Influence of building and indoor environmental parameters on designing energy-efficient buildings

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Abstract

Purpose – Arguments for the design of sustainable university buildings have emerged in South Africa. Energy being a major determinant of the sustainability of buildings, the purpose of this study was to examine the influence of various building and indoor environmental parameters on the energy performance of university buildings in South Africa.

Design/methodology/approach – A quantitative survey research method, administered within the context of university buildings in South Africa, was used. Data about 16 buildings from three universities were collected. Relevant, inferential statistical analyses were conducted to examine the relative influence of the building parameters on the energy consumed in the buildings. Also, regression models within building parameters were developed independently and in a combination that could be used to estimate energy consumption in the university buildings.

Findings – Findings suggested that building and indoor environmental parameters of humidity, indoor temperature, volume, illumination, and window width ratio (WWR), in that order, influenced energy consumption significantly, and also, had direct empirical relationships.

Practical implications – Optimising the building and indoor environmental parameters in design will enhance energy-efficiency in university buildings in South Africa.

Originality/value – This study contributes to the literature in terms of understanding the order of influence of building parameters on energy consumption in university buildings in the temperate climatic zone of South Africa. It also established empirical models between building and indoor environmental parameters and energy consumption, both independently and in combination, that could assist in designing energy-efficient and sustainable university buildings.

Keywords Building envelope, Design, Efficiency, Energy consumption, Energy performance, Sustainable buildings

Paper type Research paper

Introduction

Universities are centres of learning and research. The new knowledge and application of the knowledge that emanates from the universities contribute significantly to the sustainable development of human habitations (Francis and Moore, 2019). While being centres of knowledge creation, universities have an additional responsibility to lead through practice. Also, being sub-sets of cities, universities can lead efforts towards sustainability through research and applied action. Therefore, it is argued that universities should contribute to the sustainability of the built environment through experimentation, application and practice

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(Cortese, 2003; Francis and Moore, 2019; Lozano *et al.*, 2015; Shawe *et al.*, 2019) and set examples by becoming beneficial influencers within cities (Beck *et al.*, 2011; Filho *et al.*, 2019). Universities are undertaking several initiatives to make their campuses sustainable. The initiatives broadly include on-campus projects such as the creation of sustainable infrastructure, Greening campus programmes, integrating sustainability into teaching-learning and curricula, research, governance and outreach programmes (Lozano *et al.*, 2015; Shawe *et al.*, 2019).

The focus of many campus sustainability efforts is on issues related to infrastructure and Green Campus programmes, such as energy efficiency, smart mobility, reduction in carbon emission, waste management, recycling and water harvesting (Filho *et al.*, 2019). Creating sustainable infrastructures, such as buildings, laboratories, transportation networks, energy systems, water and waste-water systems, is vital for the sustainability and efficient operation of any university (de Figueiredo and Mazzola, 2018; Filho *et al.*, 2019). However, since energy is indispensable for the operation of most of the university infrastructure, attainment of energy efficiency or optimal energy consumption is one of the most important requirements for the sustainable development of the built environment or university buildings specifically.

University buildings should be designed or retrofitted in such a way that energy consumption is reduced. Studies have shown that building parameters, and indoor environmental parameters, such as orientation, size, form of the buildings, temperature, light and humidity, influence energy consumption (Al-Tamimi, 2011; Khoshbakht *et al.*, 2018; Pickering and Byrne, 2014). However, the influence of these parameters on the energy consumption of university buildings and the link between the building parameters and energy consumption, specifically in a climatic zone varying between semi-arid and temperate zones, have not been established to date. Moreover, most university buildings are still being designed by using conventional design processes, and criteria for energy efficacy have rarely been considered (DEAT, 2008; McIntosh *et al.*, 2008).

Currently, codes for constructing built, immovable assets, including buildings for South African universities, do not address the need for high-performance, sustainable buildings. The findings of this study can assist in understanding the relative influence of building parameters on energy consumption in university buildings in the temperate climatic zone of South Africa and could assist in the optimal design of buildings to achieve energy efficiency. The findings also contribute in terms of establishing empirical models that show the relationship between building parameters, independently and in combination, and energy consumption that could assist in designing energy-efficient and sustainable university buildings.

A succinct account of the literature reviewed is presented in the next section before the research methods are explained. Thereafter, the results and concluding remarks follow to show how designing energy-efficient buildings in South African universities can be undertaken.

Literature review

Sustainable building design and energy consumption

Sustainable building design could reduce carbon footprints and operation costs while improving resilience. The fundamental principles of sustainable building design include: optimising site potential, optimising energy use, protecting and conserving water, optimising building space and material use, enhancing indoor environmental quality (IEQ), and optimising operational and maintenance practices (Berardi, 2013). The use of energy forms one of the vital elements in achieving sustainable building environments, and energy efficiency has become one of the major concerns of campus and university sustainability programmes.

The ontology of energy consumption is argued to include occupancy, heating, ventilation, and air-conditioning (HVAC) load, artificial lighting and electrical equipment. These factors are influenced by building size (envelope), climate, materials, orientation and activity (Al-Tamimi, 2011; Efeoma and Uduku, 2014; Khoshbakht *et al.*, 2018; Pickering and Byrne, 2014), which play critical roles in achieving energy efficiency in buildings. The creation of energy-efficient buildings includes certain components, such as the pre-building phase, planning, building form, building organisation and planning, building envelope, building material, landscape design, utilisation of renewable energy sources and intended use of buildings (Filho *et al.*, 2019; Jindal *et al.*, 2018; Khoshbakht *et al.*, 2018; Onyenokporo and Ochedi, 2019; Yüksek and Karadayi, 2017). Also, universities are adopting a variety of other methods, such as HVAC energy management systems, on-site energy generation, optimising occupancy, re-scheduling of activities, retro-fitting the buildings, and using smart technology to operate and monitor energy usage (de Figueiredo and Mazzola, 2018; Filho *et al.*, 2019).

Building and environmental parameters and energy consumption

Building envelopes are a critical factor affecting energy efficiency. They separate the indoor from the outdoor environment, and thus, they are exposed to temperature fluctuations caused by humidity, rain, air movement, solar radiation and other natural factors (Ge *et al.*, 2018; Sadineni *et al.*, 2011). Building envelope components, such as shading devices, external walls, external roofs, external glazing, insulation and cooling systems in buildings, are related to energy efficiency (Al-Saadi and Budaiwi, 2007; Chen *et al.*, 2015; Ge *et al.*, 2018; Lomas, 2007; Onyenokporo and Ochedi, 2019; Sabouri, 2012). Also, energy usage is affected by the shape (length, width and height), as well as the window and width ratio (WWR) of buildings (Ghiai *et al.*, 2014; Hemsath and Bandhosseini, 2015; Parasonis and Keizikas, 2010; Zhang *et al.*, 2017a).

Building orientation, shape and exposure to solar radiation can influence the energy consumption, and therefore, energy-efficiency of buildings (Mirrahimi *et al.*, 2016). According to several scholars, building orientation has a significant impact either in the presence or absence of natural ventilation (Al-Tamimi, 2011; Chan *et al.*, 2006; Chen *et al.*, 2015; Gupta and Tiwari, 2016; Du *et al.*, 2020). Daylight and the movement of air through a building are affected by the shape of the building, which is subsequently affected by its orientation (Chen *et al.*, 2015; Lomas, 2007). Furthermore, it has been established that buildings oriented longitudinally in a north-south direction require 10% less energy consumption than buildings oriented east-west longitudinally, regardless of the building form (Kannan, 1991). Thus, orientation plays a vital role in reducing energy consumption in a building. Similarly, Parasonis and Keizikas (2010) observed that changes in the shape of a building caused changes in energy loss, although the physical characteristics of the building remained the same.

The geometric efficiency of buildings, which depends on size and proportions, also influences energy efficiency (Chen *et al.*, 2015; Parasonis *et al.*, 2012). It has been found further that the type of materials used for building components can affect a building's thermal transmittance (*U*-factors), and consequently, the energy consumption.

Thus, the total energy consumption in buildings depends on elements of the building envelope, including building and environmental parameters related to functional space, ventilation, external air infiltration, linear thermal bridges, hot water preparation, maintaining the operation of the ventilation system, and other services (Chen *et al.*, 2015; Ji *et al.*, 2019; Lomas, 2007; Parasonis *et al.*, 2012; Yaşa and Ok, 2014).

Eromobor and Das (2013) observed that, with appropriate design interventions, proper orientation, geometry, location and size of openings, and access to natural light can lead to a reduction of energy consumption. However, the influence of building parameters, and environmental factors on energy consumption in university buildings has not been studied explicitly. The focus of this study, therefore, was on the effect of physical and environmental building envelope parameters on energy consumption in university buildings (ASHRAE, AIA, IESNA, USGBC, DOE, 2011), particularly in the temperate climatic zone of South Africa.

Analytical methods and modelling approaches for predicting energy performance

Evidence from the literature shows that several methods have been used to analyse the energy performance of buildings. For example, building energy simulation (BES) models use computer programmes such as EnergyPlus (Crawley *et al.*, 2001), ESP-r (Strachan *et al.*, 2008), IDA-ICE, eQuest (2018), BLAST, DOE-2 (DOE-2, 2020), Modelica (Modelica, 2020), Ecotect (Ecotect, 2020) and BSIM (Wittchen *et al.*, 2005). These programmes help to predict the energy performance of a building (Harish and Kumar, 2016; Tian *et al.*, 2018). BES is based on a multi-zone modelling approach, in which each building zone is considered as a node with a homogeneous distribution of temperature and pressure concentration (Foucquier *et al.*, 2013; Tian *et al.*, 2018).

The computational fluid dynamics (CFD) model has also been used to predict detailed information of the airflow and the temperature distribution that influence energy consumption in buildings (Tian *et al.*, 2018). Analytical methods such as artificial neural networks (ANNs), genetic algorithms, support vector machines (SVMs), random forest (RF), gradient boosting (GB) and multiple linear regression (MLR) have also been used (Gassar and Cha, 2020). However, some of the modelling approaches are sensitive to boundary conditions (Tian *et al.*, 2018; Zhang, 2020).

Sensitivity analysis has been used as it offers information about building design parameters that have an impact on the energy performance of buildings. The use of this method at the early stages of the design process can help designers to establish a goal-setting energy model based on design variables (Hemsath and Bandhosseini, 2015). For example, the community domestic energy model (CDEM) was applied to carry out a local sensitivity analysis to identify input parameters, from a large number of highly influential parameters, to develop ways to measure household energy efficiency (Lomas and Eppel, 1992; Firth *et al.*, 2010). The models are context-specific and are applicable to understanding specific scenarios under the influence of specific parameters.

However, according to Lomas (2007), designers need simple models to work on different parameters and predict energy consumption based on the influence of the different parameters at the early stages of the design, before using sophisticated tools. Therefore, a statistical analysis and modelling approach could be suitable and relevant to predicting energy consumption at the early stages of design or while designing to retro-fit buildings (Gassar and Cha, 2020; Kim and Kim, 2007).

Methodology

A quantitative survey research method was used for this study to generate and assess data about academic buildings at three, selected universities of technology, which included (1) the Central University of Technology, Free State (CUT), (2) the Durban University of Technology (DUT) and (3) the Tshwane University of Technology (TUT). The data were analysed using relevant inferential statistics, and empirical models were built to establish the relationship between building parameters and energy consumption.

Buildings selected for case study and data generation

The generation and assessment of data about the effect of building parameters on energy consumption were focussed on 16 buildings: six buildings each from CUT and DUT and four buildings from TUT. The age of the buildings ranged from 12 to 20 years old.

The buildings were designed using conventional design methods and criteria. The scope of this study was limited to assessing data about non-residential, education buildings. The primary criterion for the selection of the buildings was their function for academic purposes. The occupancy level of the teaching and learning and library spaces ranged between 60 and 100 people per room, and offices were either single occupancy or double occupancy rooms. Most of the buildings were mechanically ventilated and used artificial lighting in general. The buildings were generally used from 7.00 a.m. to approximately 9.00 p.m. except for the office spaces, which were used until approximately 7.00 p.m. The buildings were constructed with conventional materials, such as reinforced concrete for roofs, tiles or carpets for flooring, brick masonry for walls and glass for windows. Although the buildings included teaching and learning spaces, as well as office spaces, the spaces for staff offices were relatively few. Moreover, both types of spaces were integrated and shared the same energy-related facilities, and therefore, were considered on an aggregate basis.

Physical measuring and recording of data for the parameters of the buildings selected were conducted during active periods of teaching and learning in the universities. The data were collected during both semesters of the academic year 2016. For the purpose of data collection, approval from the university authorities was obtained, and all official protocols were followed.

Quantitative data linked to building parameters, including length, breadth, and height (size and volume), functional floor area, and window width, were obtained from physical measurements using calibrated physical measuring instruments. In addition, indoor environmental parameters, such as the indoor temperature, humidity and illumination of the buildings, were measured by using a mobile weather station, indoor temperature/humidity sensors and a light meter. The instruments were calibrated before measurements were taken. Measurements were repeated to eliminate errors and check the veracity of the data. The orientation of buildings was ascertained by using a magnetic compass. The data on average annual energy consumption was obtained from the relevant authorities and records of the universities for the five years prior to 2016.

Data analysis

The data obtained from the physical investigation were analysed by using inferential statistics such as correlation, significance tests, Beta coefficients, coefficient of determination, regression analysis and sensitivity analyses. This methodological approach was chosen because designers need simple models to work with the different parameters and their influence on energy consumption at the early stages of design when the geometry of a building is still adaptable (Lomas, 2007). Once the design is well developed, a more sophisticated model might be more useful. This approach offers robust statistical analyses and easy-to-use models, which designers and architects can use to make predictions while making their initial design of the university buildings or design to retrofit the buildings. Evidence shows that such statistical approaches have been found suitable and useful to predict energy consumption, specifically when the building design is considered holistically at an early stage or while designing to retrofit the buildings (Gassar and Cha, 2020; Kim and Kim, 2007).

First, the association between different building parameters, such as length, width, floor area, volume, WWR, indoor temperature, humidity, illumination and energy consumption were established inter-dependently using correlation coefficients, significance tests (t-tests and p-values for $\alpha \leq 0.05$, with 95% confidence level and 5% confidence interval). The reason for using these techniques was that they make it possible to establish the relationships between energy consumption and different building and indoor environmental parameters and their statistical significance. The building and indoor environmental parameters were considered to be the independent parameters, and energy consumption was considered to be the dependent parameter.

Second, the relative influence of the independent parameters on energy consumption was examined by using Beta coefficients. A Beta coefficient makes it possible to compare the strength of the effect or influence of each individual independent variable on the dependent variable. Beta coefficients were determined for each independent parameter in relation to the dependent parameter of energy consumption to examine the strength of the effect or relative influence of each independent parameter. The higher the absolute value of the Beta coefficient, the stronger the effect. The Beta coefficient also provides the degree of change in the dependent parameter for every unit of change in the independent parameter (Ziglari, 2017). The Beta (β) coefficient was determined by using equation (1).

$$\beta = b\frac{SX}{SY} \tag{1}$$

Where:

β is the beta coefficient.

b is the standard regression coefficient.

SX is the standard deviation of independent variables.

SY is the standard deviation of the dependent variable.

However, the influence of the independent variables on the predictor variable was determined by the combined understanding of Beta coefficients (β) and coefficients of determination (r^2) (Ziglari, 2017).

Third, the coefficient calculations were followed by regression models that were developed to establish the relationship between the influential building parameters and energy consumption, which also gave insights into the extent to which each variable influenced the energy consumption in the university buildings. For this purpose, a simple regression model framework, as shown in Equation 2 (a and b) and a multiple regression model framework (Equation 3a and b), were used. The nature of the data set collected, and the preliminary statistical calculations indicated the suitability of the linear regression modelling. Moreover, linear regression models make it possible to establish and evaluate the relationship between independent variables and the dependent variable in a simple and quantitative manner. However, before the models were developed, co-linearity and association between the independent variable(s) and dependent variable were checked using correlation, significance tests (t values and p-values) among the independent variables. Also, while developing the models, the extreme outliers were eliminated to improve the robustness and accuracy of the models. The validity of the models was checked using the r^2, F and p ($\alpha \leq 0.05$) values. Further, the multiple linear regression model developed was used to conduct sensitivity analysis and develop simulated scenarios to predict energy consumption and variations in energy consumption according to the variations in the building and indoor environmental parameters.

$$Y = f(X) \tag{2a}$$

$$Y = mX + c \tag{2b}$$

$$Y = f(X_1, X_2, X_3, X_4 \ldots X_n) \tag{3a}$$

$$Y = m_1X_1 + m_2X_2 + m_3X_3 + m_4X_4 + \ldots m_nX_n + c \tag{3b}$$

Where Xi = independent variables; Y = dependent variable; mi = regression coefficients and c = intercept.

Results and discussion

The results showing the general status of the building parameters, the relative influence of building parameters on energy consumption, and the relationship between building parameters and energy consumption are presented in the following sub-sections.

General status of the building and indoor environmental parameters in relation to energy consumption

The location, function, hours of operation, building parameters and energy consumption of the various buildings at the three universities used for the case study are shown in Table 1. The buildings were grouped according to heating, cooling and ventilation systems used and were classified as: naturally ventilated buildings (*N*), mixed-mode ventilated buildings (mechanical and natural ventilated spaces) (NM) and mechanically ventilated buildings (*M*). It was found that eight buildings used natural and mechanical ventilation systems, six buildings used mechanical ventilation and only two buildings used natural ventilation stream. Thus, it was concluded that most of the buildings at the three universities used either a mechanical ventilation system or a combined system.

Differences in energy consumption levels according to the measurements of the various parameters of the selected buildings were revealed. It appeared that the differences in energy consumption occurred because of various factors such as the type of function/use of the buildings, size of the buildings, ventilation system used, WWR, the indoor environmental quality and illumination of the building. The energy consumption per unit area revealed that the lowest energy consumed was in Building 11 (45 Kwh/m^2/annum), and the highest consumption was in the Hotel School and ETB Buildings, which both used 216 Kwh/m^2/annum. The findings also showed that the lower demand for energy consumption in Buildings 11 and 13 could be attributed to a combination of the function of the buildings, optimal geometric parameters of the buildings, high WWR and acceptable indoor quality.

Relationship between the building and indoor environmental parameters, and energy consumption

The relative influence of the various building and indoor environmental parameters on energy consumption is shown in Table 2. For this purpose, four variables of building geometry: volume, functional floor area, width and WWR, and three indoor quality variables: temperature, humidity and illumination were considered. Relatively high correlation coefficients between three building geometry parameters and energy consumption indicated that energy consumption might increase with the increase in these parameters (volume and energy consumption = 0.76; floor area and energy consumption = 0.76 and width and energy consumption = 0.78). However, a relatively significant negative correlation coefficient between WWR and energy consumption indicated that energy consumption might decrease with the increase of WWR. Similarly, significant, negative correlation coefficients between indoor quality parameters (temperature [–0.63], humidity [–0.86], and natural illumination [–0.89]) and energy consumption indicated that energy consumption might decrease with an increase in these parameters. Furthermore, the t-stats and p-values of ≤ 0.05 (for $\alpha \leq 0.05$, with a 95% confidence level) for all the variables showed the statistical significance between energy consumption and these building parameters.

Table 1. General function, building and indoor environmental parameters of the selected buildings and energy consumption

University building	Function: T&L, Admin, library	Energy consumption Kwh/annum	Energy consumption Kwh/annum/sq.m	Width (*m*)	Floor area (m2)	Volume (m3)	WWR	Average temperature typical room °C	Average humidity of typical room %	Illumination average Lux
CUT										
BHP1 (NM)	T&L	675,238	74.3	31	2272	36,751	0.29	26	43	310
BHP2 (*M*)	T&L	1145,040	165	44	2936.9	41,014	0.09	24	35	310
BHP Amin (*M*)	Admin	251,108	143	13.5	438.9	5617.3	0.35	25	36	270
ETB (*M*)	T&L	1,037,202	216	25.5	949.7	29,723	0.36	26	36	305
Library (*M*)	Lib	756,104	107	33	2013.9	36236.7	0.32	29	37	370
Hotel school	T&L	627,598	216	28	2000.2	18,001	0.30	28	38	370
DUT										
S3 (NM)	T&L	342,176	90	12	429.4	13741.4	0.24	29	56	490
S8 (NM)	T&L	342,176	90	12	429.4	13741.4	0.24	28	58	450
Block D (NM)	T&L	785,000	72	30	1250	42,500	0.12	28	49	450
Block E (NM)	T&L	432,416	170	16	660	17,920	0.29	28	48	490
Building G (*M*)	Lib	289,480	119.0	15	675	9450	0.19	26	48	380
Block J (NM)	T&L	244,662	116.0	15	705	9870	0.23	25	35	270
TUT										
Building 2A (NM)	T&L	280,371	107.0	14	705	12658.5	0.23	30	39	550
Building 3 (*M*)	Admin	587,676	117.3	12.5	720	25,560	0.38	27	39	360
Building 11 (*N*)	T&L	106,320	45.0	11.5	886.2	10,889	0.48	27	40	600
Building 13 (*N*)	T&L	272,520	52.0	30	2271.4	36,341	0.31	27	38	305

Relative influence of building and indoor environmental parameters on energy consumption
The relative influence of the parameters on the energy consumption was established by concurrent consideration of the β values and r^2 values. From Table 2, it is evident that, in order from high to low consumption: humidity ($\beta = -1.66$, $r^2 = 0.73$), width ($\beta = 1.18$, $r^2 = 0.75$), floor area ($\beta = 0.90$, $r^2 = 0.77$), volume ($\beta = 0.74$, $r^2 = 0.86$), temperature ($\beta = -0.93$, $r^2 = 0.75$), illumination ($\beta = -0.66$, $r^2 = 0.81$) and WWR ($\beta = -0.18$, $r^2 = 0.59$), influence energy consumption in the buildings. However, since volume is a function of floor area and width and they have high co-linearity among them (correlation coefficient between volume and floor area is 0.77, and between volume and width is 0.86), volume was considered to be a proxy for size and form of the building in further analyses.

Relationship between individual building and indoor environmental parameters and energy consumption in university buildings
Humidity and energy consumption. The relationship between humidity and energy consumption is shown in Figure 1. A linear relationship exists between the two variables, which was established by Equation (4). It was found that energy consumption in university buildings decreases with an increase in the humidity. Moreover, with a 1% increase in humidity, the energy consumption decreases by 1.66%.

$$Y = 22368X_1 + (2E + 06) \tag{4}$$

Where, Y = Energy consumption in KWh/annum;
X_1 = Humidity in percentage.

Indoor temperature and energy consumption. The buildings were assessed for indoor temperature and an analysis was made to establish the relationship between temperature and energy consumption. It was found that temperatures remained within a range of 24°–29°c, which is generally the average temperature during the daytime and early evenings for most

Parameters	Correlation coefficient (r)	t Stat	P ($T \leq t$) one-tail	Beta (β) values	r^2
Temperature	−0.63	6.63	5.63E-06*	−0.93	0.75
Humidity	−0.86	6.63	5.63E-06*	−1.66	0.73
Illumination	−0.89	13.76	3.25E-10*	−0.66	0.81
WWR	−0.77	14.35	1.81E-10*	−0.18	0.59
Width	0.78	6.73	3.4E-06*	1.18	0.75
Floor area	0.76	6.71	3.49E-06*	0.90	0.77
Volume	0.76	6.42	5.73E-06*	0.74	0.86

Note(s): *$p \leq 0.05$ for $\alpha \leq 0.05$, statistically significant

Table 2. Relative influence of building and indoor environmental parameters on energy consumption

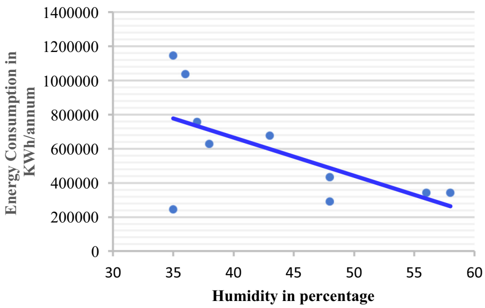

Figure 1. Relationship between humidity and energy consumption

of the year (except the winter months of June and July, and summer months of December and January) when most of the functional building spaces were used. Equation (5) was used to calculate the relationship between the indoor temperature of buildings and energy consumption shown in Figure 2. It was found that a 1% increase in temperature is expected to reduce energy consumption by 0.93% in the university buildings.

$$Y = -9757X_2 + 3E + 06 \tag{5}$$

Where, Y = Energy consumption in KWh/annum.

X_2 = Temperature in degrees centigrade.

Illumination and energy consumption. Energy consumption for lighting depends on maximising the use of daylight in buildings. In turn, daylight in buildings is linked to the design of the building envelope that includes orientation, window-to-wall ratio and U-value of materials used for windows. Equation (6) was used to calculate the relationship between illumination (from daylight) and energy consumption in the university buildings, as shown in Figure 3. It was found that illumination and energy consumption have a linear relationship where an increase of 1% in illumination from daylight decreases the energy consumption by 0.66%.

$$Y = -2785.23X_3 + (2E + 06) \tag{6}$$

Where, Y = Energy consumption in KWh/annum.

X_3 = Illumination in lux.

Volume versus energy consumption. In this study, it was found that a linear relationship existed between volume (size) of buildings and energy consumption, which was defined by Equation (7), as shown in Figure 4. It was found that energy consumption increased with an increase in the volume of the buildings. For every 1% increase in volume, the energy consumption increased by 0.74%.

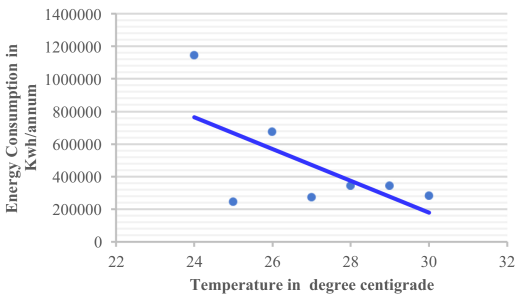

Figure 2.
Relationship between indoor temperature and energy consumption

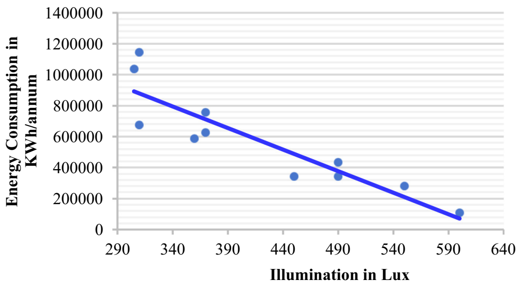

Figure 3.
Relationship between illumination and energy consumption

$$Y = 290.35X_4 + 132261 \quad (7)$$

Where, Y = Energy consumption in KWh/annum.
X_4 = Volume (size) of buildings in m^3.

Window-to-wall ratio (WWR) and energy consumption. Further analysis was conducted to establish the relationship between WWR and energy consumption, as defined by Equation (8). Figure 5 shows a linear relationship where an increase of 1.0% in WWR is expected to reduce energy consumption by 0.18%. Thus, it was established that higher WWR reduces energy consumption.

$$Y = -21848X_5 + (1E + 06) \quad (8)$$

Where, Y = Energy consumption in KWh/annum.
X_5 = WWR.

Model and sensitivity analyses for the combined effect of building and environmental parameters on energy consumption

A multiple regression model, premised upon the effect of independent building parameters on energy consumption, was developed to determine the combined effect of the various building parameters on energy consumption in the university buildings. The model was developed by considering the most influential parameters of humidity, temperature, illumination, volume and WWR. Floor area and width were not considered, despite their individual influence, because they were regarded as functions of volume because of their high co-linearity with volume. The model was defined by Equation (9). The validity of the model was also ascertained from the relatively high r and r^2 values, as well as p-value ≤ 0.05. The model can be simulated to estimate energy consumption based on the influence of each independent variable individually or in combination.

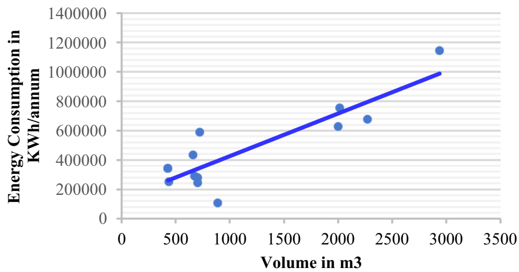

Figure 4.
Relationship between the volume of buildings and energy consumption

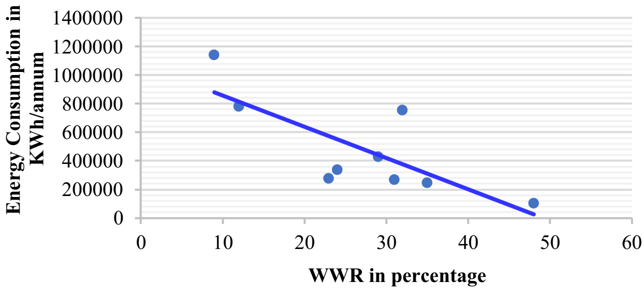

Figure 5.
Relationship between WWR and energy consumption

$$Y = -3987.84X_1 - 27213.1X_2 + 35.81X_3 + 16.50X_4 - 6158.24X_5 + 1190135 \quad (9)$$

$$\text{Multipler} = 0.81$$
$$r^2 = 0.66$$
$$\text{Adjusted } r^2 = 0.49$$
$$F = 3.861$$
$$p \text{ value} = 0.039$$

Where, Y = Energy consumption in KWh/annum;

X_1 = Humidity in percentage;

X_2 = Temperature in degrees centigrade;

X_3 = illimitation in lux;

X_4 = Volume in m^3;

X_5 = WWR in percentage.

By using the model, sensitivity analyses and simulated scenarios were developed. For the purpose of sensitivity analysis, one typical building was considered and variations (both increase and decrease from the current or business as usual scenario) in building, such as volume and WWR, and indoor environmental parameters, such as the humidity, temperature and illumination, were made and compared with the business as a usual scenario to examine energy consumption under different simulated scenarios. The simulated scenarios were created by varying the parameters independently and in combination from 1.0 to 20.0% at an increment of 1% each at a time. However, out of the several scenarios created, energy consumption in eight, important scenarios were selected for discussion and presented in Figure 6. The changes in energy consumption under these eight scenarios are presented in Figure 7.

It was found that an increase in 1–2% in humidity, temperature, illumination and WWR and a decrease in volume (Scenarios S1 and S2), independently, will reduce energy consumption marginally, by a maximum of up to 1.5%, compared with the business as usual

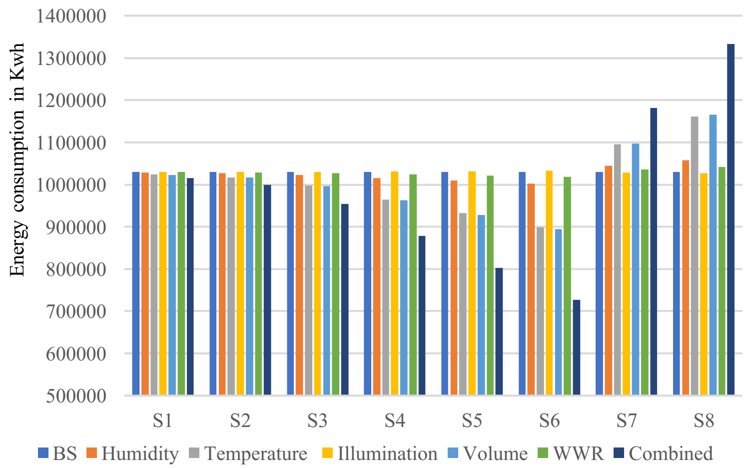

Figure 6.
Sensitivity analysis and simulated scenarios of energy consumption

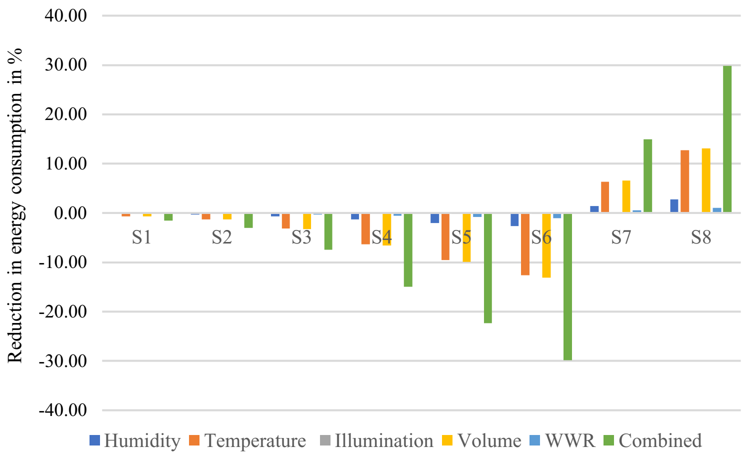

Figure 7.
Sensitivity analysis on variations of energy consumption under different simulated scenarios

scenario. However, a combined effect of these variables, with the same amount of variation as above, will reduce the energy consumption by up to 3%. A variation of 5, 10 and 15% increase in humidity, temperature, illumination and WWR and a decrease in volume, independently (S3, S4 and S5 respectively), is likely to decrease energy consumption by 0.68% up to 9.85%. However, a combined effect of these parameters (15% increase in humidity, temperature, illumination and WWR and decrease in volume together) will lead to a reduction in energy consumption of 22.05%. Similarly, an increase in 20% (S6) in humidity, temperature, illumination and WWR and a decrease in volume, independently, will decrease energy consumption by 1–13% but, in combination, will reduce energy consumption by 29.40%. In contrast, a decrease of 10% in humidity, temperature, illumination and WWR, and a 10% increase in volume (S7), will lead to an increase in energy consumption by 14.7%. Furthermore, a decrease of 20% in humidity, temperature, illumination and WWR, and a 20% increase in volume (S8), will lead to an increase in energy consumption by approximately 30%.

Thus, the sensitivity analysis showed that appropriate orientation and WWR, together with optimising the volume of the building, could increase the daylight and natural ventilation while reducing energy consumption.

Discussion

Attaining energy-efficiency in buildings, specifically in public buildings such as universities, is an important design criterion. Building parameters (both geometric and indoor environmental quality) in selected universities in South Africa, which significantly influence energy consumption, were identified in this study. These aspects included temperature, humidity, illumination, volume and WWR. In other words, orientation, size and form of the buildings influence energy consumption. According to scholars, orientation, which influences indoor aspects such as temperature, humidity and illumination, plays an important role in achieving energy efficiency. In other words, indoor temperature, humidity and illumination play crucial roles in affecting energy consumption. For example, appropriately oriented buildings receive adequate natural light, airflow and also heat from natural sources such as the sun, which help to reduce, through natural means, the energy requirements for illuminating, and managing temperature and humidity (Gracia *et al.*, 2014; Hemsath and Bandhosseini, 2015; Pacheco *et al.*, 2012; Zhang *et al.*, 2017a, b; Zomorodian and Nasrollahi, 2013).

Also, openings in the form of windows assist with airflow, as well as illumination, and thus, reduce the energy consumption. Conversely, buildings having a lower WWR, consume a higher quantity of energy. This finding was in line with the findings of other scholars such as Gracia *et al.* (2014) and Zhang *et al.* (2017a), particularly in the moderate climatic conditions of South Africa.

However, it was contrary to the findings of Ghiai *et al.* (2014), where energy consumption was found to reduce with a reduction in WWR. This might have been because of closed, transparent, glazed windows used in high-rise buildings in a different climatic condition resulting in the requirement of artificial illumination and air-conditioning in the buildings. In the current study, WWR was used for natural lighting and air movement in a temperate climatic condition. Thus, it is suggested that, in temperate climatic conditions, energy consumption decreases with an increase in WWR, unlike in hot and arid climatic conditions.

The size of the buildings (volume) also influenced energy consumption because larger buildings need more illumination, ventilation and temperature control, which consume more energy if not assisted by natural means, which was in line with the findings of Hemsath and Bandhosseini (2015) and Zhang *et al.* (2017a).

It was evident from the literature reviewed that there is a complex relationship between building parameters and energy consumption in buildings, and each parameter influences energy consumption to a certain extent, depending on the type and use of buildings and climatic conditions. From this study, it was observed that energy consumption in buildings had linear relationships with the building parameters assessed, and each parameter had a specific influence on energy consumption independently. The independent variables, in combination, also influenced energy consumption.

Moreover, the complex relationships between independent building and environmental parameters, individually and in combination, and energy consumption were established in this study. Moreover, the statistical analyses established the relative impact of each factor on energy consumption in buildings, which were found to be humidity, volume, temperature, illumination and WWR.

Also, the models developed and sensitivity analyses show quantitatively how much change in energy consumption can occur with the variations in the building and indoor environmental parameters, which would offer architects and building designers ways to design or retro-fit energy-efficient university buildings. Thus, it was observed that appropriate design intervention, considering each parameter in order, is necessary to achieve energy-efficiency in university buildings in South Africa.

Conclusions

Achieving energy-efficiency is essential to create sustainable buildings for universities in South Africa. In other words, it is necessary to design various elements of the buildings to reduce energy consumption. In order to design for optimal energy consumption, relationships between various building and indoor environmental parameters and energy consumption had to be established. The findings of this study showed that indoor temperature, humidity and illumination, which are dependent on the orientation of a building, play significant roles in energy consumption. So, appropriate orientation to harness daylight and natural ventilation is necessary to reduce energy consumption.

Similarly, the size of the functional spaces in buildings plays an important role. Larger functional building space consumes more energy. Furthermore, the proportion of window openings in the building (WWR) is also linked to energy consumption. Overall, direct relationships between building and indoor environmental parameters and energy consumption in the university buildings were established in the study, which could be used to assess the effect of building and indoor environmental parameters (independently or in combination) on energy consumption quantitatively.

Although the study relied on conventional, inferential statistical methods, the original contribution of the study is related to the influence of different building and indoor environmental parameters on energy consumption and quantifying the change in energy consumption with a unit change in the building and indoor environmental parameters. In the context of this research, originality is related to outcome and the process that produces it (Wellington, 2013). In terms of outcome, the research extends previous work in the domain by adding a new component to the whole, and in terms of process, the research explored new implications for practitioners and policymakers in the higher education sector, regarding retrofitting buildings.

In effect, it can be argued that the study has multiple implications. It will assist architects and building designers in their understanding of changes in energy consumption with variations in building and indoor environmental parameters in university buildings in temperate regions of South Africa. Also, the findings of this study, such as the relative impact of the parameters and the ability of the models to quantify energy consumption, based on the impact of the parameters independently and in combination, can assist in designing to retrofit old university buildings to make them energy efficient.

The limitation of the study was that certain parameters, such as occupancy and CO_2 that might affect energy consumption, were not considered in the evaluation of the indoor quality of buildings, which requires further investigation. However, it is argued that, while designing university buildings, the relationship between building and indoor environmental parameters, independently and in combination, should be considered and their effect should be assessed to achieve energy-efficiency, in order to develop sustainable university buildings.

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