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Energy Flow Analysis of an Academic Building

Marthinus Mynhardt Neethling

2011

Departement Meganiese en Megatroniese Ingenieurswese

Department of Mechanical and Mechatronic Engineering

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Energy Flow Analysis of an Academic Building

Marthinus Mynhardt Neethling

Master's project presented in partial fulfilment of the requirements of the degree Master of Engineering at Stellenbosch University

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December 2011

Departement Meganiese en Megatroniese Ingenieurswese

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DECLARATION

I, the undersigned, hereby declare that the work contained in this thesis is my own original work and that I have not previously in its entirety or part submitted it at any university for a degree.

Signature: ....
M.M. Neethling

Date: 20/11/2011

ABSTRACT

Increasing global concerns over the environmental impact of buildings have stimulated the popularity of and need for energy-efficient buildings. This realisation of the benefits that well-designed, so-called ‘green’ and energy-efficient buildings provide, necessitated a standard for measuring such efficacy. Various green building rating tools and national energy-efficient building standards was therefore developed.

This study assesses the annual energy performance of a new academic building at the University of Stellenbosch, Stellenbosch (South Africa), by using both the Green Building Council of South Africa’s Green Star rating system and the SANS 204 national energy-efficiency building codes. The building evaluated will be constructed on the University’s campus, adjacent to the Mechanical Engineering building in the Engineering Complex.

A comparative analysis was done between the actual building and a notional building built to SANS 204 specifications, as prescribed by the GSSA-PEB rating tool. Both the actual and notional building models however incorporated a few deviations from the GSSA-PEB rating tool to more accurately reflect the actual operating conditions of the building and SANS 204 energy-efficient building requirements. A quantitative physical modelling approach through the use of EnergyPlus as the energy- and thermal load simulation engine was furthermore utilised for these building energy simulation models.

The results indicate that the actual building is consuming 16.5% more energy annually than the notional building. A Green Star rating on the first design stage data is therefore not possible, as the GSSA-PEB energy conditional requirement is not met.

The primary causes identified for this large difference in energy consumption are the lighting and the HVAC system. The actual building was found to have a 62.9% higher lighting-power density than the notional building; and the VAV HVAC system of the notional building was found to be significantly more efficient that the fan-coil system of the actual building.

A parametric analysis of the actual building fabric and HVAC- and lighting systems was furthermore done to investigate possible energy-consumption improvement options. These results identified the significant impact that a reduction in lighting density and a more efficient HVAC system can have on the annual energy consumption of the building. A brief financial analysis on these significant energy improvement options also proved it to be a worthwhile investment. Further results showed the positive energy offset that may be accomplished by increasing the thermal mass in the external walls.

On-site renewable energy generation, a reduction in installed lighting capacity; and a more efficient HVAC system are recommended as the first vital steps in reducing the energy consumption of the building; thus enabling it to become eligible for a Green Star SA rating. In light of these recommendations was a solar PV array designed for the new building as the most viable on-site renewable energy generation option to reduce the carbon footprint of the building.

OPSOMMING

Die gewildheid van energie-doeltreffende geboue kan toegeskryf word aan die toenemende globale bewustheid rakende die impak van geboue op die omgewing. As gevolg hiervan het die voordelige eienskappe wat sogenaamde ‘groen’ en energie-doeltreffende geboue inhou, ŉ standaard vir die meet van hierdie geboue genoodsaak. Groen-gebou graderingsmetodes en nasionale standaarde vir gebou energie-doeltreffendheid was dus ontwikkel.

Dié studie maak gebruik van die Green Building Council of South Africa se Green Star graderingssisteem en SANS 204 se nasionale energiestandaarde vir geboue om die jaarlikse energiegebruik van ŉ nuwe akademiese gebou te beoordeel. Die gebou wat geëvalueer is, gaan gebou word op die kampus van die Universiteit van Stellenbosch, Stellenbosch (Suid-Afrika), langs die bestaande Meganiese Ingenieurswese-gebou in die Ingenieurswese geboue kompleks.

ŉ Vergelyking studie op die jaarlikse energie verbruik is gedoen tussen die werklike- en ŉ verwysings gebou, wat “gebou” is volgens SANS 204 standaarde soos voorgeskryf deur die GSSA-PEB graderings instrument. Beide die modelle van die werklike- en verwysingsgebou het ŉ paar afwykings van die GSSA-PEB instrument ingesluit om die werklike bedryfs-kondisies van die gebou en SANS 204 se vereistes meer akkuraat te weerspieël. Dié gebou-energie simulasiemodelle was gemodelleer deur ŉ kwantitatiewe model metode wat gebaseer is op die fisiese eienskappe van die gebou. EnergyPlus was gekies as program vir die simulasie van die gebou-energie en termiese lading.

Die resultate toon dat die werklike gebou jaarliks 16.5% meer energie verbruik as die verwysingsgebou. Volgens die eerste ontwerpstekeninge is ’n Green Star-gradering dus nie moontlik nie aangesien die primêre vereistes vir die GSSA-energie kriteria nie nagekom is nie.

Die primêre oorsake van dié groot verskil in energie-verbruik is die beligtings- en lugversorgingstelsels. Die werklike gebou toon ŉ 62.3% hoër beligtings-energie digtheid as die verwysingsgebou; en daar was gevind dat die VAV lugversorging-stelsel van die verwysingsgebou aansienlik meer doeltreffend is as die waaier-spoel sisteem van die werklike gebou.

ŉ Parametriese studie is verder uitgevoer op die werklike gebou se konstruksie en beligtings- en lugversorgingstelsels om moontlike energie-besparing moontlik-hede te ondersoek. Die resultate toon dat laer vlakke van beligtings-energieverbruik en ŉ meer effektiewe lugversorgingstelsel ŉ baie groot impak op die jaarlikse energieverbruik van die gebou kan bewerkstellig. ŉ Kort finansiële analise het ook getoon dat hierdie groot energie-besparing moontlikhede ŉ goeie belegging sal wees. Verdere resultate toon dat indien die termiese massa van die

eksterne mure verhoog word, die jaarlikse energieverbruik noemenswaardig verlaag kan word.

Om die jaarlikse energieverbruik van die geboue te verlaag en só in aanmerking te kom vir ŉ Green Star SA-gradering, word aanbeveel dat die opwekking van hernubare energie op die terrein; ŉ vermindering in beligtings-energie en ŉ meer effektiewe lugversorgingstelsel prioriteit moet neem. Met inagneming van hierdie aanbevelings was ŉ son-energie PV stelsel ontwerp as ŉ hernubare energie opsie om die koolstofvoetspoor van die nuwe gebou te verminder.

ACKNOWLEDGEMENTS

Firstly, to my wife, your continual love and support cannot be described in mere words.

I would like to express my gratitude to Mr Francois Joubert for his unwavering support and guidance throughout this project.

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NOMENCLATURE

Abbreviations

A/C	Air-conditioning
ANN	Artificial Neural Network
ASHRAE	American Society of Heating Refrigeration and Air-conditioning Engineering
BESTEST	International Energy Agency Building Energy Simulation Test and Diagnostic Method
BLAST	Building Load Analysis and System Thermodynamics
BREEAM	Building Research Establishment Environmental Assessment Method
CASBEE	Comprehensive Assessment System for Building Environmental Efficiency
CBD	Central Business Park
CFD	Computational Fluid Dynamics
COP	Coefficient of Performance
CRSES	Centre of Renewable and Sustainable Energy Studies
CTF	Conduction Transfer Function
DCR	Discount Rate
DHW	Domestic Hot Water
DOE-2	US Department of Energy Building Energy Simulation Program, Version 2
EER	Electrical Efficiency Ratio
EPW	EnergyPlus Weather data
ESKOM	National Utility (Electricity Supply Commission)
GBCSA	Green Building Counsel of South Africa
GFA	Gross Floor Area
GHG	Greenhouse Gas Emissions
GSSA	Green Star South Africa

HVAC	Heating Ventilation and Air-conditioning
IEA	International Energy Agency
IWEC	International Weather for Energy Calculation
LEED	Leadership in Environmental Energy Design
masl	Meters Above Sea Level
MIH	Myriad International Holdings
NCDC	National Climatic Data Centre
NPV	Net Present Value
PEB	Public and Education Building
PMV	Predicted Mean Vote
PPD	Percentage People Dissatisfied
PV	Photovoltaic
SA	South Africa
SABS	South Africa Bureau of Standards
SANS	South African National Standard
U.S.	United States of America
VAV	Variable Air Volume
World GBC	World Green Building Council

Symbols

A	Area
A_n	Glazing element area
C	Thermal capacitance
$C_{A,B,C}$	SANS204 energy constants
c_p	Specific heat capacity
E_a	Annual energy consumption
EI	Energy index
F_a	Façade area
h	Convection heat-transfer coefficient
h_r	Radiation heat-transfer coefficient
k	Thermal conductivity

K	Kelvin
L	Thermal load on body
M	Metabolic rate
m	Mass
Q_{DHW}	Domestic hot water heating energy
Q	Heat energy
$\dot{q}_{cond}$	Conduction heat energy
$\dot{q}_{conv}$	Convection heat energy
$\dot{q}_{lw}$	Long-wave radiation heat energy
$\dot{q}_{sw}$	Short-wave radiation heat energy
P_e	Elevator power rating
R_n	Glazing element thermal resistance
R_{cond}	Conduction thermal resistance
R_{conv}	Convection thermal resistance
R_{rad}	Radiation thermal resistance
R_T	Total thermal resistance
S_n	Glazing element SHGC
SH_n	SANS204 cooling shading multiplier
SC_n	SANS204 heating shading multiplier
t	Operational hours
T_s	Surface temperature
T_∞	Temperature of a moving fluid
T_{sur}	Surrounding environment temperature
UF	Usage factor

Greek Symbols

ε	Surface emissivity
η_{DHW}	Domestic hot water heating efficiency
σ	Stefan-Boltzmann constant
ΔT	Temperature difference

1. INTRODUCTION

1.1. Background

More than 90% of the average person's life is spent in buildings. As a result do building fabric, location and design choices have both direct and indirect influences on an individual's physical and mental health (Evans, 2003). It has, for example been shown that proper lighting; layout and ventilation design in hospital buildings improves the health- and reduces stress and fatigue levels of the staff and patients (Ulrich, et al., 2004). Further studies showed that insufficient exposure to daylight in buildings results in sadness, fatigue and in some severe cases, depression (Evans, 2003). The impact of buildings on mental health can furthermore lead to indirect environmental impacts, because a human's state of mind influences his/her interaction with the environment. A building's ability to provide a healthy and productive indoor environment is therefore crucial in ensuring the wellbeing of its occupants.

The built environment however has one of the largest carbon footprints of any industry and bears a significant environmental impact. (Gunnell, 2009) Buildings are also the largest and fastest-growing contributors to global energy demand, a fact that can be attributed predominantly to population and economic growth. The desire for improved comfort levels as a direct outcome of economic growth furthermore increases the impact of buildings on the demand for energy (Pérez-Lombard, et al., 2009).

Growth in the building sector is predicted to expand by approximately 34% in the next 20 years with an annual average growth rate of 1.5%. The leading cause behind this increase is the rapid growth in economic development of developing countries (IEA, 2006).

Most of the energy currently consumed by the global building sector has largely negative environmental impacts. This is primarily due to a few factors, including:

- Fossil fuel-dominated electricity-generation sector;
- Carbon-intensive processes required to produce the various materials that building is composed of;
- Land use and the impact of buildings on forestry and agriculture; and
- Oil-dominated transportation sector.

Approximately 40% of the total environmental burden of member countries of the European Union, for instance, is attributable to the building sector (Rey, et al., 2007). Carbon dioxide emissions from this sector are furthermore responsible for approximately 20% of the global greenhouse gas emissions (GBCSA, 2008).

The operational energy of a building typically accounts for the most significant portion of the primary energy used during the lifespan of the building. This figure is greatly influenced by building type, climatic region, building fabric performance and the expected lifetime of the building. Scheuer *et al.* (2003) for example, conducted a life-cycle primary energy analysis on a newly-constructed engineering building located on the University of Michigan's campus. The study showed that over a designed life-span of 75 years, the primary energy of the operations phase will amount to 97.7% of the total primary energy consumed. Energy-efficient designs can therefore have a significant impact on the total life-cycle primary energy use and can as a result reduce the carbon footprint of the building. The building sector has furthermore been identified as one of the most cost-effective sectors for reducing energy consumption and its carbon footprint (IEA, 2010).

The concept of green and energy-efficient buildings was subsequently developed to pursue the critical balance between occupant comfort and environmental impact of buildings. This balance in a building from a carbon emissions perspective can be achieved by designing a building envelope that maximises the use of natural resources; uses optimised building mechanical and electrical systems and ensures the creation of a healthy productive indoor environment for its occupants.

The realisation of the benefits that well-designed, so-called 'green' and energy-efficient buildings provide, resulted in the creation of various rating tools for green buildings and national energy-efficient building standards to provide a standard for measuring such efficacy. The primary focus of these tools and standards is to standardise and measure the balance achieved between occupant comfort and the environmental impact of buildings.

These green building rating tools are not directly designed to provide a cost benefit; however, a full cost benefit analysis that assess the direct and indirect benefits of green buildings would in most cases result in a good initial investment (Muldavin, 2010). The attractiveness of these green building investments is furthermore enhanced by considering the total life-cycle impact of buildings, the looming energy and water crisis in South Africa and the imminent carbon tax legislation for buildings.

1.2. New Academic Building

The building evaluated in this study is a new academic building (shown below in Figure 1) that will be constructed at the University of Stellenbosch, Stellenbosch (South Africa), adjacent to the Mechanical Engineering building on the Engineering Campus. Completion of the entire building is scheduled for early 2012.

The University's planning committee has attempted to incorporate various energy-efficiency measures in the initial design of this building. This is partly because it will be the new home of the Centre of Renewable and Sustainable Energy Studies (CRSES), an engineering department that is naturally concerned with the environmental impact of buildings.

Another building design consideration is the desire to be the first academic building in South Africa to be considered for a Green Star SA (GSSA) rating, which is discussed in more detail in Section 2.5 below. This accreditation can serve as both an advertisement and statement to demonstrate the University's commitment to reduce its environmental impact. A detailed building energy-simulation is therefore needed to assess the energy performance of the building by comparing it to national energy-efficient building standards (SABS - SANS 204, 2008).

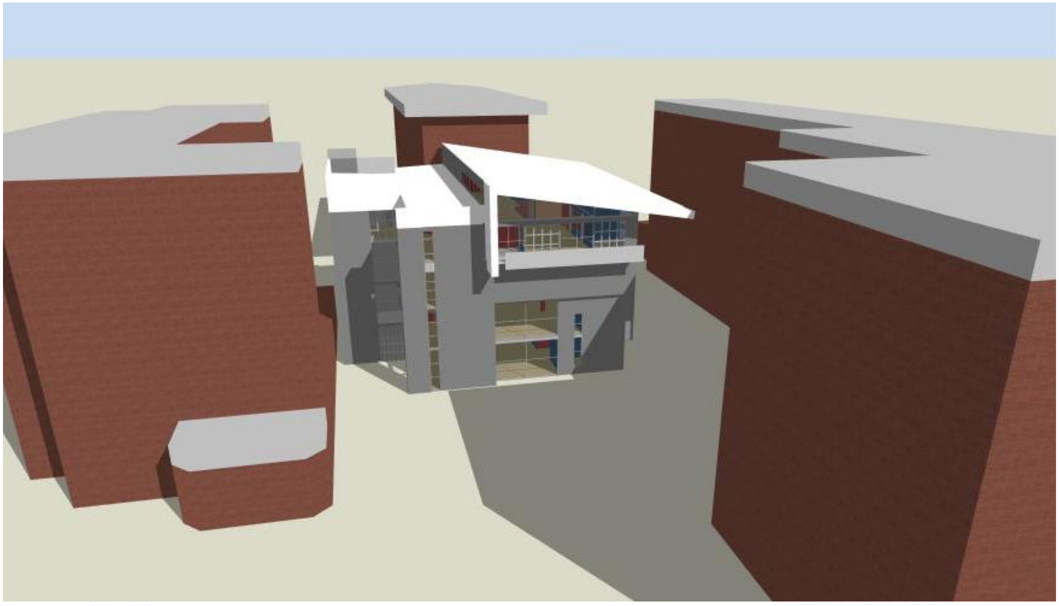


Figure 1: Three-dimensional representation of the actual building simulation model.

This study was launched as a direct and natural outcome of the University's aspirations for the new building. The general aim of the study is to assess the overall energy performance of the new academic building by using national standards and internationally accepted energy-efficiency rating tools for comparative assessments. Although each building's energy footprint is unique, this study also aims to provide more insight into typical energy consumption patterns of a tertiary education building.

The first of the outcomes of this study is to undertake a comparative energy performance assessment between the actual building and the same building built according to minimum SANS 204 requirements (referred to as the notional building), as interpreted by the GSSA Public and Educational Building (PEB) rating tool (2011).

The second outcome of the study is to do a full analysis of the actual building fabric and operational energy performance; and the effect that each of the largest energy consuming elements has on the building's overall and annual energy consumption. The third and final outcome is the evaluation and proposal of possible building fabric and operational energy-improvement options.

1.3. Format of the Study

This report is structured around five main parts. For the first part, chapters 1 and 2 document the background, concepts and theory associated with green buildings and energy modelling.

Part two is covered in Section 3.1 to 3.4 and documents the background, modelling data and processes involved in the creation of simulation models for both buildings. This section also evaluates the collective and individual simulation model properties of each building.

The third part covered in Section 3.5 consists of a discussion of the modelling and simulation data of the actual and notional building. A comparative study is also done in this section to determine the energy performance of the actual building, evaluated against the notional building results.

In the fourth part, contained in chapter 4, a detailed parametric and possible optimisation options study is done to determine which building fabric element or system in the actual building can be changed to result in a lower annual energy performance. This part also briefly evaluates the financial implications of the largest energy performance improvement options.

In the final part, which is covered by chapters 5 and 6, conclusions are drawn from the comparative and parametric analysis done on the actual building; and the possible inclusion of a PV renewable energy generation system is evaluated. Future work and recommendations are also discussed.

2. LITERATURE STUDY AND BACKGROUND INFORMATION

2.1. Building Envelope Performance

A building envelope may be regarded as an enclosed, artificially- or naturally-controlled environment that is separated from the outdoor environment. The building envelope provides thermal insulation for controlling the radiative, convective and conductive heat gains or losses.

A well-designed building envelope reduces energy requirements for artificial environmental control and maximises the use of natural energy sources to ensure sufficient comfort levels for the building's occupants (Sustaining the Legacy, 2010). A building envelope designed according to green building principles should furthermore perform consistently well throughout its proposed lifespan (Harris, 2010).

Typical effects influencing the indoor climate of a building envelope are shown below in Figure 2. These effects need to be controlled in an enclosed environment to ensure occupant comfort.

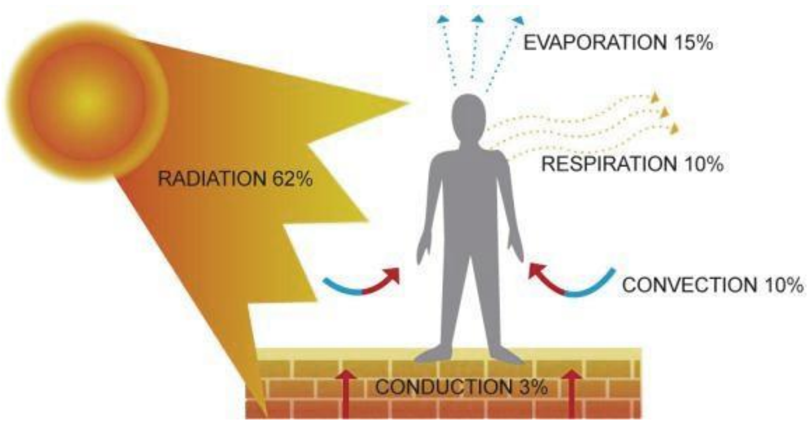


Figure 2: Typical building envelope effects (Harris, 2010).

Conventional energy-efficiency measures for building envelopes can have a significant impact on the operational energy demand and carbon footprint of buildings without compromising occupants' health and wellbeing. These measures typically include increasing the insulation of building materials; changing the building's glazing properties; and ensuring an optimum building orientation.

Over a period of 10 years, Kneifel (2010) evaluated 576 scenarios on 12 prototypical buildings simulated in 16 different cities to determine the average energy performance of these buildings. He concluded that conventional energy-efficiency measures can reduce the energy consumed in new commercial buildings by between 20% and 30% on average; whilst some scenarios even achieved an energy reduction of 40%. Further advantages include an average carbon footprint reduction of 16% and an increased return on investment.

2.2. Thermal Comfort

One of the most important features of a well-designed building in its operational phase is the ability to provide thermally comfortable conditions for its occupants. Thermal comfort as defined by ASHRAE (2004) is the "condition of the mind in which satisfaction is expressed with the thermal environment".

This means that thermal comfort cannot be reduced to a specific state condition, but is subject to a varying level of thermal sensation perceived as a state of comfort for each respective individual. Factors in the building environment that affect thermal comfort of an individual include (Auliciems & Szokolay, 2007; Djongyang, et al., 2010):

- Air temperature;
- Air velocity;
- Humidity;
- Radiant temperature;
- Individual metabolic rate; and
- Individual clothing insulation.

The indicator used for measuring the thermal comfort of the occupants in this study is the PMV-PPD index. Predicted mean vote (PMV) is a concept that was introduced by Fanger (1970) and represents the mean value of the thermal comfort votes of a large group of people. To establish the level of thermal comfort experienced, PMV index values are measured against the ASHRAE Standard 55 (2004).

Table 1: Thermal sensation scale (ASHRAE, 2004).

Value	+3	+2	+1	0	-1	-2	-3
Sensation	Hot	Warm	Slightly warm	Neutral	Slightly cool	Cool	Cold

PMV is formulated as follows:

$$PMV = [\, 0.303\, e^{-0.036\, M} + 0.028\,]\, L \qquad (1)$$

In equation (1) above is M the metabolic rate and L the thermal load on the body of the occupant. This thermal load can be defined as the difference between the internal heat production of an occupant at comfort temperature and the heat loss to the environment as a result of sweating. (Fanger, 1970)

The predicted percentage of dissatisfied (PPD) people is an index that represents the number of people who were dissatisfied with the thermal comfort index and is formulated as follows:

$$PPD = 100 - 95\, e^{-(0.03353\, PMV^4 + 0.2179\, PMV^2)} \quad (2)$$

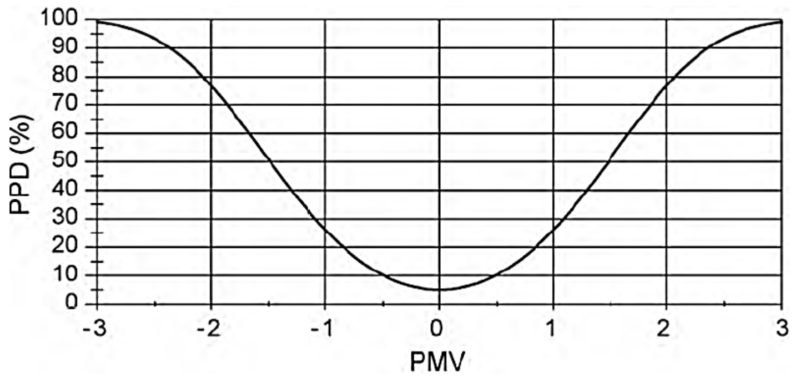


Figure 3: Relationship between PMV and PPD (ASHRAE, 2004).

The ASHRAE (2004) standard for building comfort requirements allows PMV values between -0.5 and +0.5 to be regarded as thermally comfortable for human occupancy. These values enable a prediction that the amount of people who will be dissatisfied with the thermal conditions, will range between five (5) and ten (10) per cent (refer to Figure 3 above).

It should also be noted from Figure 3 that even if thermal neutrality is maintained, there will always be dissatisfied people because of differences in perception of thermal comfort.

2.3. Green Buildings

The concept of energy-efficient buildings dates as far back as 1851, when the Crystal Palace in London (Great Britain) – a cast-iron and glass building originally erected to house a major exhibition in Hyde Park – used passive systems for improving the quality of the indoor environment. The decisive starting point of the green building movement, however, may be traced to the early 1970s, when a group of forward-thinking environmentalists, ecologists and architects began to investigate the applicability of energy-efficient building principles. World Earth Day in April 1970 and the 1973 OPEC oil embargo served as catalysts to transform their efforts into the so-called green building movement (USGBC, 2003).

A ‘green building’ is defined as an energy-efficient building created by using environmentally-responsible and resource-efficient processes for the purpose of minimising the total life-cycle environmental impact of a building. The key elements of a green building are (U.S. Environmental Protection Agency, 2010; GBCSA, 2008):

- Energy efficiency;
- Resource efficiency;
- Minimal waste production and pollution;
- Improving occupant productivity;
- Improving occupant health; and
- Protecting the natural environment.

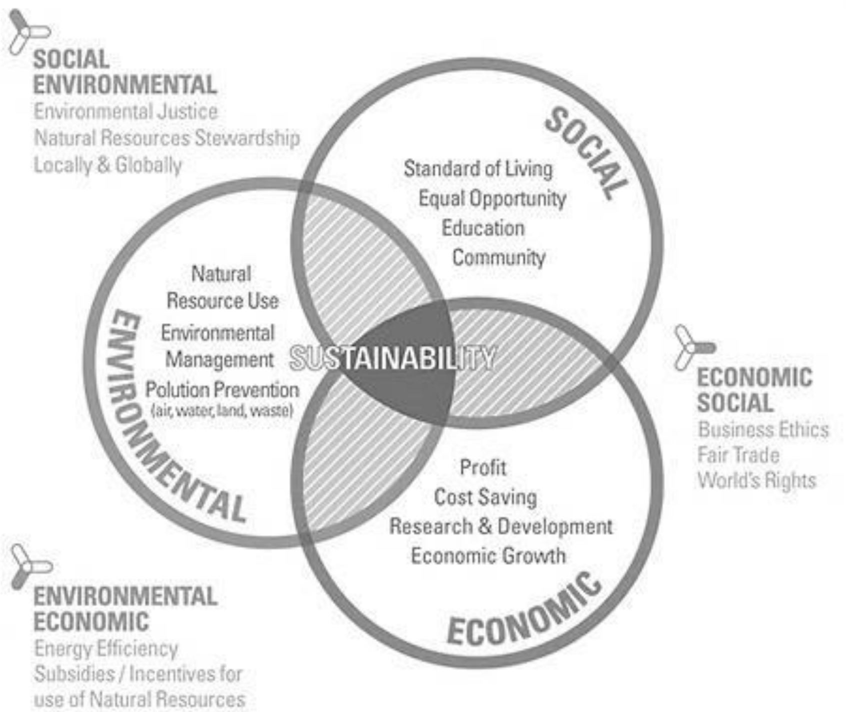


Figure 4: Triple bottom line (Senmit, 2011).

The green building concept revolves around the triple bottom line approach of sustainability, depicted in Figure 4 above. This approach denotes that a sustainable future can only be realised by establishing a well-balanced scenario between human comfort requirements, sound economic opportunities and environment protection (Lützkendorf & Lorenz, 2005).

In green buildings, however, the emphasis is placed on determining how to attain the best balance between people (social), the planet (environmental) and profit (economic) to ensure a minimum negative environmental impact.

2.4. Green Building Rating Tools

Buildings are very complex structures with numerous subsystems, materials, operations, and functions. These systems also have a high degree of interaction with the outside environment (Rey, et al., 2007). The evaluation of the performance of buildings is therefore a complex exercise if one wishes to obtain realistic results (Horvat & Fazio, 2005).

To address these complexities, building rating tools like, for example, Green Star SA (South Africa); LEED (USA); BREEAM (United Kingdom); and CASBEE (Japan) have been developed. Each of these building rating tools addresses the unique environmental concerns and imperatives for different building types and their respective life-cycle phases in every diverse, designated region.

The general objective of green building rating tools is to reward buildings for achieving a good balance between occupant comfort and productivity; energy and the environment. In Figure 5 below an example of a conceptual model of LEED green building principles, which has been implemented at Cornell University in the USA, is shown.

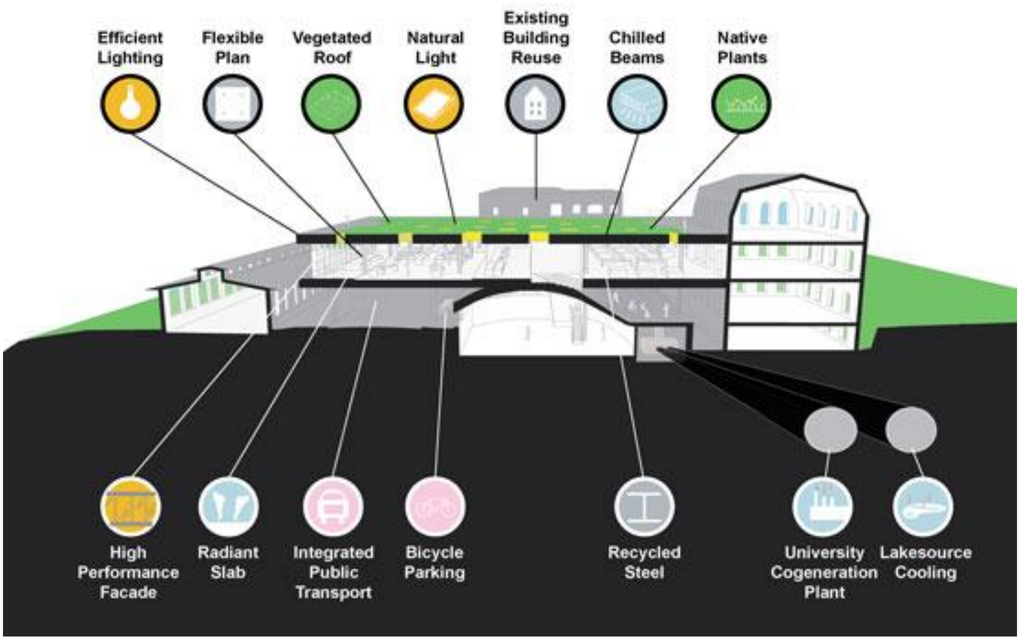


Figure 5: Example of a green academic building (Cornell University, 2011).

Due to the location of the study subject, namely South Africa, the Green Star SA standard will be discussed in more detail below.

2.5. Green Star SA

Green Star SA is a standard of measurement for green buildings located in South Africa, and was introduced in 2008 by the Green Building Council of South Africa (GBCSA), which is also a member of the World Green Building Council (World GBC).

The relatively young South African Green Star rating system is based on the well-established Australian Green Star rating model. This is mostly due to the similarities in climate, building materials and general building practices between the two countries. The Australian Green Star rating model is in turn derived from the well-established LEED and BREEAM rating systems to ensure that global experiences in the green building sector is utilised to the benefit of all.

A number of green building rating tools for different market sectors have been released since the launch of the GSSA rating system. Currently available under the GSSA canopy are the Office v1; Multi-Unit Residential v1; and the Retail Centre v1 tools. The GSSA are also in the process of testing a future Public and Educational Building rating tool. The main objectives of GSSA rating tools include the provision of a standard of measurement for green buildings; the recognition of environmental leadership; raising public awareness of green buildings; encouraging integrated whole building design; and reducing the environmental impact of buildings (GBCSA, 2008).

GSSA rating tools are divided into nine different categories that represent the different environmental impacts of a building. Each of these categories is subdivided into credits. The credits represent design initiatives that may improve the environmental performance of a building. Points are awarded to each of these credits to rate the level of achievement of the desired objective (GBCSA, 2008).

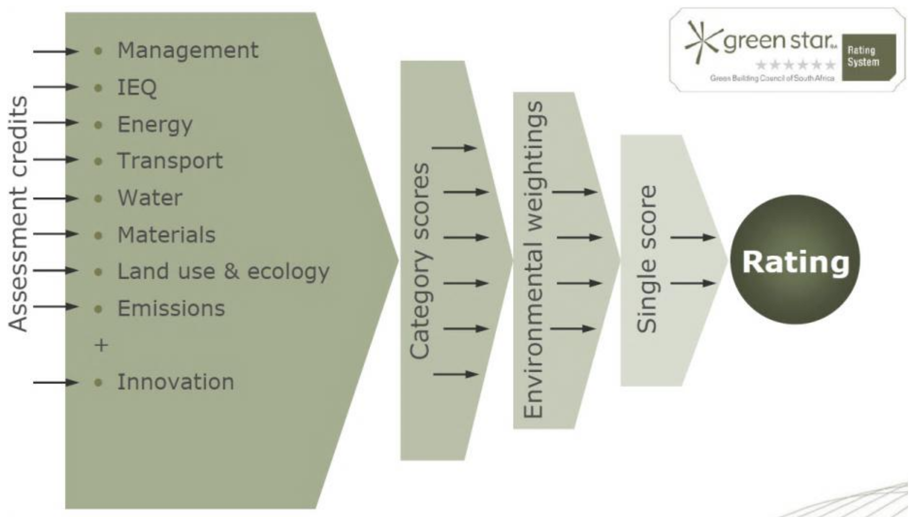


Figure 6: Green Star SA Rating System (GBCSA, 2008).

After a full assessment of all the credits in the each category, category scores are calculated as percentages. Environmental weighting factors are then multiplied to the score of each category as a representation of the different environmental concerns and imperatives for building types and their respective life-cycle phases.

The final GSSA rating is then calculated as a sum of the scores of all the weighted categories. A maximum possible value of 100 can be achieved for the sum of all the weighted categories, excluding innovation. The latter is regarded as a way to recognise and reward the use of innovative technologies and is therefore rewarded over and above the maximum value of 100 for the other categories (GBCSA, 2008). The GSSA only awards market leaders in the field of green and efficient buildings and will therefore only award and certify projects with four, five and six star ratings, as shown below in Table 2.

Table 2: Green Star SA – ratings.

Score	Rating	Outcome
10-19	One star	No certification
20-29	Two star	No certification
30-44	Three star	No certification
45-59	Four star	Best practice
60-74	Five star	South African excellence
75+	Six star	World leadership

GSSA certification can be achieved in either “Design” or “As Built” format. A building can be awarded a “Design” certification if it can be demonstrated that sufficient green building principles have been incorporated in the building design stage. The “As Built” certification can be awarded to a building that can verify the implementation and procurement of green building principles.

2.5.1. Green Star SA – Eligibility Criteria

A building is only eligible for a GSSA rating if a series of eligibility criteria are met. As the building assessed in this project is an educational building, requirements for the GSSA Public and Educational Building (PEB) rating tool is used. These criteria include spatial use and –differentiation; timing of certification; and conditional requirements. The new academic building satisfies both the spatial use and differentiation requirements as set forth in the *GSSA – Public & Education Building Pilot Eligibility Criteria* document (GBCSA, 2011).

Conditional requirements in the PEB rating tool are the minimum required scores for the ecology and energy categories that must be met to qualify for certification regardless of other category scores (GBCSA, 2011). The ecology category’s conditional requirement is not assessed in this study. For further information on the energy conditional requirement, refer to Section 2.5.2 below.

2.5.2. Green Star SA – Energy Criteria

The main objective of the GSSA energy category is to minimise the overall energy consumption of buildings and to encourage energy generation by alternative sources.

A building's total life-cycle carbon and other GHG emissions can be reduced substantially by reducing the annual operational energy consumption of the building. This is especially true in a South-African context where the energy generation sector is dominated by coal-fired power plants. Another benefit of reducing power consumption is to ease the load on the struggling electricity-generating sector in South Africa and to thereby reduce the possibility of load-shedding (GBCSA, 2008).

As mentioned in Section 2.5.1 above, the energy category is one of two categories of the PEB rating tool that has a conditional requirement. In accordance with this requirement, the actual building should perform equally to or better than a notional building constructed to the 'deemed-to-comply' fabric- and building service clauses of *SANS 204:2008 Energy Efficiency in Buildings* (SABS - SANS 204, 2008).

To demonstrate compliance to this criterion for a mechanically-ventilated building, the following routes may be followed (GBCSA, 2008; GBCSA, 2011):

- Compliance route 1: Energy modelling to show that the actual building outperforms the notional building; or
- Compliance route 2: Full compliance to the *ASHRAE Advanced Energy Design Guide for Small Office Buildings* (ASHRAE, 2000) and a proven HVAC energy consumption reduction of 20%; or
- Compliance route 3: Full compliance to the SANS 204:2008 *Energy Efficiency in Buildings* (SABS - SANS 204, 2008) 'deemed-to-comply' clauses.

The most important credit in the GSSA-PEB Energy category is the greenhouse gas emissions credit. This credit's purpose and relevance to this study is discussed in further detail below.

2.5.3. Green Star SA – Greenhouse Gas Emissions Credit

The purpose of the energy credit is to reward greenhouse gas emission reductions associated with the efficient operational energy consumption of buildings (GBCSA, 2008).

Compliance to the credit criteria can be demonstrated by either following compliance route 1 or 2, as discussed in Section 2.5.2 above. The academic building examined in this project will however be evaluated in accordance with compliance route 1. This route has been chosen because it requires a full performance assessment of the annual energy requirements and awards the most points for energy-efficient building design.

Compliance route 1 prescribes the awarding of points for the percentage of carbon emission improvement of the actual building over the SANS 204 notional building. This is done by comparing the energy modelling outcome of the actual and notional building and translating the energy improvement to a reduction in carbon emissions. Energy produced by on-site renewable energy sources, however, is subtracted from the annual energy consumption of the actual building before comparing it to the notional building energy consumption.

The relationship between energy efficiency and carbon emission reductions, as used by the current GSSA–PEB V0 energy calculator, is 1.2 $kg\ CO_2/kWh$ (ESKOM, 2007; GBCSA, 2011). Points are awarded on a linear scale with zero (0) points for a carbon emission improvement of less than five (5) per cent over the SANS 204 notional building and 20 points for a net zero emissions building (GBCSA, 2008). Net zero emissions for a building is only achievable if all the energy consumed annually by the building is produced by on-site renewable energy sources.

2.6. National Standards

To demonstrate the energy- and environmental performance of the new academic building evaluated in this study, compliance route 1 for the GSSA – PEB Energy Criteria will be used as a guideline (refer to Section 2.5.3 for an explanation hereof). Building performance will be evaluated against the ‘deemed-to-comply’ requirements of *SANS 204:2008 Energy Efficiency in Buildings* (SABS - SANS 204, 2008).

The objective of SANS 204 is to reduce energy consumption in buildings without compromising the occupant’s comfort levels. Whereas compliance to this standard is voluntary for new developments, the South African government will make the ‘deemed-to-comply’ SANS 204 requirements mandatory as soon as it is economically viable for them to do so (Ashpole, 2009). The primary focus of this standard is to improve heat-energy flows. This is done by changing the building fabric according to the insulation properties specified for each climatic zone and by reducing energy requirements of building systems (Reynolds, 2010).

The ‘deemed to satisfy’ thermal requirements of SANS 204 are based on six designated climatic zones, as depicted in Figure 7. For each of these zones, minimum thermal resistance R-values are specified for building fabric elements.

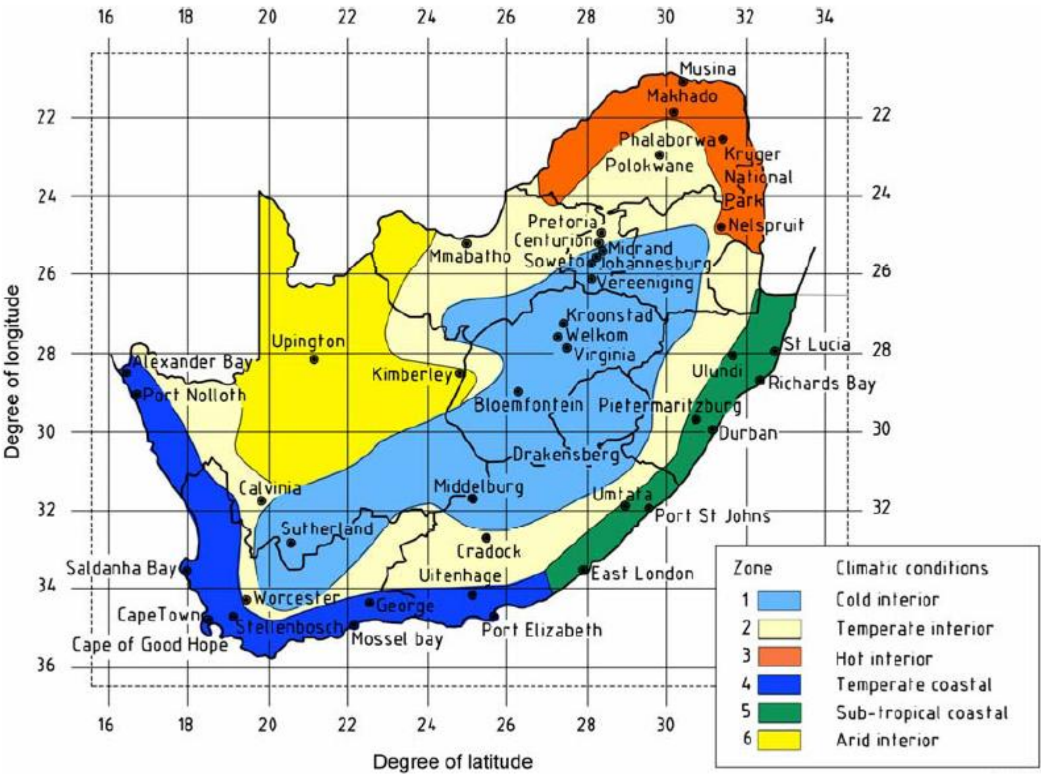


Figure 7: SANS 204 climatic zones (SABS - SANS 204, 2008).

2.7. Energy Flow Assessment in Buildings

The most common methods of forecasting building energy consumption include prediction by multi-objective optimisation methods and simulation models based on physical principles of buildings. Irrespective of which method is used for forecasting energy consumption in buildings, there will always be some margin of uncertainty. This can mainly be attributed to the fact that occupant behaviour is near impossible to predict (Neto & Sanzovo, 2008) and global warming has unknown effects on long-term weather patterns.

2.7.1. Multi-Objective Optimisation Methods

As a result of the non-linear nature of the input variables, gradient-free optimisation methods are showing great promise for building energy prediction (Magnier & Haghighat, 2009). When solving complex non-linear problems, the most favourable method is the use of artificial neural networks (ANN) and derivatives thereof (Li, et al., 2011; Yang, et al., 2005; Magnier & Haghighat, 2009; Ekici & Aksoy, 2007). ANN algorithms are based on mathematical models used to simulate biological neural networks. These algorithms have the ability to extrapolate results for new situations by investigating the underlying principle governing previous situations (Neto & Sanzovo, 2008).

Due to ANN's learning abilities, training is required to produce the desired set of outputs and may be accomplished by providing the algorithm with data that closely resembles desired output patterns. The data is then set up to identify statistical patterns in the input parameters and to provide it with an intermediate form of the previous two types of learning. The application of these ANN models is therefore mostly based on previous measurements of existing models and not on new developments.

Forecast applications of ANN building energy consumption suggest that very accurate predictions can be achieved with relative ease compared to conventional models based on physical principles (Cheng-wen & Jian, 2010; Ekici & Aksoy, 2007; Magnier & Haghighat, 2009; Wong, et al., 2008; Neto & Sanzovo, 2008). The main disadvantage of forecasting building energy by such a complex mathematical model is that it acts as a "black box"; thereby limiting the ability to explicitly identify possible contributors to a particular output. Another disadvantage includes that computational time of ANN models to converge to an optimum may greatly exceed the computational time of physical models where a large amount of input parameters is used (Tu, 1996).

Neural network optimisation algorithms are therefore more promising where the optimisation of existing efficiency strategies is pursued (Neto & Sanzovo, 2008) and as a quick and efficient tool to provide information on building energy consumption at an early design stage (Cheng-wen & Jian, 2010). Physical models are, however still the method of choice for applications when detailed, transparent building energy simulation is needed.

2.7.2. Quantitative Physical Property Modelling

Models based on physical principles, like EnergyPlus, make use of prediction by combing the physical properties of all foreseen energy sinks and sources; usage profiles; uncertainties and the effect of external parameters (Neto & Sanzovo, 2008). These models typically require highly-detailed and -defined building properties to obtain an accurate energy consumption prediction (Yezioro, et al., 2007). The advantage of using highly defined input parameters includes the ability to make detailed assessments to identify the level of contribution of each of the energy consuming components. Building design and -operation can therefore be optimised easily by exploring methods for reducing the energy consumption contributions of each of its components.

2.7.2.1. EnergyPlus

In the context of this study, were EnergyPlus used for its ability to do comprehensive whole-building energy and thermal load simulations, based on the physical properties of buildings. This programme inherited the best capabilities and features and addressed the shortcomings of two robust and proven building energy simulation programmes, BLAST and DOE-2 (Crawley, et al., 2001).

Both BLAST and DOE-2 are comprised of various subroutines to simulate heat and energy flows in a building, with the difference that the one uses a zone heat balance and the other a room weighing factor approach (Crawley, et al., 2001). EnergyPlus has been created to provide a modular, open-source approach to building energy simulation to simplify and promote the continuous evolvement of the code (US DOE, 2010). Figure 8 below illustrates this modular approach by providing a high-level outline of the most important subroutines incorporated in the EnergyPlus simulation manager. This integration of modules furthermore enables one to investigate the influence each element has on the overall building energy performance.

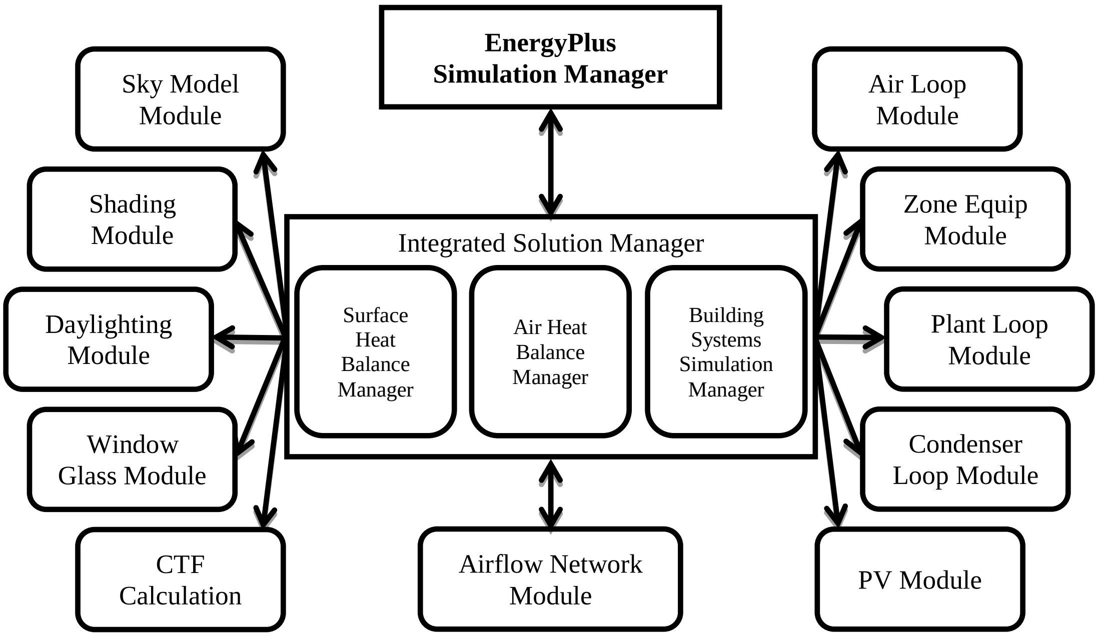


Figure 8: EnergyPlus diagrammatical representation (adapted from EnergyPlus, 2010).

The primary shortcoming of both BLAST and DOE-2, which is addressed and rectified in EnergyPlus, is the inability to correctly handle feedback between the three major parts of a building's HVAC system, namely building zones; air handling system; and cooling and/ or heating plant. Feedback in EnergyPlus is accomplished by successive substitution iteration between the supply and demand sides, as shown in Figure 9 below (EnergyPlus, 2010).

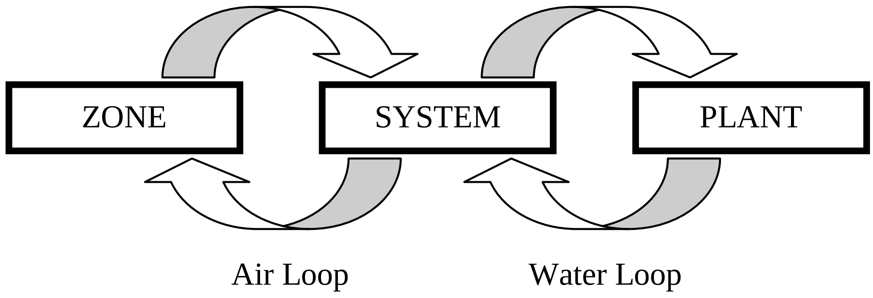


Figure 9: EnergyPlus Successive Substitution Iteration

The internal workings of EnergyPlus can be explained by dividing it into three core components, namely a simulation manager; a building systems simulation manager; and a heat- and mass balance module. The simulation manager acts as an easily-controllable and modifiable module management shell wherein all the major simulation loops and processes are contained. The building systems simulation manager, however, controls the simulation of the systems, loads and the HVAC plant of a building and then updates the zone-air conditions.

Air and surface heat- and mass balance modules form the core of the thermal energy flow analysis of the EnergyPlus simulation engine. Both these modules are controlled by the integrated solution manager (see Figure 8 above), which acts as an interface between these modules and the building systems simulation manager. A fundamental assumption underlying the air heat- and mass balance module is that all air within each zone is assumed to be stirred well and maintained at a uniform temperature. Assumptions for the surface heat- and mass balance module include that zone surfaces, for example walls, windows, ceilings and floors, have uniform surface temperatures; consistent long- and short wave radiation; diffuse radiating surfaces and only one-dimensional heat conduction. Although these assumptions do not reflect reality precisely, it provides a good and far less computationally-intensive thermal assessment than using complex CFD models for each zone (Crawley, et al., 2005).

The underlying principle of computing heat- and mass balance in these modules is the application of the first law of thermodynamics between building element or air interfaces and the control volumes around air masses in each zone. As heat conduction in a building is time-dependent, transient heat conduction in these heat-balance models are assessed using conduction-transfer functions (CTFs) (Strand, et al., 1999). After the completion of a successful heat-balance simulation in a time step, the building systems simulation manager is called to control the simulation of the systems, loads and the HVAC plant to update the zone-air conditions (Crawley, et al., 2005).

EnergyPlus has been comprehensively tested and validated by both the BESTEST procedure (DesignBuilder, 2010), which was created by the IEA as an accreditation tool for building energy simulation software. Further successful testing and validation through the ASHRAE Standard 140-2001 procedure was also accomplished (Crawley, et al., 2004). EnergyPlus is therefore the building energy simulation programme of choice for the new academic building project due to robust and proven performance and full compliance with the GSSA – PEB energy modelling requirements (GBCSA, 2011).

2.7.2.2. DesignBuilder

DesignBuilder was selected for this study predominantly as a result of its ability to provide a user-friendly, third-party graphical user interface for EnergyPlus. Figure 10 below illustrates the high-level interaction between DesignBuilder and EnergyPlus, where DesignBuilder is used as the third-party interface. This interaction is limited to the creation of an input file and displaying of calculation results.

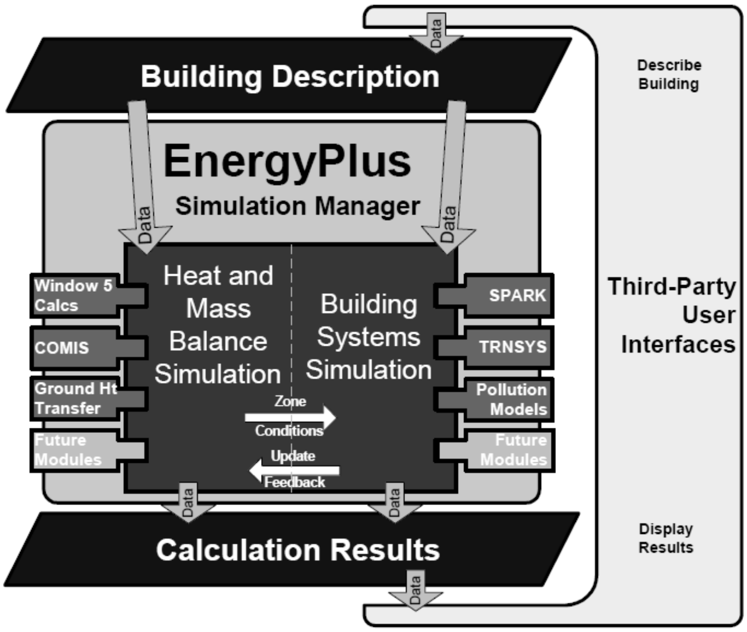


Figure 10: EnergyPlus User Interfaces (Crawley, et al., 2005)

Other deciding factors for choosing DesignBuilder include the inclusion of a three-dimensional, OpenGL geometric modeller; good visualisation capabilities; well-defined graphical representation of building energy and environmental performance data; and the ability to do building fabric performance comparisons. A further advantage of using DesignBuilder as a user interface for EnergyPlus above similar programmes like, for example, Sketchup-OpenStudio (Google, 2011) or Ecotect (Autodesk, 2011), is the availability of extensive data templates for numerous building types. These fully-customisable templates provide a good guideline that prescribes to what magnitude of input variable is typically expected for certain building types.

2.7.3. Building Fabric Energy Flow Fundamentals

In the pursuit of understanding the factors influencing the rate and amount of energy flows occurring through the building fabric, certain fundamental thermodynamic principles should be discussed.

Energy flow characteristics of a building construction element can be defined in terms of its thermal properties. Whenever a temperature gradient exists between a construction element and its surrounding environment, heat energy is transferred. Heat energy can be transferred in three different modes, namely conduction through a solid or stationary fluid; convection between a surface and a moving fluid; and radiation between two surfaces (Incropera & De Witt, 2002). In Figure 11 below this heat-balance for a typical building construction surface is demonstrated in terms of the rate of heat transfer per unit area normal to the direction of heat transfer ($\dot{q}$) (Cengel, 2006).

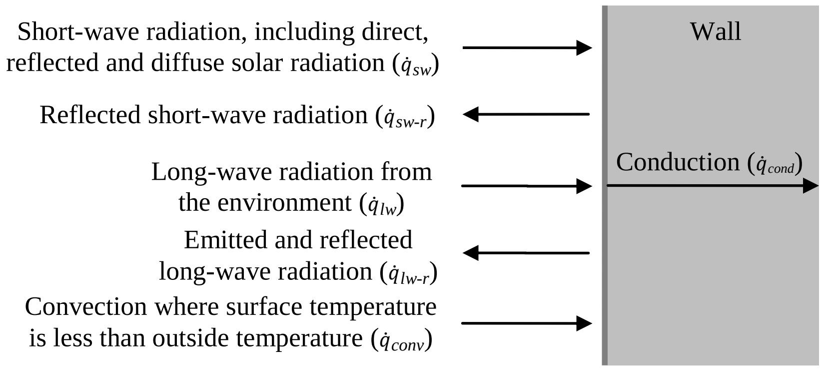


Figure 11: External wall heat flux balance (adapted from EnergyPlus, 2010).

EnergyPlus calculates these energy flows by applying the first law of thermodynamics to determine the heat flux balance in building elements (EnergyPlus, 2010), as portrayed in equation (3):

$$\dot{q}_{sw} + \dot{q}_{lw} + \dot{q}_{conv} + \dot{q}_{cond} = 0 \qquad (3)$$

The thermal conduction of the various elements in the building fabric is evaluated in terms of equivalent thermal resistance *R*-value. This value is a measure of the material's ability to resist heat flow (q) across its thickness L in the direction where there exists a temperature difference ($T_{s,1}$ - $T_{s,2}$) between surfaces. The conduction *R*-value can be formulated as (Incropera & De Witt, 2002):

$$R_{cond} = \frac{T_{s,1} - T_{s,2}}{q_{cond}} = \frac{L}{kA} \quad (4)$$

In equation (4), k is its thermal conductivity and A the area over which conduction occurs. Similarly, as with conduction, an equivalent thermal resistance for heat convection can be formulated (Incropera & De Witt, 2002) as follows:

$$R_{conv} = \frac{T_s - T_\infty}{q_{conv}} = \frac{1}{hA} \quad (5)$$

In equation (5), T_∞ is the temperature of the moving fluid and h the convection heat-transfer coefficient.

Lastly, a thermal resistance equivalent for heat radiation can be formulated (Incropera & De Witt, 2002) in accordance with equation (6) below:

$$R_{rad} = \frac{T_s - T_{sur}}{q_{rad}} = \frac{1}{h_r A} \quad (6)$$

In the equation above, T_{sur} is the temperature of the surrounding environment and h_r can be formulated, where reasonable assumptions for building loads are made (Chapman, 1984), as (Incropera & De Witt, 2002):

$$h_r = \varepsilon\sigma(T_s + T_{sur})(T_s^2 + T_{sur}^2) \quad (7)$$

where ε is the surface emissivity and σ the Stefan-Boltzmann constant.

There is an analogy between thermal resistance and electrical resistance, because as thermal resistance is associated with heat conduction, electrical resistance is associated with electricity conduction. These analogies make it possible for thermal resistances to be modelled and calculated in the same manner as electric resistive circuits (Incropera & De Witt, 2002). The equivalent thermal resistance for a system can therefore be modelled and calculated as shown in Figure 12 and Figure 13 below:

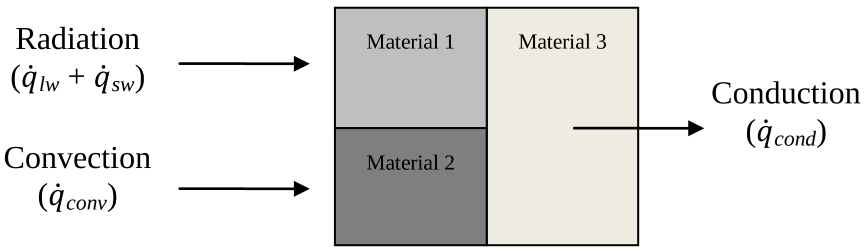


Figure 12: Construction element material composition example.

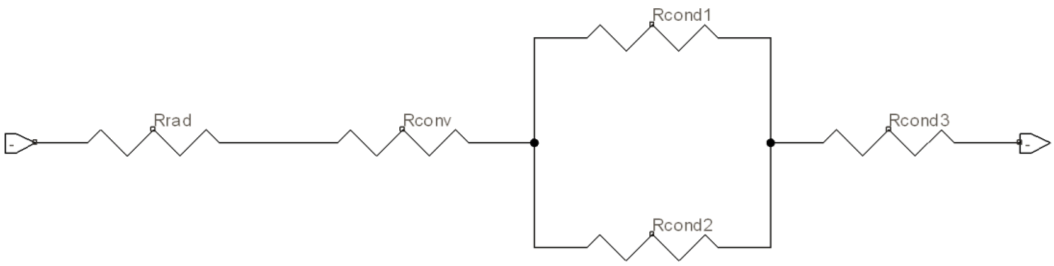


Figure 13: Equivalent thermal resistance circuit of Figure 12.

The combined thermal resistance effects of heat conduction, convection and radiation on the construction element shown in Figure 12 and Figure 13 are:

$$R_T = R_{rad} + R_{conv} + (R_{cond1} + R_{cond2})^{-1} + R_{cond3} \tag{8}$$

Another thermal energy flow property of building construction elements is the ability to provide thermal capacitance, otherwise known as thermal mass. The thermal energy storage ability of a material is determined by its mass and specific heat capacity and is formulated as follows (Incropera & De Witt, 2002):

$$C = mc_p \tag{9}$$

In equation (9), m is the mass of the object and c_p is the specific heat constant of the material. The heat energy stored in such an object can therefore be determined by applying fundamental thermodynamic principles (Incropera & De Witt, 2002):

$$q = C\Delta T \tag{10}$$

where q is the heat energy and ΔT the temperature difference across the object.

3. BUILDING MODELLING

3.1. Overview

The building energy modelling method selected for this study was quantitative physical property modelling, as noted in Section 2.7.2 above. This method was chosen for its ability to assess the level of contribution that any specific building component or operational characteristic has on the building's energy consumption; and furthermore because measured data for an actual operational building was not available. Quantitative physical property modelling requires a detailed description of the building fabric and its operational characteristics. This is illustrated in the high level modelling breakdown of Figure 14 below.

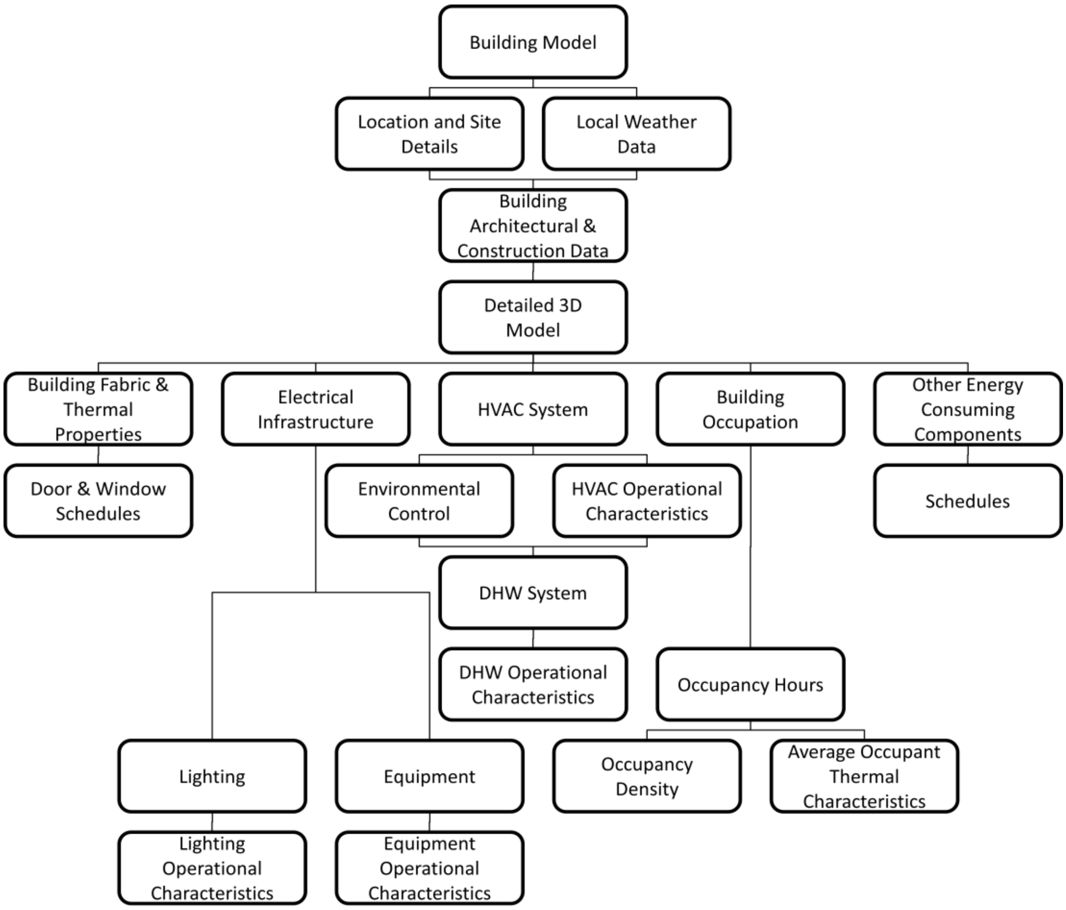


Figure 14: High-level, quantitative physical building property-modelling breakdown.

Building energy modelling can be done using a variety of methods. These range from very accurate and complex, time-consuming models to basic, less accurate and inexpensive models. This accuracy cost trade-off can usually be justified by the predicted error margin resulting from the uncertainties of variables influencing the energy consumption of the building model.

Uncertainties that have the largest impact on the energy consumption of academic buildings are the following, listed in order of significance:

- Occupancy density and –hours;
- Occupants' comfort perception and behaviour;
- Weather patterns; and
- Differences between the design version on which the modelling is based and the completed physical building design.

Due to these uncertainties, approximations, for example, fixed occupancy density and predefined occupancy schedules have to be made. The general method used by the GSSA (2008) building energy rating system is to specify fixed occupant comfort conditions, and schedules for occupancy and other energy consuming components. This ensures that the building energy performance can be evaluated with greater accuracy against reference models.

As the GSSA-PEB rating mechanism applicable to the building evaluated in this study is only in pilot phase, the Green Star Office V1 tool was used as a reference due to the similarities between the Office V1 and PEB Pilot rating tools. The *Energy Calculator & Modelling Protocol Guide - Version 0* (GBCSA, 2011) of the GSSA-PEB Pilot tool was however used as a guideline for energy modelling. These guidelines serve as an aid for pursuing accreditation when a full GSSA-PEB rating study is conducted.

Another benefit of following these well-documented and internationally-recognised guidelines is the ability to model and determine the applicability of possible energy-saving initiatives between models with a fixed baseline. Each of these initiatives can also be assessed to verify whether it will compromise occupant comfort at the expense of saving energy.

Finally, these guidelines provide the ability to assess the energy performance of the actual building measured against national standards. This is achieved by comparing its energy performance to the same building built according to SANS 204 minimum energy-efficient building standards.

3.2. General Building Modelling Data

3.2.1. Software

As noted in Section 2.7.2.1 above, EnergyPlus was chosen as part of the simulation package requirements of the GSSA–PEB *Energy Calculator and Modelling Protocol Guide* (GBCSA, 2011). This simulation package passed both the BESTEST and ANSI/ASHRAE Standard 140-2001 validation tests; of which only one is required (GBCSA, 2011). DesignBuilder was furthermore used as a graphical user interface to EnergyPlus. For both the actual and notional building, were the energy flow simulations done with DesignBuilder version 3.0.0.48 and EnergyPlus version 6.0.0.037.

3.2.2. Weather

The weather data used for energy flow modelling of the new academic building was an international weather for energy calculation (IWEC) data file generated for the Cape Town International Airport, Cape Town (South Africa). The new academic building is located exactly 25.22 km in a straight line from the Cape Town International Airport, and therefore fully conforms to the GSSA-PEB (2011) requirements.

The IWEC weather file contains long-term typical weather data derived from up to 18 years of historic hourly data acquired by the National Climatic Data Centre (NCDC, 2011). A typical summer week of the weather data file used in the academic building simulation models is depicted in Figure 15 below.

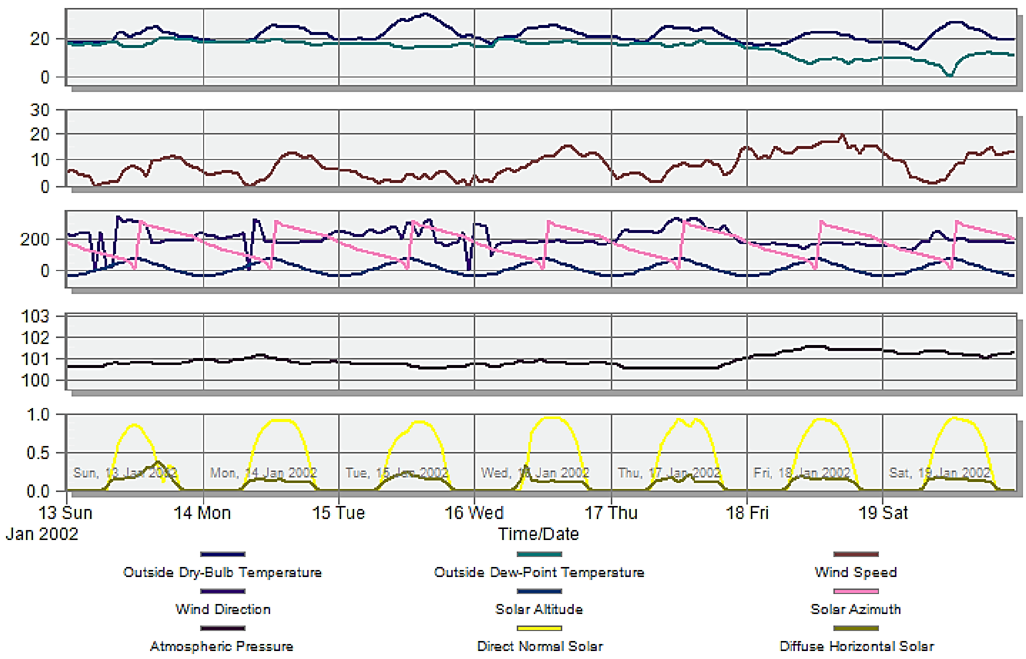


Figure 15: Cape Town International Airport IWEC weather data.

To simulate the effect that ground conditions have on the energy consumption of the building, monthly temperatures provided by the IWEC weather data file was used. This average monthly data is more than adequate for detailed building simulation because ground temperatures vary slightly and slowly throughout the year. A good rule of thumb for ground temperatures under large, conditioned buildings is that it is 2°C less than the average monthly indoor space temperature (DesignBuilder, 2010). The data used for this building was taken at a standard soil diffusivity of 0.00232 m^2/day and at a depth of 0.5 meter.

3.2.3. Location

The new academic building that forms the basis of this study will be situated at the Stellenbosch University Engineering Campus, adjacent to the current Mechanical Engineering building. The exact location details are depicted in Table 3 below.

Table 3: Site location details.

Site attribute	Value
Latitude	33°55'45.03" South
Longitude	18°51'57.34" East
Elevation above sea level	119.0 m
Site orientation (clockwise from true north)	23°
Building site type	Greenfield
Building site footprint	1031.9 m^2
Prevailing wind direction (clockwise from true north)	180°

From Figure 16 it is evident that both sunlight and wind will to a large extent be restricted from this building due to the proximity of adjacent buildings. The new building will however be ideally located between the main engineering departments and will thus have the ability to make beneficial use of walkways and to smoothly integrate with existing buildings.

Figure 31 in Appendix A shows a plan view of the academic building simulation model and an indication of each façade orientation. This figure also demonstrates that all the major buildings adjacent to the new academic building have been incorporated into the simulation model. These buildings greatly influence the external environment conditions, for example solar radiation and wind speed, of the new building.

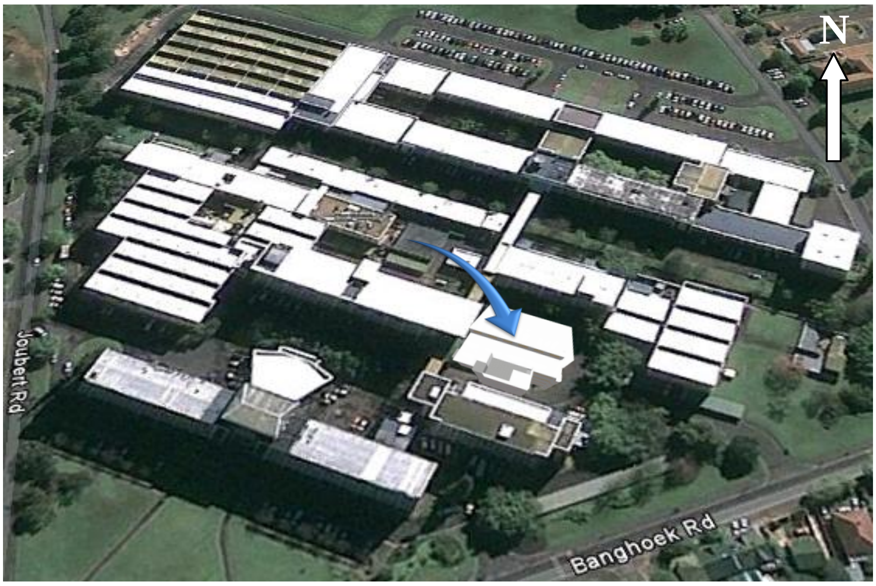


Figure 16: Academic building location (indicated by blue arrow) (adapted from Google, 2011).

3.2.4. Building Design

This building will be used exclusively for academic purposes and will consist of two levels of library space on the first and second floor; two lecture halls on the third floor and the MIH media laboratory and CRSES on the fourth floor and mezzanine.

The main spatial characteristics of the simulation model of the new academic building are listed in Table 4 below. It is important to note that all these characteristics were derived from the first architectural building design data and is therefore subject to variation as minor changes may be implemented throughout the construction and revision process.

Table 4: Characteristics of new academic building.

Spatial Characteristic	**Unit**	**Value**
Total building floor area (GFA)	m^2	3265
Total building volume	m^3	13754
Net conditioned building area	m^2	2709
Net conditioned building volume	m^3	11282
Unconditioned building area	m^2	555
External wall area	m^2	2967
External window glass area	m^2	544
External window–wall ratio: façade on the 23° orientation	%	7.8

External window–wall ratio: façade on the 113° orientation	%	39.4
External window–wall ratio: façade on the 203° orientation	%	30.1
External window–wall ratio: façade on the 293° orientation	%	5.1

3.2.5. Building Operational Schedules

Building operational schedules are nearly impossible to predict accurately. The best method for evaluating the total building energy performance is therefore to use fixed schedules that reflect the typical assumed operational profile of the building.

In Appendix D of the *GSSA–PEB Pilot v0 Energy Calculator & Modelling Protocol Guide* (2011), fixed schedules for the typical operational parameters associated with an educational building are specified. The GSSA-PEB tool provides a schedule for each general category generally found in an education building. Each zone in the building has therefore been classified to fall under the most relevant GSSA-PEB tool category.

The accuracy of the profiles used in the simulation models is not crucial as the aim of the study is to assess the building energy performance and not to predict the precise annual energy consumption. In Figure 17 below an example of one of the profiles used in the simulation model, as prescribed by the GSSA-PEB tool, is shown.

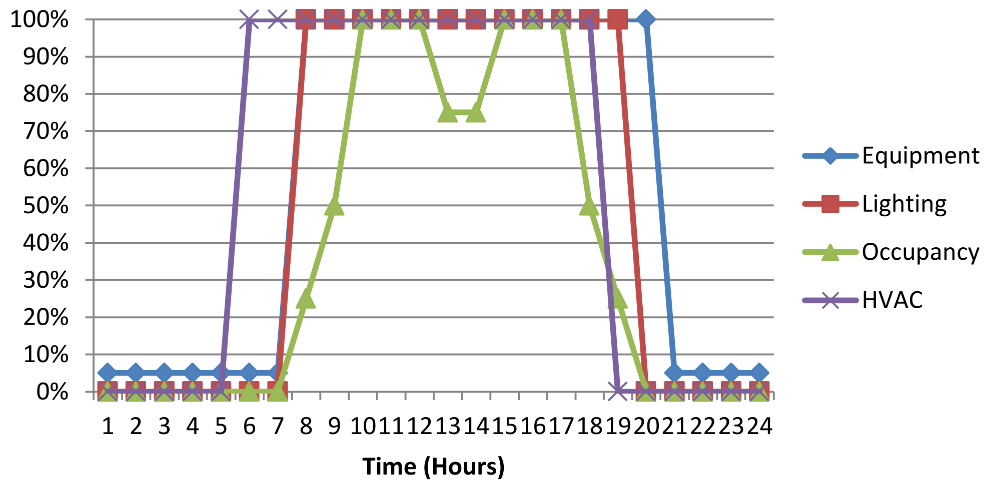


Figure 17: GSSA-PEB cellular office weekday profile.

Further profiles adopted in both the actual and notional building simulation models can be found in the *GSSA-PEB Modelling Activity Schedules* document on the GBCSA's website (GBCSA, 2011).

3.3. Actual Building Modelling

3.3.1. Criteria

The GSSA-PEB tool requirements specify that the actual building should be modelled as designed with a few operational exceptions. These exceptions include all operational schedules presented in Section 3.2.5 above.

An additional operational exception incorporated in the actual building model is the internal design temperatures. Indoor climate-control parameters at the first design stage was unknown and as a result, internal design temperatures of 24°*C* in the summer and 20°*C* in the winter, as prescribed for the notional building, was used. A fresh air delivery rate of 8 *l/s* per person was furthermore used, which was derived from minimum SANS 204 building requirements (SABS - SANS 204, 2008).

The GSSA-PEB tool requirements were used for most of the operational parameters, but a few deviations, as portrayed in Table 5 below, were incorporated to ensure that the building evaluated for the study is more closely resembled (refer to Appendix E for detailed data regarding these deviations). Further data on PEB rating tool requirements for the actual building can be found in the *GSSA–PEB Pilot v0 Energy Calculator & Modelling Protocol Guide* (GBCSA, 2011).

Table 5: Deviations from Green Star SA parameters (GBCSA, 2010).

Modelling Parameter	Reference
Internal design: Occupancy	Estimation based on architect and electrical engineer's data (Thomson, 2011; Arendse, 2011)
Internal design: Equipment	Estimation based on architect's data (Thomson, 2011)

3.3.2. Modelling Data

The data presented in this section is only applicable to the simulation model of the actual building. It should also be noted that all the building fabric data was derived from an early design phase, and as result some elements may differ from the completed physical building.

Only the most important aspects of the simulation model of the actual building are discussed in this section. Further detailed information can be obtained by contacting the author to examine the data file of the building's simulation model.

3.3.2.1. Construction

Table 6 below gives a short description of the actual building's construction elements that are regarded by the GSSA-PEB Energy Modelling Protocol Guide (2011) as the elements with the largest possible impact on the energy performance of the building fabric. These construction elements are the roof, external walls and windows.

Table 6: Actual building construction elements.

Construction element	**Thermal resistance (m^2K/W)**	**External surface**	
		Characteristic	Value
Roof[1]	4.6	Emissivity	0.90
		Absorptivity	0.26
External walls[2]	1.01	Emissivity	0.94
		Absorptivity	0.50
Single glazing windows[3]	0.17	SHGF	0.78
Double glazing windows[3]	0.37	SHGF	0.60

Notes: **1**) Data acquired from ATI (2011) and the default DesignBuilder (2011) library. **2**) Data acquired from Corobrick (2009) and the default DesignBuilder (2011) library. **3**) Data acquired from the default DesignBuilder (2011) library.

At the time this study was conducted (2011), very limited information was available on the shading devices or 'blinds' for the external windows. The only windows where shading was incorporated into the design were the large windows of the library on the 113°-façade; the large windows on each side of the lecture halls; the large electronic classroom window; and the library window above the large electronic classroom window.

Window shading control in the simulation model is managed by controlling the amount of solar energy entering the room. All other external glazing was modelled without window blinds due to the lack of available shading data.

3.3.2.2. Building Electrical Loads

Actual building electrical loads, excluding the electrical loads associated with the HVAC system, can be subdivided into four categories: lighting, equipment, domestic hot water (DHW) and elevator energy-usage.

All equipment and lighting loads simulated in the actual building model were the actual design loads. These were obtained from the design data of the architect (Thomson, 2011) and consulting electrical engineer (Arendse, 2011). All the operational energy consumption levels were simulated according to the operational schedules defined in Section 3.2.5 above.

The internal lighting density of the building was calculated as 15.51 W/m^2 and the total internal power rating for lighting as 55.06 kW. The power rating of external lighting was also calculated as 1.07 kW (DesignBuilder, 2011; Arendse, 2011).

All internal lighting was modelled as suspended luminaries. The thermal effect of these luminaries was modelled by dividing the lighting-energy into four fractions that abide the following formula:

$$Return\ air\ fraction + Radiant\ fraction + Visible\ fraction + Convected\ fraction = 1 \tag{11}$$

Where:

- The return air fraction is zero (0), because no luminary ventilation is provided;
- A typical radiation fraction of 0.42 for fluorescent luminaries is assumed (DesignBuilder, 2011);
- A typical visible fraction of 0.18 for fluorescent luminaries is assumed (DesignBuilder, 2011); and
- The convective fraction is determined by Equation 11 above as 0.40.

The primary aim of the lighting system design was to provide robust, proven technologies within a very limited budget. No intelligent lighting controls or LED energy-efficient lighting products were therefore incorporated at the initial design stage (Arendse, 2011). Further detailed lighting design data is given in Appendix C, Table 23.

Electrical equipment loads were derived from architectural spatial usage data (Thomson, 2011) and typical equipment power usage specifications, as consulted with the University of Stellenbosch planning committee (refer to Appendix E, Table 25). Some of the basic assumptions made for each person occupying an office space are shown in Table 7 below. The total electrical equipment (excluding the HVAC system and elevator) energy density of the building measured over the GFA was calculated as 17.46 W/m^2. To simulate the thermal effect of this equipment, a radiant fraction of 0.2 was used (DesignBuilder, 2011).

Table 7: Assumptions for an office's electrical equipment requirements. (Whitehead, 2011)

Appliance	Typical Wattage
Desktop Computer	400
Laptop Computer	100
Printers and Small Power	150

The GSSA-PEB rating tool specifies a very crude approximation of elevator energy-use. Its annual energy consumption approximation for an elevator is based on the assumption that the elevator operates for 75% of a 12-hour day for 365 days of the year. Due to the difficulty of predicting the actual operating profile of the elevator, the GSSA-PEB rating tool approximation was used (GBCSA, 2011):

$$E_a = \sum_{i=1}^{N} UF * Pe_i * t \tag{12}$$

In Equation 12, E_a is the annual energy consumption, N is the number of elevators, Pe is the elevator motor-power rating of each elevator, UF is the prescribed 75% usage-factor and t is the number of operational hours per year.

Only one Kone 3000 P13 elevator (KONE, 2006) will be installed in the actual building. The resulting annual energy consumption of the elevator, when substituting the variables specified by the GSSA-PEB tool (2011) and the Kone elevator specifications is therefore 19.05 *MWh*.

The domestic hot water (DHW) requirements for the building were calculated by using the DHW specifications of the GSSA-PEB tool for each zone type (refer to Appendix D). This amounted to a daily requirement of 424.4 *l/day* for the entire building. The annual energy requirement Q_{eff} for domestic hot water (DHW) was thus calculated as follows:

$$Q_{DHW} = \frac{mc_p\Delta T}{\eta_{DHW}} \tag{13}$$

In Equation 13, m is the mass of the water, c_p is the specific heat capacity of water, ΔT is the temperature difference between boiler water inlet- and outlet temperature and η_{DHW} is the energy efficiency of the DHW system.

In the calculation of annual DHW electricity power consumption, certain assumptions have however been made, including:

- Water inlet temperature is constant throughout the year at 15*°C*;
- Supply water temperature is constant at 55*°C*;
- Specific heat capacity (c_p) of the water is constant at 4180 *J/kg/K*;
- Efficiency of the whole DHW system is 95% due to the predominant use of instant water heaters and geysers with very short distribution design (Thomson, 2011);
- One (1) kilogram of water is equal to one (1) litre of water; and
- DHW is consumed 365 days of the year.

The water usage specifications per zone type (refer to Appendix D) set forth in Appendix C of the *GSSA–PEB Pilot v0 Energy Calculator & Modelling Protocol Guide* (2011) was used. The resulting annual DHW power consumption, in accordance with the GSSA-PEB requirements, is 7.57 *MWh*.

3.3.2.3. HVAC

An HVAC system is typically one of the largest energy consuming components of a mechanically air-conditioned building's annual energy consumption (Al-Sanea, et al., 2012).

The HVAC system to be implemented in the new academic building has two chillers with a combined cooling capacity of 511 *kW*. Both units are connected to a coolant storage tank from where the coolant is redistributed to the fan-coil air-conditioning units in each zone (Meyer, 2011). The operational energy consumption for each of these chillers is determined by the following three curves (Hydeman & Gillespie, 1999; EnergyPlus, 2010) :

- Cooling capacity as a function of evaporator and condenser temperatures;
- Energy input to cooling output ratio as a function of evaporator and condenser temperatures; and
- Energy input to cooling output ratio as a function of percentage unloading.

An accurate model for each chiller used in the new academic building (depicted in Table 8 below) can be created by using linear regression techniques on a broad range of measured performance data of each chiller. Hydeman *et al.* (1999) developed a least-squares linear regression technique for calculating these curves when adequate performance data is available.

Unfortunately performance data of the chillers used in the new academic building could not be obtained from relevant suppliers. A further complication was that the simulation model could only accommodate a single chiller unit. An equivalent model for both chillers, that takes into account the effect of the storage tank and interconnections, was therefore necessary.

Hydeman *et al.* (1999) tested chiller operational power characteristics against a wide variety of well-documented models that are publicly available. The researchers concluded that the DOE2 reference electric chiller model developed by the U.S. Department of Energy provided the smallest RMS error at an average of 1.8%. As a result Hydeman *et al.* recommend the use of a similar, well-documented and -tested chiller model operating at reference conditions to be used when insufficient operational data about the actual chillers is available (Hydeman & Gillespie, 1999).

Table 8: HVAC system chiller properties (Meyer, 2011).

Chiller type	Climaveneta NECS /B 1614	Climaveneta NECS -Q /B 0512
Cooling capacity	396 *kW*	115 *kW* (cooling mode only)
Heating capacity	-	136.5 *kW* (heating mode only)
Cooling EER (at 100% load and 34°C inlet air temperature)	2.53	2.47
Heating EER (at 100% load)	-	3.11
Cooling fluid pump power	11 *kW*	4 *kW*
Heating fluid pump power	-	2.2 *kW*
Evaporator flow rate	68.2 m^3/h	19.8 m^3/h
Heat recovery exchanger flow rate	-	17.5 m^3/h

A reference curve that best matched the specifications of the chillers to be installed in the actual building was therefore used, as proposed by Hydeman *et al.* (1999). The reference chiller chosen for this study, which best reflects the characteristics of the chillers described in Table 8, was the DOE air-cooled chiller model (DesignBuilder, 2011).

The heating- or cooling energy efficiency of each chiller is rated in terms of its energy-efficiency ratio. This ratio indicates the heating or cooling energy produced by the unit relative to the amount of electrical energy required to generate it. The higher the EER, the more energy efficient the chiller unit will therefore be. An approximated reference chiller EER, chosen to reflect the combined EER of both chillers, was calculated by linear interpolation between the known EER values at the same reference conditions of each chiller. This was done by using the following formula:

$$EER = \frac{EER_{Chiller1} * Q_{Chiller1} + EER_{Chiller2} * Q_{Chiller2}}{Q_{Chiller1} + Q_{Chiller2}} \quad (14)$$

In Equation 14, $Q_{Chiller1}$ and $Q_{Chiller2}$ are the cooling capacities of each chiller. This is however a fairly simplistic approximation, as the true interconnected operation of these chillers is unknown. Full operational EER versus normalised load for both the actual building chillers are shown in Figure 18 below.

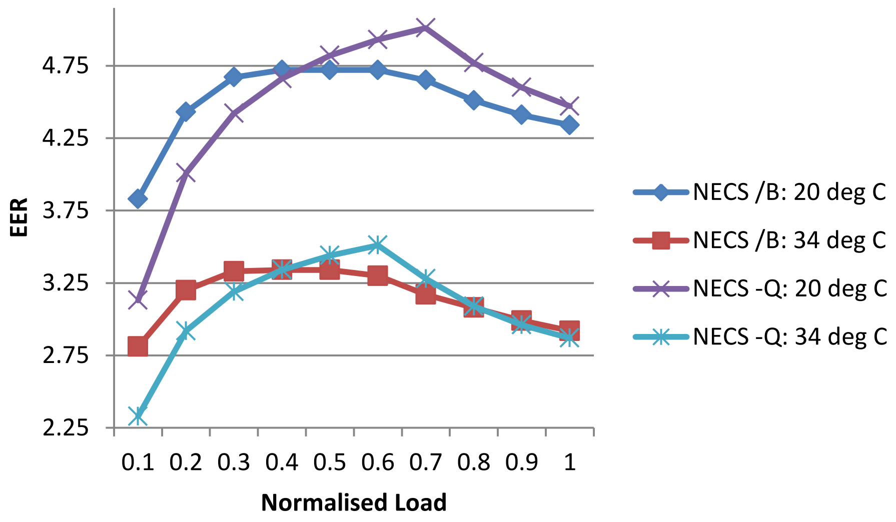


Figure 18: Actual building HVAC operational performance (Mienie, 2011).

The majority of the heating energy in the actual building will be provided by the Climaveneta NECS –Q /B 0512 heat-recovery chiller and the rest by electric elements. These elements were chosen as the best cost-effective method to provide heating energy to the smaller zones on levels 1 and 2 (Meyer, 2011). Further detailed information of the HVAC system to be installed in the actual building is provided in Appendix F, Table 26.

The reference boiler EER for heating energy-consumption calculations in zones where heating is provided by the NECS –Q chiller, is specified in Table 8 above. Operational characteristics of the boiler were simulated by using a fixed EER of 3.11. The EER of all the electric elements in each zone was used as one (1), as nearly all the electrical energy is converted into thermal energy.

Each zone utilises a simple fan-coil unit for air conditioning, as depicted in Figure 19 below (Meyer, 2011). A fan power consumption value of 2.1 *W/l/s* was used as per SANS 204–3:2008 (2008) specifications. This value was chosen due to the lack of manufacturer data and is regarded as a good estimation of the typical total fan power consumption in HVAC units.

The 2.1 *W/l/s* includes all the losses through switchgear and controls of the fan units that supply and exhausts air from the building (SABS - SANS 204, 2008). As per GSSA-PEB rating tool requirements, air density in all ventilation calculations was determined at 30°.

Fresh air ventilation fan power consumption was also specified for the actual building in accordance with SANS 204–3:2008 (2008) specifications. These requirements specify a power consumption of 1.6 *W/l/s* for fresh air fans. The HVAC system design for the actual building also does not make use of economisers to improve efficiency levels.

Cooling- and heating distribution losses for this system were approximated roughly at five (5) per cent (Meyer, 2011). Accurate distribution losses can only be determined once the entire system is installed due to the large amount of possible energy losses that may occur throughout the building.

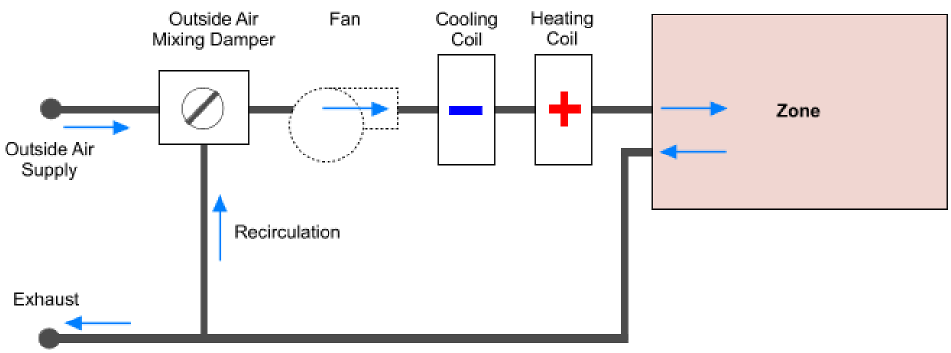


Figure 19: Fan Coil unit (DesignBuilder, 2010).

3.4. Notional Building Modelling

3.4.1. Criteria

The notional SANS 204 building is modelled in the same location with an identical geometry to the actual building, as specified by the GSSA-PEB tool (2011). Further requirements include that the notional building be modelled with pre-defined fabric performance parameters; mechanical- and electrical system performance; and wall-to-window ratios. These pre-defined parameters are generally stipulated by the SANS 204-3 (2008) deemed-to-comply requirements.

As with the actual building, the notional building model also incorporated the deviations from the GSSA-PEB rating tool, shown in Table 5 above.

An additional internal design deviation from the GSSA-PEB tool has however been included, namely that the same fresh air ventilation rate of 8 *l/s* per person used for the entire conditioned area of the actual building, is also used for the notional building. All GSSA-PEB tool (2011) operational schedules (see Section 3.2.5) and climate-control parameters (refer to Section 3.3.1 above) were furthermore implemented in the notional building model.

A further deviation from the GSSA-PEB rating tool is that the notional building incorporates the glazing specifications established by SANS 204-3 (2008) deemed-to-comply requirements. These requirements also form part of the reference GSSA *Office V1 Energy Calculator and Modelling Protocol Guide* (GBCSA, 2010).

3.4.2. Modelling Data

The data presented in this section is only applicable to the simulation model of the notional building. Only the most important aspects regarding the simulation model of the notional building are discussed in this section.

3.4.2.1. Construction

The notional building relies on fixed fabric-performance parameters, as specified by SANS 204-3 (2008) for buildings built according to the minimum requirements of energy-efficient buildings. The building envelope performance parameters specified by the GSSA-PEB tool is unique for each climate zone in South Africa. This building falls under climatic zone 4, namely 'temperate coastal' (refer to Section 2.6 above).

In Table 9 the GSSA-PEB tool specification of the major energy-consumption related structural components for the climate zone 4 is shown. No surface emissivity or absorptivity values for the roof or walls are specified by SANS 204 (2008), and as a result the actual building data was used.

Table 9: Notional building construction elements (GBCSA, 2010).

Construction element	**Thermal resistance (m^2K/W)**	**External surface**	
		Characteristic	Value
Roof	3.7[1]	Emissivity	0.90
		Absorptivity	0.26
External walls	2.2	Emissivity	0.94
		Absorptivity	0.50
All external windows	0.127[2]	SHGF	0.81

Note: **1**) Defined as per climatic zone of Figure 7. **2**) Based on a clear single glazing element with an aluminium frame.

SANS 204 requires an energy-efficient building to conform to the façade-glazing requirements formula for each orientation section of the building (SABS - SANS 204, 2008):

$$F_a * EI = \sum_n A_n \left[S_n (C_A * SH_n + C_B * SC_n) + \frac{C_C}{R_n} \right] \tag{15}$$

Where

F_a	is the façade area;
EI	is the energy index value for the specific climatic zone provided by SANS 204;
A_n	is the area of each glazing element;
S_n	is the SHGC of each glazing element;
$C_{A,B,C}$	is the energy constant provided by SANS 204;
SH_n	is the heating-shading multiplier provided by SANS 204;
SC_n	is the cooling-shading multiplier provided by SANS 204; and
R_n	is the thermal resistance value of each glazing element (more generally defined as a U-value, which is the reciprocal of the R-value).

This formula can however be simplified to provide the percentage of glazing required for the notional building in each of the four building façade orientations (as measured from true North). The simplification is done by replacing some variables with known values for minimum SANS 204 (2008) requirements.

Table 10: SANS 204 (2008) minimum glazing requirements.

Variable	Value	Reason
EI	0.22	Provided as a fixed constant.
Sn	0.77	Minimum required SHGC for climatic zone 4[1].
C_A - 23° orientation	-0.38	Provided as a fixed constant for each specific building façade orientation[2].
C_A - 113° orientation	-0.82	
C_A - 203° orientation	-0.90	
C_A - 293° orientation	-0.61	
C_B - 23° orientation	1.66	Provided as a fixed constant for each specific building façade orientation[2].
C_B - 113° orientation	0.80	
C_B - 203° orientation	0.66	
C_B - 293° orientation	1.34	
C_C - 23° orientation	-0.01	Provided as a fixed constant for each specific building façade orientation[2].
C_C - 113° orientation	0.11	
C_C - 203° orientation	0.13	

C_C - 293° orientation	0.03	
SH_n	1.00	Based on minimum SANS 204 assumptions[3].
SC_n	1.00	Based on minimum SANS 204 assumptions[3].
R_n	0.179	Minimum required R-value for climatic zone 4[1].

Notes: **1**) Climatic zones are as defined in Figure 7 above. **2**) The four building façade orientations are measured from true North and constants are defined for each orientation section as defined in Figure 3 of the SANS 204 – 3: 2008 energy-efficient building regulations (SABS - SANS 204, 2008). **3**) To meet minimum SANS 204 requirements it has been assumed that all overhangs are distanced more than 1.2 m apart from the top of each glazing element. SANS 204 specifies a value of one (1) in climate zone 4 for both SH_n and SC_n under such conditions (SABS - SANS 204, 2008).

By substituting the variables listed in Table 10 into Equation 12, each of the building façade orientation window-to-wall percentages can be calculated. These window-to-wall percentages are provided in Table 11 and demonstrated in Figure 20 below.

Table 11: Notional building window-to-wall percentage.

Building façade orientation	Window-to-wall percentage
23°	23.67 %
113°	36.63 %
203°	40.50 %
293°	30.13 %

Figure 20: 113° Façade glazing representation of the actual building (left) and the notional building (right).

Glazing element shading in the notional building is the same as with the actual building. Neither SANS 204 nor the GSSA-PEB rating tool specifies shading for notional buildings other than the actual fitted data.

3.4.2.2. Building Electrical Loads

Both the actual and notional buildings were simulated with the same equipment loads (refer to Appendix E). All assumptions in the calculation of equipment loads and thermal effects incorporated in the notional building simulation model were the same as for the actual building (refer to Section 3.3.2.2 above).

The GSSA-PEB rating tool's internal lighting power densities, as specified by the *UK Department of Communities and local Government: National Calculation Method* (DCLG, 2008), was used for the notional building. This was achieved by matching each building zone with the most relevant GSSA-PEB rating tool category.

The general methodology of the GSSA is to encourage the use of energy-efficient lighting designs whilst achieving the appropriate light intensity levels. Typical GSSA lighting intensity specifications are 400 lux at a working desk and 100 lux in walkways (GBCSA, 2008). For an education building, therefore, the notional building has a relatively low lighting power density of 9.76 W/m^2.

The elevator energy usage has also been calculated according to Equation 12 above. The only difference in elevator energy usage between the notional and actual building is that the GSSA-PEB tool specifies a 10kW elevator drive motor for each elevator installed in the building. By substituting the 5.6 *kW* KONE drive motor with a 10 *kW* GSSA-PEB specified motor; the annual elevator energy consumption is calculated as 32.850 MW.

DHW energy use was furthermore calculated according to Equation 13 with the same volume of water as the actual building DHW, but with five (5) per cent less efficiency. This results in an annual DHW power consumption of 7.994 *MWh*.

3.4.2.3. HVAC

All HVAC system design parameters for the notional SANS 204 building were based on SANS 204 (2008) specifications, as specified by the GSSA-PEB tool. These parameters are shown Table 12 below.

Table 12: Notional building HVAC design parameters (GBCSA, 2010) (SABS - SANS 204, 2008).

Design parameter	Value
Cooling	Provided by air- cooled chiller with performance characteristics based on Figure 22. Supply air temperature is 12°*C*.
Heating	Thermal electric reheat. Supply air temperature is 30°*C*.

Chilled water pumps	Pump power consumption is based on 349 *W/l/s*.
Air handling units	Fan power is 2.1 *W/l/s*. This includes all losses associated with supply and extraction fans.
Fresh air fans	Fan power consumption is based on 1.6 *W/l/s*.

The air distribution system used for this building is based on a variable air volume (VAV) supply system. Due to the ability to supply air according to the demand of each zone, these systems are more efficient that constant volume systems.

Air supply and -demand in a VAV system are managed by controlling the central fan speed to maintain static pressure in the air ducts and by adjusting the dampers in the VAV control boxes located in each air-conditioned zone (Moult, 1999). These VAV terminal units in the notional building simulation model were configured to restrict air supply to a minimum of 30% of the designed air flow to each zone.

Heating in the notional building is provided by terminal reheat coils in the zone terminal unit, as prescribed by the GSSA-PEB rating tool. Further GSSA-PEB requirements incorporated into the notional building HVAC design were to ensure that no HVAC system heat recovery is done and no economisers are used for energy demand reduction. Air distribution or leakage losses were furthermore not accounted for in the ventilation system and HVAC system controls were set to prevent both the heating and the cooling of air at the same time.

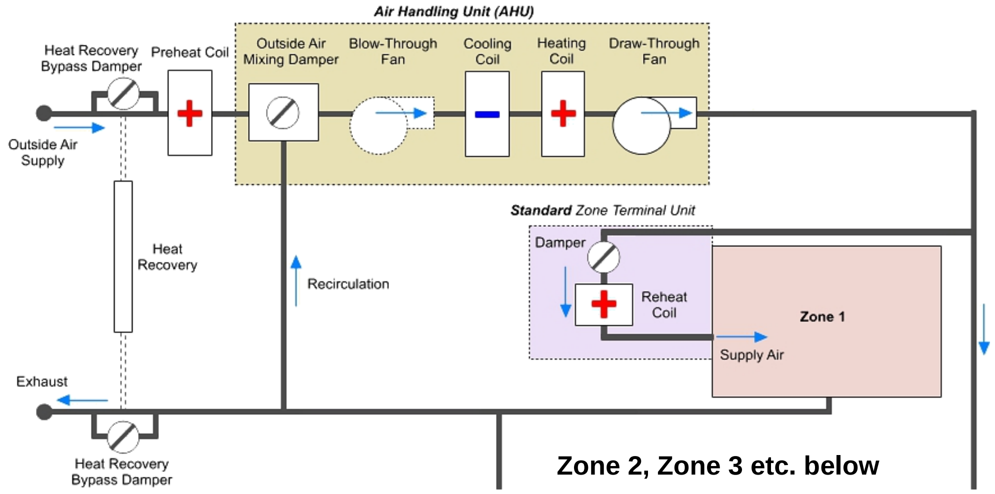


Figure 21: VAV air handling unit (adapted from DesignBuilder, 2010).

The notional building's chiller performance characteristics are based on the ASHRAE standard 90.1-2007 and rated at COP $\geq$ 2.80 and IPLV $\geq$ 3.05 (ASHRAE, 2007). These notional chiller operational performance characteristics are depicted in Figure 22 below.

A full performance analysis and comparison of the actual and notional building chillers is presented in Section 3.5 below.

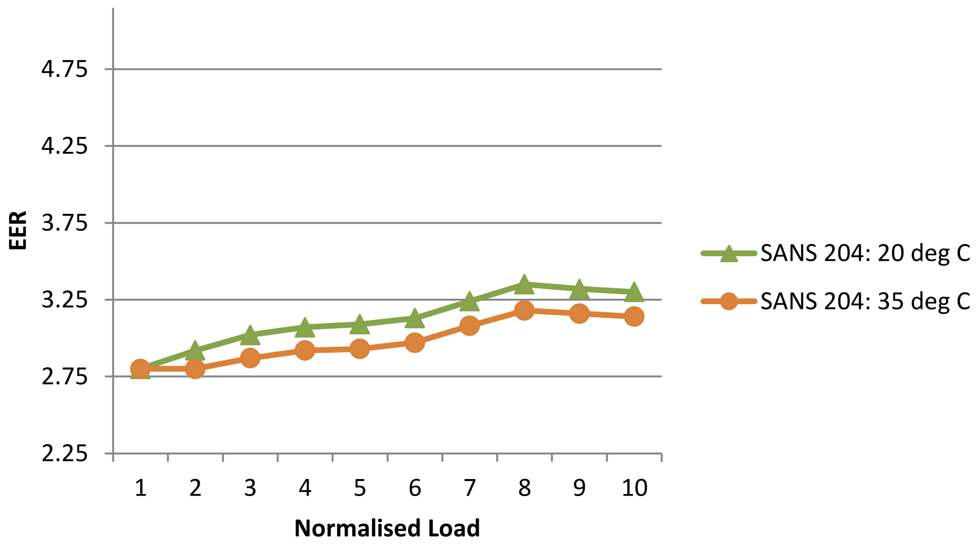


Figure 22: Notional building chiller performance curve (GBCSA, 2011).

3.5. Simulation Data

3.5.1. Simulation Methodology

DesignBuilder was used to determine the fabric and ventilation performance data; internal gains; and occupants' comfort assessments on both buildings. Raw EnergyPlus data was however used to determine the annual HVAC energy consumption information. This approach was chosen due to the small HVAC result interpretational differences between EnergyPlus and DesignBuilder.

The convection algorithms used in both buildings were the EnergyPlus Adaptive Convection Algorithm (2010) for inside convection and the DOE-2 Convection Algorithm (EnergyPlus, 2010) for outside convection. Internal environment control was achieved by controlling the air and not the operative temperature. All surrounding buildings were furthermore included in shading calculations and the effects of shading and reflections were included in the measurement of ground-reflected solar.

The notional building's energy flow data was calculated by editing the raw EnergyPlus input file produced by DesignBuilder to reflect the operating conditions of the SANS 204 chiller. After running the EnergyPlus simulation, the data was imported back into DesignBuilder for building fabric- and comfort assessments. Notional building HVAC data was however interpreted directly from the EnergyPlus output file.

Chiller interpretation of the actual building was done in DesignBuilder; the editing of raw EnergyPlus data was therefore not necessary. Only the HVAC pump energy consumption was calculated in the actual building EnergyPlus file.

The mechanical ventilation fan's airflow rate in the actual building was determined by substituting the fan-coil ventilation system with a VAV system and re-simulating the model with EnergyPlus. This was done because it is assumed that the air supply of each fan-coil unit will be varied according to the demand in each zone.

Heating energy in the actual building was furthermore calculated by defining a simple HVAC system that has all the characteristics of the actual system, but with the ability to accommodate different COP heating values for each zone (refer to Appendix F, Table 26).

Table 13: Simulation results data origination.

Category	**Data origination**	
	Actual building	**Notional building**
Building fabric and ventilation performance	DesignBuilder model	DesignBuilder model
PMV comfort	DesignBuilder model	DesignBuilder model
Heating	DesignBuilder model with simple HVAC system definition	DesignBuilder model
Cooling	Raw EnergyPlus data	Raw EnergyPlus data
Pumps	Raw EnergyPlus data	Raw EnergyPlus data
Fans	Raw EnergyPlus data from VAV HVAC DesignBuilder model	Raw EnergyPlus data
Extract & Misc. fans	GSSA-PEB calculation	GSSA-PEB calculation
Lighting	DesignBuilder model	DesignBuilder model
Equipment	DesignBuilder model	DesignBuilder model
Vertical transportation	GSSA-PEB calculation	GSSA-PEB calculation
DHW	GSSA-PEB calculation	GSSA-PEB calculation

The first design stage data of the actual building used in this study included no on-site renewable energy sources. No annual energy deductions were therefore made to the actual building in the comparative analysis between the actual and notional building (refer to section 2.5.3).

3.5.2. Simulation Results

Building energy performance evaluations are done by assessing the contribution that each of the more significant building elements has on the annual energy consumption. The energy performance of each of these elements in the actual building is also compared to the corresponding element in the notional building. This comparative analysis will furthermore provide a clear insight into where both efficient and inefficient design choices were made in the actual building.

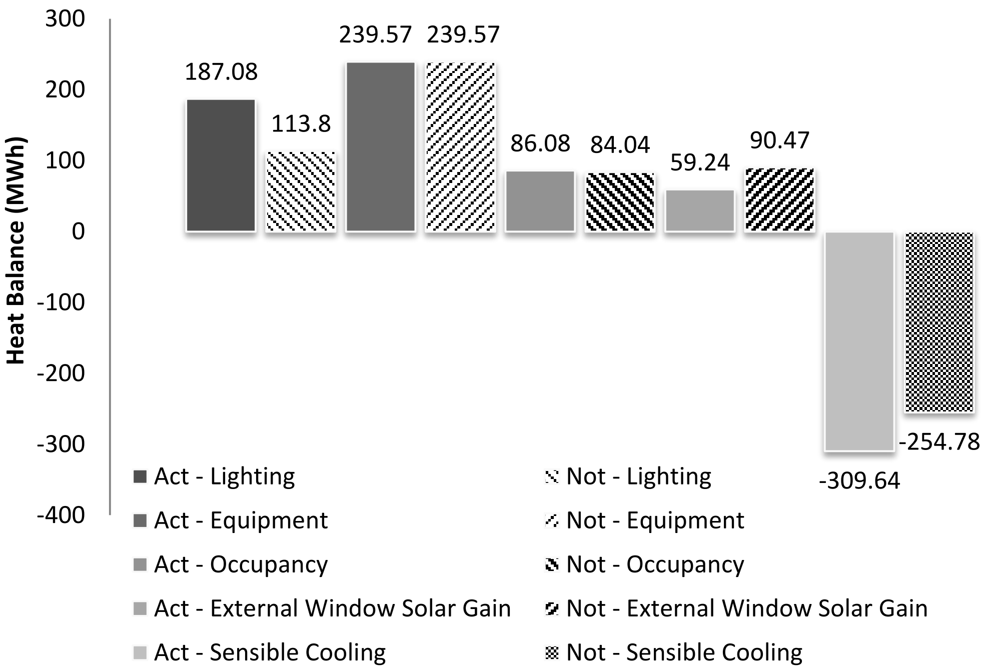


Figure 23: Annual building internal heat gains comparison between the actual ("Act") and notional ("Not") building.

From Figure 23 it is clear that the annual internal lighting power consumption of the actual building is far higher than that of the notional building. This large difference is the result of a 62.9% higher average designed lighting power density in the actual building than prescribed by the GSSA-PEB rating tool for the notional building.

The 73.28 *MWh* annual lighting energy difference furthermore has negative impacts on the overall building energy consumption. As a large amount of the lighting energy is transformed into heat energy, the HVAC system needs to work much harder to get rid of the excess thermal energy produced. To put this into perspective was the lighting power density of the actual building changed to reflect the lighting power density of the notional building. The findings are that a 73.28 *MWh* annual lighting energy difference translated into 104.27 *MWh* difference in annual electric energy consumption when the extra HVAC energy needed was included.

A further observation made from Figure 23 is that the notional building has considerably more solar thermal energy gain than the actual building. The reason for this can be found by comparing the glazing SHGF (Table 6 and Table 9) and area (Table 4 and Table 11) in each building. This data indicates that the substantial difference between solar heat gain of the notional and actual building is a result of a larger glazing area, higher SHGF and higher thermal conduction capacity of the glazing elements in the notional building. Figure 24 however shows that these properties of the notional building glazing elements also result in more heat loss in the winter.

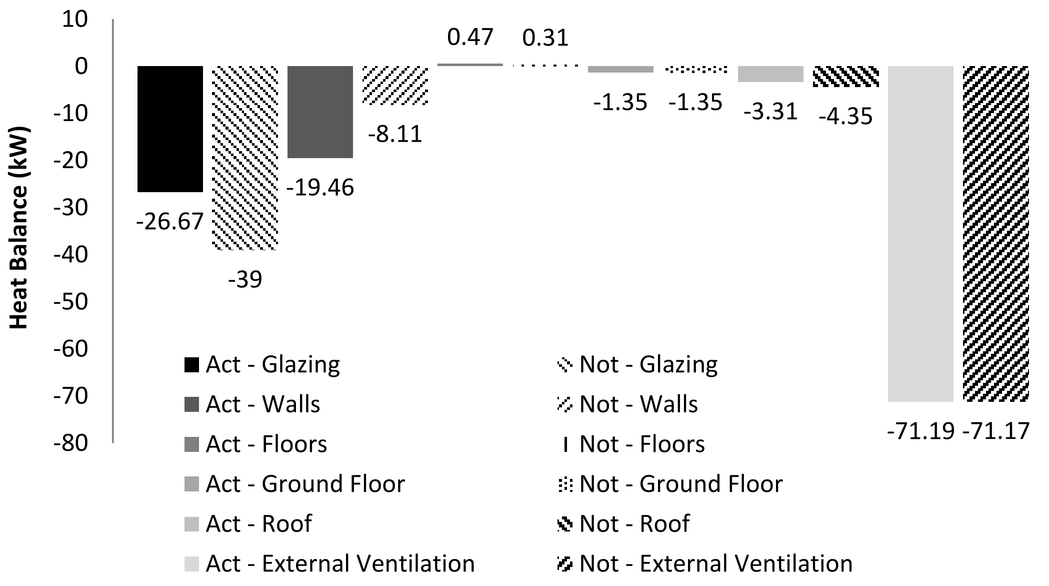


Figure 24: 3.8° Celsius building fabric performance comparison between the actual ("Act") and notional ("Not") building.

From Figure 24 one also notices the large difference in heat loss through the external walls. This can be attributed firstly to the 1.188 m^2K/W difference in external wall thermal insulation between the notional and actual building; and secondly to the difference in external wall area as a result of the window-to-wall ratios.

Another fairly significant difference between the fabric performance data of the actual and the notional building is the roof insulation. The actual building roof is 23.7% better-insulated than the notional building roof, and thus permits less heat flow to occur in the winter.

Figure 24 furthermore shows the heat energy storage capabilities of the thermal mass in the building floors (excluding the ground floor) and the effect of ground temperatures on the ground floor. The reason why the ground temperatures have a large impact on the ground floor is because the actual building ground floor design incorporates no insulation layers. Heat loss through the ground floor in this building, however, is beneficial due to the large internal heat loads.

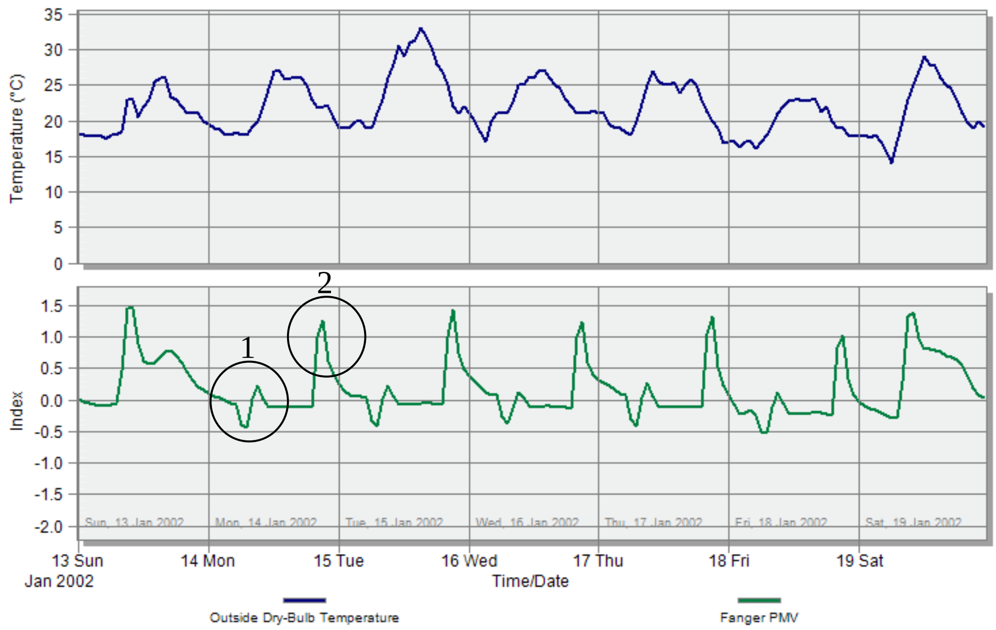


Figure 25: Actual building Open Plan Office 2 summer design week PMV.

The typical occupant comfort to be expected in Open Plan Office 2 on the fourth floor of the actual building (refer to Appendix B) during a typical hot summer week in January is shown in Figure 25 above. The comfort level pursued in this zone is a PMV index of zero (0) during occupancy hours to ensure an optimally comfortable environment for the occupants (refer to Section 2.2).

Because the HVAC system has the largest impact on occupant comfort in a mechanically air-conditioned building, the operational characteristics of the HVAC system are typically reflected in the PMV index. This is also evident in the PMV data presented in Figure 25 where the GSSA-PEB rating tool occupancy hours specified for this zone range between 7am and 8pm on weekdays.

The cooling overshoot shown in data point 1 of Figure 25 can be attributed to a relatively small zone served by a fan-coil unit that has the ability to cool the zone at a faster rate as opposed to a big central unit with more thermal inertia. This slow response of the high thermal inertia in the notional building's central VAV HVAC system is seen in the PMV data of Figure 26 for the same zone and timeframe as the actual building data of Figure 25 above.

Data point 2 in Figure 25 shows a rapid internal environment temperature change when the HVAC system is turned off. This steep decline in thermal comfort can be attributed to the combined effect of thermal energy stored in the external building envelope and the outdoor temperature.

Further detailed simulation analysis results for Open Plan Office 2 are given in Appendix H. This was done to evaluate the annual energy performance of the building fabric and systems on a zone level.

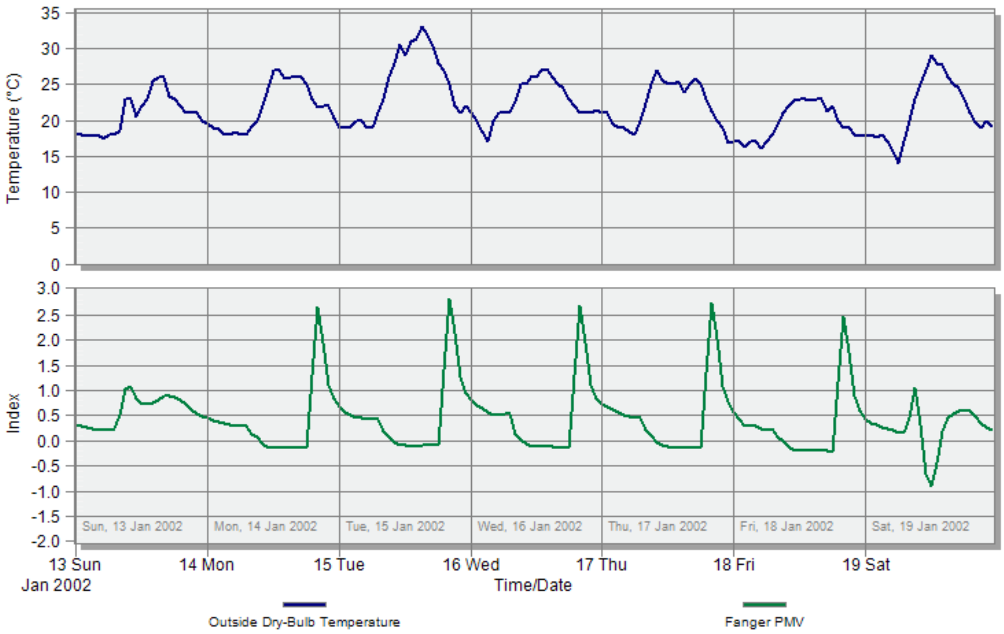


Figure 26: Notional building Open Plan Office 2 summer design week PMV.

As mentioned in Section 3.2.5 above, all building occupancy and operational loads are controlled by fixed schedules. The effects that these schedules have on heat gain in both buildings, and the resulting cooling energy needed to create a comfortable environment, are seen in Figure 27 and Figure 28 below.

These figures also show that collective heat gain of the building's operational loads far exceeds the heating energy required throughout the largest part of the day. There is however a short period in the morning when HVAC heating energy is needed. This period spans between the time when the HVAC system is switched on and the time when the combined thermal effect of the building operational loads and solar energy exceeds the building heating requirement.

These figures furthermore illustrate why a central VAV unit is more energy-efficient than numerous small fan-coil units. This energy efficiency advantage is due to an intelligent whole-building supply and demand control system; less fan and piping losses; and the dampening effect caused by a large amount of thermal inertia in the VAV ventilation system.

Neither the notional building- nor the actual building HVAC system incorporates economisers. This implies that both the actual and notional building will have to provide cooling energy through the HVAC system to balance the heating effects of operational loads. The reason for this is that constant partial recirculation occurs in the ventilation system of both buildings and only a fraction of the air is replaced with fresh air (depending on zone occupancy). The resulting relatively warm combination of fresh and recirculated air therefore requires HVAC cooling energy through most of the winter.

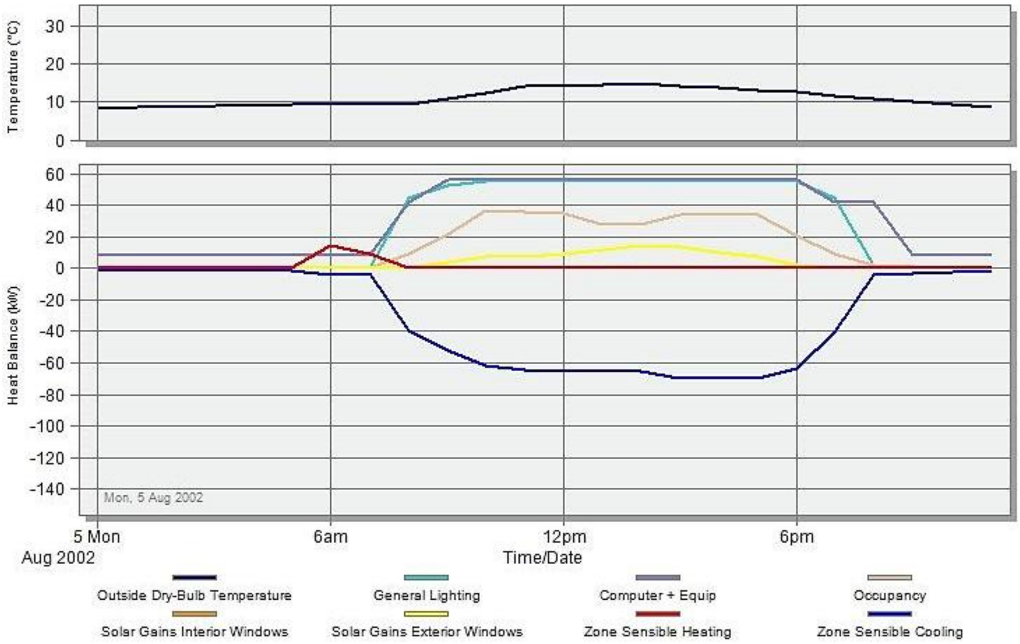


Figure 27: Actual building typical winter day hourly internal gains.

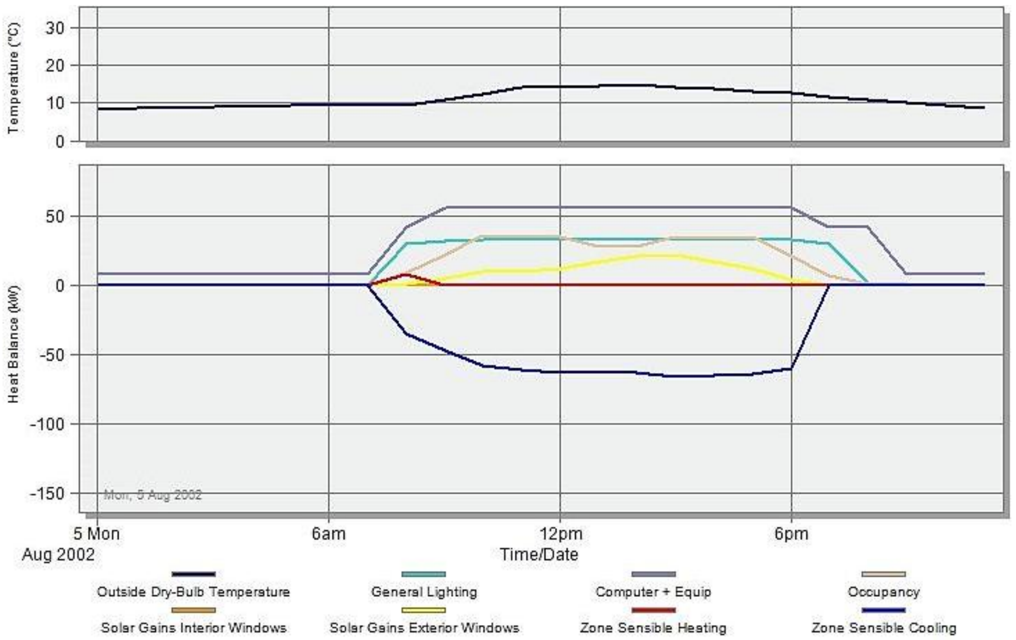
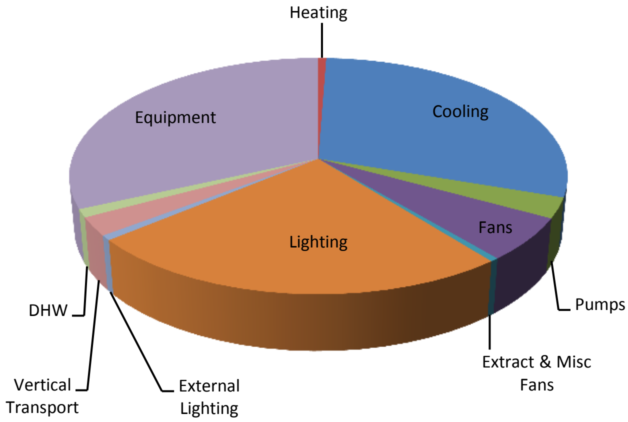


Figure 28: Notional building typical winter day hourly internal gains.

The contribution of each energy category to the annual energy consumption of both buildings is depicted in Figure 29 below. It should however be noted that this building energy performance analysis is based on typical operational conditions derived from GSSA-PEB tool requirements and will therefore only be an approximation of the annual energy consumption per category.



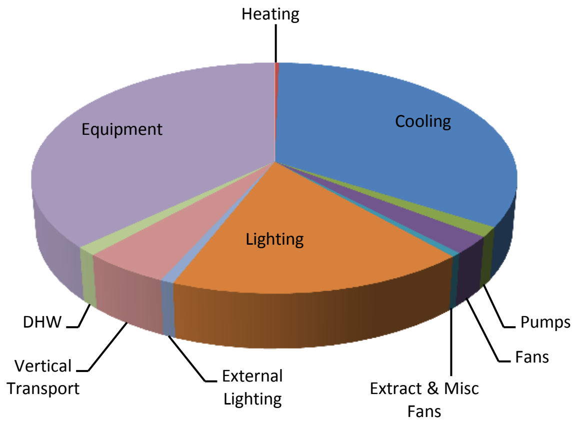


Figure 29: Energy consumption category comparison between the actual building (top) and the notional building (bottom).

It should furthermore be noted that both models incorporated deviations from the GSSA-PEB rating tool to do a more realistic building energy performance comparison. Due to the large difference in lighting energy requirements and the relatively small possible impact of the GSSA-PEB rating tool deviations, however, this building does not fulfil the conditional requirements of the GSSA-PEB rating tool (refer to Section 2.5.1), given that no renewable energy is generated on-site.

Table 14 below shows the results of a comparative annual building energy performance assessment done between the actual and notional building. The actual building energy performance percentage of each category listed in Table 14 is calculated as a percentage the difference in energy consumption between the actual and notional building in each category, has on the total annual energy consumption of the notional building.

Table 14: Actual building's energy performance evaluation.

Energy category	Actual building annual electrical energy use (kWh)	Notional building annual electrical energy use (kWh)	Actual building energy performance
Heating	4503	2124	-0.37%
Cooling	224786	219324	-0.84%
Pumps	21212	9120	-1.86%
Fans	44752	16360	-4.36%
Extract & Misc. Fans	3706	3794	0.01%
Lighting	187078	113800	-11.25%
External Lighting	5077	5077	0.00%
Vertical Transportation	19053	32850	2.12%
DHW	7573	7994	0.06%
Equipment	241062	241062	0.00%
Total	**758802**	**651505**	**-16.47%**

The carbon footprint of both buildings is calculated by using the conversion factor of 1.2 $kg\ CO_2/kWh$ provided by ESKOM (2007). This results in an annual carbon footprint for the actual building of 911 ton CO_2 and 782 ton CO_2 for the notional building.

A further comparative analysis was done to determine the energy performance of the building area that the new Centre for Renewable and Sustainable Energy Studies (CRSES) will occupy. The zones included in this assessment are shown in Table 27, Appendix G. It should however be noted that this assessment only gives an indication of the energy performance of the zones which CRSES is comprised of and does not take into account the effect of the other adjacent building zones. Simulation results of this analysis are shown below in Table 15.

The actual building CRSES energy performance difference depicted in Table 15 gives an indication which energy category has the largest influence on the overall energy performance comparison between CRSES in that actual and CRSES in the notional building.

Table 15: Actual building's CRSES area energy performance evaluation.

Energy category	**Actual building CRSES annual electrical energy use (kWh)**	**Notional building CRSES annual electrical energy use (kWh)**	**Actual building CRSES energy performance**
Heating	647	228	-0.06%
Cooling	42447	38758	-0.57%
Pumps	3987	1560	-0.37%
Fans	8835	3450	-0.83%
Extract & Misc. Fans	2746	2397	-0.05%
Lighting	20621	19391	-0.19%
DHW	1807	1908	0.02%
Equipment	44521	44521	0.00%
Total	**125611**	**112213**	**-2.06%**

The data presented in Table 15 shows that the primary reason for the 2% higher energy use in the actual building is the difference in energy requirement of the HVAC systems. This difference is for the most part the result of a more efficient VAV HVAC system installed in the notional building and to a lesser extent the slightly better building fabric performance in the notional building CRSES zone.

4. PARAMETRIC ANALYSIS

As a result of the large energy performance differences between the actual and notional building, a parametric analysis was done to investigate the possibility of improving the actual building energy performance. The objective of this analysis was to determine the effect that a change in building fabric and building systems operational efficiency may have on the annual energy consumption of the building. Each of these possible improvements was assessed in three main categories, which are building fabric, HVAC and lighting.

4.1. Building Fabric

The building fabric properties identified in Section 3.5 as elements in the actual building that have the most room for improvement are as follows:

- External wall insulation and thermal mass properties;
- Glazing type and building wall-to-window ratio; and
- Roof insulation properties.

4.1.1. External walls

External wall insulation and thermal mass properties were changed by filling the 50mm air cavity between the two 110mm brick layers of the actual building external walls with materials that has different thermal resistance and mass properties. Each of the filling materials chosen for this parametric wall test was materials that can be used to fill the air cavity at an advanced stage of construction.

Table 16 below shows the results of an annual energy performance comparison on the actual building where the external wall properties was changed for each parametric simulation. The energy performance difference depicted in this table shows an annual energy performance improvement as a negative difference and vice versa.

Table 16: Annual building energy performance in terms of external wall's cavity-filling material.

Cavity filling material	Total wall R-value (m^2K/W)	Annual energy performance difference (kWh)
Dense concrete	0.87	-10190
Aerated concrete	1.00	-2987
Air	1.01	0
EPS polystyrene	1.92	2700
Polystyrene beads	2.22	3304

From Table 16 it can be seen that walls with a better insulation increases annual energy consumption in this building. This anti-insulation behaviour can predominantly be attributed to the large internal heat load generated by building operational loads; a relatively warm climate throughout the year; and the cooling set-point temperature of the HVAC system. Masoso & Grobler (2008) describe this behaviour as a “point of thermal inflection” where a higher thermal resistance of the external building fabric insulation increases the annual energy consumption of the building.

The reason why the aerated and dense concrete cavity filling reduces annual energy consumption may be contributed to the combination of an increase in thermal mass and, to a lesser extent, the reduction of thermal resistance. An increase in thermal inertia of building walls reduces the internal air temperature variation of the building, and thus lowers the mechanical air-conditioning load (Balaras, 1995). Effective utilisation of this natural cooling and heating source is however greatly influenced by the thermodynamic properties of the materials that the thermal mass are composed of; the level of thermal mass access; and the heat transfer efficiency between the zone and the thermal mass (Shaw, et al., 1994).

4.1.2. Glazing

The actual building’s glazing properties were evaluated by determining the effect of a variation in external window-to-wall ratio and glazing type. Figure 30 below shows the annual energy consumption increase as a function of window-to-wall ratio.

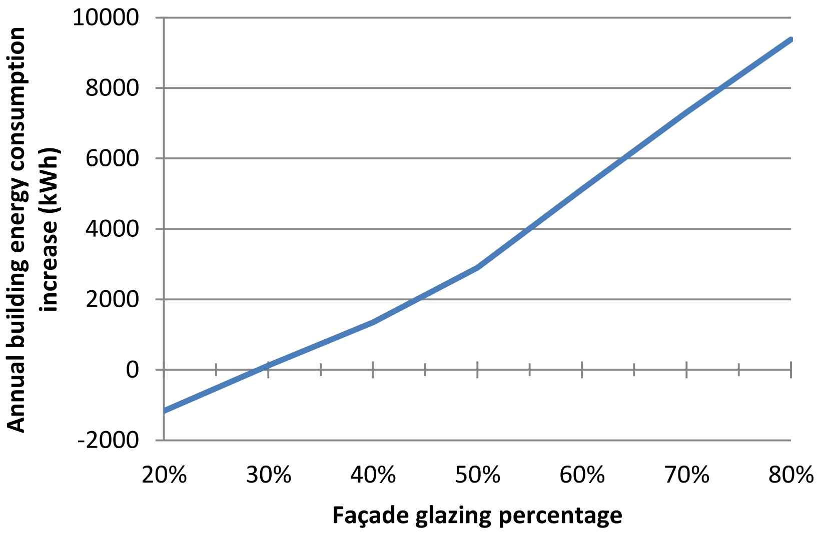


Figure 30: Building façade glazing effect on annual energy consumption.

Figure 30 above shows that increasing the façade glazing by more than 28% will increase the annual energy consumption of the building. The primary reason for this is that an increase in window area results in an increase of internal solar heat gain and a reduction in the amount of thermal mass due to a smaller external-wall area. A secondary reason is that at higher glazing percentages the amount of heat loss through the glazing area increases rapidly and as a result, increases the mechanical air-conditioning load. The reason for this heat-loss increase is that the window thermal resistance is lower than the wall thermal resistance it replaces.

A further glazing parametric analysis was conducted to determine the effect of replacing the actual building glazing type, as shown in Table 17. The actual building glazing incorporates both single and double glazing windows, which leads to the double SHGF and thermal resistance values shown in the first row of Table 17.

Table 17: Annual building energy consumption increase in terms of building glazing type.

Glazing Type	SHGF	Glass R-value (m^2K/W)	Energy performance difference (kWh)
Actual glazing	0.775 single	0.173 single	0
	0.604 double	0.372 double	
Double LOE clear 6mm/13mm air	0.568	0.568	3404
Single clear 3mm	0.861	0.170	4131
Single clear low iron 5mm	0.898	0.172	5518
Double clear 3mm/13mm air	0.764	0.368	6477

It should be noted that Table 17 does not include the effect of window frames and only evaluates a few standard glazing types. The comparative energy consumption results presented in Table 17, however, shows that the actual building glazing will outperform the other glazing types analysed.

4.1.3. Roof

To determine the effect the roof has on the overall annual energy consumption of the building, different insulation thicknesses in the actual building roof were evaluated. The insulation material for which the thickness is varied in the actual building roof is 50 kg/m^3 glass wool. Table 18 below presents the results of this evaluation.

Table 18: Annual building energy performance in terms of roof insulation properties.

50 kg/m^3 glass wool roof insulation thickness	Roof R-value (m^2K/W)	Energy performance difference (kWh)
26mm	2.58	224
63mm	3.58	95
100mm	4.58	0
130mm	5.58	-26
167mm	6.58	-79

From Table 18 it is evident that a variation in roof insulation properties has a minimal effect on the total annual energy consumption of the building. The local energy consumption and occupant comfort impact on the fourth-floor and mezzanine will however be higher. An R-value of lower than 2.5 was thus not considered for the evaluation to ensure that the occupant comfort index experienced on the mezzanine is taken into account.

4.2. Lighting System Efficiency

As mentioned in Section 3.5, a simulation model was created to determine the annual energy consumption of the actual building when the actual building's lighting system is replaced with the lighting system of the notional building. The reason for this analysis is that the notional building lighting system has a significantly smaller installed lighting capacity of 33 350 *kW* compared to the 55 062 *kW* of the actual building (refer to Appendix C).

The simulation results revealed that the 21 712 *kW* excess lighting power installed in the actual building translates into an annual lighting energy consumption difference of 73 278 *MWh*. This excess lighting power furthermore results in a HVAC load increase of 30 992 *kWh*.

The total annual energy consumption difference between the actual and notional building is 108 188 *kWh*. The difference however between the annual energy consumption of the actual building and the actual building with a notional building lighting power density is 104 270 *kWh*. Therefore, by only reducing the lighting energy density of the actual building to the lighting energy density of the notional building, the resulting energy performance difference between the two buildings is reduced to only 0.6%.

From a cost perspective would a 62.9% reduction in the lighting power density of the actual building not necessarily imply a lower initial capital expenditure. The cost implications however of reducing the annual energy consumption of the actual building by reducing the lighting levels to the levels specified for the notional building over the projected lifetime of the building is significant. To put this into perspective was a 5 year cost analysis done where zero (0) excess initial capital expenditure is assumed and a fixed annual operational and maintenance cost of R 16 500 is deducted (2% of total lighting cost). The results of this analysis are shown in Table 19 below.

Table 19: Cost summary of lighting system energy reduction.

Year	Present value of annual income/expense(1)	Net present value	Annual electricity price increase(2)	Electricity price per kWh (3)
2011	R 0.00	R 0.00	-	R 1.14
2012	R 94 785.00	R 94 785.00	25.90%	R 1.44
2013	R 114 158.57	R 208 943.57	10.00%	R 1.58
2014	R 117 582.44	R 326 526.02	10.00%	R 1.74
2015	R 120 972.70	R 447 498.71	10.00%	R 1.91
2016	R 124 335.89	R 571 834.61	10.00%	R 2.10

Note: **1**) Annual income calculated by determining the energy cost equivalent of 104,270 MWh. **2**) The first year price increase was determined from ESKOM (2011) data. Price increases for year two and further was estimated at 10% annually. **3**) Data obtained from Krige (2011).

The annual cost savings presented in Table 19 was determined by calculating the present and net present value of an annual energy saving of 104,270 *MWh* when the effect of rising electricity costs and inflation is included. The net present value (*NPV*) of money used in Table 19 abides by the following formula:

$$NPV = \sum_{i=1}^{N} \frac{R_i}{(1+DCR)^i} \tag{16}$$

In equation (16), *R* is the net cash flow of each year, *N* is the time in years and *DCR* is the opportunity cost of capital or discount rate. For the *NPV* values presented in Table 19, was a annual *DCR* of 8% used to reflect the estimated inflation for the next five years and the net cash flow used as the annual energy cost equivalent of 104 270 *MWh.* The present values shown in Table 19 above gives an indication of what the value of the energy cost saving each year is when it is discounted to the year 2011. These values were calculated by using *N* = 1 in Equation 16 for each specific year.

4.3. HVAC System Efficiency

A further parametric simulation was done to determine the difference in annual energy consumption that the actual building will have when it's fan-coil HVAC system is replaced with a VAV system. The addition of a temperature-controlled economiser to the VAV HVAC unit was also evaluated. The results of this parametric analysis are presented in Table 20.

Table 20: Annual building energy performance in terms of HVAC system configuration.

HVAC system type	**Energy performance difference (kWh)**
Fan-coil	0
VAV	-103517
VAV & economiser	-106847

From Table 20 the benefits of having a large central VAV HVAC unit that adjusts supply according to demand are evident. In this parametric simulation, however, it is assumed that the fan-coil HVAC incorporates constant volume fans and that the VAV HVAC system is operating at optimum efficiency with no sensor errors. The annual energy performance results depicted in Table 20 therefore shows that the efficiency of the actual building HVAC system in the first design phase can be improved considerably.

A preliminary analysis was done to determine the financial viability of substituting the fan-coil HVAC system in the actual building with a VAV system. The cost implications for changing the system design are given in Table 21 below.

Table 21: Cost implications for changing HVAC system designs

Actual building HVAC system design cost	R 3 874 000[(1)]
VAV system cost for actual building	R 4 444 000[(1)]
Annual energy saving when substituting the fan-coil HVAC system with a VAV HVAC system	103 517 *MWh*
Annual discount rate (including inflation)	8%
Annual operational and maintenance cost (1% of total HVAC system cost)	R 44 440

Note: **1**) Data obtained from Meyer (2011).

From Table 21 the extra capital expenditure required to change the fan-coil HVAC system design of the actual building to a VAV system is calculated as R 570 000. To determine whether this investment is worthwhile, the effect of an annual energy saving of 103 517 *MWh*, an initial extra capital expense of R 570 000 and an annual operational and maintenance cost of R 44 440 was calculated. The results for this analysis are presented in Table 22.

The financial data in Table 22 was calculated the same way as for Table 19 (refer to Section 4.2). Present and net present values presented in this table therefore shows the results of the time value of money discounted back to the year 2011 at a rate of 8%. This rate represents the annual estimated inflation rate for the next ten years.

Table 22: Cost summary of HVAC system design change from fan-coil to VAV.

Year	Present value of annual income/expense[(1)]	Net present value	Annual electricity price increase[(2)]	Electricity price per kWh[(3)]
2011	-R 570 000.00	-R 570 000.00	-	R 1.14
2012	R 68 119.80	-R 501 880.20	25.90%	R 1.44
2013	R 89 277.96	-R 412 602.25	10.00%	R 1.58
2014	R 94 459.04	-R 318 143.20	10.00%	R 1.74
2015	R 99 474.76	-R 218 668.45	10.00%	R 1.91
2016	R 104 341.39	-R 114 327.05	10.00%	R 2.10
2017	R 109 074.12	-R 5 252.93	10.00%	R 2.31
2018	R 113 687.04	R 108 434.10	10.00%	R 2.54
2019	R 118 193.31	R 226 627.41	10.00%	R 2.80
2020	R 122 605.18	R 349 232.59	10.00%	R 3.08
2021	R 126 934.08	R 476 166.67	10.00%	R 3.38

Note: **1**) Annual income calculated by determining the energy cost equivalent of 103,570 MWh. **2**) The first year price increase was determined from ESKOM (2011) data. Price increases for year two and further was estimated at 10% annually. **3**) Data obtained from Krige (2011).

The break-even point, shown in Table 22 above, for recovering the extra initial expenditure is between year six and seven. This preliminary financial analysis therefore shows that a VAV system substitution is a good investment, given that a typical building has a 50 year life-cycle.

5. CONCLUSIONS

The aim of this study was to determine and evaluate the energy performance of the new academic building to be built at Stellenbosch University. These evaluations were done by comparing the actual building's annual energy consumption with a notional building that is built according to minimum SANS 204 energy-efficient building requirements, as interpreted by the GSSA-PEB green building rating tool.

Building energy consumption improvement options identified in this study did not take into account the outcome of a comprehensive cost-benefit analysis over the lifetime of the building. The emphasis was rather placed on the reduction of energy consumption of the inefficient components in the building to a level where the GSSA energy criteria conditional requirements would be satisfied.

The energy modelling comparison revealed that the actual building is consuming 16.5% more energy than the notional building on an annual basis, and therefore does not qualify for a GSSA accreditation. However, as noted in Section 3.5, is this annual energy performance difference subject to variation as changes to the initial design may be implemented throughout the building construction phase. The annual energy consumption results of both buildings are furthermore subject to the operational profiles of general education buildings and typical loads specified by the GSSA-PEB tool due to the unavailability of actual operational data in the building design phase.

One of the primary reasons identified for the poor energy performance of the actual building in comparison with the notional building, is the designed lighting density. This internal lighting density proved to be 63% higher than the GSSA-PEB rating tool's recommended lighting density. The overall impact on the annual energy consumption proved to be even more due to the larger amount of cooling energy necessary to offset the excess heat energy produced by the luminaries.

The cause of the high lighting power density in the actual building may partially be attributed to the fact that all the lighting circuits in the building are manually triggered and in some zones multiple lighting circuits are installed, for example the lecture halls, to cater for different lighting requirements. Both these lighting design properties have negative impacts on the annual energy consumption of the building. The reason for this is that even though all the lights in the room are not switched on every time a person walks into the room, the GSSA argues that the person has the ability to switch on all the lights if no intelligent lighting control is installed (GBCSA, 2008). All the lights in a zone that has no intelligent lighting control are therefore modelled as either fully on or fully off, depending on the lighting schedule of the room.

To reduce the internal lighting density of the actual building, however, it is not just as simple as reducing the amount of luminaries. A good energy-efficient lighting design should provide the optimum balance between:

- Initial cost;
- Maintenance cost;
- Lighting power density;
- Minimum lighting level building regulations; and
- Lighting level uniformity and aesthetic appearance.

A brief financial analysis however revealed that a reduction in the lighting energy density of the actual building to the levels specified for the notional building would result in a considerable saving over the lifetime of the building.

The HVAC energy consumption in the actual building was also identified as one of the components that can significantly influence the annual energy consumption of the building. This is mostly because the ventilation system incorporated in the actual building is significantly less efficient than a variable air volume system. The parametric results presented in section 4.3 indicate that replacing the designed fan-coil system with a VAV system can reduce the annual energy consumption with 13% and result in a worthwhile investment over the building lifetime.

Comparative results of the building fabric performance furthermore revealed that the actual building performs slightly better than the notional building. The actual building's fabric parametric analysis also showed that the cavity in the building walls can be filled with concrete (or any substance with a low R-value and high thermal mass) to improve the total annual energy consumption of the building. This also emphasised the positive energy offset effect that a good thermal mass design has on the building and the anti-insulation behaviour of the building fabric.

To ensure that a GSSA accreditation for the academic building is possible, the primary focus should however be on reducing the lighting power density; improving the efficiency of the HVAC system of the actual building; and incorporating on-site renewable energy generation sources. An annual energy performance improvement over the notional building for the actual building can be accomplished by only reducing the lighting density of the building to the recommended GSSA-PEB levels and marginally improving the energy efficiency of the HVAC system.

The option of incorporating an on-site renewable as a possible energy offset for the actual building was investigated in Appendix I. PV technology was chosen for this investigation because a PV array is considered to be the only viable large on-site renewable energy generation option for the new academic building. This investigation showed that a solar system that is designed within the limits of what CRSES can afford, can deliver an estimated 24 323 kWh of clean renewable energy annually.

6. RECOMMENDATIONS AND FUTURE WORK

At the stage when this study was completed, a number of assumptions necessarily had to be made as certain design choices were still to be finalised. It is therefore recommended that the actual building simulation model be changed to reflect the final design data and re-simulated to determine if small design changes made through the design phase have enabled the building to be more energy efficient.

The comparative analysis between the notional and actual building also included a few GSSA-PEB tool deviations to more closely reflect the expected operational conditions of the building in this study. Even though the results presented in this study closely reflect the energy performance difference between the actual and notional building, the simulation model should be changed to fully conform to GSSA-PEB requirements for a full GSSA accreditation assessment.

It is furthermore recommended that the design of the lighting- and HVAC system be re-assessed with the primary aim of reducing the annual energy consumption. The energy optimisation options identified in this study should also be evaluated in terms of a full building, life-cycle cost-benefit scenario with the emphasis on obtaining a green building energy efficiency rating.

An investigation should also be launched to determine the optimum efficient operational profiles and procedures for building HVAC and electrical systems. Such energy efficiency measures would typically result in a significant reduction in annual energy consumption and life-cycle carbon emissions of the building.

It is lastly recommended that PV array on the roof of the new building (refer to Appendix I) be considered as a natural renewable energy source for on-site renewable energy generation to off-set the carbon footprint of the building.

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APPENDIX A: BUILDING FAÇADE ORIENTATION

Figure 31 below shows a plan view of the actual building model and the surrounding buildings. The shadows in the figure represents the shadows generated on a cloudless day by the building evaluated in this study and the surrounding buildings at 08:00 on the 25'th of November.

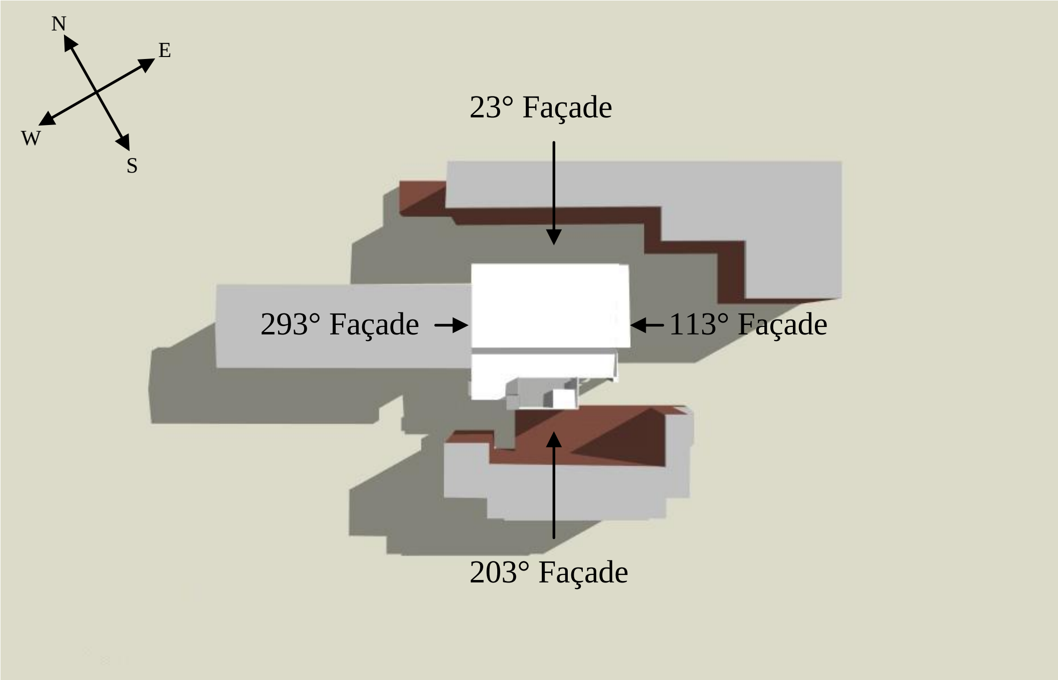

Figure 31: Plan view of actual building with façade orientation indication.

APPENDIX B: SIMULATION MODEL FLOOR PLANS

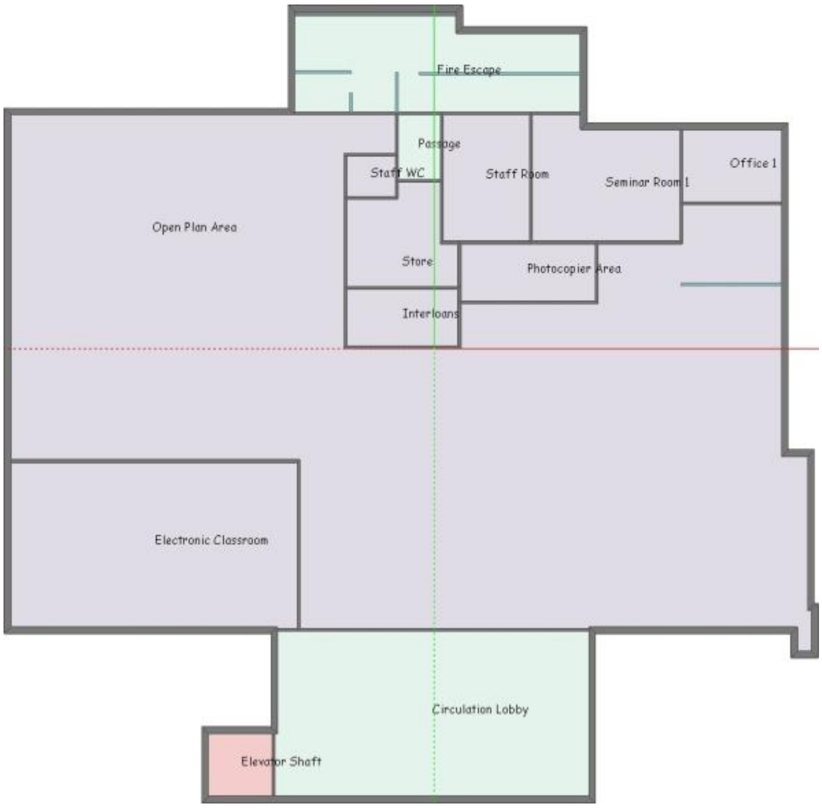

Figure 32: Floor 1 - Library.

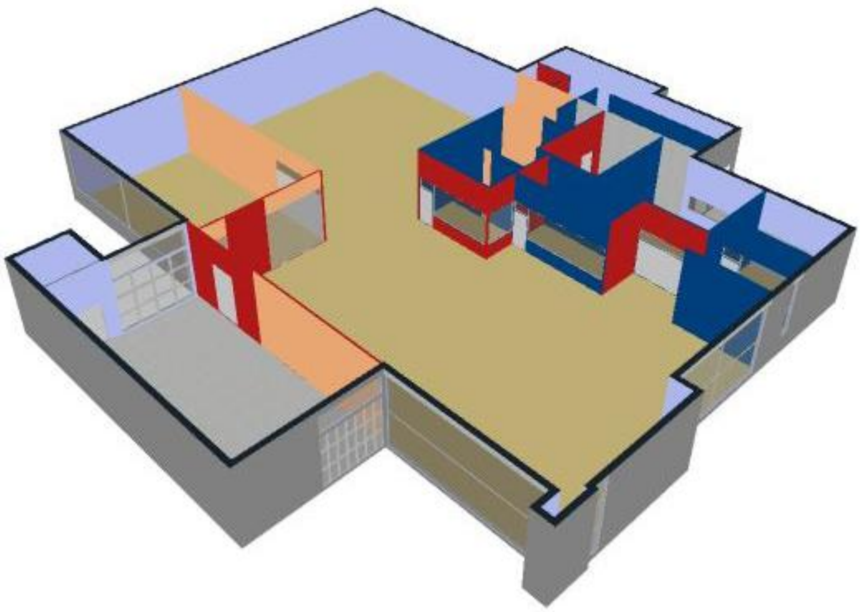

Figure 33: Three dimensional representation of floor 1.

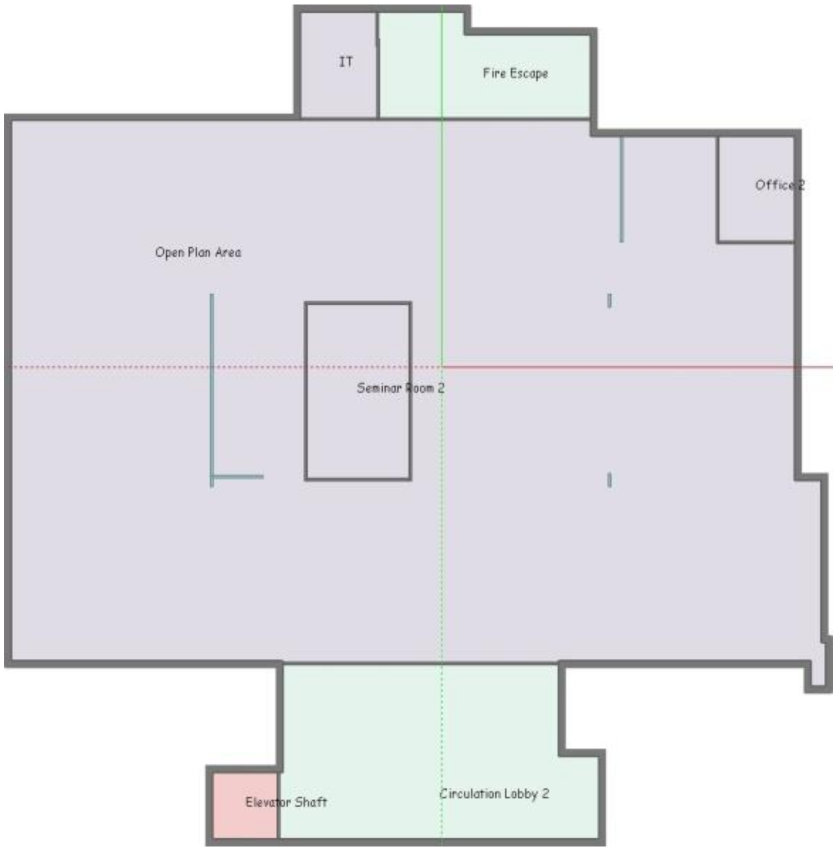

Figure 34: Floor 2 - Library.

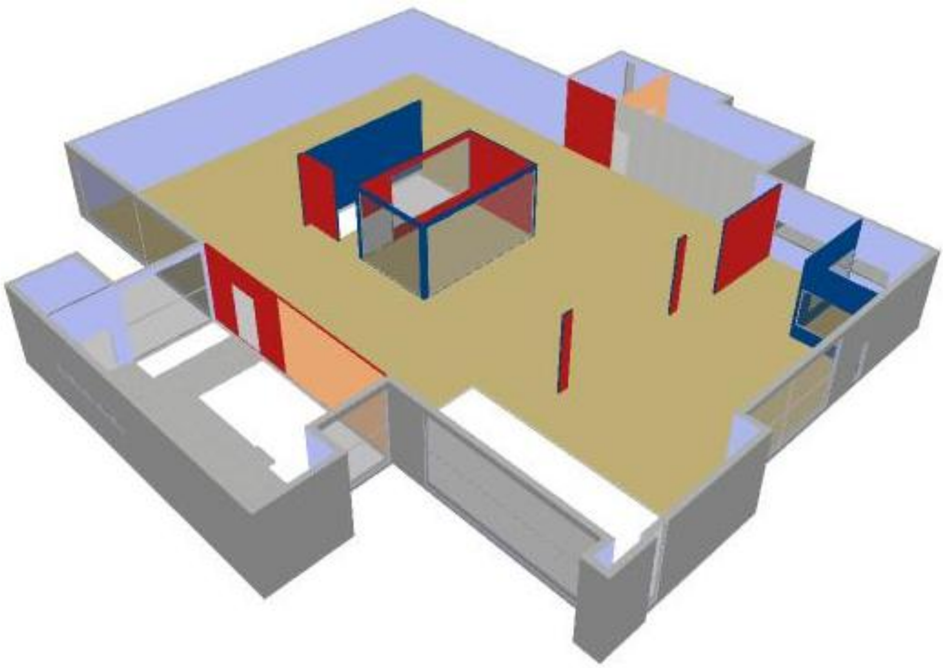

Figure 35: Three dimensional representation of floor 2.

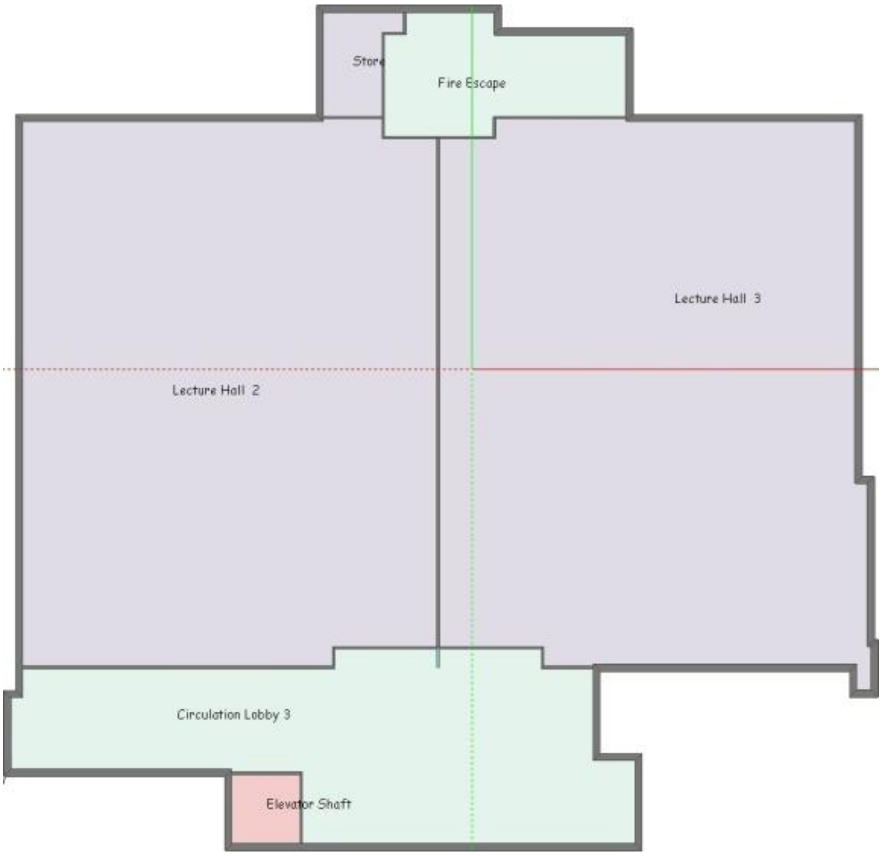

Figure 36: Floor 3 - Lecture halls.

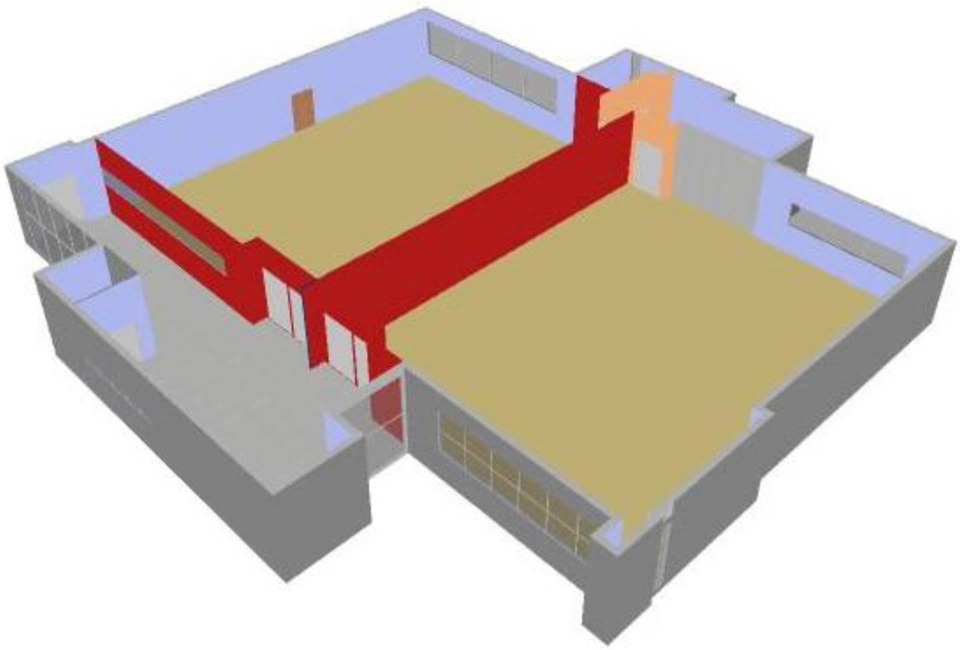

Figure 37: Three dimensional representation of floor 3.

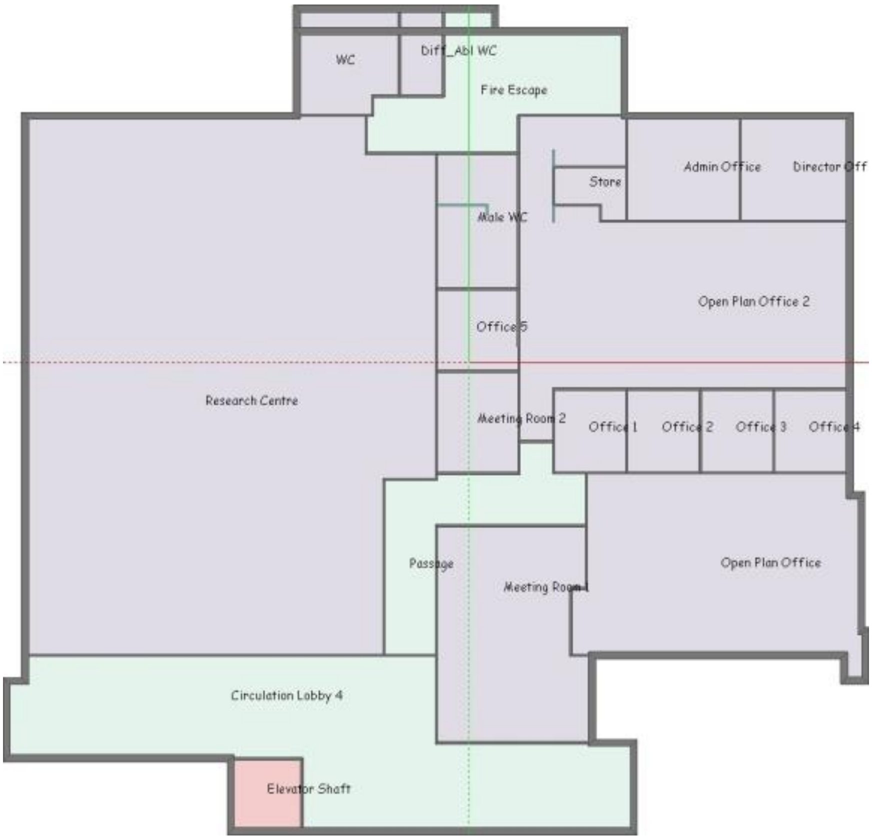

Figure 38: Floor 4 - MIH and CRSES.

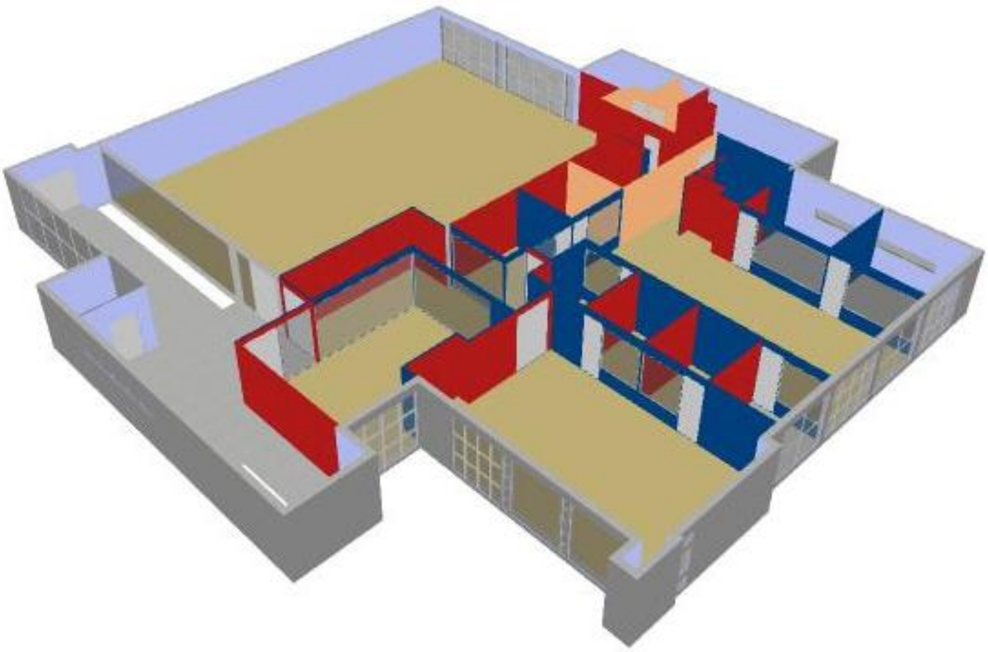

Figure 39: Three dimensional representation of floor 4.

APPENDIX C: ACTUAL BUILDING LIGHTING DESIGN

Table 23: Lighting design comparison between actual design and GSSA-PEB rating tool specifications.

Building zone	Actual design light: 1X80W	Actual design light: 2X54W	Actual design light: 2X26W	Actual design light: 2X13W	Actual design light: 2X58W	Actual design light: 1X18W	Actual design light: 1X50W	Actual design light: 1X100W	Zone gross floor area (m^2)	Actual total lighting (W)	GSSA-PEB total lighting (W)	Actual lighting power density (W/m^2)	GSSA-PEB lighting power density (W/m^2)
Floor_1 - Fire Escape	3	-	-	-	5	1	-	-	42.53	838	145	19.70	3.40
Floor_1 - Seminar Room 1	-	-	-	-	-	8	-	1	28.80	244	490	8.47	17.00
Floor_1 - Office 1	-	2	-	-	-	-	-	-	12.00	216	163	18.00	13.60
Floor_1 - Open Plan Area	57	2	22	9	-	10	3	-	458.73	6484	3119	14.13	6.80
Floor_1 - Circulation Lobby	13	-	-	-	-	2	-	-	84.08	1076	286	12.80	3.40
Floor_1 - Store	2	-	-	-	-	-	-	-	16.62	160	57	9.62	3.40
Floor_1 - Photocopier Area	-	2	-	-	-	-	-	-	13.24	216	45	16.31	3.40
Floor_1 - Interloans	-	2	-	-	-	-	-	-	11.01	216	211	19.62	19.20
Floor_1 - Staff WC	-	-	-	-	-	1	-	-	3.54	18	24	5.08	6.80
Floor_1 - Passage	-	-	-	-	-	1	-	-	4.88	18	17	3.69	3.40
Floor_1 - Staff Room	2	-	-	-	-	-	-	-	18.67	160	190	8.57	10.20
Floor_1 - Electronic Classroom	-	-	35	-	-	-	-	-	77.29	1820	788	23.55	10.20
Floor_2 - Open Plan Area	68	23	20	-	-	3	-	4	533.84	9418	3630	17.64	6.80
Floor_2 - Circulation Lobby 2	13	-	-	-	-	-	-	2	42.70	1240	145	29.04	3.40
Floor_2 - Fire Escape	4	-	-	-	2	-	-	-	30.01	552	102	18.39	3.40
Floor_2 - Office 2	-	1	2	-	-	-	-	-	12.28	212	167	17.27	13.60
Floor_2 - Seminar Room 2	2	-	10	-	-	-	-	-	27.92	680	475	24.36	17.00
Floor_2 - IT	-	2	-	-	-	-	-	-	12.52	216	128	17.25	10.20
Floor_3 - Circulation Lobby 3	3	-	28	-	-	-	-	-	127.73	1696	434	13.28	3.40
Floor_3 - Fire Escape	3	-	-	-	2	-	-	-	28.70	472	98	16.45	3.40
Floor_3 - Lecture Hall 3	72	-	42	-	-	-	-	-	327.28	7944	5400	24.27	16.50

Floor_3 - Lecture Hall 2	72	-	42	-	-	-	-	-	323.38	7944	5336	24.57	16.50
Floor_3 - Store	-	-	-	-	1	-	-	-	9.74	116	33	11.91	3.40
Floor_4 - Fire Escape	3	-	-	-	1	-	-	-	26.05	356	89	13.67	3.40
Floor_4 - Open Plan Office 2	16	-	-	-	-	-	-	-	97.35	1280	1324	13.15	13.60
Floor_4 - Director Office	2	-	-	-	-	-	-	-	16.17	160	220	9.89	13.60
Floor_4 - Office 4	-	1	2	-	-	-	-	-	9.08	212	123	23.36	13.60
Floor_4 - Open Plan Office	12	-	-	-	-	-	-	-	74.41	960	1012	12.90	13.60
Floor_4 - Meeting Room 1	2	-	12	-	-	-	-	-	47.30	784	804	16.57	17.00
Floor_4 - Circulation Lobby 4	13	-	1	-	-	10	-	-	86.67	1272	295	14.68	3.40
Floor_4 - WC	-	-	-	-	-	6	-	-	14.56	108	99	7.42	6.80
Floor_4 - Diff_Abl WC	-	-	-	-	-	1	-	-	5.56	18	38	3.24	6.80
Floor_4 - Male WC	-	-	-	-	-	6	-	-	16.62	108	113	6.50	6.80
Floor_4 - Store	1	-	-	-	-	-	-	-	4.86	80	17	16.46	3.40
Floor_4 - Admin Office	2	-	-	-	-	-	-	-	17.30	160	235	9.25	13.60
Floor_4 - Research Centre	50*	-	-	-	-	-	-	-	310.40	4000	4221	12.89	13.60
Floor_4 - Passage	-	-	6	-	-	-	-	-	27.32	312	93	11.42	3.40
Floor_4 - Meeting Room 2	1	-	4	-	-	-	-	-	12.50	288	212	23.04	17.00
Floor_4 - Office 1	-	1	2	-	-	-	-	-	9.22	212	125	22.99	13.60
Floor_4 - Office 2	-	1	2	-	-	-	-	-	9.22	212	125	22.99	13.60
Floor_4 - Office 3	-	1	2	-	-	-	-	-	9.22	212	125	22.99	13.60
Floor_4 - Office 5	-	1	2	-	-	-	-	-	10.12	212	138	20.95	13.60
Mezzanine - Research Centre	16*	-	-	-	-	-	-	-	107.58	1280	1463	11.90	13.60
Mezzanine - Open Plan Office	11*	-	-	-	-	-	-	-	73.18	880	995	12.03	13.60
TOTAL	**443**	**39**	**234**	**9**	**11**	**49**	**3**	**7**	**3239**	**55062**	**33350**	**682**	**430**
AVERAGE												**15.51**	**9.76**

Note: *****) Assumption based on actual design trends due to the unavailability of data at the first design stage.

APPENDIX D: GSSA-PEB AREA CLASSIFICATION FOR NEW ACADEMIC BUILDING

Table 24: GSSA-PEB area classification for new academic building.

Zone	Cellular office	Reception	Circulation Area	Lecture hall	Staff room	Storage area	High Density IT	IT Equipment	Meeting Room	Open plan office	Toilet	Library circulation area	Zone area (m^2)
Floor_1 - Fire Escape	-	-	42.53	-	-	-	-	-	-	-	-	-	42.53
Floor_1 - Seminar Room 1	-	-	-	-	-	-	-	-	28.80	-	-	-	28.80
Floor_1 - Office 1	12.00	-	-	-	-	-	-	-	-	-	-	-	12.00
Floor_1 - Open Plan Area	-	-	-	-	-	-	-	-	-	-	-	458.73	458.73
Floor_1 - Circulation Lobby	-	-	84.08	-	-	-	-	-	-	-	-	-	84.08
Floor_1 - Store	-	-	-	-	-	16.62	-	-	-	-	-	-	16.62
Floor_1 - Photocopier Area	-	-	-	-	-	-	13.24	-	-	-	-	-	13.24
Floor_1 - Interloans	-	11.01	-	-	-	-	-	-	-	-	-	-	11.01
Floor_1 - Staff WC	-	-	-	-	-	-	-	-	-	-	3.54	-	3.54
Floor_1 - Passage	-	-	4.88	-	-	-	-	-	-	-	-	-	4.88
Floor_1 - Staff Room	-	-	-	-	18.67	-	-	-	-	-	-	-	18.67
Floor_1 - Electronic Classroom	-	-	-	-	-	-	77.29	-	-	-	-	-	77.29
Floor_2 - Open Plan Area	-	-	-	-	-	-	-	-	-	-	-	533.84	533.84
Floor_2 - Circulation Lobby 2	-	-	42.70	-	-	-	-	-	-	-	-	-	42.70
Floor_2 - Fire Escape	-	-	30.01	-	-	-	-	-	-	-	-	-	30.01
Floor_2 - Office 2	12.28	-	-	-	-	-	-	-	-	-	-	-	12.28
Floor_2 - Seminar Room 2	-	-	-	-	-	-	-	-	27.92	-	-	-	27.92
Floor_2 - IT	-	-	-	-	-	-	-	12.52	-	-	-	-	12.52
Floor_3 - Circulation Lobby 3	-	-	127.73	-	-	-	-	-	-	-	-	-	127.73
Floor_3 - Fire Escape	-	-	28.70	-	-	-	-	-	-	-	-	-	28.70
Floor_3 - Lecture Hall 3	-	-	-	327.28	-	-	-	-	-	-	-	-	327.28
Floor_3 - Lecture Hall 2	-	-	-	323.38	-	-	-	-	-	-	-	-	323.38
Floor_3 - Store	-	-	-	-	-	9.74	-	-	-	-	-	-	9.74
Floor_4 - Fire Escape	-	-	26.05	-	-	-	-	-	-	-	-	-	26.05

Floor_4 - Open Plan Office 2	-	-	-	-	-	-	-	-	-	97.35	-	-	97.35
Floor_4 - Director Office	16.17	-	-	-	-	-	-	-	-	-	-	-	16.17
Floor_4 - Office 4	9.08	-	-	-	-	-	-	-	-	-	-	-	9.08
Floor_4 - Open Plan Office	-	-	-	-	-	-	-	-	-	74.41	-	-	74.41
Floor_4 - Meeting Room 1	-	-	-	-	-	-	-	-	47.30	-	-	-	47.30
Floor_4 - Circulation Lobby 4	-	-	86.67	-	-	-	-	-	-	-	-	-	86.67
Floor_4 - WC	-	-	-	-	-	-	-	-	-	-	14.56	-	14.56
Floor_4 - Diff_Abl WC	-	-	-	-	-	-	-	-	-	-	5.56	-	5.56
Floor_4 - Male WC	-	-	-	-	-	-	-	-	-	-	16.62	-	16.62
Floor_4 - Store	-	-	-	-	-	4.86	-	-	-	-	-	-	4.86
Floor_4 - Admin Office	17.30	-	-	-	-	-	-	-	-	-	-	-	17.30
Floor_4 - Research Centre	-	-	-	-	-	-	-	-	-	310.40	-	-	310.40
Floor_4 - Passage	-	-	27.32	-	-	-	-	-	-	-	-	-	27.32
Floor_4 - Meeting Room 2	-	-	-	-	-	-	-	-	12.50	-	-	-	12.50
Floor_4 - Office 1	9.22	-	-	-	-	-	-	-	-	-	-	-	9.22
Floor_4 - Office 2	9.22	-	-	-	-	-	-	-	-	-	-	-	9.22
Floor_4 - Office 3	9.22	-	-	-	-	-	-	-	-	-	-	-	9.22
Floor_4 - Office 5	10.12	-	-	-	-	-	-	-	-	-	-	-	10.12
Mezzanine - Research Centre	-	-	-	-	-	-	-	-	-	107.58	-	-	107.58
Mezzanine - Open Plan Office	-	-	-	-	-	-	-	-	-	73.18	-	-	73.18
TOTAL	**104.61**	**11.01**	**500.67**	**650.66**	**18.67**	**31.23**	**90.53**	**12.52**	**116.52**	**662.91**	**40.28**	**992.57**	**3239**

Further information regarding the GSSA-PEB rating tool requirements for each specified area can be found by consulting the *Green Star SA – Public & Educational Building Pilot: Energy Calculator & Modelling Protocol Guide - Version 0* (GBCSA, 2011).

APPENDIX E: BUILDING OCCUPANCY AND EQUIPMENT ZONE DATA

Table 25: Occupancy and equipment data per zone.

Zone	**Average Maximum Occupancy (*People*)**	**Average Maximum Occupancy Density (*People/m²*)**	**Total Equipment Power Rating (*W*)**	**Total Equipment Energy Density (*W/m²*)**
Floor_1 - Fire Escape	5	0.120	75	1.805
Floor_1 - Seminar Room 1	5	0.174	500	17.362
Floor_1 - Office 1	1	0.083	600	50.000
Floor_1 - Open Plan Area	40	0.087	8400	18.312
Floor_1 - Circulation Lobby	10	0.119	150	1.784
Floor_1 - Store	0.5	0.030	100	6.015
Floor_1 - Photocopier Area	2	0.151	1000	75.512
Floor_1 - Interloans	2	0.182	900	81.736
Floor_1 - Staff WC	1	0.282	0	0.000
Floor_1 - Passage	0.5	0.103	10	2.051
Floor_1 - Staff Room	2	0.107	200	10.714
Floor_1 - Electronic Classroom	26	0.336	10800	139.743
Floor_2 - Open Plan Area	50	0.083	7600	12.575
Floor_2 - Circulation Lobby 2	10	0.127	100	1.275
Floor_2 - Fire Escape	5	0.167	50	1.666
Floor_2 - Office 2	1.5	0.122	800	65.157
Floor_2 - Seminar Room 2	10	0.358	900	32.236
Floor_2 - IT	1	0.080	4000	319.438
Floor_3 - Circulation Lobby 3	10	0.078	100	0.783
Floor_3 - Fire Escape	5	0.142	50	1.424
Floor_3 - Lecture Hall 3	100	0.306	800	2.444
Floor_3 - Lecture Hall 2	100	0.309	800	2.474
Floor_3 - Store	1	0.103	50	5.133
Floor_4 - Fire Escape	5	0.148	50	1.483

Floor_4 - Open Plan Office 2	10	0.103	4300	44.169
Floor_4 - Director Office	1	0.062	600	37.106
Floor_4 - Office 4	1	0.110	400	44.077
Floor_4 - Open Plan Office	18	0.242	1500	20.159
Floor_4 - Meeting Room 1	4	0.085	500	10.570
Floor_4 - Circulation Lobby 4	5	0.049	150	1.465
Floor_4 - WC	2	0.137	0	0.000
Floor_4 - Diff_Abl WC	1	0.180	0	0.000
Floor_4 - Male WC	1.5	0.090	0	0.000
Floor_4 - Store	0.5	0.103	50	10.286
Floor_4 - Admin Office	1	0.058	600	34.680
Floor_4 - Research Centre	30	0.097	5500	17.719
Floor_4 - Passage	2	0.073	100	3.660
Floor_4 - Meeting Room 2	2	0.160	200	16.001
Floor_4 - Office 1	1	0.108	400	43.375
Floor_4 - Office 2	1	0.108	400	43.375
Floor_4 - Office 3	1	0.108	400	43.375
Floor_4 - Office 5	1	0.099	400	39.522
Mezzanine - Research Centre	8	0.087	1600	17.333
Mezzanine - Open Plan Office	12	0.164	1450	19.815
TOTAL	**496.5**	**-**	**56585**	**-**
AVERAGE	**-**	**0.137**	**-**	**29.496**

APPENDIX F: ACTUAL BUILDING HVAC DATA

Table 26: Actual Building HVAC Data

Zone	A/C Cooling	A/C Heating	Supply Air (*l/s*)	Fresh Air (*l/s*)	Return Air (*l/s*)	Electric Heating (*kW*)	Fan Power (*W*)	Ventilation
Floor_1 - Fire Escape	-	-	-	-	-	-	-	-
Floor_1 - Seminar Room 1	Yes	-	354	60	294	1.5	220	-
Floor_1 - Office 1	Yes	-	245	15	230	1	225	145 *l/s* @ 150Pa
Floor_1 - Open Plan Area	Yes	Yes	2964	360	2604	-	3000	-
Floor_1 - Circulation Lobby	-	-	-	-	-	-	-	-
Floor_1 - Elevator Shaft	-	-	-	-	-	-	-	-
Floor_1 - Store	-	-	-	-	-	-	-	-
Floor_1 - Photocopier Area	Yes	-	475	60	415	1.5	152	-
Floor_1 - Interloans	Yes	-	147	10	137	0.5	78	-
Floor_1 - Staff WC	-	-	-	-	-	-	40	25 *l/s* @ 60Pa
Floor_1 - Passage	-	-	-	-	-	-	-	-
Floor_1 - Staff Room	Yes	Yes	177	*	*	-	-	-
Floor_1 - Electronic Classroom	Yes	-	1320	130	1190	6	600	-
Floor_2 - Open Plan Area	Yes	Yes	5967	655	5312	5	4576	260 *l/s* @ 150Pa
Floor_2 - Circulation Lobby 2	-	-	-	-	-	-	-	-
Floor_2 - Fire Escape	-	-	-	-	-	-	-	-
Floor_2 - Office 2	Yes	-	243	15	228	1	125	-
Floor_2 - Seminar Room 2	Yes	-	288	60	228	1.5	134	-
Floor_2 - IT	-	-	-	-	-	-	-	-
Floor_2 - Elevator Shaft	-	-	-	-	-	-	-	-
Floor_3 - Circulation Lobby 3	-	-	-	-	-	-	-	-
Floor_3 - Fire Escape	-	-	-	-	-	-	-	-
Floor_3 - Lecture Hall 3	Yes	Yes	3803	1435	3803	-	5500	-
Floor_3 - Lecture Hall 2	Yes	Yes	4187	1555	4187	-	5500	-
Floor_3 - Store	-	-	-	-	-	-	-	-

Floor_3 - Elevator Shaft	-	-	-	-	-	-	-	-
Floor_4 - Fire Escape	-	-	-	-	-	-	-	-
Floor_4 - Open Plan Office 2	Yes	Yes	1199	65	1134	-	1100	-
Floor_4 - Director Office	Yes	Yes	271	20	251	-	134	-
Floor_4 - Office 4	Yes	Yes	271	15	256	-	134	-
Floor_4 - Open Plan Office	Yes	Yes	1070	90	980	-	576	-
Floor_4 - Meeting Room 1	Yes	Yes	774	100	674	-	440	-
Floor_4 - Circulation Lobby 4	-	-	-	-	-	-	-	-
Floor_4 - WC	-	-	-	-	-	-		
Floor_4 - Diff_Abl WC	-	-	-	-	-	-	180	320 *l/s* @ 130Pa
Floor_4 - Male WC	-	-	-	-	-	-		
Floor_4 - Store	-	-	-	-	-	-	-	-
Floor_4 - Admin Office	Yes	Yes	245	10	235	-	125	-
Floor_4 - Research Centre	Yes	Yes	3766	188	3578	-	2156	-
Floor_4 - Passage	-	-	-	-	-	-	-	-
Floor_4 - Meeting Room 2	Yes	Yes	238	20	208	-	125	-
Floor_4 - Office 1	Yes	Yes	144	15	129	-	78	-
Floor_4 - Office 2	Yes	Yes	144	15	129	-	78	-
Floor_4 - Office 3	Yes	Yes	144	15	129	-	78	-
Floor_4 - Office 5	Yes	Yes	144	15	129	-	78	-
Floor_4 - Elevator Shaft	-		-	-	-	-	-	-
Mezzanine - Research Centre	Yes	Yes	1003	65	938	-	1100	-
Mezzanine - Director Office	-		-	-	-	-	-	-
Mezzanine - Open Plan Office	Yes	Yes	1199	65	1134	-	1100	-
Mezzanine - Admin Office	-		-	-	-	-	-	-
TOTAL	**-**	**-**	**30782**	**5053**	**28532**	**18**	**27632**	**-**

Note: *****) No ventilation data for zone was available at the first design stage.

APPENDIX G: CRSES BUILDING ZONES

The new academic building zones which CRSES will occupy are shown in Table 27 below. Some of these zones will however be used by MIH as well, but for a better overall energy performance assessment was all the overlapping zones included. The location of these zones is shown in Figure 38, Appendix B.

Table 27: Building zones which CRSES is comprised of.

Floor_4 - Open Plan Office 2
Floor_4 - Director Office
Floor_4 - Office 4
Floor_4 - Open Plan Office
Floor_4 - Meeting Room 1
Floor_4 - WC
Floor_4 - Diff_Abl WC
Floor_4 - Male WC
Floor_4 - Store
Floor_4 - Admin Office
Floor_4 - Passage
Floor_4 - Meeting Room 2
Floor_4 - Office 1
Floor_4 - Office 2
Floor_4 - Office 3
Floor_4 - Office 5
Mezzanine - Director Office
Mezzanine - Open Plan Office
Mezzanine - Admin Office

APPENDIX H: OPEN PLAN OFFICE 2 SIMULATION RESULTS

To better understand the actual building energy performance on a zone level, the Open Plan Office 2 zone on the fourth floor was chosen for further investigation. Figure 40 below shows a wireframe representation of Open Plan Office 2 with windows outlined in yellow, doors outlined in blue and openings outlined in green.

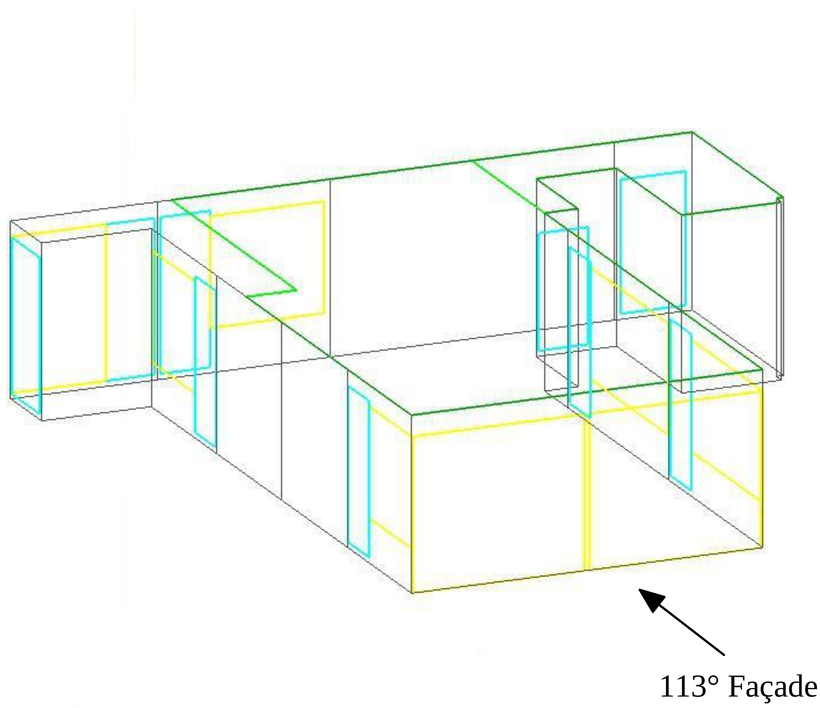

Figure 40: Actual building Open Plan Office 2 zone wireframe representation.

From Figure 31 and Figure 40 it is evident that the large glazing area of Open Plan Office 2 on the 113° façade of the actual building will have a large impact on the early morning solar energy gains. The internal heat gains resulting from this building fabric design feature is shown in the summer design day (15 January 2002) internal heat balance data of Figure 41 below.

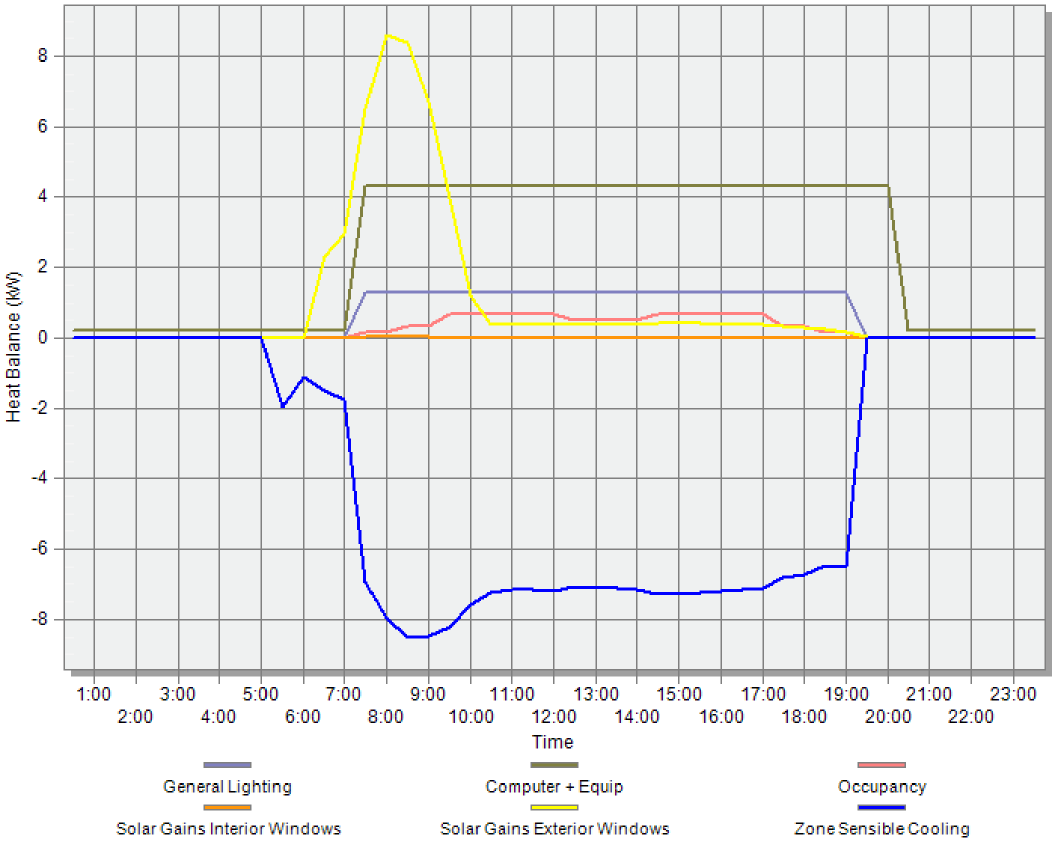

Figure 41: Actual building Open Plan Office 2 summer design day internal gains.

Maximum solar energy gain occurs at 08:00 as depicted in Figure 41 above. This large heat energy results in a rapid increase in the cooling requirement of the zone. For the rest of the day, a large and reasonably constant cooling energy load is required to sustain internal thermal comfort temperatures due to the GSSA-PEB operational profiles shown in Figure 17 (applicable to this zone on the day the data depicted in Figure 41 was acquired).

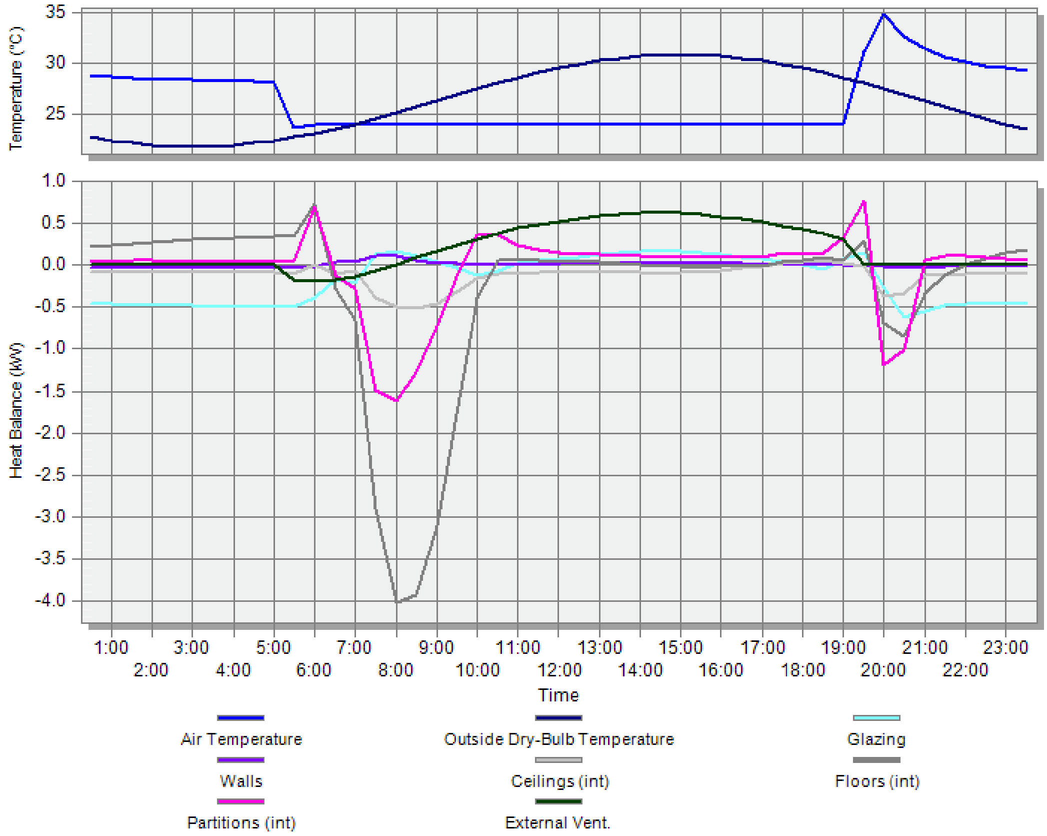

Figure 42: Actual building Open Plan Office 2 summer design day fabric and ventilation performance results.

The Open Plan Office 2 building fabric heat balance simulation data depicted in Figure 42 above shows the heat retention characteristics of the most significant building fabric components. An important observation made from this data is the ability of the internal building floors to release a large amount of stored cooling energy early in the morning when the large solar energy heat gain shown in Figure 41 occurs. This positive natural energy offset is predominantly attributed to the large amount of thermal capacitance as a result of the mass, density and specific heat capacity of concrete in the internal floors.

The internal partitions has less thermal capacitance per unit area than the internal concrete floors, but because this zone has a large amount of internal partition surface does the combined thermal capacitance provide a notable positive offset in heat energy gain.

A further simulation was done on a winter design temperature of 3.8° Celsius to determine the building fabric performance of Open Plan Office 2. The data obtained in this simulation is presented in Figure 43 below.

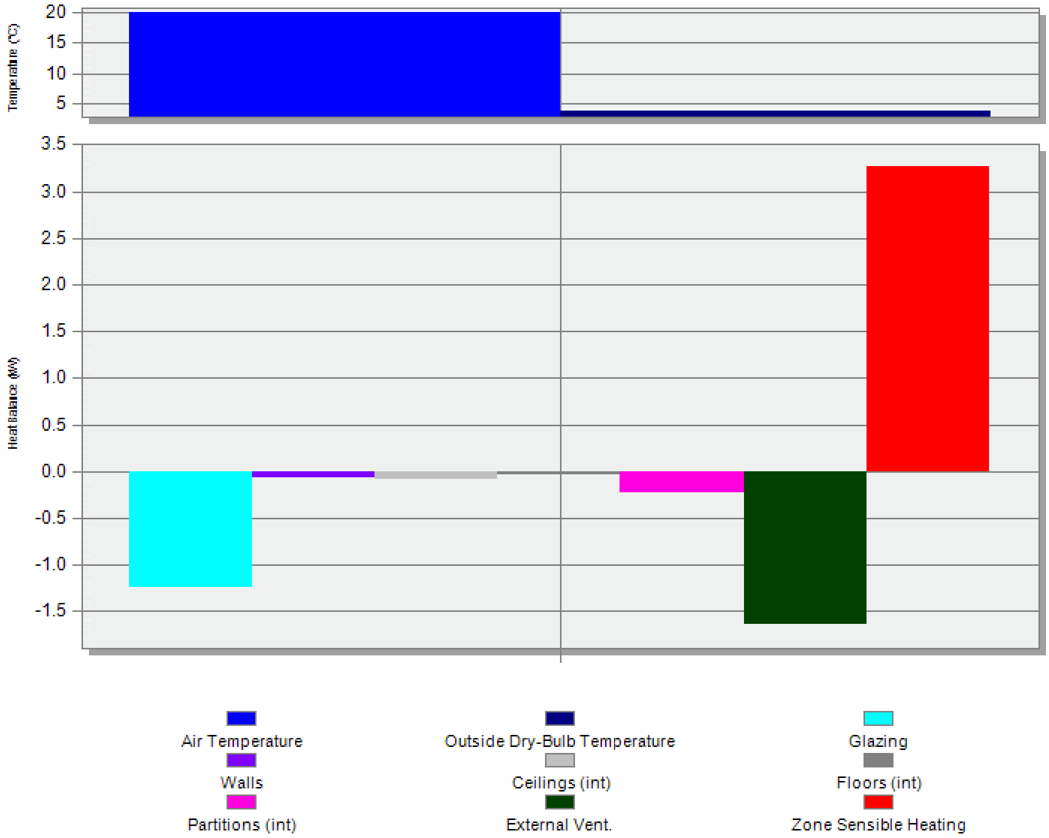

Figure 43: Actual building Open Plan Office 2 winter design temperature and heat loss results.

Figure 43 shows that the most significant building fabric heat loss occurs through the building façade glazing area of Open Plan Office 2. This is because of the low thermal resistance provided by the 6mm single glazing used in the external wall windows and doors. The large internal loads of this zone as depicted in Figure 41 however, provides more heating than needed to offset the heat losses resulting from the building fabric and fresh air ventilation requirements. A low building façade fabric thermal resistance therefore is beneficial for this zone.

APPENDIX I: SOLAR PHOTOVOLTAIC ROOF ARRAY

The primary design considerations for the PV panel array on the roof of the new academic building were to use a robust technology within a very limited budget and ensure that the panels can be mounted flush to the roof. A secondary design consideration was to design the size and placement of the PV array on the roof surface such that local shading by the adjacent buildings is minimised. This was done by analysing the shading effects of the adjacent buildings on the solar equinox and solstice days. Figure 44 below shows the placement of the PV panel array on the roof of the new building and the shading created by the surrounding buildings at 08:00 on the solar equinox day of 20 March.

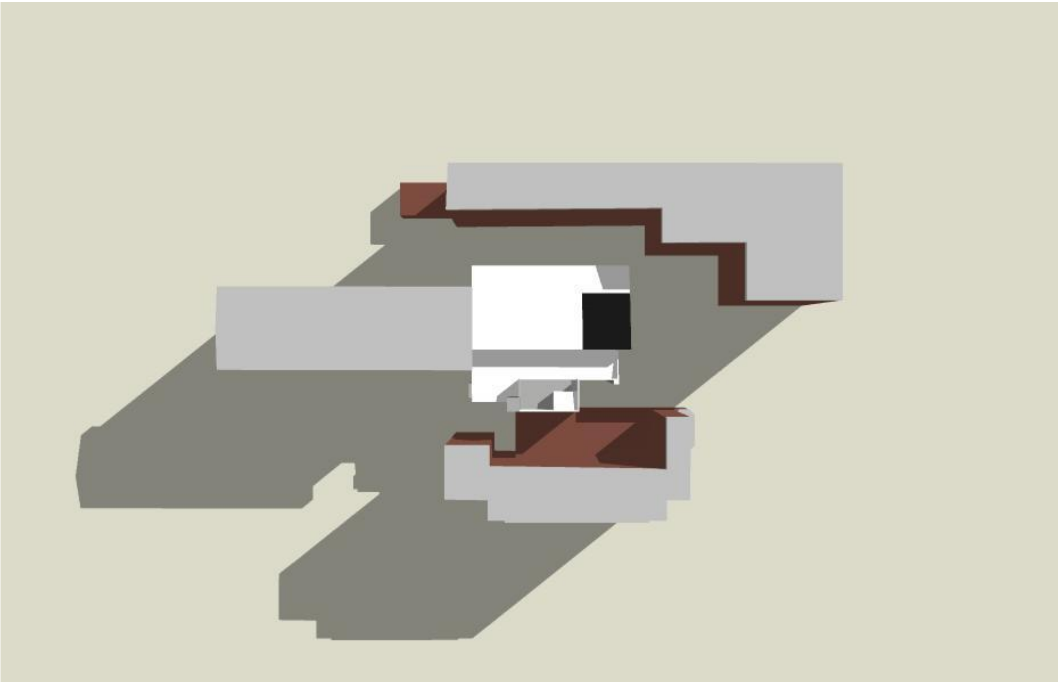

Figure 44: Plan view of academic building with PV array on roof (black rectangle).

An analysis of the shading created by the surrounding buildings on the solar equinox and solstice days revealed that the location of the PV array (shown above in Figure 44) will receive a very small amount of shading very early in the mornings and late afternoon. To compensate for this effect a 5% DNI solar shading factor has been incorporated into the simulation.

The technical specifications of the PV panel array chosen for the new academic building are defined in Table 28 below.

Table 28: PV array specifications.

Solar cell technology used	Monocrystalline silicon
PV array panel count	80 panels
PV array dimensions	10.62 *m* long and 12.64 *m* wide
PV array area	134.24 m^2
PV array tilt angle	10°
Total PV panel array weight	1600 *kg*(1)
PV panel array cost	R 360 000(2)
PV array maximum power rating	16 kW(3)
Inverters for 240 VAC power generation	5 X Solaris 3500 XP 240V (SAM, 2011)

Note: 1) Only applicable to the panels. 2) Quoted in South African Rand by Mantech Electronics (2011). 3) Rated at an irradiance level of 1000 W/m^2 and an air mass spectrum of 1.5 per cell.

To calculate the total annual PV system energy output, a simulation was done in the Solar Advisor Model software provided by the NREL (SAM, 2011). The weather file used in this software to simulate the annual solar irradiance levels was the same weather file used for simulating the annual building energy consumption (refer to section 3.2.2). The simulation results are tabulated below in Table 29 and the monthly energy output is shown below in Figure 45.

Table 29: PV array simulation results.

Total system electrical derate between PV panel array and 240 VAC inverter output	15%
Total system performance factor	0.76
Total system annual energy output	24 323 kWh

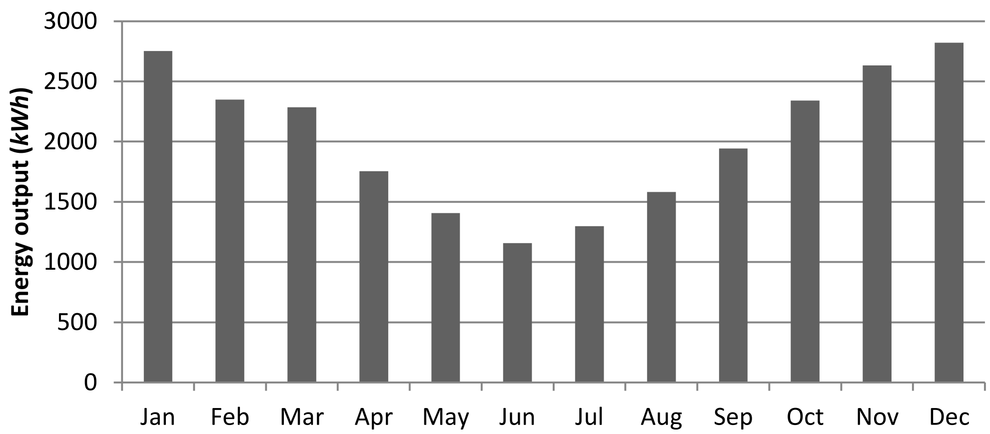

Figure 45: PV array monthly energy output.

End