highest WWR ratio (0.48), consumes the lowest energy per square meter per annum. The BHP 2 building has the lowest WWR ratio (0.09) and relatively high consumption of energy. The highest consumers of energy, namely the ETB building and the Hotel School, have a WWR of 0.36 and 0.30 respectively.

Thus, it is noted that in WWR results in reduction in energy consumption in the assessed university buildings, although other factors such as building function, -orientation and -geometry also contribute to high energy consumption.

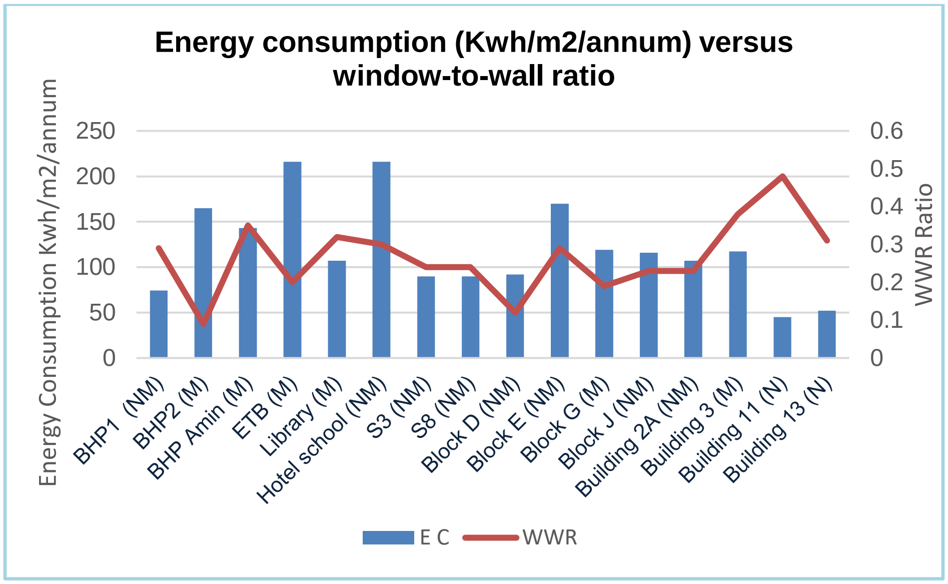

Figure 5.9 Relation between energy consumption and WWR

5.3.6 Building envelope design: Electrical energy consumption versus indoor temperature

The buildings were evaluated for indoor temperature and an analysis was made to establish the linkage between temperature and energy consumption. Average interior temperatures were measured in each building during the period indicated in table 4.32. Figure 5.10 and equation 5 (Eq. 5) present the linkage between indoor temperature of buildings and energy consumption. It is noted that the two variables are fairly correlated (correlation coefficient of -0.739) with a linear relation between these two variables. Regression analysis shows that R^2 = 0. 0.5458, and P-value = 0.001077835 which further validates the association between the 2 variables. It also established that EC increases with the reduction of indoor temperature.

$Y = -(4E-06)\ X_5 + 28.865$ (Eq. 5)

Where Y= Energy consumption in Kwh/annum

X_5= Temperature in degree centigrade

R^2 = 0. 0.5458, P-value = 0.001077835

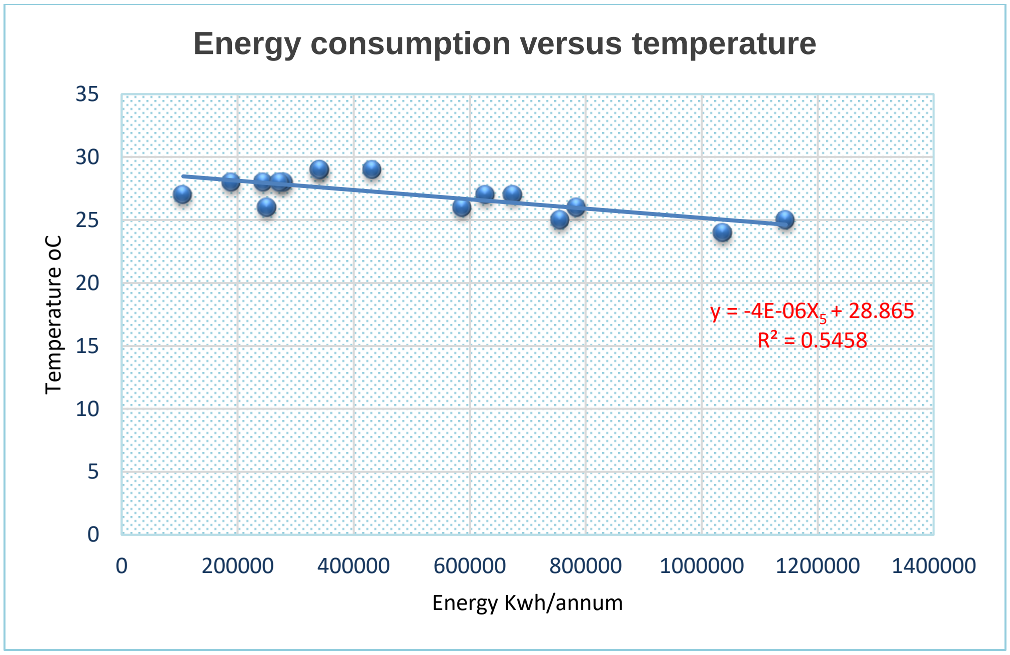

Figure 5.10 Linkage between energy consumption and indoor temperature of assessed buildings.

Figure 5.11 also indicates the association of internal temperature measurements with energy consumption of the individual buildings evaluated. It was noted that buildings with the lower interior temperatures are the air-conditioned buildings. Results indicated that though the air-conditioned buildings generate cooler and more comfortable temperatures, they consume more energy. For instance, BHP2 with average temperature of interior lecture rooms of 25°C (which is among lower temperatures recorded), consumes 1,145 040 Kwh/annum of energy. On the other hand, building 11 which is naturally ventilated and cooled and with average lecture room temperature of 27°C, uses the lowest amount of energy (106,320 Kwh/annum). Although temperature in building 11 is not as comfortable as that in the BHP 2 building, it is established that rooms with lower and comfortable temperatures require higher energy consumption.

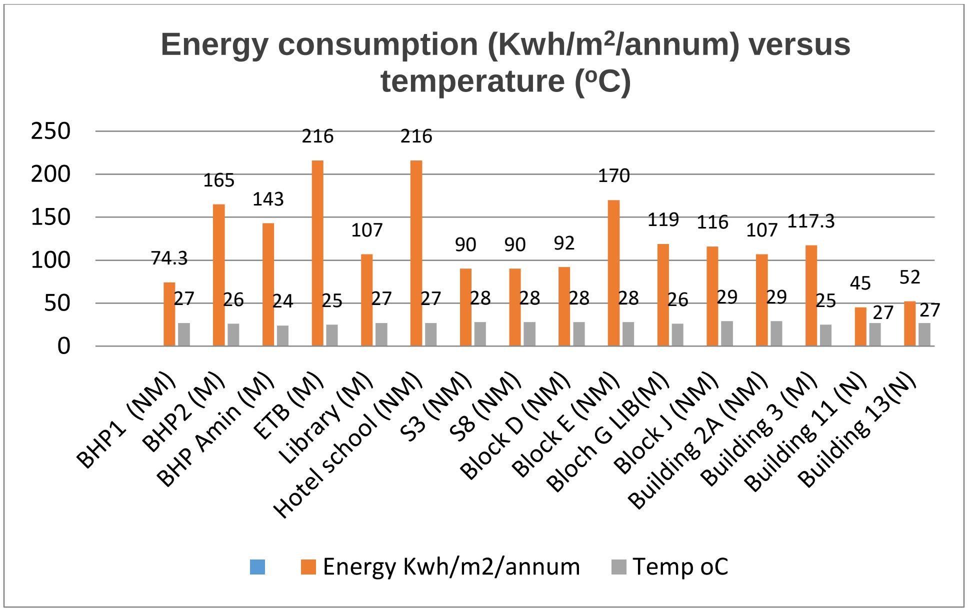

Figure 5.11 Comparison of energy consumption and temperature

5.3.7 Building envelope design (Illumination)

Energy consumption due to lighting depends on maximising the use of daylight in buildings. In turn, daylight in buildings is linked to building envelope design that includes proper orientation, window-to-wall ratio and U-value of materials used for windows. As indicated in section 2.8.7.2, the International Energy Agency noted that in a typical office building, artificial lighting consumes the bulk of the energy, followed by cooling and heating operation. Thus, in this investigation, an attempt was made to observe the relation between building envelope design (with regards to illumination) and energy consumption, as illumination is directly linked to building envelope design. Equation 6 (Eq. 6) and Figure 5.12 present the linkage between illumination and energy consumption in the university buildings. It is noted that illumination and energy consumption are fairly correlated (correlation coefficient = -0.8913) and have a linear relation where energy consumption increases with lower illumination due to daylighting. Regression analysis shows that R^2 = 0.79445, and P-value = 0.00001875 which further validates the association between the 2 variables.

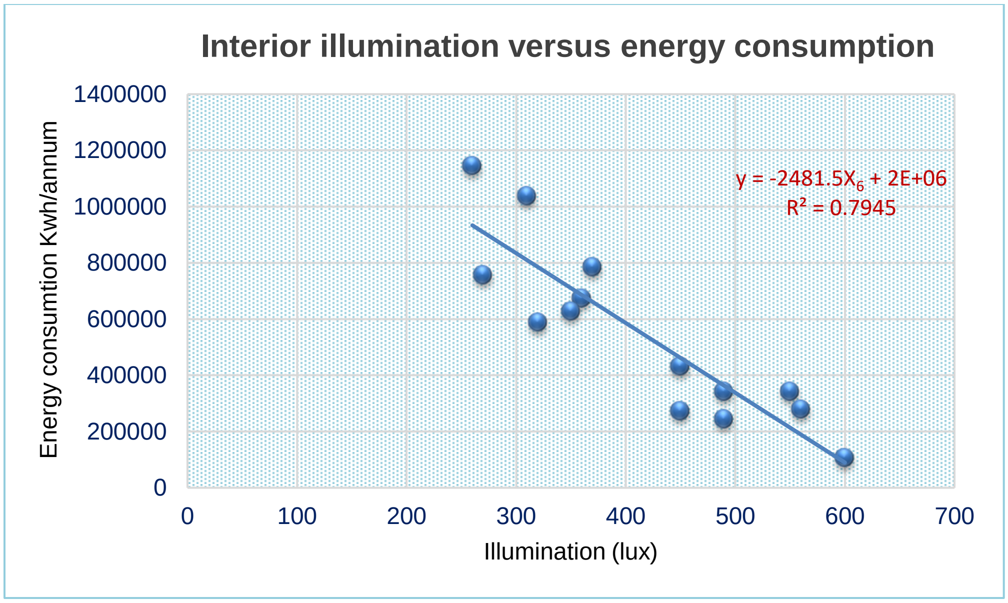

Figure 5.12 Linkage between energy consumption and illumination of assessed buildings

$Y = -2481.5 X_6 + (2E+06)$ (Eq. 6)

Where Y= Energy consumption in Kwh/annum

X_6= Illumination in lux

R^2 = 0.7945, P-value = 0.00001875.

Figure 5.13 shows the association between Illumination (lux), EC (Kwh/m2/annum) and WWR ratios (%) of individual buildings. It is noted that building 11, which uses the least amount of energy, also has the highest illumination level 675v(lux) due to daylighting as a result of the highest WWR ratio of 48%. It is also observed that BHP 2 has the lower illumination (daylight) of 326 lux because of the lowest WWR ratio of 9% and thus has relatively high energy consumption of 165 Kwh/m^2/annum. Thus, it is established that energy consumption increases with lower illumination because of poor use of daylight on account of poor WWR.

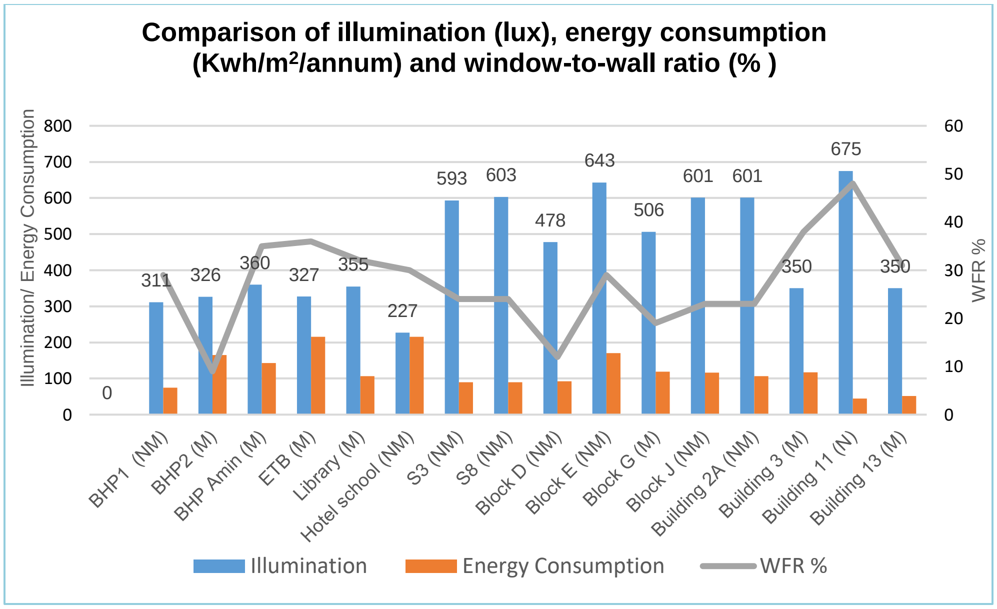

Figure 5.13 Association between illumination, energy consumption and window-to-wall ratio

5.4 Evaluation of IEQ perception of building users

As indicated in section 2.9, building envelope design is affected by building form/size and materials used, which influences the IEQ conditions, and subsequently provision of adequate IEQ can influence EC. The IEQ conditions are measured by comfort level, which is influenced by temperature, air quality, ventilation, and illumination in the buildings. However, availability of quantitative data on these aspects is a challenge and was not available in continuous manner. Further, IEQ conditions are related to the satisfaction level and perception of the occupants and users of the buildings. ASHRAE (2013) specifies a method for measuring perceptions of building users based on responses to occupancy surveys. The method stipulates that surveys should be solicited from the entire occupancy or a representative sample thereof. If more than 45 occupants are solicited, the response rate must exceed 35%. If solicited occupants number between 20 and 45, at least 15 must respond. For under 20 solicited occupants, 80% must respond. (ASHRAE, 2013). Since the goal of the building design is to achieve maximum satisfaction levels in the buildings, a similar approach for measuring perception levels was adopted in this study. Values for perception of comfort were measure and compared with values for perception of temperature, air quality, ventilation and illumination. Comparison of comfort perceptions was also made with values of actual temperature, illumination and energy consumption. The purpose of these comparisons was to determine the performance of the buildings by establishing how the perception of the building users with regards to overall comfort relates to temperature, air quality, ventilation and illumination. The parameters analysed with regards to perception of satisfaction of IEQ and comfort are:

- Satisfaction in relation to temperature
- Satisfaction in relation to air quality
- Satisfaction in relation to ventilation
- Satisfaction in relation to illumination

5.4.1 Responses to questionnaire on building users for IEQ

Acceptability and satisfaction are directly determined from the responses of occupants using the scales and comfort limits. Thermal satisfaction shall be measured with a scale ending with the choices: "very satisfied" and "very dissatisfied." (ASHRAE, 2013). In this study the respondents were asked to rate the spaces on a Likert scale (1=very unsatisfied to 5= very satisfied). Scale 2 represents unsatisfied, scale 4 satisfied and scale 3 is a neutral option. The Likert scale was applied for all parameters. The overall responses to the questions on all parameters are presented in Table 5.2 and Table 5.3. However, responses on the individual buildings are presented in Appendix 6. As shown in Table 5.3, it is clear that 61% of respondents were either satisfied or very satisfied with illumination in the buildings, Table 5.2 shows that 22% were satisfied and 39% were very satisfied. 39% also represents the highest positive value for maximum satisfaction for any parameter. 14 % of respondents were satisfied with air quality in all buildings while 15% were very satisfied. 15% represents the lowest value for maximum satisfaction in all parameters. 16% of respondents were very satisfied with temperature and ventilation, while 15% were satisfied with temperature conditions and 23% were satisfied with ventilation. For overall comfort, 22% of respondents were satisfied and 16% of respondents were very satisfied.

It is clear from Table 5.3 that a majority of respondents were either satisfied or very satisfied with illumination conditions. For IEQ, temperature, ventilation, air quality and overall comfort conditions majority of respondents were neither satisfied nor very satisfied.

Table 5.2 Overall perception of all parameters in percentages

Parameters For all Buildings	Perceptions in %						
	Very unsatisfied 1	Unsatisfied 2	Somewhat satisfied 3	1 - 3	Satisfied 4	Very satisfied 5	4 - 5
Temperature	15	19	36	70	15	16	31
Ventilation	8	15	32	55	23	16	39
Illumination	4	14	29	47	22	39	61
Air quality	13	25	32	70	14	15	29
Overall comfort	8	14	40	62	22	16	38

5.4.2 Perception of comfort

As discussed above (section 5.4), comfort is associated with temperature, air quality, ventilation and illumination. Consequently, comfort level is also associated with energy consumption as these four parameters influence energy consumption in buildings. This principle was used to determine satisfaction levels of building users in all evaluated buildings. Figure 5.14 illustrates the comparison between perception of comfort at the highest level of satisfaction (very satisfied) and energy consumption (EC). It was noted that the majority of respondents perceived mechanically ventilated buildings as highly comfortable and they were very satisfied with the comfort level of the buildings. For example, according to respondents, building BHP Admin (24%) and Building 3 – another administrative building – (23%), have very high satisfaction levels with regards to level of comfort. On the other hand, buildings 11 and 13 have a relatively high score for comfort level (20% each) where respondents were satisfied with the comfort level of these buildings. However, the Hotel School has a relatively lower satisfaction level for level of comfort. Furthermore, when compared to energy consumption, buildings with mechanical ventilation are highly comfortable but have high energy consumption, whereas buildings 11 and 13 that also have a relatively higher comfort level, have relatively lower energy consumption. On the other hand, the Hotel School which had the highest consumption of EC, had a relatively lower level (17%) satisfaction. This indicates that although comfort level is related to energy consumption because of use of mechanical ventilation and artificial illumination, other factors such as natural lighting and natural ventilation are also important to attain high comfort level in the buildings.

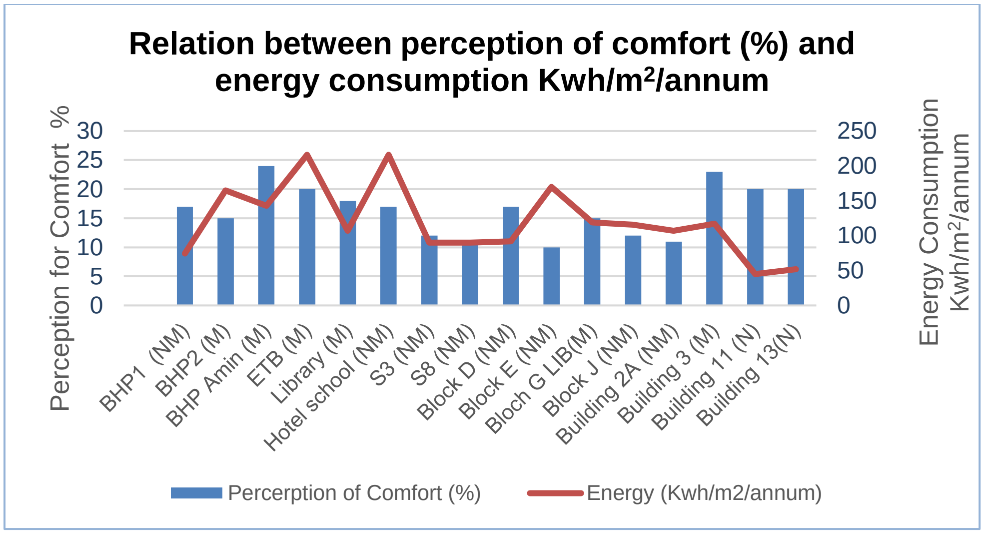

Figure 5.14 Relation between perception of comfort (%) and energy consumption in Kwh/m^2/annum

5.4.3 Temperature

The perception of temperature was performed to evaluate the satisfaction level of building users with regards to heat conditions in the building. Building users' level of satisfaction with regards to temperature was compared with their level of satisfaction with regards to comfort to observe the linkage between the two. The level of satisfaction with regards to comfort due to temperature is presented in Figure 5.15. It is noted that most of the mechanically ventilated buildings received high levels of satisfaction with regards to comfort due to temperature. For example, building BHP admin had the lowest recording for actual average temperature (24^{o}C) and the highest percentage satisfaction levels for perception of comfort due to temperature (28%). On the other hand, buildings without or partial mechanical ventilation system were observed to have lower satisfaction levels of comfort as temperatures on those buildings are found to be relatively high (>26^0 C).

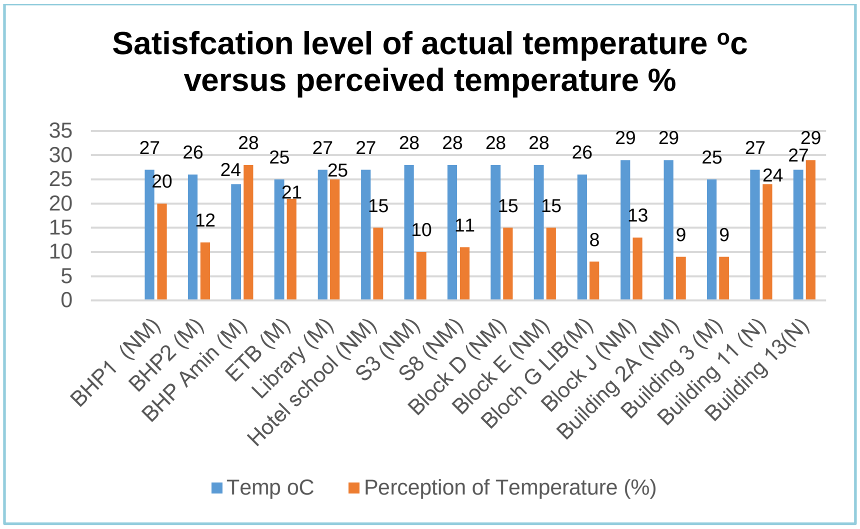

Figure 5.15 Satisfaction level of actual temperature in ºC versus perceived temperature

In Figure 5.16, the perception of temperature versus perception of comfort indicates that the high levels of satisfaction for temperature directly impact the levels of satisfaction for comfort. As indicated earlier, the BHP admin building (mechanically ventilated and heated) has a satisfaction level of 28%for perception of temperature and a 24% satisfaction level for perception of comfort. Buildings 13 had the highest (29%) satisfaction level for perception of temperature and 20% for comfort. This indicates that although temperature is a vital parameter for IEQ, other parameters such as air quality also influence the building users' satisfaction level of temperature.

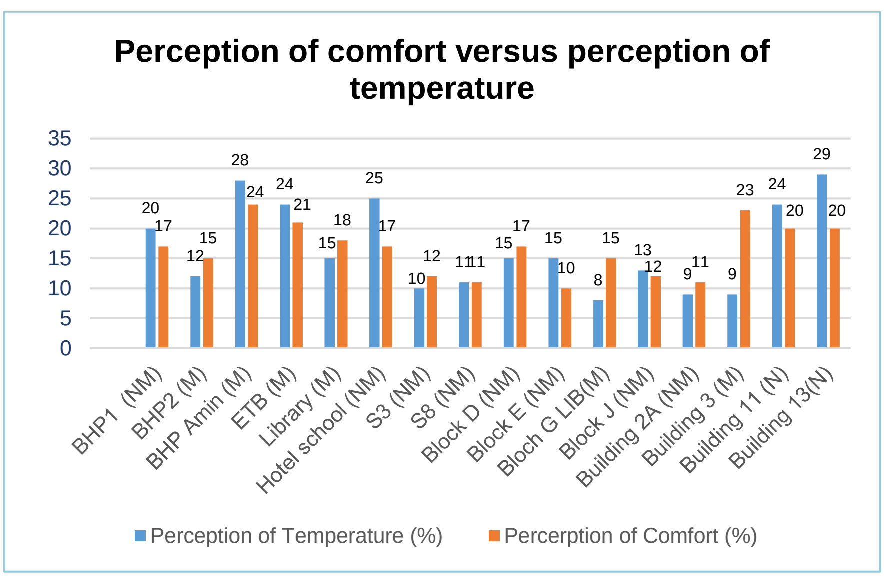

Figure 5.16 Perception of satisfaction level of temperature versus perception of satisfaction level of comfort

A regression analysis was also done to establish the correlation between temperature and comfort level. The relation is presented in figure 5.17. A linear relation between temperature and comfort level with a fairly high correlation coefficient (correlation coefficient = 0.8749) was established. The relation is defined by equation 7 (Eq. 7). Regression analysis shows that R^2 = 0.76545, and P-value = 0.000009179 which further validates the association between the 2 variables.

It is observed that a higher percentage of people perceive that temperature is correlated with comfort level. In other words, as temperature increases within a certain range, comfort level also increases.

$$Z = 0.5647T + 6.7627 \qquad \text{(Eq. 7)}$$

Where z= perception comfort level a

T = Perception temperature

R^2 = 0.76545, P-value = 0.000009179

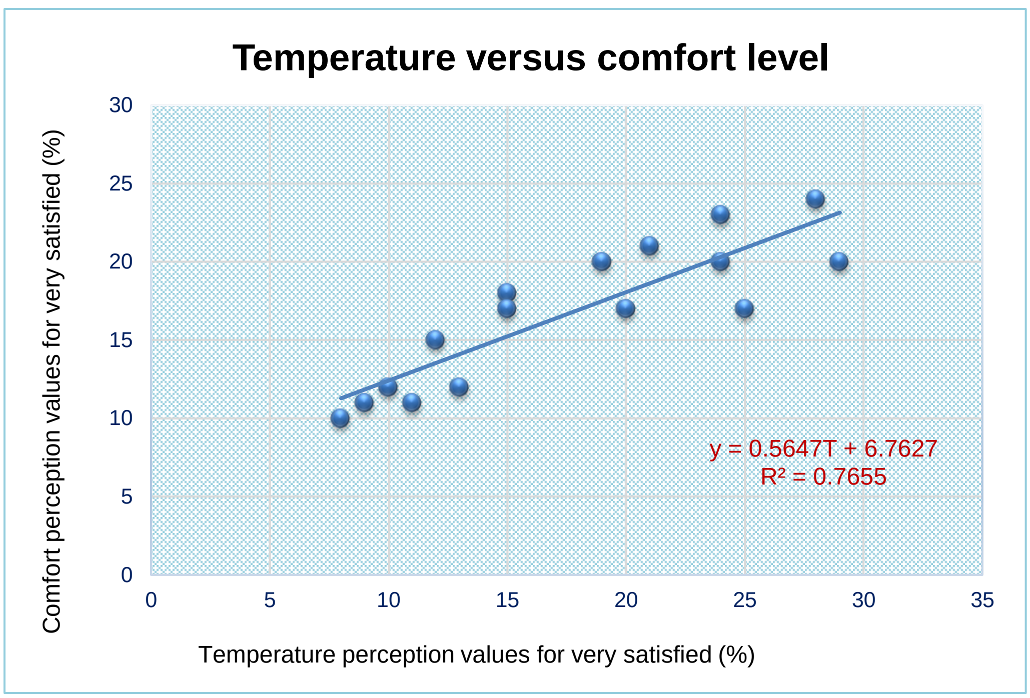

Figure 5.17 Perceptions of temperature versus comfort level

5.4.4 Air quality

An analysis of perception of air quality versus comfort level was conducted to explore how air quality influences comfort level. Figure 5.18 presents the perception of air quality versus comfort level. It was noted that mechanically ventilated/ air-conditioned buildings such as the library building in CUT has better air quality than the other assessed buildings and people perceive such buildings as having a higher comfort level. However, the comfort level in other buildings without mechanical ventilation system and air conditioning are low, and therefore the overall perception for comfort level of the case study buildings is (17%). As noted in sections 4.2.3.5 and 4.2.3.6, in building 11 and 13 the air is not conditioned but passive stack ventilation is used, thus leading to poor air quality and poor comfort level.

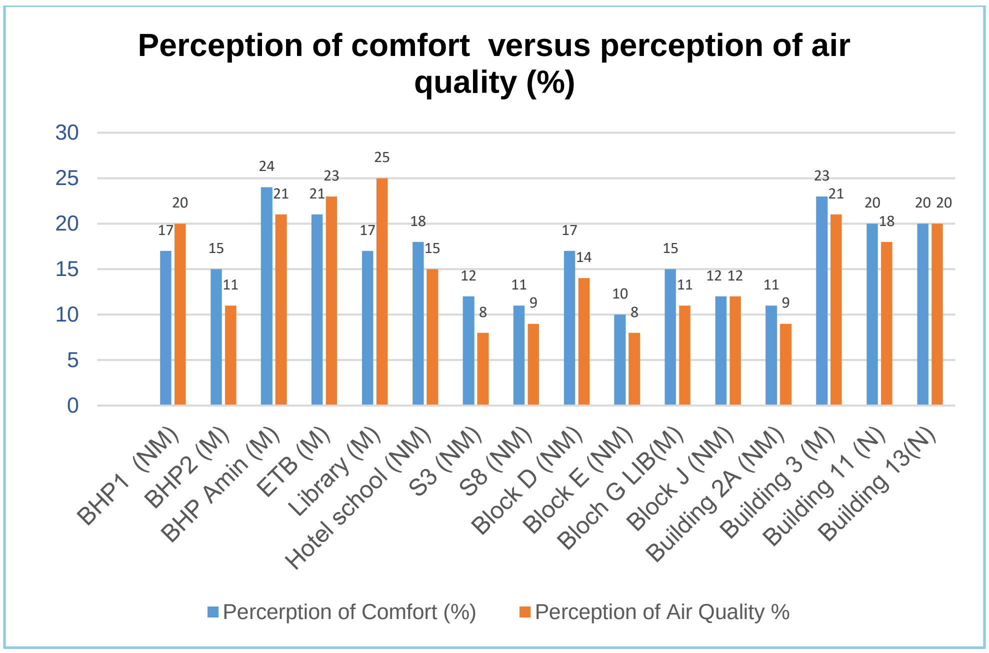

Figure 5.18 Perception of air comfort and air quality

The regression analysis between air quality and comfort level indicates a linear relation between the two parameters with a relatively high correlation coefficient of 0.81909. Regression analysis shows that R^2 = 0.6709, and P-value = 0.000103868 which further validates the association between the 2 variables. The relation is presented by equation 8 (Eq. 8). It was noted that increase in percentage for air quality is associated with increase in comfort level. This shows that air quality has a significant effect on overall comfort in the building.

$$Y = 0.6926x + 6.1009 \qquad \text{(Eq. 8)}$$

Where Y= perception comfort level a

X_A = Perception air quality

$R^2 = 0.6709$, P-value = 0.000103868

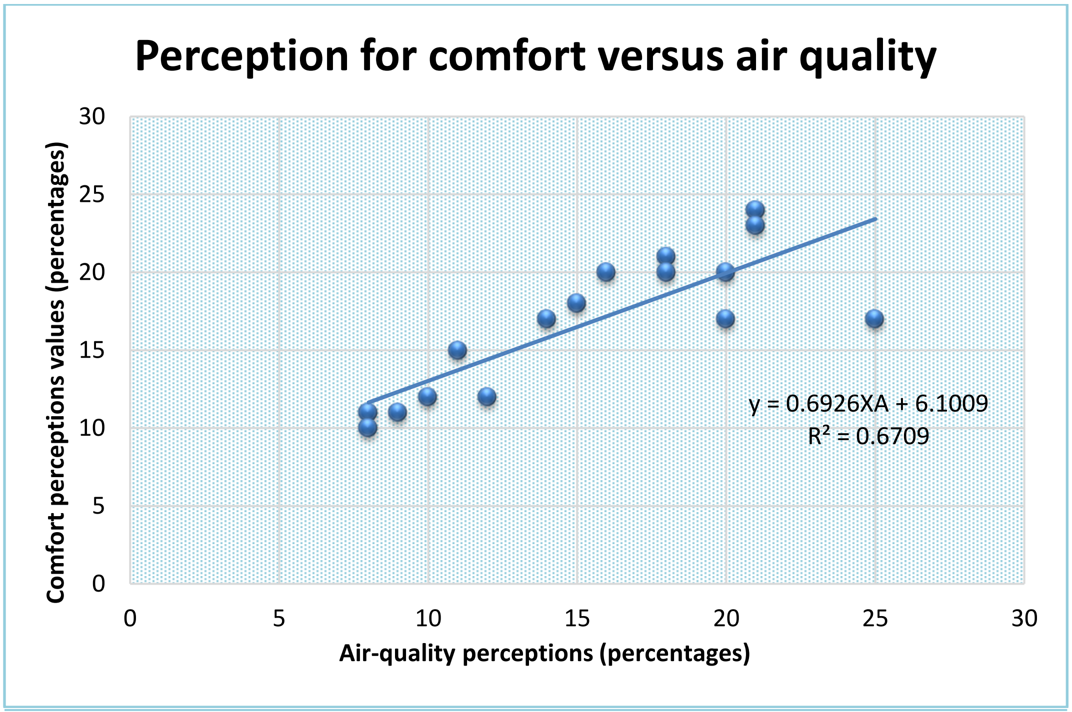

Figure 5.19 Interlinkage between perceptions of air quality and perceptions of comfort level

5.4.5 Ventilation

Perception of ventilation was compared to perceptions of comfort to explore the effect of ventilation on the overall comfort of users of the building. In this regard, Figure 5.20 presents the perception of comfort with respect to perception of ventilation. The pattern was observed to be similar to conditions where buildings used mechanical ventilation (air-conditioning) (c.f: section 4.6.2.). It is observed that higher percentages of people perceive higher (very satisfied) comfort levels in buildings using mechanical ventilation systems than in buildings using mixed mode of ventilation. For example, the BHP admin building which uses a fully mechanical ventilation system, had the highest perception of comfort level (28%). On the other hand, building S8 which has a mixed mode of ventilation, has the lowest perception of comfort level (8%). Thus, it was noted that a ventilation system has a significant effect on satisfaction levels for comfort, which is also established in Figure 5.20. A linear relation between the two variables with a significant correlation coefficient (0.906). Regression analysis shows that R^2 = 0.8218, and P-value = 0.0000013 which further validates the association between the 2 variables. This can be observed in Figure 5.21. This relation is defined by equation 9 (Eq. 9) which shows that increase in ventilation level increases the level of comfort.

$Y = 0.5586X_V + 7.0089$ (Eq. 9)

Where Y= perception comfort level a

X_V= Perception ventilation level

R^2 = 0.8218, P-value = 0.0000013

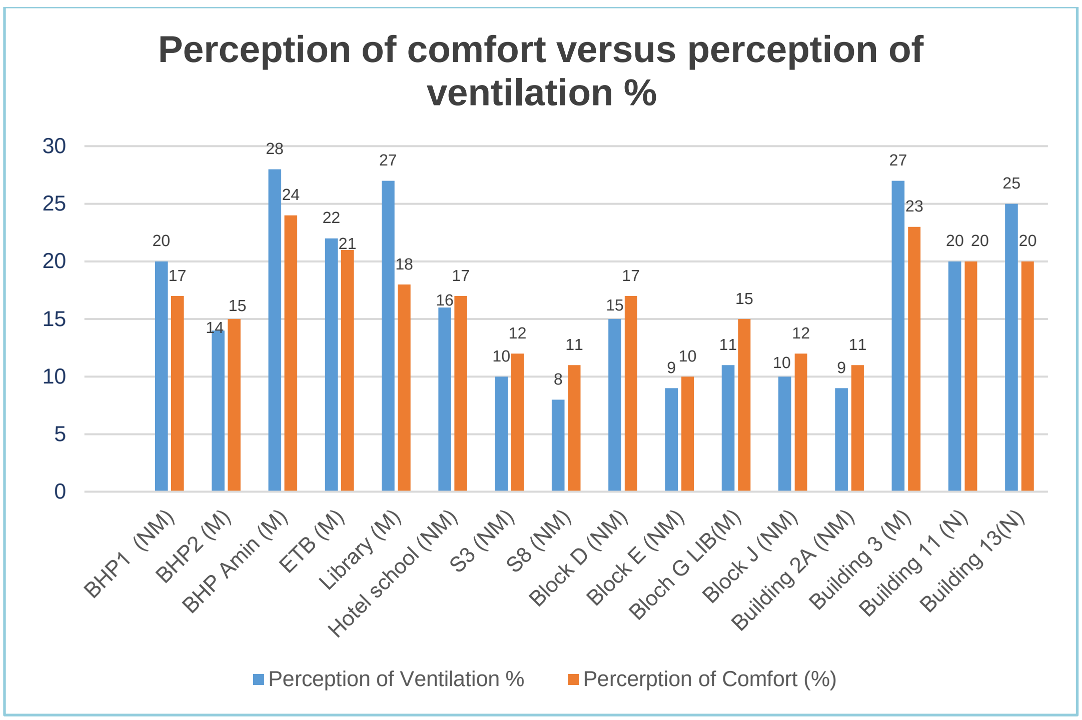

Figure 5.20 Ventilation and comfort perceptions in %.

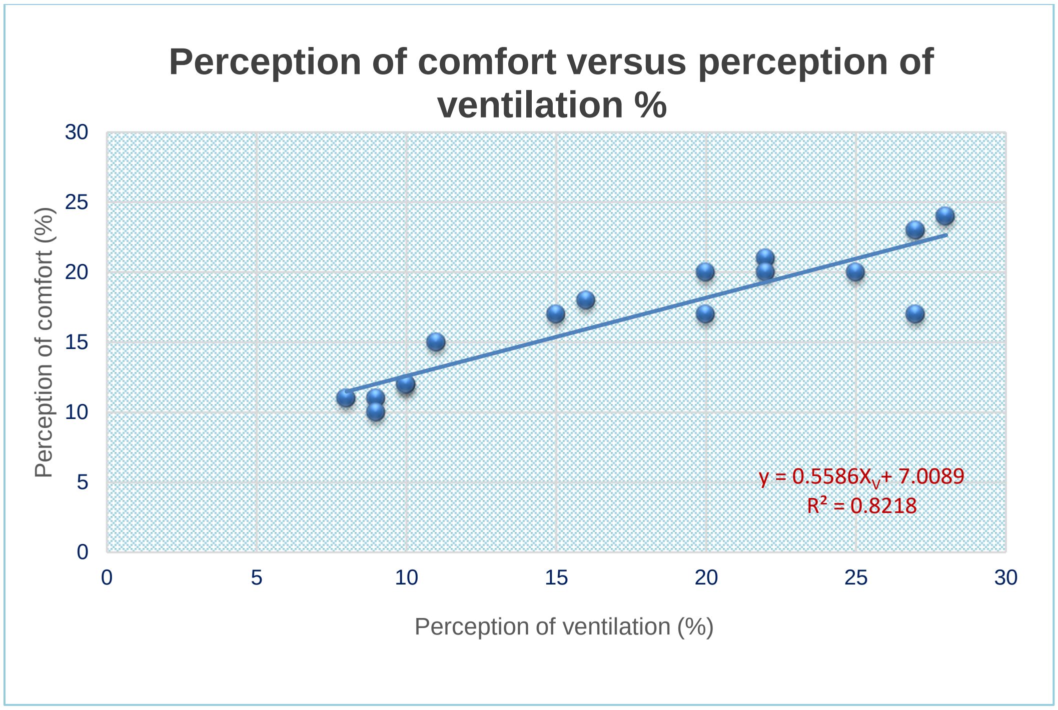

Figure 5.21 Interlinkage between ventilation- and comfort perception.

5.4.6 Illumination

Illumination is one of the essential elements for IEQ. Therefore, the perception of illumination (lighting condition) in the rooms was compared to the comfort level perception of occupants and users and presented in Figure 5.22. According to the perception of users, buildings with high illumination levels have relatively better comfort levels. For example, buildings BHP 1, BHP admin, building 3, and building 11 provide higher comfort levels because of higher illumination levels compared to other buildings such as S3, S8, Block G (Lib M), and building 2A, which have lower illumination levels and offer lower comfort levels.

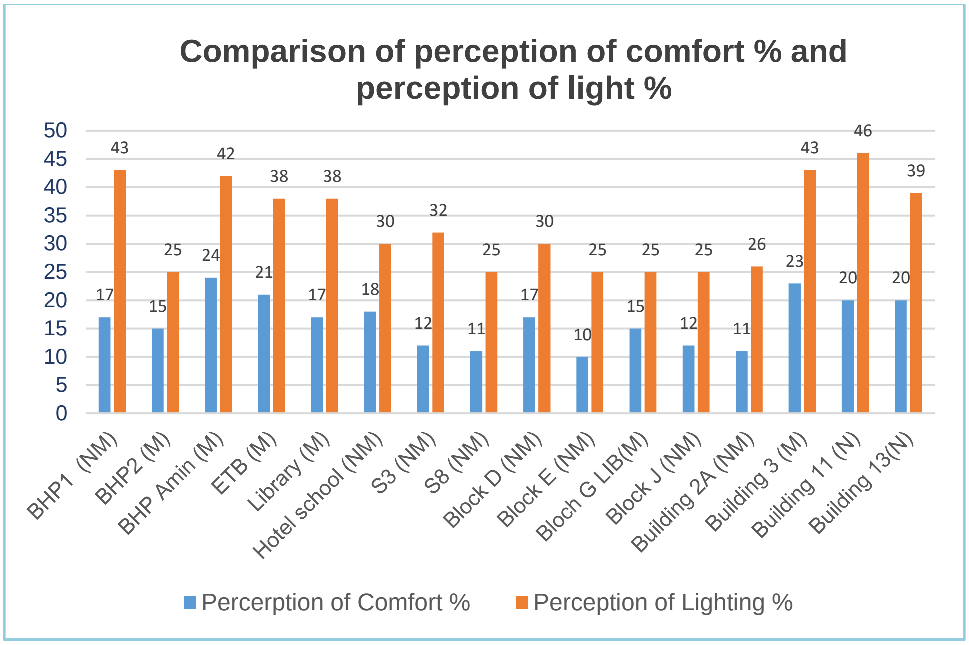

Figure 5.22 Illumination- and comfort perceptions

It is also significant to note that the buildings with the highest perception for lighting also had high values for WWR (buildings 11, 13). Thus, provision of adequate daylighting conditions in buildings offers conditions for higher comfort levels. It is also noted that the two variables such as illumination level and comfort level are fairly correlated (correlation coefficient = 0.719). Regression analysis shows that R^2 = 0.51825, and P-value = 0.001663542 which further validates the association between the 2 variables. The linear relation between the two variables (Figure 5.23) is defined by equation 10 (Eq. 10).

$Y = 0.4103\ X_L + 2.8267$ (Eq. 10)

Where Y= perception comfort level a

X_L= Perception ventilation level

R^2 = 0.51825, P-value = 0.001663542

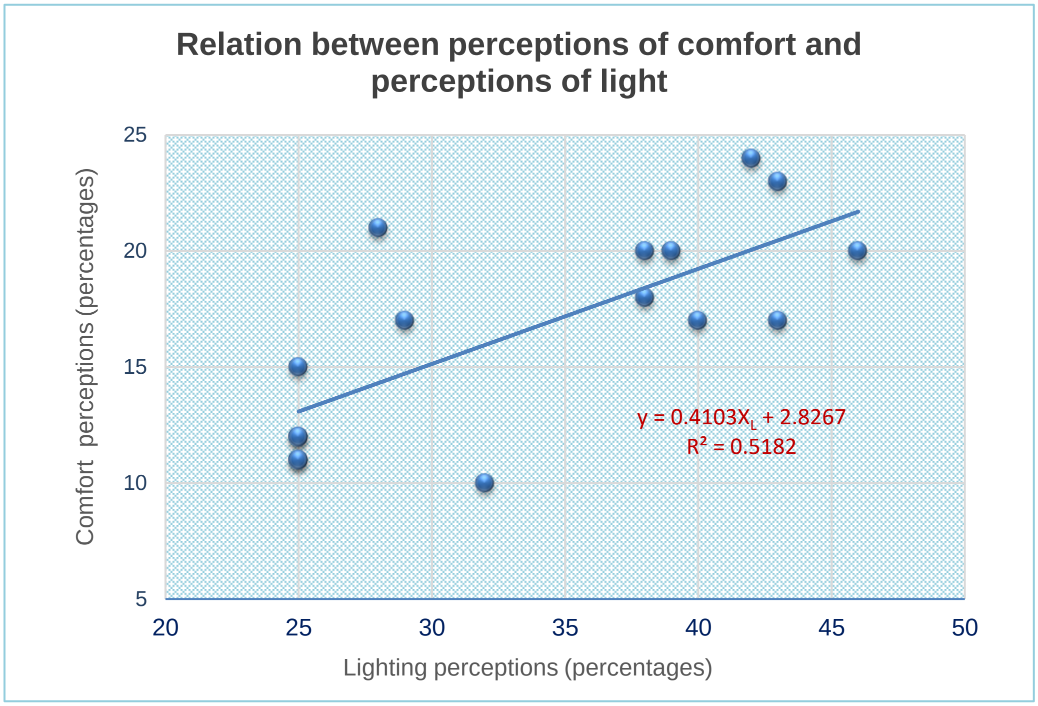

Figure 5.23 Interlinkage between illumination- and comfort perceptions

In addition to the above discussed analyses between comfort level and user perception of influential parameters, comparison between the comfort level and actual temperature and actual illumination level inside the buildings was analysed to have in-depth understanding of the interlinkages and how the comfort level is influenced under practical situations

5.4.7 Comfort level versus actual interior temperature °C

An evaluation of the relation between perception of comfort and actual interior temperatures of the assessed buildings indicated an interlinkage between them, as shown in figure 5.24. There is a high negative correlation coefficient (-0.8797). Regression analysis shows that R^2 = 0.7739, and P-value = 0.0000070678 which further validates the association between the 2 variables. This is presented by equation 11 (Eq. 11). The negative correlation indicates that comfort level increases along lower temperature. For example, the values indicate that buildings that depended on air-conditioning (M) have lower values for temperature and higher values of comfort. Thus, the trend line shows that user satisfaction increased as temperature reduced. The lowest temperature in the plot was 24°C. A comparison of the relation between perception of temperature and comfort level (Figure 5.17 and section 5.4.2) on the one hand and actual temperature and comfort level on the other hand, indicate that the comfort level increases within a certain limit of temperature (i.e. between 24^{0}C to 27^{0}C). This corroborates the recommendations of the Adaptive Comfort Temperatures as defined in ASHREA 55-2004 (presented in section 2.9.1; Table 2.2) that for outside temperatures of 30^{o}C, the range of accepted temperatures for indoor temperatures is from 23.5°C-30.5°C (ASHREA 2004; GBCSA 2014).

$Y = 0.2933X_C + 31.821$ (Eq. 11).

Where Y is Temperature in degrees C and X is Comfort perceptions

$R^2 = 0.7739$, P-value = 0000070678

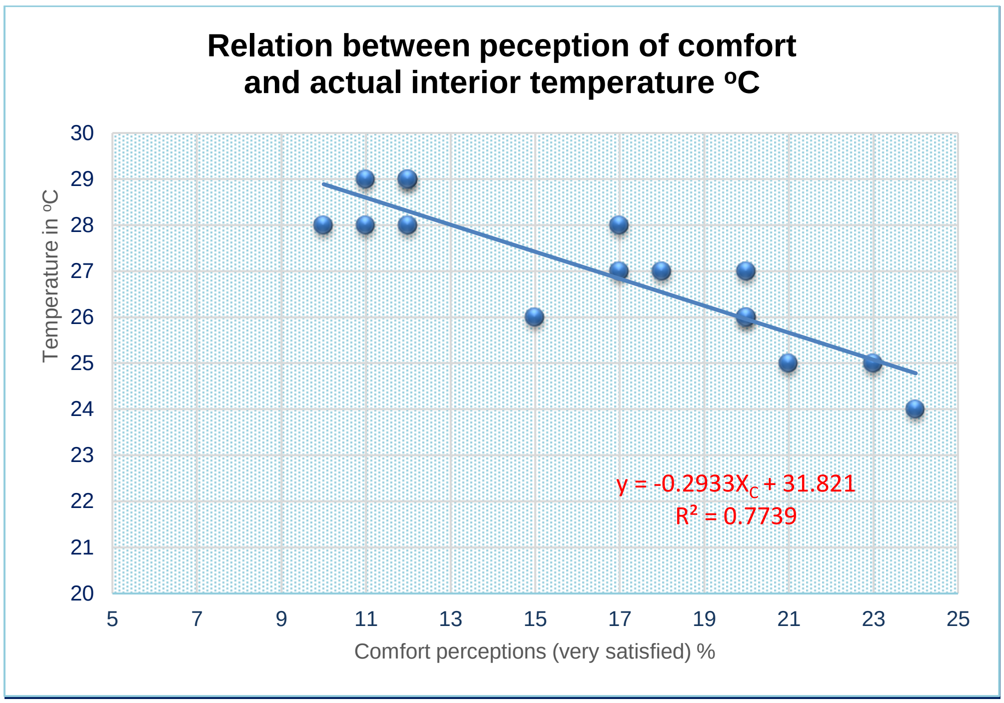

Figure 5.24 Linkage between perception of comfort and actual temperature (ºC)

5.4.8 Comfort level versus actual illumination

Figure 5.25 presents the perception of comfort against actual illumination level. It is noted that comfort level is higher within a certain moderate range of illumination (i.e. within the range of 250-400 lux), after which the comfort level appears to decrease. As shown in Figure 5.26, there is a linear relation (with high correlation coefficient of -0.92276) between actual temperature and comfort level (Eq. 12). Regression analysis shows that R^2 = 0.85148, and P-value =0.0000009620 which further validates the association between the 2 variables. This also shows that comfort level decreases along a higher illumination level beyond 400 lux. However, as mentioned earlier, higher comfort level is attained at the illumination level varying between 250-400 lux. As indicated in section 5.3.7, building 11 has the highest values for illumination, even though the building uses the least amount of energy per square meter. However, there is one exception – building 11, which is highly comfortable at the highest illumination level. The indication is that in this building, variables such as temperature, ventilation and air quality have a greater effect on comfort than illumination. This is partly due to the high WWR, as other buildings with lower WWR depend more on artificial lighting.

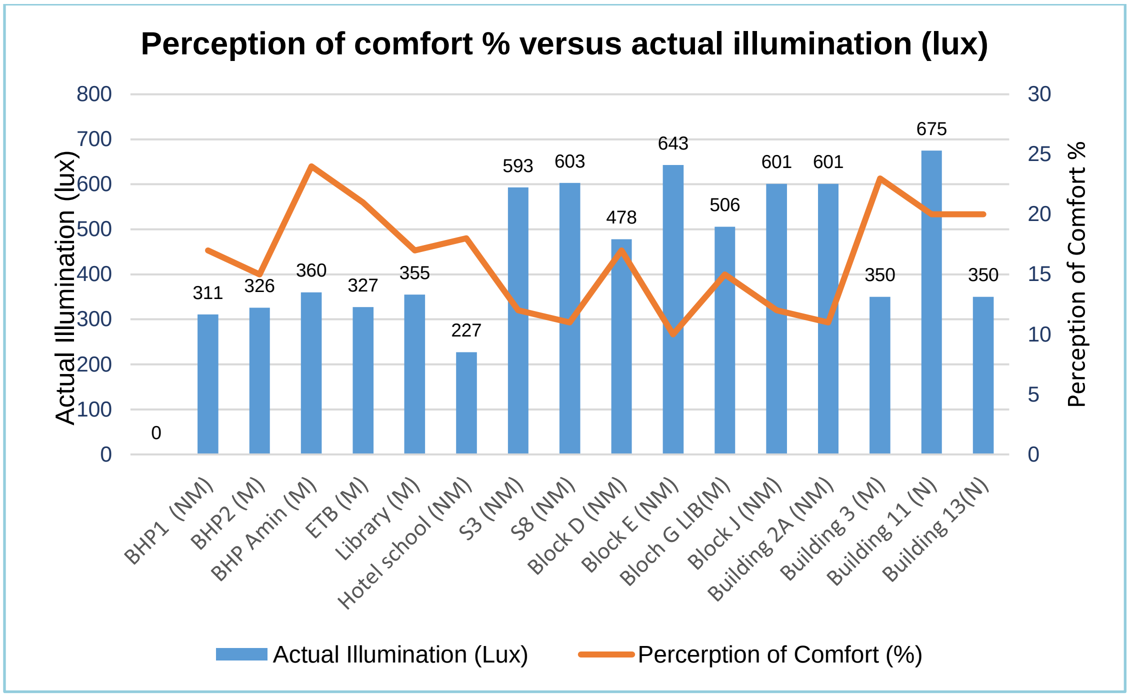

Figure 5.25 Perception of comfort versus actual illumination

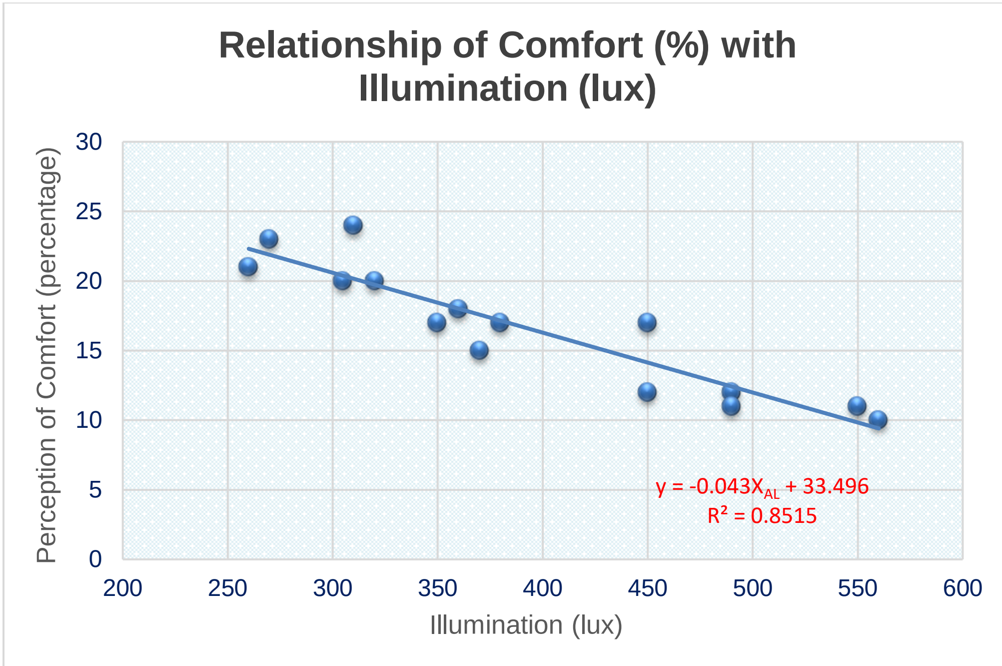

Figure 5.26 Linkage between actual illumination and perception of comfort

Eq. 11 which shows that illumination levels increases as perception of comfort reduces

$Y = 0.0238X_{AL} + 26.296$ (Eq. 12)

Where Y= Perception of comfort

X_{AL}= Actual illumination

R^2 = 0.85148, P-value = 0.0000009620

5.5 Hypothesis testing

Two hypotheses were tested to establish the interrelations between the building parameters, energy use and improvement in IEQ. It is noted that a hypothesis is an idea or proposition that can be tested for association or causality by deducing logical consequences which can be tested against empirical evidence (Collis and Hussey, 2003). Therefore, the hypotheses in this thesis were to establish the propositions that will assist in developing design guidelines for development of sustainable built infrastructure or buildings at the universities of South Africa.

As indicated in section 1.5, for the purpose of investigation, the following two hypotheses were formed:

Hypothesis 1: *Improved design by using green building principles with optimal use of daylight will reduce electrical energy consumption and improve the indoor quality of a building*. In other words, appropriate building parameters in terms of floor space area (Area FS), Volume (m3), breadth (B), WWR, Temperature (^{0}C) and illumination (Lux) will lead to energy efficiency.

Hypothesis 2: *The use of appropriate building materials for new construction and renovations / retrofits will improve quality of indoor environment and energy efficiency in buildings.*

Based on these two premises, as indicated in section 3.2.3, a multiple case study approach was used in obtaining quantitative data from field observation and measurements, survey of perception and retrieval of data from archives. In order to test claims of the hypotheses, relevant data were tested to either support or reject claims of the hypotheses. In order to determine the weight of the data for accepting the claims of the hypotheses, the tests of correlation and statistical significance were applied. These two tests were summarized and presented in Tables 5.2, 5.3, 5.4 and 5.5.

5.5.1 Analytical procedures adopted for hypothesis testing

Two methods for testing the evaluated data were implemented, namely the significance test (paired t-test) and Correlation. Test of data for parameters was applied by entering the data into computer database software packages (Microsoft Excel 2016 and Vassar Stats t-Test online calculator) and printing of reports to provide the required information. In these packages, quantitative data were entered for inferential statistics to test the hypotheses. In order to test claims of the hypotheses, relevant data were evaluated that can be tested to either support or reject claims of the hypothesis.

5.5.1.1 Testing of hypothesis 1

Table 5.2 shows the correlation coefficients of the various parameters such as functional space area (Area FS), volume (m3), breadth (B), WWR, temperature (^{0}C) and illumination (Lux) with energy inefficiency. As discussed in section 5.3, these parameters are derived from the categories of building function, size and form which affect EC. It was noted that energy consumption correlated fairly with all these variables, such as with functional space area (correlation coefficient= 0.752, R^2 = 0.6747), volume, (correlation coefficient= 0.759, R^2 = 0.775), breadth (correlation coefficient= 0.778, R^2 = 0.9365), WWR (correlation coefficient= -0.790, R^2 = 0.7296), temperature (correlation coefficient= -0.739, R^2 = 0.545) and illumination (correlation coefficient= 0.741, R^2 = 0.545). Thus, it is plausible that these variables are fairly related to energy consumption and influence energy efficiency in the buildings.

Table 5.3 Correlation coefficient between energy consumption and design variables of the assessed buildings

Parameters	***Energy consumption (Kwh/anum)***	***Functional area FS***	***Volume (m3)***	***Breadth (m)***	***WWR***	***Temperature oC***	***Illumination (Lux)***
Energy consumption (Kwh/annum	1						
Area FS	0.752, (R^2= 0.67)	1					
Vol (m3)	0.759, (R^2= 0.77)	0.956	1				
B (m)	0.778, (R^2= 0.94)	0.827	0.858165	1			
WWR	-0.790, (R^2= 0.73)	-0.413	-0.48436	-0.657	1		
Temp ºC	-0.739 (R^2= 0.54)	-0.597	-0.53508	-0.564	0.436	1	
Illum (Lux)	-0.741, (R^2= 0.79)	-0.575	-0.53648	-0.629	0.689	0.749	1
Temp: Temperature, Vol: Volume, FS : Functional Area, Illum: Illumination							

In order to support or reject hypothesis 1, a further test of significance was applied. In the test of significance, the research hypothesis or the alternative hypothesis as indicated below was:

H_a: *Improved design by using green building principles with optimal use of daylight will reduce electrical energy consumption and improve the indoor quality of a building*.

The null hypothesis was:

H_o: *Improved design by using green building principles with optimal use of daylight will not reduce energy consumption and will not improve indoor quality of a building*.

The statistical significance test was done by calculating the probability of error (p-value) by the t ratio. The difference between the two variables is deemed to be statistically significant when p=0.05 or less for a 95% confidence level (for α= 0.05). As indicated in in the t-test (Table 5.3), the difference in variables for energy consumption was compared with functional area, volume, breadth, WWR, illumination and temperature. The results of the t-test indicated that all the variables have both single-tailed and two-tailed p values of less than 0.05 ($p^*<0.05$ and $p^{**}<0.05$ for α= 0.05) for a 95% confidence level. All the results were statistically significant, which established that energy consumption is linked to the building design variables and that energy efficiency can be attained if design is done by considering these variables as per the green building principles.

Table 5.4 Significance test (t-test) results between design variables and energy consumption of the assessed buildings

Parameters	*t*	*df*	*P**	*P***
Energy consumption / functional area of the buildings	6.67	30	0.00000011	0.00000022
Energy consumption /Volume of buildings	6.42	30	0.00000022	0.00000043
Energy consumption / Breath of the buildings	6.73	30	0.00000009	0.00000018
Energy consumption /Window to façade ratio	6.73	30	0.00000009	0.00000018
Energy Consumption / Indoor Temperature	6.73	30	0.00000009	0.00000018
Energy Consumption /Illumination	6.72	30	0.0000001	0.00000019

5.5.1.2 Testing of hypothesis 2

Hypothesis 2 being tested was "*The use of appropriate building materials for new construction and renovations / retrofits will improve quality of indoor environment and energy efficiency in buildings".*

In this case, it is noted that in 14 out of the 16 assessed buildings (excluding buildings 11 and 13) appropriate energy efficiency materials were not used. To establish the relation between IEQ and use of appropriate building materials for new construction and renovations/retrofits, a correlation coefficient and significance test (t-test) between comfort level and variables related to materials – such as air quality (in perception), ventilation (in perception), temperature (in °C) and illumination (in lux) – were conducted. Table 5.4 shows that comfort level and the four variables such as air quality (correlation coefficient = 0.838 / R^2 = 0.671), ventilation (correlation coefficient = 0.872 / R^2 = 0.822), temperature (correlation coefficient = -0.861 / R^2 = 0.765) and illumination (correlation coefficient = - 0.703 / R^2 = 0.851 are fairly correlated. This indicates that a strong association exists between IEQ and building materials used in buildings as these variables are influenced by building materials.

Table 5.5 Correlation coefficients between comfort level (IEQ) parameters and such as air quality, ventilation, temperature and illumination

	Comfort	*Air quality*	*Ventilation*	*Temperature °C*	*Illumination (lux)*
Comfort	1				
Air quality	0.838, (R^2=0.671)	1			
Ventilation	0.872, (R^2=0.822)	0.983	1		
Temperature oC	-0.861, (R^2=0.774)	-0.582	-0.665	1	
Illumination (lux)	-0.825, (R^2=0.852)	-0.505	-0.510	0.749	1

The test of significance:

In order to support or reject hypothesis 2, a further significance test (t-test) was conducted. In the significance test, the research hypothesis or the alternative hypothesis as indicated below was:

H_a: *The use of appropriate building materials for new construction and renovations/ retrofits will improve quality of indoor environment and energy efficiency in buildings*

The null hypothesis was:

H_o**:** *The use of appropriate building materials for new construction and renovations/retrofits will not improve quality of indoor environment and energy efficiency in buildings*.

As indicated in Table 5.5, the results of the t-test indicated that all the variables have both single-tailed and two-tailed p values of more than 0.05 ($p^*>0.05$ and $p^{**}>0.05$ for $\alpha = 0.05$) for a 95% confidence level. Thus, these results are statistically insignificant, which establishes that if inappropriate building materials are used, appropriate IEQ cannot be attained in the buildings. Consequently, it supported the research hypothesis that use of appropriate building materials for new construction and renovations/retrofits will improve quality of indoor environment and energy efficiency in buildings.

Table 5.6 Significance test (t-test) between IEQ and variables such as air quality, ventilation, temperature and illumination

Parameters	***t***	***df***	***P****	***P*****
Comfort / Air quality	0.79	30	0.217864	0.435728
Comfort /ventilation	-0.32	30	0.3982645	0.796529
Comfort / temperature	-0.82	30	0.7906581	0.41868379
Comfort / Illumination	-0.57	30	0.266561	0.572922

5.6 Assessment of water use efficiency

Water use is an essential component of sustainable built infrastructure at universities. Arguments have emerged that water should be sustainably and responsibly used at universities, particularly in water scarce countries such as South Africa. In this regard, efforts are being made at the various universities of South Africa to use water sustainably and accordingly relevant infrastructures and services are being retrofitted or installed. Therefore, in this section the various aspects related to water use/consumption in buildings, with specific emphasis on university buildings, have been analysed. This section has two parts. The first part includes analysis and discussion of various water uses in educational buildings; water consumption and building envelope design; water consumption and energy efficiency; and alternate sources of water. In the second part, an assessment of water use in the case study buildings is conducted.

5.6.1 Water consumption in educational buildings

The various water uses in buildings include domestic water use, heating and cooling, landscaping, laboratory works, exceptional or emergency demands such as for construction or in case of fire, and leakages. Each of these water uses are discussed in the following sections.

5.6.1.1 Domestic water use

Domestic use of water at educational institutions or universities include use of water for drinking, lavatories, restaurants and kitchens (Fowler & Rauch, 2011). Although, the normal demand is about 40 litres per person per day, it is observed the university buildings receive water through a continuous supply system. The quantum of domestic water use depends on the number of users (students and staff) and number of operational hours. Compared with weekends, water use increases during weekdays because of a higher number of users and longer operational hours.

5.6.1.2 Heating/cooling

Mechanical heating and cooling requires water. In addition to this, losses from a cooling system which incorporates one or more cooling tower, leaks from the reticulation network, evaporation from the cooling tower itself, cooling tower overflows, drift losses and blow-down (also called bleed-off) of concentrated cooling water, are the important components through which water is consumed in the buildings because of heating and cooling. The sum of the water requirement for mechanical heating and cooling and losses constitute the water use for heating and cooling in buildings.

5.6.1.3 Landscaping

Landscaping is an essential element of buildings – particularly public and educational buildings. A significant amount of water is consumed to create and maintain landscaping. However, water for irrigation depends on the area of landscaping, climate, type of plants and turf. In a dry climate, landscaping typically uses about 25 gallons of water per square foot per season (1018.65 litres per square meter). However, use of native and drought-tolerant plants can reduce irrigation needs to about 5 to 10 gallons per square foot (204 to 407 litres per square meter) per season (Fowler & Rauch, 2011).

5.6.1.4 Laboratory

Laboratories are an integral part of universities, particularly those which offer science and engineering education. Laboratories require water for performing experiments. The demand of water depends on the type of laboratory and experiments performed. For example, hydraulics and water engineering laboratories require significantly more water than other electrical engineering or physics laboratories.

5.6.1.5 Exceptional and Emergency use

Exceptional cases such as construction works, and emergency situations such as fire, also consume a significant quantity of water and influence water use at universities, although the demand could be for a very short period.

5.6.1.6 Water consumption due to leaks

Leakage is observed to significantly influence water consumption and consequently sustainability of water use in buildings. The various common sources of leakage in office and public buildings include cooling towers, taps (especially in high usage areas where tap water wear is high), urinals, cistern flapper and filler ball valves, fire hose reels, underground pipes and control valves (Quinn et al, 2006), which need to be considered while designing buildings.

5.7 Building envelope design and water consumption

As indicated in section 1.6, one of the specific objectives of the study was to assess the energy and water use efficiency in existing buildings at South African universities, based on green building principles. In order to determine the effects of building envelope design on water consumption, it is important to understand the effects of envelope design – including size (volume), and functional spaces – on energy consumption. However, water consumption for domestic also use depends on the number of occupants in the building. Fowler and Rauch (2011) noted that domestic water consumption depends on human operation and fixed equipment efficiency.

In the context of this investigation, the function of the assessed educational buildings as indicated in section 4.4.1 and 5.3.2 determined the usage of air-conditioning, artificial lighting and length of time these services were used. As discussed in section 5.3.2, the library buildings used air-conditioning not only for thermal comfort, but also for protection of their books. Therefore, libraries depend on air-conditioning for heating cooling and ventilation. Services of lighting and air-conditioning were required for the duration of use of the building. The two office buildings depended on air-conditioning for heating, ventilation and cooling. Out of all 16 assessed buildings, only 2 buildings depend on natural ventilation for heating, cooling and ventilation.

As discussed in section 5.2, building envelope parameters include orientation, size of building and size of windows and energy efficiency is dependent on various parameters such as building function, building orientation, building configuration/geometry, size of the building, size of windows, external window-to-façade ratio and building materials (type and property of materials used for building envelope), which consequently influence water use efficiency. For example, building function affects energy consumption due to use of mechanical means for providing heating, cooling and ventilation, which significantly affects the water consumption in the building. Building orientation is important for natural light, heating/cooling and ventilation; thus, proper orientation would improve natural heating/cooling and ventilation, which would lead to reduction in the use of air-conditioning and lighting. Consequently, there would be reduction in consumption of water. Increase in building size of an air-conditioned building such as the library or office buildings, would lead to increase in energy consumption and subsequently water usage. Use of proper building materials would affect energy consumption of naturally ventilated buildings by improving internal heating/cooling and thus minimizing the amount of energy required for heating/cooling to attain appropriate IEQ, that would also result in reduction of water consumption.

5.8 Discussion of effect of water use on energy consumption

According to the Stakeholder Accord on Water Conservation (2009), water use due to amenities depends on the frequency of use, duration of use and flow rate during use (or volume with each use) for all plumbing fittings. The consumption of water can be quantified by using data on flow rate or volume, which can be obtained from manufacturer's specifications. However, the US Federal Water Use Indices have developed reference data that can be used for calculating a water use baseline. According to Fowler & Rauch (2011), the indices provide basic guidance on typical water usage for different building types. This has been applied in calculations for water consumption in this study. Indoor water use for office buildings is estimated at an average of 15 gallons (57 litres) per occupant per day with a range of 8 to 20 gallons (30 to 76 litres) per occupant per day, (Fowler & Rauch, 2011). According to Figure 5.27 domestic water consumption is 42% (41 % for toilets and taps and 1% for kitchen) of the total amount of water consumed (Fowler & Rauch, 2011).

Based on the above norms, an assumed amount of 30 litres per person per day was adopted in this study to calculate the domestic water consumption. Table 5.7 indicates the occupancy of the assessed buildings obtained from university records. This calculation was done due to lack of availability of water consumption data for the assessed buildings. The calculation is also based on using 305 days, the period the universities are opened and in full attendance during the academic year.

It is important to note that since increase in air-conditioned spaces is related to increase in energy consumption and water consumption for heating and cooling, it was included in the calculation of water consumption in the assessed buildings.

Water use increased along increase in size of buildings and functions. Smaller buildings and low functional buildings have used less water. However, it is also noted that the mechanically heated and cooled buildings (e.g. buildings BHP2, BHP Admin, ETB, Hotel School at CUT, Block D in DUT, and building 3 at TUT) consume additional water for air-conditioning purposes in comparison to a naturally heated/cooled/ventilated building. However, the two benchmark buildings 11 and 13 did not depend on mechanical heating/cooling and therefore did not require water for this purpose. Figure 5.27 indicates the comparison of energy consumption, occupancy, area and estimated water use. Thus, it is construed that compared with buildings which require air conditioning and artificial ventilation, buildings that depend on natural ventilation for heating and cooling do not consume much water.

Table 5.7 Occupancy of assessed buildings

Building	Occupancy
BHP1 (NM)	1280
BHP2 (M)	1978
BHP Amin (M)	988
ETB (M)	930
Library (M)	905
Hotel school (NM)	488
S3 (NM)	561
S8 (NM)	561
Block D (NM)	1879
Block E (NM)	422
Bloch G (M)	370
Block J (NM)	264
Building 2A (NM)	422
Building 3 (M)	512
Building 11 (N)	198
Building 13(M)	283

5.9 Comparison of building features with water and energy consumption

Figure 5.28 presents the domestic water consumption and water used for air-conditioning/ heating and cooling. It is found that the buildings which consume higher energy, also consume more water. The influencing factors for energy consumption are building function, which affects building envelope design which in turn will determine the level of mechanical services required for heating, cooling and ventilation, which essentially increases the water consumption and vice versa. In the case of the two benchmark buildings (Building 11 and Building 13) mechanical services for heating, cooling and ventilation were not required because the building envelope design was deemed to be sufficient to cater for appropriate IEQ and consequently resulted in a reduction of water use. Figure 5.27 and BHP 2 used the highest quantity of water 18,098Kl/annum and energy. The building is occupied by a comparatively high number of users 1,978, this indicates that water use depends on occupancy level and function, however electricity consumption was mainly due to design. Comparison of building BHP 2 and block D indicated that both buildings had a similar number of occupants, and similar area or size, however BHP2 used 100% mechanical means for heating cooling and ventilation and block D used 70% mechanical ventilation for heating cooling and ventilation. Consequently, Building D consumed 31.4% less electrical energy and 29.1% less water compared to BHP2 (Figures 5.29 and 5.30)

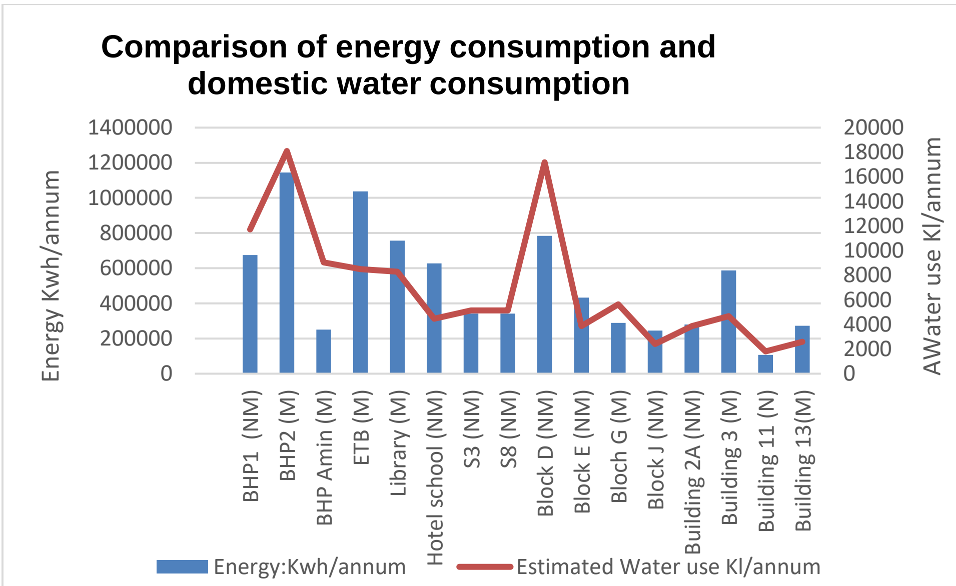

Figure 5.27 Comparison of energy consumption, occupancy, area and estimated water use

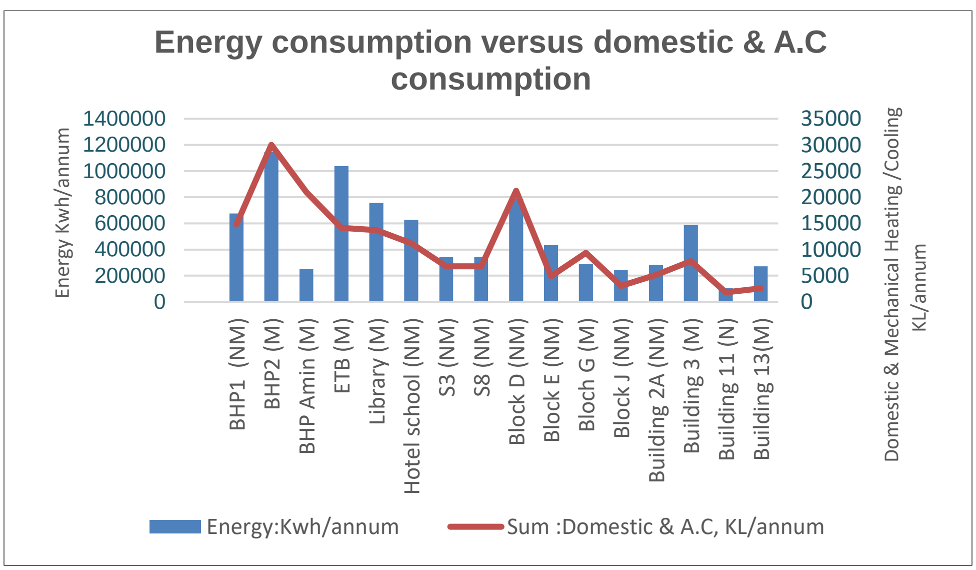

Figure 5.28: Energy Consumption versus Water for Domestic & Mechanical heating and cooling

5.10 Chapter Summary:

In this chapter, analysis of parameters relating to energy consumption and energy efficiency, IEQ and water use in university buildings was conducted by using data from sixteen buildings at three universities in South Africa. Linkages between various building parameters and energy efficiency and IEQ were developed. The two hypotheses were tested and relations between building parameters for attaining energy efficiency, appropriate IEQ and WUE in university buildings at South Africa were established. Based on the findings of the analysis conducted in this chapter, conceptual SD models were developed and presented in the next chapter.

CHAPTER 6: MODEL DEVELOPMENT AND EVALUATION

6.1 Introduction

It is evident from the analysis and findings in chapter 5 that energy efficiency, IEQ and efficient water usage are three essential components of sustainable built infrastructure at universities and that they are dependent on a number of physical building and environmental variables. It has also been established that these three essential components are linked with each other and influence each other's performance. Concurrently the variables influencing these components are also interdependent, interlinked and influence one another. Therefore, it can be construed that there is a need for an integrated approach to achieve sustainable development of built infrastructure at universities.

A systems approach – or in other words an Applied Systems Dynamics (ASA) paradigm – was envisaged to be an appropriate approach to analyse and develop policy interventions for such challenges.

Sustainable buildings require an interdisciplinary approach which needs to analyse interdependencies of engineering and geometric considerations. In this particular investigation, an ASA inspired conceptual causal feedback relation, and development of a SD model over and above the results of the statistical analyses, were resorted to. The reason for this approach being that ASA can be put to effective and distinctive use in problem solving. Moreover, a conceptual causal feedback relation (model) is a consistent and unifying theory of behaviour taken from bits of information about the real world. However, in this investigation the scope of the ASA inspired SD modelling was limited to development of conceptual models because the conceptual models have the ability to elicit of the linkage among the variables and enable the designer to understand the dynamics among these variables that can affect sustainability of the built infrastructure or buildings. Besides, there is a lack of appropriate and adequate data for development of quantitative models and validation of the models.

Therefore, in this investigation conceptual models based on the ASA paradigm and by using SD modelling principles for each subsystem, were developed independently and were then be integrated. The causal feedback relations and conceptual models once initially crafted were discussed with the experts in an iterative manner (at least two times) to verify, correct and validate them. The corrected causal feedback relations were used to develop the conceptual models and also verified with the experts to validate. Then all the independent conceptual models were integrated to develop the integrated model to elicit policy or strategic design interventions that will assist in attaining sustainable buildings or built infrastructure at university buildings.

6.2 ASA paradigm for sustainable built infrastructure and buildings

All the three components EE, IEQ, WUE are interlinked to each other and develop a sustainable building system (Fig 6.1). Further, each component or subsystem is influenced by several endogenous variables such as geometric design variables form, volume, size, (length, breadth, height), opening, WFR, orientation and exogenous variable such as temperature, ventilation, air quality, water supply system, etc., and functions as system in itself. Therefore, a building becomes a system of systems and thus needs an integrated approach.

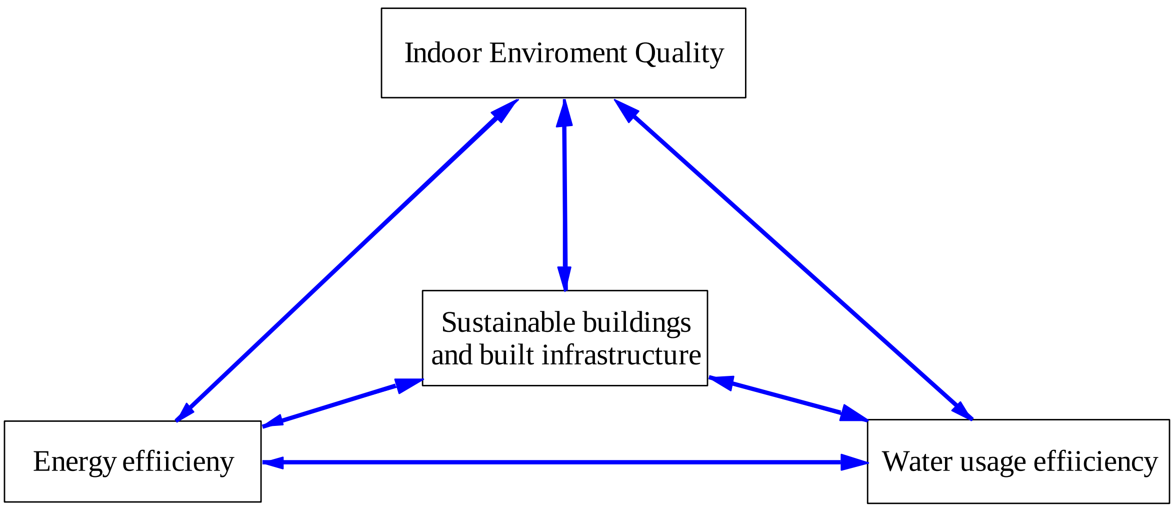

Figure 6.1 ASA paradigm for sustainable buildings

6.3 Causal feedback relations within the SD model for energy efficiency

Energy efficiency is a function of energy consumption in buildings. The lower the energy consumption in a building, the higher the energy efficiency. As evident from the analysis (c.f: section 5. 3, chapter 5), energy consumption is dependent on the geometry, size, shape and form of the building as well as function of the building and type of ventilation and lighting system. Therefore, by considering these variables of a building, ASA inspired causal feedback relations and conceptual SD models were developed that would lead to attainment of energy efficiency in university buildings of South Africa. The causal feedback relations and SD models are presented in Figure 6.2, 6.3 and 6.4. As seen in Figure 6.2, energy consumption in a building occurs because of the use of the buildings, which is dependent on the type of function, number of functional areas and duration of use of the building. In other words, higher energy consumption occurs if the building performs a higher number of functions because the functions require a higher quantity of energy and a longer duration of use of the building. Thus, building use and energy consumption develop a causal feedback relation through a disrupting or balancing mechanism (B1) that contributes to higher energy consumption or less energy efficiency. However, while the functions of the buildings may not be reduced, energy consumption can be reduced by designing the building with appropriate geometric parameters. For example, if the shape, size and form of the building are appropriate and there are ample window openings of adequate size that lead to apposite window-to-wall ratio (WWR), then the building will use natural ventilation and natural lighting instead of mechanical ventilation and artificial lighting, thus reducing energy consumption. Thus, WWR, building geometry and energy consumption (energy efficiency) develop a reinforcing feedback mechanism (R1), that would assist in reduction in energy consumption. The reinforcing feedback mechanism R1 balances the disrupting feedback mechanism B1 and consequently reduces energy consumption and increases energy efficiency (Figure 6.2).

Furthermore, indoor environment quality (IEQ) is an important parameter for efficient use of buildings. However, IEQ in a building is dependent on temperature, humidity, air quality, lighting and outdoor environment. In general, in many university buildings appropriate IEQ is achieved by use of artificial lighting and mechanical ventilation systems such as air-conditioning. However, as seen from figure 6.3, on account of undesirable outdoor environment and to create appropriate IEQ in the buildings, the use of mechanical ventilation systems, air-conditioning and artificial lighting increases the energy consumption and vice versa. Besides, indoor quality is also affected by the building materials being used in the various elements such as roofs, floors, walls and openings. However, conventional materials may increase energy consumption depending on the outdoor environment. Consequently, energy consumption of buildings and IEQ develop a disruptive feedback mechanism (B2) that cause higher energy consumption in the buildings. However, as evidenced from the analysis (c.f: sections 5.3.5, 5.3.6, 5.3.7, chapter 5), orientation of buildings plays an important role. Orientation of a building assists in providing adequate light, air and heat (during cold weather). Therefore, if the orientation of the building is appropriate and the building has an appropriate geometry (shape, size and form) as well as adequate window openings leading to apposite WWR, then the building will receive adequate natural light and will have natural ventilation, thereby reducing the demand for energy. As a result, there shall be reduced energy consumption in the buildings. Energy consumption and orientation of a building develop a reinforcing feedback mechanism (R2) resulting less energy consumption. The reinforcing mechanism R2 balances the disrupting feedback mechanism B2 of higher energy consumption. This results in reduction of energy consumption in the buildings and leads to higher energy efficiency.

Based on this analysis, Figure 6.4 presents the integrated conceptual SD model for energy efficiency. As seen from the figure and discussed above, there are two disruptive mechanisms, B1 (because of building use) and B2 (IEQ), which cause higher energy consumption. On the other hand, there are two reinforcing mechanisms R1 and R2 because of appropriate geometry and orientation of buildings that cause reduction in energy consumption. Thus, the energy consumption of a building has a clear interlinkage with the various parameters of a building such as orientation, building use, geometry and indoor quality. Hence, while building usage may not be reduced because of the demand for usage, and maintaining appropriate IEQ is necessary for higher efficiency of users, energy consumption can be reduced by appropriate geometry (WWR) and orientation of the building as suggested from the conceptual SD models. In other words, based on the causal feedback relations, it is envisaged that energy consumption will increase by the use of artificial lighting, use of air conditioning, increased function of the buildings, higher number of functional areas, higher duration of use of buildings and inappropriate use of materials. However, on the other hand energy consumption will be reduced by using natural systems. The natural system is influenced by WWR (number of openings influenced by appropriate orientation for natural lighting and natural ventilation), size of the building, and use of appropriate materials if possible.

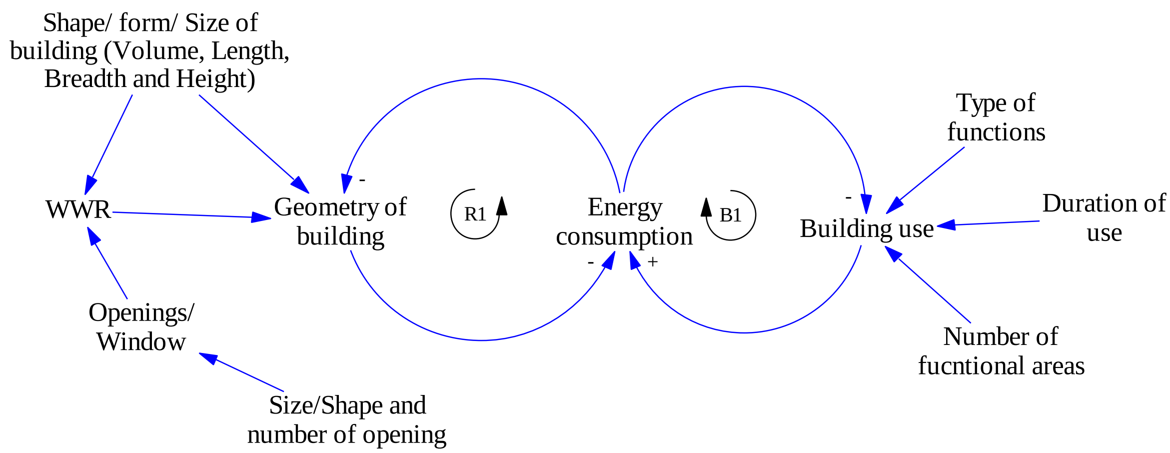

Figure 6.2 SD model for energy consumption based on use- and geometry of buildings

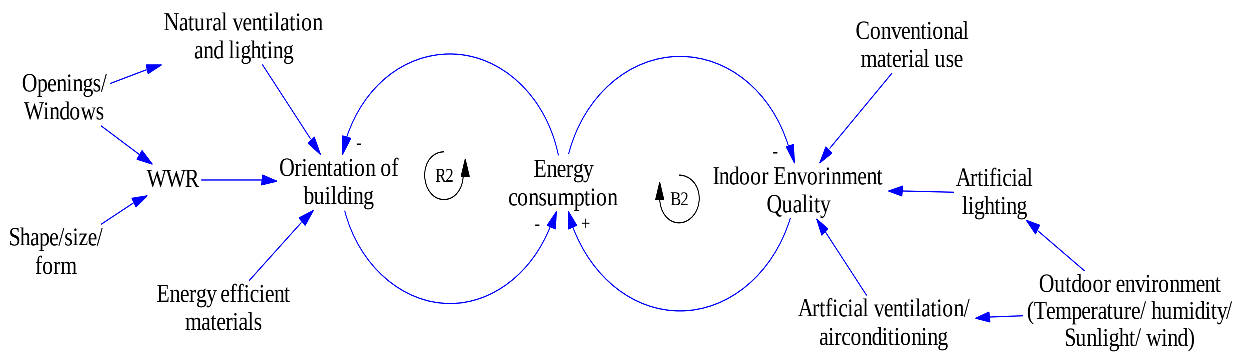

Figure 6.3 SD model for energy consumption based on IEQ and orientation of the building

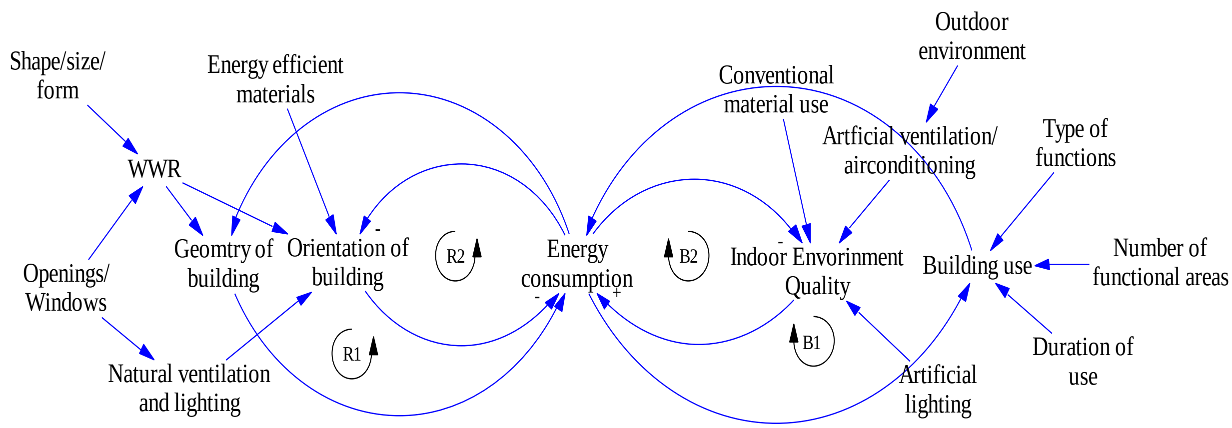

Figure 6.4 Integrated SD model for energy consumption based on building use, IEQ and geometry- and orientation of the building

6.4 Causal feedback relations within the SD model for IEQ

As discussed in the previous section, IEQ is an important parameter for sustainable buildings at universities of South Africa. It essentially influences the performance and efficiency of occupants of the buildings as well as impacts the energy consumption in the buildings. In the previous section (6.3) the linkage between IEQ and energy consumption was established. However, in this section, a conceptual SD model – based on the causal feedback relations among influential variables – has been developed to attain appropriate IEQ in buildings. In Figure 6.5 the causal feedback relations among influential variables are demonstrated in the conceptual SD model. As observed from the figure, outdoor environment if not soothing – influenced by high temperature, humidity, poor ventilation, and poor lighting – reduces the level of IEQ through disrupting feedback mechanism B3. Furthermore, conventional materials used in the buildings (if not congenital) exacerbate the poor conditions of illumination, humidity and temperature and influence IEQ negatively through disrupting feedback mechanism B4. On the other hand, air-conditioning/artificial ventilation/artificial lighting enhances IEQ in buildings through reinforcing feedback mechanism R3, although it impacts energy consumption (c.f. section 6.3). Moreover, appropriate orientation – which can enable natural ventilation and lighting – enhances IEQ in buildings through feedback mechanism R4. Besides, appropriate materials – by use of advanced materials –develop a reinforcing mechanism with IEQ in terms of maintaining temperature, humidity and adequate lighting in the buildings (R5), which enhances the indoor environment. Thus, while IEQ of buildings is adversely affected by mechanisms B1 and B2 because of poor outdoor environment and use of inappropriate materials respectively – thus reinforcing mechanisms R3, R4 and R5 through artificial ventilation, lighting and air-conditioning – appropriate orientation and use of proper materials respectively will balance the negative impacts and in turn will improve IEQ. Outdoor vegetation too can assist in improving IEQ in buildings.

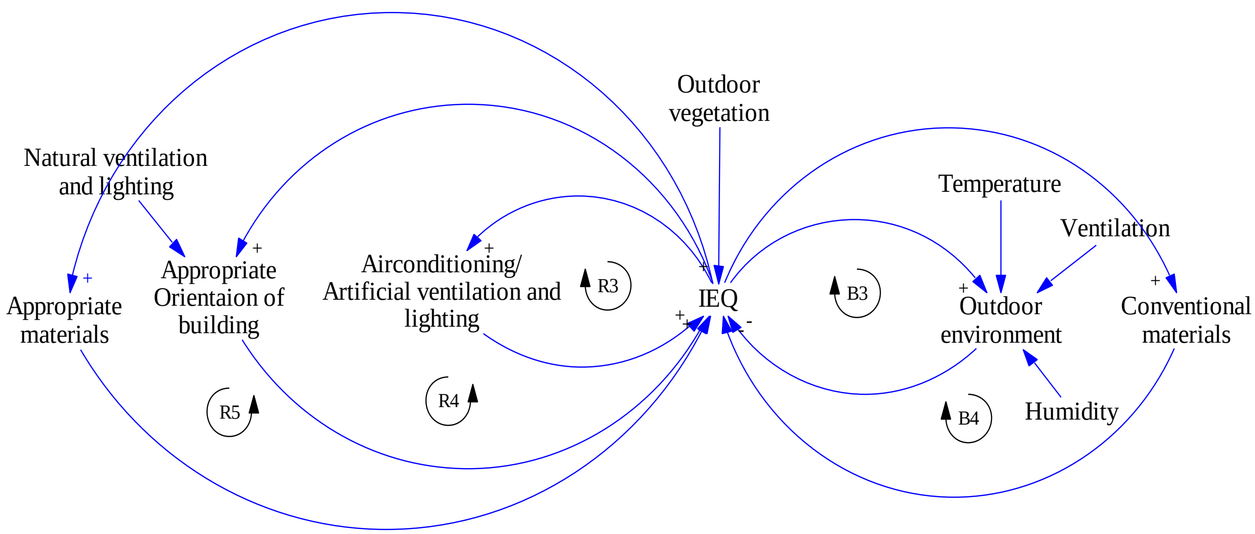

Figure 6.5 SD model for IEQ in the building

6.5 Causal feedback relations within SD model for water usage

Water usage is one of the most important parameters for sustainability of built infrastructure or buildings at universities. Water usage is dependent on water demand for domestic use, by laboratories and for air conditioning and cooling. Therefore, causal relations exist between these parameters and water usage in the buildings. For example, water usage increases with the increase in water demand for domestic consumption, laboratory use, air-conditioning, heating and cooling purposes. As evidenced from the analysis in sections 5.6.1.2 and 5.9 of chapter 5, buildings which use air-conditioning and mechanical ventilation, use more water than buildings without these systems. The causal feedback mechanism is depicted by a disruptive mechanism (B5) that could lead to unsustainability of buildings from a water usage point of view (Figure 6.6). On the other hand, saving of water on account of natural ventilation, systems for greywater recycling and water harvesting in buildings, will not only reduce water usage in buildings through reinforcing feedback mechanism R6, but also supplement the existing water supply and reduce the water demand (Figure 6.6). Consequently, there shall be a reduction in water usage in buildings, contributing to the sustainability of these buildings.

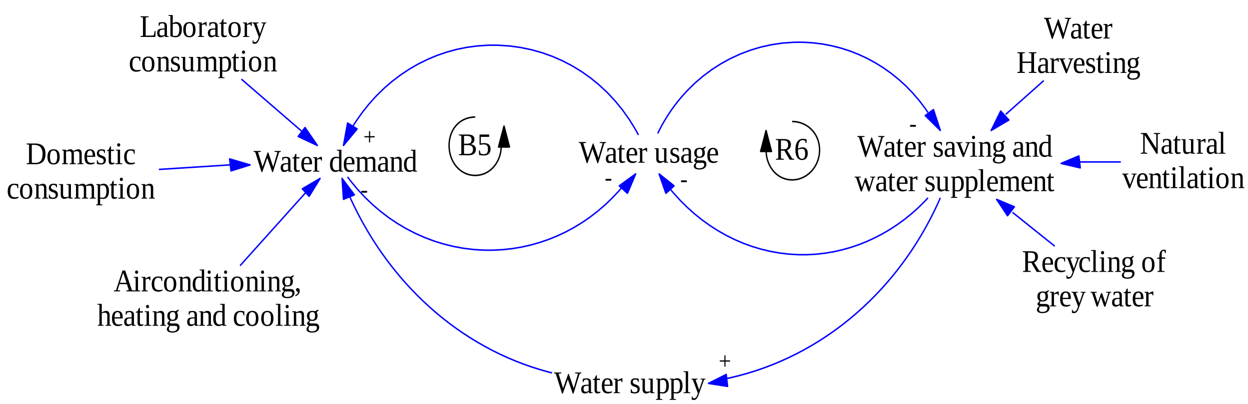

Figure 6.6 SD model for water usage in the building

6.6 Integrated conceptual SD model for sustainable buildings at universities

As mentioned earlier, sustainability of university buildings or built infrastructure is a function of energy efficiency, IEQ and water usage. There is a need for attaining sustainability in all three these parameters in order to develop sustainable built infrastructure of buildings at universities. As evidenced from the various causal feedback relations and conceptual SD models for energy consumption, IEQ and water usage, there exists a linkage among the various variables of these three essential parameters. For example, IEQ influences energy consumption and vice versa. Similarly, water usage and energy consumption are interlinked. Therefore, an integrated conceptual model was developed to observe the mechanism which would lead to sustainable development of buildings at universities. The integrated model and the cause trees for energy efficiency, IEQ, water usage and development of sustainable buildings are presented in Figures 6.7, 6.8, 6.9, 6.10 and 6.11 respectively. As seen from Figure 6.7, sustainable development of buildings can be achieved through reinforcing feedback mechanism R7 involving IEQ, and energy efficiency (Figures 6.7 and 6.8). The mechanism is further strengthened by use of appropriate materials, natural ventilation and lighting (as against artificial ventilation and lighting – if not necessary) through appropriate orientation and building geometry (leading to appropriate WWR) (Figures 6.7 and 6.9). Similarly, reduction in water use and reduction in water demand by supplementing water supply through recycling of greywater and water harvesting in buildings, will reinforce sustainability of buildings through feedback mechanism R8 (Figures 6.7 and 6.10). Outdoor vegetation would further reinforce these two mechanisms. Thus, reinforcing feedback mechanisms R7 and R8 will lead to sustainable development of buildings at universities by use of natural systems, appropriate orientation, and proper geometry (along with window openings and WWR). This leads to natural ventilation and lighting, use of appropriate materials, reduction in water usage and supplementing water supply through recycling of greywater and water harvesting in the buildings (Figure 6.7 and 6.11).

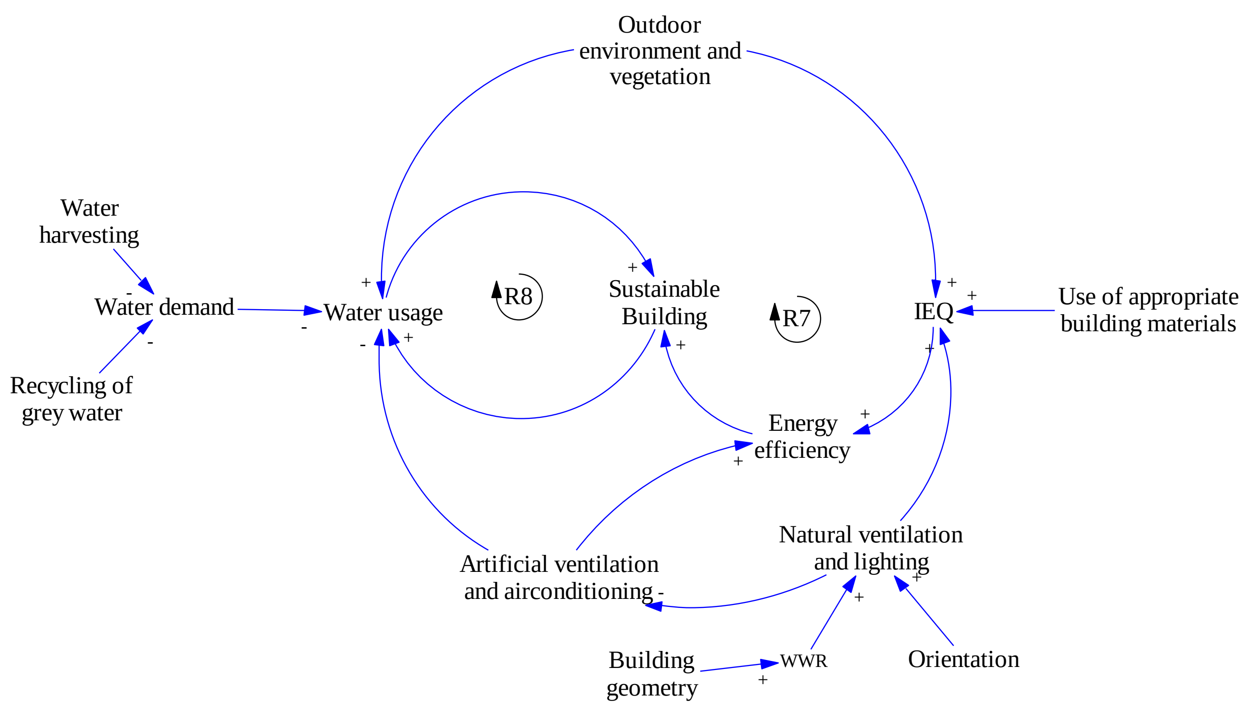

Figure 6.7 Integrated SD model for sustainable buildings at Universities

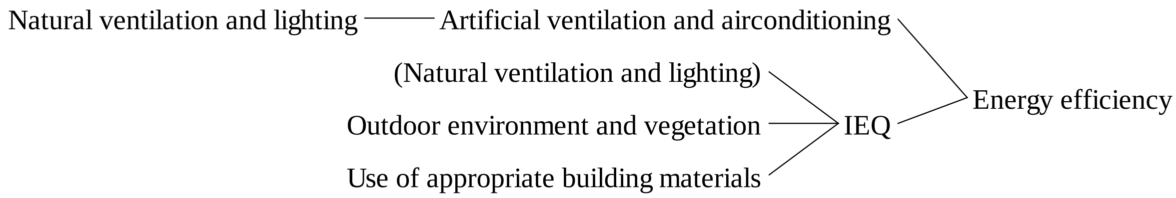

Figure 6.8 Causal tree for IEQ and energy efficiency

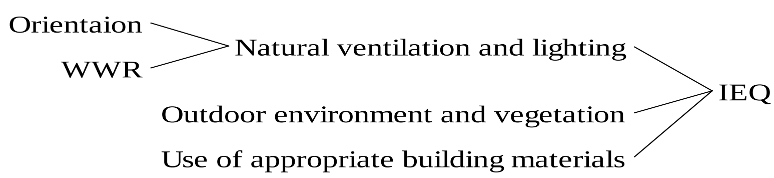

Figure 6.9 Causal tree for IEQ

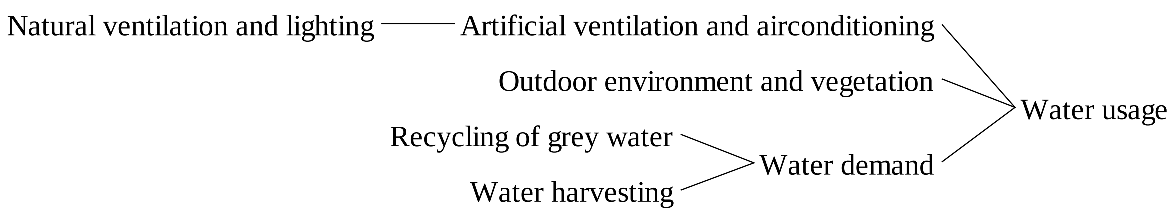

Figure 6.10 Causal tree for water usage

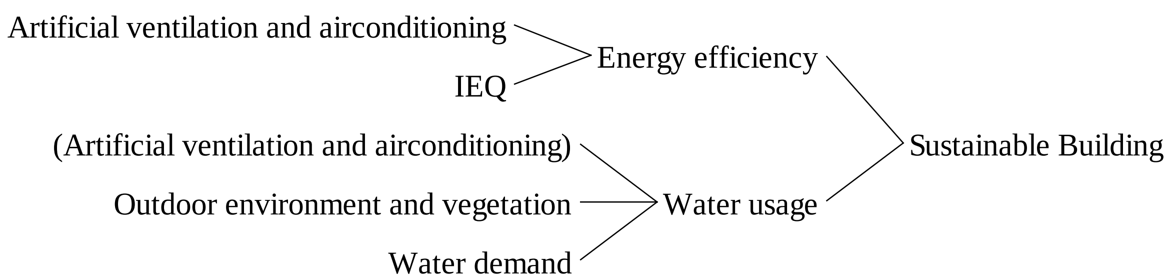

Figure 6.11 Causal tree for sustainable buildings

6.7 Chapter Summary

In this chapter, ASA premised causal feedback mechanisms and conceptual SD modelling were done for each parameter – such as energy consumption, IEQ and water usage – independently. In addition, the three independent conceptual models were combined to develop an integrated conceptual SD model and consequent cause trees (mechanisms) to elicit how energy efficiency, appropriate IEQ and efficient water usage can be achieved in university buildings, which in combination can lead to development of sustainable buildings or green buildings at universities of South Africa. However, as mentioned earlier, the scope of the modelling was limited to conceptualisation and developing causal relations. It is noted that mathematical quantitative SD modelling would have provided more insight to the behaviour and performance of the buildings under the influence of different variables under different scenarios, which – although out of scope of the current investigation – offers opportunities for further research in this area of study. The findings from the ASA premised SD models elicited in this chapter – along with findings in chapter 5 – will form the base for plausible recommendations and design guidelines for development of sustainable buildings/built infrastructure in university buildings of South Africa.

CHAPTER 7: CONCLUSION AND RECOMMENDATIONS

7.1 Introduction

This chapter provides a summary of key findings of the research and conclusions with particular reference to the research problem and research objectives identified in chapter 1. It also states the contribution to knowledge, areas for further research and recommendations.

7.2 General summary of the study

This research is concerned with design of sustainable built infrastructure for South African universities in the context of high performance, especially in the categories of energy efficiency (EE), indoor environmental quality (IEQ), water use efficiency (WUE). This thesis is concerned with the re-engineering of university infrastructure to become forces for good in the city, so that cities can become forces for good for the entire province and country. To provide a solution to this challenge, the thesis explored building performance in the categories of EE, IEQ, and WUE in order to evolve plausible solutions to be incorporated in building design codes for improving and re-engineering the design process for sustainable buildings and infrastructure, which will serve as a force for good for the cities where the universities are located.

Review of literature disclosed an association between building design approach and building performance in relation to EE. This association indicated the necessity of proper envelope design that maximizes passive systems for heating/cooling and lighting and use of high performance building materials in order to reduce the energy demand required by mechanical systems and services. The literature review identified the key performance measures/indicators that affect EE, IEQ and WUE in educational buildings. These included the association of building envelope constituents such as building materials, geometric configuration (building form), orientation, and function with EC, IEQ and WUE (discussed in sections 2.8.3 and 5.3). It was established that a building performance evaluation of these parameters – specifically with regards to how they affect EE, IEQ and WUE in educational buildings – would be necessary to determine the current status of performance of the university buildings. In pursuing the aim and objectives of the research, a multiple case study approach was adopted which permitted various methods of obtaining quantitative data from observation, survey of perception, and retrieval of data from archives. The assessment was conducted on existing academic buildings at South African universities. The physical structures themselves were assessed and the users of these structures were questioned with regards to the performance of these buildings. The case studies in the research presented a reasonable unit for analysis to evaluate building performance with regards to EE, IEQ and WUE. Accordingly, a set of linear regression models was developed for energy consumption and IEQ, based on the geometry and IEQ variables that could assist in design of sustainable buildings at South African campuses. Furthermore, water usage in university buildings was analyzed. Premised on the results and findings of these analyses, causal feedback relations among various variables influencing energy consumption, IEQ and water usage were developed. Consequently, conceptual models – by using the ASA paradigm and SD modelling principles – were developed and presented in chapter 6. However, development of plausible policy interventions and strategic or design guidelines requires comprehensive understanding and application of the crucial findings of the various analyses being conducted and the ASA inspired SD model being developed.

Data and information obtained from the quantitative research instruments were used to test the hypotheses. Accordingly, two hypotheses guided the collection and analyses of data and the interpretation of results related to the research problems and objectives. The thesis has endeavoured to provide analyses of buildings – based on observation of their performance in the categories of EE, IEQ and WUE – and to suggest how plausible solutions can be applied in building codes and design guides.

7.3 Conclusion based on study research questions and research objectives

7.3.1 Conclusion based on study research questions

In summary, the research problem indicated at the onset of this research is also justified through the findings of the study that are presented under the following headings:

Energy Efficiency (EE),

- **Energy Consumption (EC) due to building form:** As indicated in figure 5.8, increase in length or decrease in breadth of buildings led to reduction in energy consumption. However only a limited number of buildings maximized geometric configuration in this way as a strategy to increase WWR and subsequently reduce energy consumption.
- **EC due to use of building materials:** High-performance building materials, especially use of insulation for walls floors and roofs, were not used in a majority (88%) of the assessed buildings, which significantly affected EE or energy savings due to reduction in heat gain/loss. This also affected IEQ because more energy was required to provide adequate IEQ. Only two buildings out of sixteen observed incorporated insulation materials.

- **EC to maintain interior temperature:** As indicated in figure 5.10, buildings with lower interior temperatures were air-conditioned buildings that generated cooler and more comfortable temperatures but consumed more energy.
- **EC due to access to daylight:** Window to wall ratios (WWR) were used to analyze access to daylight. Observations indicated that the majority of buildings had low WWR or inadequate access to daylight. As indicated in figure 5.14, this affected EE because they depended more on artificial lighting ().
- **EC due to orientation:** Although 62% of the assessed buildings had appropriate orientation (North-South), the majority of these buildings had inadequate WWR and thus did not maximize the potentials offered by good orientation.
- **EC due to lighting controls:** None of the universities applied automated controls or occupancy sensors for control of lighting, which affected EE, because there was no control of energy wastage.

Indoor environmental quality (IEQ)

- **Materials**: Literature review and analyses indicated that use of high-performance building materials can improve IEQ of naturally ventilated buildings by reducing heat loss / gain through proper insulation. A majority of assessed buildings did not use high performance building materials such as insulation, which affected the IEQ of these buildings.
- **Daylight:** The analyses indicated that factors such as natural light is important for building users in their perception of comfort. Due low WFR and in some cases poor orientation, a limited number of the assessed buildings optimized access to natural light.
- **Temperature, air quality and ventilation:** The trend line in figure 5.18, 5.19 and 5.20 indicated that increase in satisfaction perception for temperature, air-quality and ventilation were linked with increase in satisfaction perception for comfort. The highest levels of satisfaction from all three perception questionnaires for IEQ were achieved in the air-conditioned buildings. However, due to lack of use of insulation in the majority of buildings, the mechanically heated and cooled buildings required more energy to create the best conditions for temperature, air quality and ventilation for good IEQ.

Water use efficiency (WUE):

- **EE and water consumption:** Figures 6.2 and 6.3 showed a linear correlation between energy consumption and water consumption Air-conditioned buildings used the most amount of water. Given that none of the air-conditioned buildings used insulation to reduce heat gain and loss from building materials, more energy and water were required to compensate for heat loss/gain and maintain adequate temperatures for comfort.

- **Efficiency of domestic water use:** As indicated in section 5.10.1, none of the buildings assessed incorporated water efficient appliances to reduce water consumption levels of the buildings.
- **Use of alternative water sources:** Only one of the sixteen assessed buildings used rainwater harvesting as an alternative source of water. None of the buildings observed incorporated greywater re-use or black water harvesting.

7.3.2 Conclusions based on the study research objectives

For purposes of clarity, the summary of key findings of this research has been linked to the objectives originally being set out to guide the research process. As earlier stated, the aim of this research was to develop design guidelines and performance options in order to improve existing building codes relevant for the planning and design of university buildings. The main focus was on energy use reduction, indoor environment improvement, and appropriate material usage. The achievement of each of the five research objectives is discussed in the following subsections.

7.3.2.1 Objective 1

Based on green building principles, assess the energy efficiency, in existing buildings at South African universities.

Analysis of the data showed that EC was affected by the key performance indicators identified in literature review. For the purpose of comparing sustainability, an existing rated green building (which is considered as a sustainable building) was compared with the university buildings.
The assessment established that only two buildings were designed using green building principles and indicated significantly lower energy consumption levels when compared to the other buildings. The linear regression models showed trend lines that indicated that for the majority of buildings, the poor design due to geometric configuration, WFR, orientation and building materials contributed to increase in EC. The two buildings (11 and 13) that incorporated green building features were observed to be the lowest consumers of energy.

7.3.2.2 Objective 2

Based on green building principles, assess the indoor quality of existing buildings at South African universities.

Review of literature indicated an association between building design approach and building performance in relation to IEQ. As with objective 1, this association indicated that proper building envelope design uses high-performance building materials and maximizes passive systems for heating/cooling and lighting to reduce the energy demand required by mechanical systems and services to provide appropriate IEQ.

Survey questionnaires were utilized as part of the multi case study approach. Analysis of data involved examination of the results of perception for satisfaction of associated parameters of IEQ such as temperature, humidity, ventilation and overall comfort. The highest perceptions for all four parameters were recorded for the air-conditioned buildings. However, due to lack of use of insulation in all the mechanically heated and cooled buildings, more energy was required to create the best conditions for temperature, air quality and ventilation for good IEQ. The analyses also indicated that factors such as natural light were important for building users in their perception of comfort. However, due low WWR and in some cases poor orientation, a limited number of buildings exploited access to natural light.

7.3.2.3 Objective 3

Evaluate the performance of building materials being used in the existing buildings with respect to energy efficiency and indoor quality.

Analyses involved comparison of the only two buildings that applied insulation materials with the other fourteen buildings which did not have insulation materials. As indicated in sections 4.2.3.5 and 4.2.3.6, it was determined that these two buildings showed significant savings in EC due to reduction of heat gain/loss. These two buildings (11 and 13) were the lowest consumers of energy and depended on natural ventilation. The two buildings were scored higher levels of comfort with regards to temperature and illumination. However, because of other factors such as air quality and ventilation, the satisfaction level for comfort was lower. This indicates that natural ventilation alone cannot guarantee good air quality and that ventilation influences the overall comfort level in buildings. However, since factors such as air quality and ventilation are associated with the energy efficiency and indoor quality, the role of building materials could not be ascertained concussively.

7.3.2.4: Objective 4

Establish theoretical models for improving energy efficiency, for use of materials and indoor environmental quality.

To improve energy efficiency, the findings from the conceptual SD models by application of systems analysis are:

- Energy consumption and building use have a causal feedback mechanism. Energy consumption is dependent on use of the buildings, which is dependent on the type of function, number of functional areas and duration of use of the building.
- Appropriate shape, size and form of the building with ample window openings of adequate size leading to suitable window-to-wall ratio (WWR), will enable the buildings to use natural ventilation and natural lighting instead of mechanical ventilation and artificial lighting and will reduce energy consumption.
- Orientation of a building plays a crucial role in providing appropriate IEQ in the buildings and develop causal feedback relations with energy efficiency.
- Use of inappropriate or conventional materials in buildings cause poor conditions of illumination, humidity and temperature and influence IEQ negatively.
- Air-conditioning/artificial ventilation/ artificial lighting enhances IEQ in buildings through a reinforcing feedback mechanism with IEQ, but it increases energy consumption.
- Water usage is influence by demand of water for domestic use, laboratories and air conditioning and cooling.
- Buildings using air-conditioning and mechanical ventilation consume more water than buildings without them.
- Natural ventilation, use of recycled greywater and water harvesting in buildings will reduce the demand of water and consequently water usage in buildings.
- Sustainable development of buildings can be achieved through a reinforcing feedback mechanism involving IEQ and energy efficiency.
- The mechanism will be reinforced by use of appropriate materials, natural ventilation and lighting through appropriate orientation and building geometry.
- Reduction in water use and in water demand by supplementing water supply through recycling of greywater, and water harvesting in buildings will reinforce sustainability of buildings through a positive feedback mechanism.
- Sustainability in buildings can only be achieved if sustainability in energy use, IEQ and water use are attained.

7.3.2.5: Objective 5

Evolve plausible guidelines for designing sustainability compliant built immovable assets at South African universities.

The following design approaches were derived from analyses of the case study and from the conceptual system dynamic model:

Guidelines should stipulate the dependency of EE, IEQ and WUE on type of function, number of functional areas, duration of use of the building, appropriate shape, size/form of building, size of window openings, window-to-wall ratio (WWR), and materials.

The interlinkage of these parameters should be emphasized. The crucial role of building orientation and its effect on other parameters is vital. Guidelines should provide direction for appropriate use of water for domestic use. Additionally, optimization of building form and orientation (vital in maximizing natural ventilation) is crucial in reducing water usage for laboratories and air conditioning. Furthermore, reduction of water usage can be achieved by supplementing the water supply by rainwater- and greywater harvesting.

7.4 General Conclusion

Testing of the hypotheses by analysis of data, investigation of the physical structures and questionnaire surveys, supported all claims of the problem statement and proved the data to have good correlation and statistical significance. The results suggest three primary reasons for the majority of the existing built infrastructure and services at South African universities not being sustainability compliant: Firstly, inefficient use of energy which is affected by geometric configuration, building materials, orientation, inappropriate daylight and ventilation, which also affect IEQ. Secondly, the provision of satisfactory temperatures and indoor air-quality depend on air-conditioning which affect energy consumption. Thirdly, inefficient use of water which is affected by inappropriate appliances and reliance on municipal water supply rather than on other alternative sources of water. Therefore, there is a need to address all three these aspects in order to achieve sustainable development of buildings at universities of South Africa.

Findings suggest that appropriate shape, size and form of the building, with ample window openings of adequate size leading to suitable WWR, will enable the buildings to use natural ventilation and natural lighting instead of mechanical ventilation and artificial lighting that will assist in achieving energy efficiency. Orientation of buildings need to considered as high priority. Use of suitable materials in buildings will assist in attaining proper illumination, humidity, temperature and IEQ without consuming much energy. Air-conditioning/artificial ventilation/ artificial lighting should only supplement the natural systems if necessary. Furthermore, natural ventilation, use of recycled greywater and water harvesting in buildings will reduce the demand of water in buildings and consequently water usage. Thus, it is construed that energy efficiency, appropriate IEQ and efficiency in water usage – which can contribute to the sustainable development of buildings at South African universities – can be attained by less use of air conditioning, mechanical ventilation and illumination and more use of natural means such as orientation, window openings, appropriate geometry of buildings, suitable building materials, and recycling of greywater and water harvesting respectively.

7.5 Contribution to knowledge

The key contributions to the body of knowledge in this research include:

- The research has developed a clear theoretical understanding of performance of educational buildings in the categories of EE, IEQ and WUE.
- The research has developed a methodology to achieve its objective of evaluating the performance of educational buildings in South Africa in the categories of EE, IEQ and WUE.
- The research has identified performance problems due to design flaws within parameters associated with EE, IEQ and WUE
- The research has generated a quantitative assessment of building performance at South African universities and established definite statistical models.
- An integrated approach was used for considering three major aspects of buildings such as energy use, water use and IEQ and developing conceptual models and causal mechanisms based on the ASA paradigm and SD modelling principles that would enable architects, designers and engineers to understand the linkage explicitly and plan, design and construct buildings appropriately.

7.6 Recommendations

Based on the research findings and results of this study, the following recommendations are made as effective means for the sustainable design of university buildings for new construction and renovations.

7.6.1 Recommendations for architects, engineers and construction managers

- Architects, engineers and construction professionals should understand that there are causal relations between building parameters. In design of building envelope for efficiency in EE, IEQ and WUE, scenarios of these causal relations should be explored by incorporating information regarding these causal interlinkages in design models.
- For the purpose of achieving high performance in design of buildings, it is recommended that industry professionals adopt a sustainable approach to design and construction. This refers to a design approach that analyses complete systems – including building form, materials, energy efficiency and IEQ – rather than analysis of individual parts.
- Building information modeling (BIM) should incorporate dynamic modeling of building envelope parameters for best possible considerations for EE, IEQ and WUE.
- Orientation of buildings should be carefully considered before design of the buildings.
- To achieve maximum comfort levels in university buildings, dependency on natural ventilation alone for heating and cooling may not be sufficient; industry professionals should first reduce energy demand for heating, cooling and ventilation by proper building envelope design and then apply mechanical means for heating and cooling to meet comfort needs at the lowest possible energy demand.
- To reduce the demand for water consumption, appropriate envelope design is required that reduces the demand for energy for heating/cooling and ventilation.
- To improve energy efficiency, it is recommended that control measures be applied in university buildings for the automated control of switching from natural heating/cooling/ventilation and lighting to artificial means. A recommendation for the design flow is presented in Figure 7.1

7.6.2 Recommendations for researchers/academics

Further research and evaluation of buildings for performance in EE, IEQ and WUE, especially with regards to how university neighborhoods effect their cities. Universities should adopt use of live-in laboratories for continuous research in building performance. Measuring instruments should be used for continuous assessment of new and existing buildings. In addition, quantitative modeling should be done and simulated scenarios need to be developed to attain deeper knowledge of the problem and find optimal solutions.

7.6.3 Recommendations for facilities managers

Further training is recommended for facilities managers for measuring performance of existing buildings, especially for EE, IEQ and WUE. For instance, facility mangers should monitor EE and WUE in buildings by sub-metering and understand how to apply control measures to limit waste in energy consumption and water consumption. Proper monitoring ensures identification of the type of prescriptive measures that can be applied to renovations or new construction at these universities.

7.6.4 Recommendations for universities / institutes of higher education

In order to contribute towards addressing the problems of climate change and conform with the South African government policy towards protecting the environment, it is recommended that universities in South Africa should adopt the following measures:

- Future construction of educational buildings or renovation of existing buildings should be designed and built for best possible performance in EE, IEQ and WUE.
- A culture of continuous monitoring of energy use, quality indoor environment and water use/waste is important for continuous assessment of performance of building infrastructure on campuses.
- Students and staff should be aware of the importance of green campuses to foster behavior that nurtures the ideals of sustainability of university neighborhoods so that they can become models for positive change in the city and country.

7.6.5 Recommendations for South African Building Standards / Green Building Councils

Measures identified in the findings of this thesis are recommended to improve or enhance existing standards for high performance. There are specific recommendations for EE, IEQ and WUE which include:

- **For EE, IEQ and WUE:** Standards should incorporate the effect of linkages between EE, IEQ and WUE parameters, and causal effects of orientation, building envelope design, geometric configuration, WWR, building materials and inappropriate daylight on energy consumption. Depending on its function, modeling/simulation of the building should determine the best possible outcome for EE, IEQ & WUE.
- **Day light:** Adopt the use of WWR with links to orientation and EE as a means of determining standards for size of fenestrations and windows.
- **Thermal Comfort:** Energy Loads required for air-conditioning should be based on reductions from linkages of Orientation, building volumes and insulation. Where possible buildings should adopt dual means (natural / mechanical) for ventilation with use of automation to switch either way, based on daily / seasonal changes in temperature.
- **Photovoltaics:** Prior to use of photovoltaics it is appropriate to establish amount of energy required based reductions from natural systems and use of insulation. This should be encouraged for new construction and retrofitting.
- **Water harvesting:** WUE standards should mandate new construction and renovations of university buildings to incorporate use of water meters to determine and quantify water recycling measures required to improve water supply at the universities and reduce dependency on municipal supply of water.

The standards organizations/councils should evaluate these recommendations and adopt appropriate strategies such as benchmarking against best practices or consulting experts or professionals in building performance evaluations for the purpose of adoption.

A design flow of recommendations for industry professionals is presented in Figure 7.1

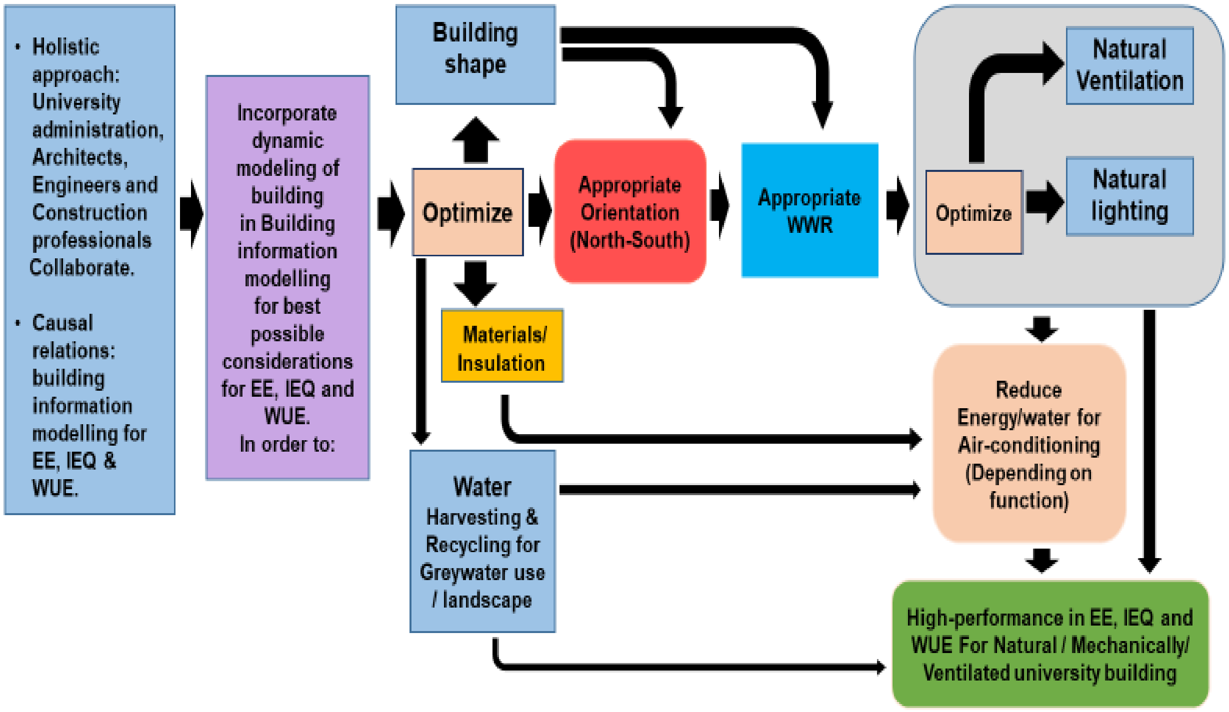

Figure 7.1 Recommendations for design flow for sustainable design of university buildings

7.7 Limitations and further research

The investigation has some limitations. The scope of the study was limited to only sixteen buildings (that include academic and non-academic) at three universities, which does not allow for generalization of findings. The detailed investigation conducted was based on primary survey data from limited sample size and case study analyses, as structured statistical data were not readily available. The measurements of the parameters were also taken for a limited period because of the accessibility of the buildings. Furthermore, the ASA premised SD modelling was limited to development of causal feedback relations among variables and conceptual models. However, it is acknowledged that quantitative SD models could provide opportunities for developing simulated scenarios, based on which optimal scenarios can be developed and appropriate design interventions can be made at the design and construction stage. However, this is considered as a further scope of this investigation. Also, another scope of further research is to extend the study from university buildings to neighborhoods and then to city level. For WUE more investigation can have conducted to determine links between water use and waste water use in the university with the surrounding neighborhoods, and city.

The next section looks at the references used in the research as well as the appendices of documentation used in the conduct of the research.

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Appendix 1

Permission letter to conduct field surveys (CUT)

Central University of Technology, Free State

■ ACADEMIC PLANNING

YEARS AS A UNIVERSITY OF TECHNOLOGY

TO:	**MR STEPHEN EROMOBOR (PERSONNEL NR: 15480)**
COMPILED BY:	ACADEMIC PLANNING
SUBMITTED BY:	DR DARYL BALIA
DATE:	20 FEBRUARY 2014
SUBJECT:	**PERMISSION TO CONDUCT RESEARCH: ACCESS TO CUT BUILDING PLANS**

Dear Mr S Eromobor

This is to confirm that you have been granted permission for research/study and access to data at the CUT in connection with your registered study programme.

The conditions of the permission are:

- The survey will not interrupt any of the official activities at the CUT;
- You will supply us with the copy of your report;
- The cost of all related activities will be covered by yourself;
- Recruitment of participants is the sole responsibility of yourself;
- Voluntary nature of the potential participant's decision to consent to participate should be strictly observed;
- You should not disclose a potential participant's decision to participate or otherwise to any other party;
- Permission does not compel, in any sense, participation of staff members or students in your survey.

DIRECTOR: ACADEMIC PLANNING

DR DM BALIA

Academic Planning Unit here • Private Bag X20539 • Bloemfontein • SOUTH AFRICA • 9300 •
Tel: +27 051 507 0000 • **Fax:** +27 051 507 0000 • **E-mail:** email@cut.ac.za • **Website:** www.cut.ac.za

Appendix 2

Permission letter to conduct field surveys (DUT)

DUT
DURBAN UNIVERSITY OF TECHNOLOGY

Directorate for Research and Postgraduate Support
Durban University of Technology
Tromso Annexe, Steve Biko Campus
P.O. Box 1334, Durban 4000
Tel.: 031-3732576/7
Fax: 031-3732946
E-mail: moyos@dut.ac.za

21st October 2015

Mr Stephen Eromobor
c/o Department of Civil Engineering and Department of Built Environment
Faculty of Engineering and Information Technology
Central University of Technology

Dear Mr Eromobor

PERMISSION TO CONDUCT RESEARCH AT THE DUT

Your email correspondence in respect of the above refers. I am pleased to inform you that the Institutional Research Committee (IRC) has granted permission for you to conduct your research "Sustainable Design of Built Infrastructure and Engineering Services for South African Universities" at the Durban University of Technology.

We would be grateful if a summary of your key research findings can be submitted to the IRC on completion of the project.

Kindest regards.
Yours sincerely

PROF. S. MOYO
DIRECTOR: RESEARCH AND POSTGRADUATE SUPPORT

Appendix 3

Questionnaire: Central University of Technology (CUT)

Private Bag X20539
BLOEMFONTEIN 9300

21 September 2015

Dear Sir / Madam

SUSTAINABLE DESIGN OF BUILT INFRASTRUCTURE AND ENGINEERING SERVICES FOR SOUTH AFRICAN UNIVERSITIES

A survey is a significant part of an on-going research project at the Central University of Technology, Free State (CUT), which is aimed at meeting the requirements for Doctor of Technologiae: Civil Engineering qualification. The research which is supervised by Dr DK Das and Prof FA Emuzeis, aims at the collection of primary data for a systems dynamic model that would provide a way forward in terms of engendering improved indoor Environmental Quality (IEQ) in buildings.

In terms of national relevance, this study is supported by grants from the National Research Foundation (NRF), Department of Higher Education and Training (DHET) and the African Union of Universities (AAU).

Please complete the accompanying questionnaire and return it to Stephen Eromobor, Rm 151 Deparmentt of Built Environment Faculty of Engineering & Information Technology, or by e-mail to seromobor@cut,ac,za

Please note that the confidentiality of your response is assured.

Thank you in anticipation for your response.

Mr Stephen ,Eromobor
DTech Candidate

Dr Dillip Das PhD,
Promoter

Prof Fidelis Emuze PhD,
Co-Promoter

QUESTIONNAIRE

SUSTAINABLE DESIGN OF BUILT INFRASTRUCTURE AND ENGINEERING SERVICES FOR SOUTH AFRICAN UNIVERSITIES

September 2015

Demographics Section

1. Please indicate your gender, by a tick in the appropriate box.

Gender	Tick✓
1. Male	
2. Female	

2. Please indicate your age, by a tick in the appropriate box

Age	Tick✓
1. Below 20	
2. 20-24	
3. 25-39	
4. 40-49	
5. 50-59	
6. 60+	

3. Please indicate your position, by a tick in the appropriate box

Age	Tick✓
1. Student	
2. Technical Assistant	
3. Assistant Lecturer	
4. Junior Lecturer	
5. Lecturer	
6. Senior Lecturer	
7. Associate Professor	
8. Professor	

SECTION 2:

2.0 Staff and Student perception of Indoor Environmental Quality of Lecture rooms of selected buildings at the CUT campus

The following questions are to be answered by the Students and Staff at the Central University of technology (CUT) Campus. Please rate the comfort level in the lecture room due to IEQ. Please indicate your answer, by a tick (✔) in the appropriate box.

LECTURE HALLS

	BHP1	BHP2	BHP ADMIN	ETB	LIBRARY	HOTEL SCHOOL
2.1 Indicate for the level of satisfaction for temperature (During Summer) (1-5), very unsatisfied to very satisfied.	1□2□3□ 4□5□	1□2□3□ 4□5□	1□2□3□ 4□5□	1□2□3□ 4□5□	1□2□3□ 4□5□	1□2□3□ 4□5□
2.2 Indicate for the level of stuffiness of the air (1-5) very unsatisfied to very satisfied.	1□2□3□ 4□5□	1□2□3□ 4□5□	1□2□3□ 4□5□	1□2□3□ 4□5□	1□2□3□ 4□5□	1□2□3□ 4□5□
2.3 Indicate level of unpleasant odours in the air (1-5) 1: very unsatisfied to very satisfied.	1□2□3□ 4□5□	1□2□3□ 4□5□	1□2□3□ 4□5□	1□2□3□ 4□5□	1□2□3□ 4□5□	1□2□3□ 4□5□
2.4 Indicate your perception of ventilation levels of the room (1-5) very unsatisfied to very satisfied.	1□2□3□ 4□5□	1□2□3□ 4□5□	1□2□3□ 4□5□	1□2□3□ 4□5□	1□2□3□ 4□5□	1□2□3□ 4□5□
2.5 Indicate your perception of the lighting conditions of the lecture room (1-5), very unsatisfied to very satisfied.	1□2□3□ 4□5□	1□2□3□ 4□5□	1□2□3□ 4□5□	1□2□3□ 4□5□	1□2□3□ 4□5□	1□2□3□ 4□5□
2.6 Indicate the level of comfort in the room (1-5) very unsatisfied to very satisfied.	1□2□3□ 4□5□	1□2□3□ 4□5□	1□2□3□ 4□5□	1□2□3□ 4□5□	1□2□3□ 4□5□	1□2□3□ 4□5□

3.0 Staff perception of Indoor Environmental Quality at offices in selected buildings at the CUT campus

The following questions are to be answered by the Staff at the Central University of technology (CUT) Campus. Please rate the comfort level in the offices due to IEQ, the rating is a scale of 1-5, please indicate your answer, by a tick in the appropriate box

OFFICES/ NON ACADEMIC AREAS

	BHP1	BHP2	BHP ADMIN	ETB	LIBRARY	HOTEL SCHOOL
3.1 Indicate the level of satisfaction in your office for temperature (During Summer) (1-5), very unsatisfied to very satisfied	1□2□3□ 4□5□	1□2□3□ 4□5□	1□2□3□ 4□5□	1□2□3□ 4□5□	1□2□3□ 4□5□	1□2□3□ 4□5□
3.2 Indicate the level of stuffiness of the air within your office (1-5) very from unsatisfied to very satisfied	1□2□3□ 4□5□	1□2□3□ 4□5□	1□2□3□ 4□5□	1□2□3□ 4□5□	1□2□3□ 4□5□	1□2□3□ 4□5□
2.2 Indicate level of unpleasant odours in the air (1-5) very unsatisfied to very satisfied.	1□2□3□ 4□5□	1□2□3□ 4□5□	1□2□3□ 4□5□	1□2□3□ 4□5□	1□2□3□ 4□5□	1□2□3□ 4□5□
3.3 Indicate your perception of ventilation levels of the room (1-5) very unsatisfied to very satisfied.	1□2□3□ 4□5□	1□2□3□ 4□5□	1□2□3□ 4□5□	1□2□3□ 4□5□	1□2□3□ 4□5□	1□2□3□ 4□5□
3.4 Indicate your perception of the lighting conditions of the lecture room (1-5), very unsatisfied to very satisfied.	1□2□3□ 4□5□	1□2□3□ 4□5□	1□2□3□ 4□5□	1□2□3□ 4□5□	1□2□3□ 4□5□	1□2□3□ 4□5□
3.5 Indicate the level of comfort in the room. (1-5) very unsatisfied to very satisfied.	1□2□3□ 4□5□	1□2□3□ 4□5□	1□2□3□ 4□5□	1□2□3□4 □5□	1□2□3□ 4□5□	1□2□3□ 4□5□

4.0 Student and Staff perception of Indoor Environmental Quality at Laboratories in selected buildings at the TUT campus

The following questions are to be answered by the Students and Staff at the Central University of technology (CUT) Campus. Please rate the comfort level in the laboratories due to Indoor Environmental Quality (IEQ). The rating is a scale of 1-5, please indicates your answer, by a tick in the appropriate box.

LABORATORIES / COMPUTER LABS

	BHP1	BHP2	BHP ADMIN	ETB	LIBRARY	HOTEL SCHOOL
4.1 Indicate for the level of satisfaction for temperature (During Summer) (1-5), very unsatisfied to very satisfied	1□2□3□ 4□5□	1□2□3□ 4□5□	1□2□3□ 4□5□	1□2□3□ 4□5□	1□2□3□ 4□5□	1□2□3□ 4□5□
4.2 Indicate the level of stuffiness of the air (1-5) very unsatisfied to very satisfied.	1□2□3□ 4□5□	1□2□3□ 4□5□	1□2□3□ 4□5□	1□2□3□ 4□5□	1□2□3□ 4□5□	1□2□3□ 4□5□
4.3 Indicate level of unpleasant odours in the air (1-5), very unsatisfied to very satisfied.	1□2□3□ 4□5□	1□2□3□ 4□5□	1□2□3□ 4□5□	1□2□3□ 4□5□	1□2□3□ 4□5□	1□2□3□ 4□5□
4.4 Indicate your perception of ventilation levels of the room (1-5), very unsatisfied to very satisfied.	1□2□3□ 4□5□	1□2□3□ 4□5□	1□2□3□ 4□5□	1□2□3□ 4□5□	1□2□3□ 4□5□	1□2□3□ 4□5□
4.5 Indicate your perception of the lighting conditions of the lecture room (1-5), very unsatisfied to very satisfied.	1□2□3□ 4□5□	1□2□3□ 4□5□	1□2□3□ 4□5□	1□2□3□ 4□5□	1□2□3□ 4□5□	1□2□3□ 4□5□
4.6 Indicate the level of comfort in the room. (1-5) very unsatisfied to very satisfied.	1□2□3□ 4□5□	1□2□3□ 4□5□	1□2□3□ 4□5□	1□2□3□ 4□5□	1□2□3□ 4□5□	1□2□3□ 4□5□

Thank you for your participation in this survey.

Appendix 4

Private Bag X20539
BLOEMFONTEIN 9300

21 November 2015

Dear Sir / Madam

SUSTAINABLE DESIGN OF BUILT INFRASTRUCTURE AND ENGINEERING SERVICES FOR SOUTH AFRICAN UNIVERSITIES

A survey is a significant part of an ongoing research project at the Central University of Technology, Free State (CUT), which is aimed at meeting the requirements for Doctor of Technologiae: Civil Engineering qualification. The research, which is supervised by Dr DK Das and Prof FA Emuzeis, aims at the collection of primary data for a systems dynamic model that would provide a way forward in terms of engendering improved indoor Environmental Quality (IEQ) in buildings.

In terms of national relevance, this study is supported by grants from the National Research Foundation (NRF), Department of Higher Education and Training (DHET) and the African Union of Universities (AAU).

Please complete the accompanying questionnaire and return it to Stephen Eromobor, Rm 151 Deparment of Built Environment Faculty of Engineering & Information Technology, or by e-mailing to seromobor@cut,ac,za

Please note that the confidentiality of your response is assured.

Thank you in anticipation for your response.

Mr Stephen ,Eromobor
DTech Candidate

Dr Dillip Das PhD,
Promoter

Prof Fidelis Emuze PhD,
Co-Promote

QUESTIONNAIRE

SUSTAINABLE DESIGN OF BUILT INFRASTRUCTURE AND ENGINEERING SERVICES FOR SOUTH AFRICAN UNIVERSITIES

November 2015

Demographics Section

1. Please indicate your gender, by a tick in the appropriate box.

Gender	Tick✓
3. Male	
4. Female	

2. Please indicate your age, by a tick in the appropriate box

Age	Tick✓
7. Below 20	
8. 20-24	
9. 25-39	
10. 40-49	
11. 50-59	
12. 60+	

3. Please indicate your position, by a tick in the appropriate box

Age	Tick✓
9. Student	
10. Technical Assistant	
11. Assistant Lecturer	
12. Junior Lecturer	
13. Lecturer	
14. Senior Lecturer	
15. Associate Professor	
16. Professor	

SECTION 2
2.0: Staff and Student perception of Indoor Environmental Quality of Lecture rooms of selected buildings at the DUT campus

The following questions are to be answered by the Students and Staff at the Durban University of Technology (DUT) Campus. Please rate the comfort level in the lecture room due to IEQ. Please indicate your answer, by a tick in the appropriate box.

LECTURE HALLS

	S 3	S 8	BLOCK D	BLOCK E	BLOCK G	BLOCK J
2.1 Indicate for the level of satisfaction for temperature (During Summer) (1-5), very unsatisfied to very satisfied	1☐2☐3☐ 4☐5☐	1☐2☐3☐ 4☐5☐	1☐2☐3☐ 4☐5☐	1☐2☐3☐ 4☐5☐	1☐2☐3☐ 4☐5☐	1☐2☐3☐ 4☐5☐
2.2 Indicate for the level of stuffiness of the air (1-5), very from unsatisfied to very satisfied	1☐2☐3☐ 4☐5☐	1☐2☐3☐ 4☐5☐	1☐2☐3☐ 4☐5☐	1☐2☐3☐ 4☐5☐	1☐2☐3☐ 4☐5☐	1☐2☐3☐ 4☐5☐
2.3 Indicate level of unpleasant odours in the air (1-5) 1: very unsatisfied to very satisfied	1☐2☐3☐ 4☐5☐	1☐2☐3☐ 4☐5☐	1☐2☐3☐ 4☐5☐	1☐2☐3☐ 4☐5☐	1☐2☐3☐ 4☐5☐	1☐2☐3☐ 4☐5☐
2.4 Indicate your perception of ventilation levels of the room (1-5), very unsatisfied to very satisfied.	1☐2☐3☐ 4☐5☐	1☐2☐3☐ 4☐5☐	1☐2☐3☐ 4☐5☐	1☐2☐3☐ 4☐5☐	1☐2☐3☐ 4☐5☐	1☐2☐3☐ 4☐5☐
2.5 Indicate your perception of the lighting conditions of the lecture room (1-5), very unsatisfied to very satisfied.	1☐2☐3☐ 4☐5☐	1☐2☐3☐ 4☐5☐	1☐2☐3☐ 4☐5☐	1☐2☐3☐ 4☐5☐	1☐2☐3☐ 4☐5☐	1☐2☐3☐ 4☐5☐
2.6 Indicate the level of comfort in the room (1-5) 1 being very unsatisfied and 5 very satisfied	1☐2☐3☐ 4☐5☐	1☐2☐3☐ 4☐5☐	1☐2☐3☐ 4☐5☐	1☐2☐3☐ 4☐5☐	1☐2☐3☐ 4☐5☐	1☐2☐3☐ 4☐5☐

3.0: Staff perception of Indoor Environmental Quality at offices in selected buildings at the DUT campus

The following questions are to be answered by the Staff at the Durban University of Technology (DUT) Campus. Please rate the comfort level in the offices due to IEQ, the rating is a scale of 1-5, please indicate your answer, by a tick in the appropriate box

OFFICES/ NON ACADEMIC AREAS

	S 3	S 8	BLOCK D	BLOCK E	BLOCK G	BLOCK J
3.1 Indicate the level of satisfaction in your office for temperature (During Summer) (1-5), very unsatisfied to very satisfied	1□2□3□ 4□5□	1□2□3□ 4□5□	1□2□3□ 4□5□	1□2□3□ 4□5□	1□2□3□ 4□5□	1□2□3□ 4□5□
3.2 Indicate the level of stuffiness of the air within your office (1-5), very from unsatisfied to very satisfied	1□2□3□ 4□5□	1□2□3□ 4□5□	1□2□3□ 4□5□	1□2□3□ 4□5□	1□2□3□ 4□5□	1□2□3□ 4□5□
2.3 Indicate level of unpleasant odours in the air (1-5) very unsatisfied to very satisfied.	1□2□3□ 4□5□	1□2□3□ 4□5□	1□2□3□ 4□5□	1□2□3□ 4□5□	1□2□3□ 4□5□	1□2□3□ 4□5□
3.3 Indicate your perception of ventilation levels of the room (1-5), very unsatisfied to very satisfied.	1□2□3□ 4□5□	1□2□3□ 4□5□	1□2□3□ 4□5□	1□2□3□ 4□5□	1□2□3□ 4□5□	1□2□3□ 4□5□
3.4 2.5 Indicate your perception of the lighting conditions of the room (1-5), very unsatisfied to very satisfied.	1□2□3□ 4□5□	1□2□3□ 4□5□	1□2□3□ 4□5□	1□2□3□ 4□5□	1□2□3□ 4□5□	1□2□3□ 4□5□
3.5 2.7 Indicate the level of comfort in the room (1-5), very unsatisfied to very satisfied.	1□2□3□ 4□5□	1□2□3□ 4□5□	1□2□3□ 4□5□	1□2□3□ 4□5□	1□2□3□ 4□5□	1□2□3□ 4□5□

4.0: Student and Staff perception of Indoor Environmental Quality at Laboratories in selected buildings at the DUT campus

The following questions are to be answered by the Students and Staff at the Durban University of Technology (DUT) Campus. Please rate the comfort level in the laboratories due to Indoor Environmental Quality (IEQ). The rating is a scale of 1-5, please indicates your answer, by a tick in the appropriate box.

LABORATORIES / COMPUTER LABS

	S 3	S 8	BLOCK D	BLOCK E	BLOCK G	BLOCK J
4.1 Indicate the level of satisfaction in your venue for temperature (During Summer) (1-5), very unsatisfied to very satisfied	1□2□3□ 4□5□	1□2□3□ 4□5□	1□2□3□ 4□5□	1□2□3□ 4□5□	1□2□3□ 4□5□	1□2□3□ 4□5□
4.2 Indicate the level of stuffiness of the air within your venue (1-5), very unsatisfied to very satisfied.	1□2□3□ 4□5□	1□2□3□ 4□5□	1□2□3□ 4□5□	1□2□3□ 4□5□	1□2□3□ 4□5□	1□2□3□ 4□5□
4.3 Indicate level of unpleasant odours in the air (1-5) very unsatisfied to very satisfied.	1□2□3□ 4□5□	1□2□3□ 4□5□	1□2□3□ 4□5□	1□2□3□ 4□5□	1□2□3□ 4□5□	1□2□3□ 4□5□
4.4 Indicate your perception of ventilation levels of the venue (1-5), very unsatisfied to very satisfied.	1□2□3□ 4□5□	1□2□3□ 4□5□	1□2□3□ 4□5□	1□2□3□ 4□5□	1□2□3□ 4□5□	1□2□3□ 4□5□
4.5 Indicate your perception of the lighting conditions of the venue (1-5), very unsatisfied to very satisfied.	1□2□3□ 4□5□	1□2□3□ 4□5□	1□2□3□ 4□5□	1□2□3□ 4□5□	1□2□3□ 4□5□	1□2□3□ 4□5□
4.6 Indicate the level of comfort in the room. (1-5) very unsatisfied to very satisfied	1□2□3□ 4□5□	1□2□3□ 4□5□	1□2□3□ 4□5□	1□2□3□ 4□5□	1□2□3□ 4□5□	1□2□3□ 4□5□

Thank you for your participation in this survey.

Appendix 5

Central University of Technology, Free State

Private Bag X20539
BLOEMFONTEIN 9300

21 September 2015

Dear Sir / Madam

SUSTAINABLE DESIGN OF BUILT INFRASTRUCTURE AND ENGINEERING SERVICES FOR SOUTH AFRICAN UNIVERSITIES

A survey is a significant part of an ongoing research project at the Central University of Technology, Free State (CUT), which is aimed at meeting the requirements for Doctor of Technologiae: Civil Engineering qualification. The research which is supervised by Dr DK Das and Prof FA Emuzeis, aims at the collection of primary data for a system dynamic model that would provide a way forward in terms of engendering improved indoor Environmental Quality (IEQ) in buildings.

In terms of national relevance, this study is supported by grants from the National Research Foundation (NRF), Department of Higher Education and Training (DHET) and the African Union of Universities (AAU).

Please complete the accompanying questionnaire and return it to Stephen Eromobor, Rm 151 Deparmentt of Built Environment Faculty of Engineering & Information Technology, or by e-mailing to seromobor@cut,ac,za

Please note that the confidentiality of your response is assured.

Thank you in anticipation for your response.

Mr Stephen ,Eromobor
DTech Candidate

Dr Dillip Das PhD,
Promoter

Prof Fidelis Emuze PhD,
Co-Promoter

QUESTIONNAIRE

SUSTAINABLE DESIGN OF BUILT INFRASTRUCTURE AND ENGINEERING SERVICES FOR SOUTH AFRICAN UNIVERSITIES

September 2015

Demographics Section

1. Please indicate your gender by a tick in the appropriate box.

Gender	Tick✓
5. Male	
6. Female	

2. Please indicate your age by a tick in the appropriate box

Age	Tick✓
13. Below 20	
14. 20-24	
15. 25-39	
16. 40-49	
17. 50-59	
18. 60+	

3. Please indicate your position by a tick in the appropriate box

Age	Tick✓
17. Student	
18. Technical Assistant	
19. Assistant Lecturer	
20. Junior Lecturer	
21. Lecturer	
22. Senior Lecturer	
23. Associate Professor	
24. Professor	

SECTION 2
Staff and student perception of indoor environmental quality of Lecture rooms of selected buildings at the TUT campus

The following questions are to be answered by the Students and Staff at the Tshwane University of Technology (TUT) Campus.
Please rate the comfort level in the lecture room due to IEQ. Please indicate your answer by a tick in the appropriate box.

LECTURE HALLS

	BD 2A	BD 3	BD11	BD13
2.1 Indicate for the level of satisfaction for temperature (During Summer) (1-5) very unsatisfied to very satisfied.	1□2□3□ 4□5□	1□2□3□ 4□5□	1□2□3□ 4□5□	1□2□3□ 4□5□
2.4 Indicate for the level of stuffiness of the air (1-5) very unsatisfied to very satisfied.	1□2□3□ 4□5□	1□2□3□ 4□5□	1□2□3□ 4□5□	1□2□3□ 4□5□
2.5 Indicate level of unpleasant odours in the air (1-5) very unsatisfied to very satisfied.	1□2□3□ 4□5□	1□2□3□ 4□5□	1□2□3□ 4□5□	1□2□3□ 4□5□
2.6 Indicate your perception of ventilation levels of the room (1-5) very unsatisfied to very satisfied.	1□2□3□ 4□5□	1□2□3□ 4□5□	1□2□3□ 4□5□	1□2□3□ 4□5□
2.7 Indicate your perception of the lighting conditions of the lecture room (1-5), very unsatisfied to very satisfied.	1□2□3□ 4□5□	1□2□3□ 4□5□	1□2□3□ 4□5□	1□2□3□ 4□5□
2.8 Indicate the level of comfort in the room (1-5) very unsatisfied to very satisfied.	1□2□3□ 4□5□	1□2□3□ 4□5□	1□2□3□ 4□5□	1□2□3□ 4□5□

3.0: Staff perception of indoor environmental quality at offices in selected buildings at the TUT campus

The following questions are to be answered by the Staff at the Tshwane University of Technology (TUT) Campus. Please rate the comfort level in the offices due to IEQ, the rating is a scale of 1-5. Please indicate your answer by a tick in the appropriate box.

OFFICES/ NON ACADEMIC AREAS

	BD 2A	**BD 3**	**BD11**	**BD13**
3.1 Indicate the level of satisfaction in your office for temperature (During Summer) (1-5), very unsatisfied to very satisfied	1□2□3□ 4□5□	1□2□3□ 4□5□	1□2□3□ 4□5□	1□2□3□ 4□5□
3.2 Indicate the level of stuffiness of the air within your office (1-5) very from unsatisfied to very satisfied	1□2□3□ 4□5□	1□2□3□ 4□5□	1□2□3□ 4□5□	1□2□3□ 4□5□
3.3 Indicate level of unpleasant odours in the air (1-5) very unsatisfied to very satisfied.	1□2□3□ 4□5□	1□2□3□ 4□5□	1□2□3□ 4□5□	1□2□3□4 □5□
3.4 2.4 Indicate your perception of ventilation levels of the room (1-5) very unsatisfied to very satisfied.	1□2□3□ 4□5□	1□2□3□ 4□5□	1□2□3□ 4□5□	1□2□3□ 4□5□
3.5 Indicate your perception of the lighting conditions in your office (1-5). very unsatisfied to very satisfied.	1□2□3□ 4□5□	1□2□3□ 4□5□	1□2□3□ 4□5□	1□2□3□ 4□5□
3.6 Indicate the level of comfort in the room (1-5) very unsatisfied to very satisfied.	1□2□3□ 4□5□	1□2□3□ 4□5□	1□2□3□ 4□5□	1□2□3□4 □5□

4.0 Staff perception of indoor environmental quality at laboratories in selected buildings at the TUT campus

The following questions are to be answered by the Students and Staff at the Tshwane University of Technology (TUT) Campus. Please rate the comfort level in the laboratories due to Indoor Environmental Quality (IEQ). The rating is a scale of 1-5. Please indicate your answer by a tick in the appropriate box.

LABORATORIES / COMPUTER LABS

	BD 2A	BD 3	BD11	BD13
4.1 Indicate the level of satisfaction in your venue for temperature (During Summer) (1-5), very unsatisfied to very satisfied	1□2□3□ 4□5□	1□2□3□ 4□5□	1□2□3□ 4□5□	1□2□3□ 4□5□
4.2 Indicate the level of stuffiness of the air within your venue (1-5) very from unsatisfied to very satisfied	1□2□3□ 4□5□	1□2□3□ 4□5□	1□2□3□ 4□5□	1□2□3□ 4□5□
4.3 Indicate level of unpleasant odours in the air (1-5) very unsatisfied to very satisfied.	1□2□3□ 4□5□	1□2□3□ 4□5□	1□2□3□ 4□5□	1□2□3□ 4□5□
4.4 Indicate your perception of ventilation levels of the venue (1-5) very unsatisfied to very satisfied.	1□2□3□ 4□5□	1□2□3□ 4□5□	1□2□3□ 4□5□	1□2□3□ 4□5□
4.5 Indicate your perception of the lighting conditions of the venue (1-5), very unsatisfied to very satisfied.	1□2□3□ 4□5□	1□2□3□ 4□5□	1□2□3□ 4□5□	1□2□3□ 4□5□
4.6 Indicate the level of comfort in the room for all parameters (1-5) very unsatisfied to very satisfied.	1□2□3□ 4□5□	1□2□3□ 4□5□	1□2□3□ 4□5□	1□2□3□ 4□5□

Thank you for your participation in this survey.

Appendix 6

Responses to the questionnaire

Scale 1-5:

1. **Very unsatisfied**
2. **Unsatisfied**
3. **Neutral (unsure)**
4. **Satisfied**
5. **Very satisfied**

Table 6.1: Perception of comfort:

Perception of comfort from very unsatisfied to very satisfied to very satisfied (1-5)					
Building	Perception (%)				
	1	2	3	4	5
BHP1 (NM)	12	16	38	18	17
BHP2 (M)	10	15	43	17	15
BHP Amin (M)	11	14	37	14	24
ETB (M)	2	10	40	28	20
Library (M)	7	14	28	33	17
Hotel school (NM)	5	13	47	17	18
S3 (NM)	6	8	51	23	12
S8 (NM)	4	11	45	29	11
Block D (NM)	7	8	45	23	17
Block E (NM)	9	10	46	25	10
Bloch G LIB(M)	7	7	48	23	15
Block J (NM)	9	17	44	18	12
Building 2A (NM)	12	23	42	12	11
Building 3 (M)	11	20	34	12	23
Building 11 (N)	10	15	27	28	20
Building 13(N)	13	17	24	26	20
Averages	8	14	40	22	16

Responses to questionnaires

Table 6.2: Perception of temperature:

Perception of temperature from very unsatisfied to very satisfied (1-5)					
Building	Perception (%)				
	1	2	3	4	5
BHP1 (NM)	19	21	26	18	16
BHP2 (M)	20	22	23	20	12
BHP Amin (M)	11	14	37	14	28
ETB (M)	14	10	31	21	24
Library (M)	8	17	29	37	18
Hotel school (NM)	17	11	31	16	25
S3 (NM)	11	21	48	10	10
S8 (NM)	7	17	50	15	11
Block D (NM)	16	19	40	10	15
Block E (NM)	13	19	44	8	15
Bloch G LIB(M)	10	16	46	20	8
Block J (NM)	11	18	46	12	13
Building 2A (NM)	31	24	30	6	9
Building 3 (M)	20	27	38	6	9
Building 11 (N)	10	22	28	16	24
Building 13(N)	11	14	21	25	29
Average	15	19	36	15	16

Responses to questionnaires

Table 6.3: Perception of air quality

Perception of air quality from very unsatisfied to very satisfied (1-5)					
Building	Perception (%)				
	1	2	3	4	5
BHP1 (NM)	16	18	23	23	20
BHP2 (M)	21	24	26	18	11
BHP Amin (M)	6	18	27	28	21
ETB (M)	10	14	30	24	23
Library (M)	16	17	20	22	25
Hotel school (NM)	19	28	24	14	15
S3 (NM)	20	30	32	10	8
S8 (NM)	12	23	41	15	9
Block D (NM)	14	27	40	5	14
Block E (NM)	7	31	46	4	8
Bloch G LIB(M)	4	30	41	14	11
Block J (NM)	4	36	42	6	12
Building 2A (NM)	19	33	31	8	9
Building 3 (M)	20	25	28	6	21
Building 11 (N)	10	17	33	21	18
Building 13(N)	15	15	28	22	20
Average	13.	25	32	14	15

Responses to questionnaires

Table 6.4: Perception of ventilation

Perception of ventilation from very unsatisfied to very satisfied (1-5)					
Building	Perception (%)				
	1	2	3	4	5
BHP1 (NM)	17	17	35	14	17
BHP2 (M)	10	12	34	29	15
BHP Amin (M)	12	8	30	26	24
ETB (M)	7	17	26	30	20
Library (M)	14	14	29	26	17
Hotel school (NM)	15	17	30	20	18
S3 (NM)	11	13	37	27	12
S8 (NM)	12	11	38	27	11
Block D (NM)	4	14	36	29	17
Block E (NM)	8	18	36	28	10
Bloch G LIB(M)	6	14	33	32	15
Block J (NM)	8	16	35	29	12
Building 2A (NM)	4	36	36	13	11
Building 3 (M)	7	22	35	13	23
Building 11 (N)	3	13	35	29	20
Building 13(N)	3	18	40	19	20
Average	8	15	32	23	16

Responses to questionnaires

Table 6.5: Perception of illumination

Perception of lighting from very unsatisfied to very satisfied (1-5)					
Building	Perception (%)				
	1	2	3	4	5
BHP1 (NM)	0	8	28	21	43
BHP2 (M)	0	20	35	20	25
BHP Amin (M)	0	8	28	22	42
ETB (M)	3	10	22	27	38
Library (M)	6	11	28	17	38
Hotel school (NM)	8	15	29	18	30
S3 (NM)	0	14	36	18	32
S8 (NM)	0	10	39	26	25
Block D (NM)	0	25	30	15	30
Block E (NM)	0	31	26	18	25
Bloch G LIB(M)	4	7	34	30	25
Block J (NM)	4	11	25	35	25
Building 2A (NM)	12	14	24	24	26
Building 3 (M)	12	10	23	12	43
Building 11 (N)	0	19	11	20	46
Building 13(N)	0	19	20	22	39
Average	4	14	29	22	32

Responses to questionnaires