Triangulation Method to Assess Indoor Environmental Conditions and Occupant Comfort and Productivity towards Low Energy Buildings in Malaysia

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Triangulation Method to Assess Indoor Environmental Conditions and Occupant Comfort and Productivity towards Low Energy Buildings in Malaysia

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Abstract: Saving energy and cutting costs without compromising indoor comfort conditions are challenging, especially in hot and humid regions such as Malaysia. This study explores a new approach to reducing energy consumption without compromising staff comfort in office buildings. This study aims to develop a method for lowering Building Energy Index (BEI) and maintaining acceptable indoor conditions while increasing productivity in office buildings. A developed triangulation method using Building Use Studies (BUS) for evaluating occupant satisfaction, physical measurements, and simulation modelling was implemented to measure indoor performance in an office building. The results indicated that enhancing six variables of building conditions managed to improve ~~the~~ occupant satisfaction by 44%. Hence, the productivity of staff in the building increased by 16%. The findings demonstrated that a reduction of 3 h in the operating times of chillers while an increase in chillers' temperature by 1.5 °C maintained an acceptable indoor environment and reduced the building's BEI to 89.48 kWh/m^2/year, with an energy saving of 21.51%, turning the case study into a low energy building.

Keywords: triangulation method; indoor comfort; indoor environmental conditions; productivity; low energy building; tropics

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1. Introduction

Global environmental issues require further investigations to reduce carbon emissions and energy consumption in the built environment. The concept of net zero buildings is relatively new and has been generally introduced in the last decade. More efforts have been exerted to enhance existing buildings to use less energy [1]. Sustainable buildings can be developed to achieve zero or near zero energy by utilizing passive, active, or hybrid interventions. In tropical buildings such as ~~in~~ Malaysia, studies have indicated that most energy is used to control air temperature, provide dehumidification, and increase air circulation [2]. However, it is not simple to lower energy while maintaining comfortable indoor environmental conditions [3]. Holopainen et al. [4] corroborated the notion by describing a comfortable environment as achieving satisfactory indoor conditions while maintaining an optimum use of energy and running costs as ways to promote good dynamics and high performance for its occupants. On the other hand, the influence of thermal comfort on occupants' working conditions, such as productivity, has been studied extensively in the literature [5–7]. Some studies showed that enhancing indoor thermal conditions could save several billion dollars annually by saving energy usage in building operations and maintenance [8].

The World Green Building Council [9] defines a net zero carbon building (NZCB) as a building that is highly energy efficient and fully powered by on-site and/or off-site renewable energy sources. On the other hand, several researchers have described NZCB as an approach that can be achieved by decreasing energy needs through the productivity of occupants [10]. Strategies of passive energy design towards zero fossil energy goals have been studied since the mid-twentieth century [11]. However, it is challenging to reduce energy without compromising indoor conditions, especially in hot and humid regions such as Malaysia. In such an environment, heat stress represents a severe issue [12,13].

Hot and humid conditions in working places may lead to heat-related side effects or sicknesses such as overwhelming sweating, lack of hydration, low circulatory strain, and salt lopsidedness, which promote sharp muscle agony [5,14]. As employees spend most of their day in office spaces, indoor environmental conditions play an important role in providing comfort and satisfaction. The comfort conditions have a direct influence on employees' performance [15,16]. There is an immediate connection between the indoor comfort factors of enclosed spaces and the productivity of the users [17].

Previous studies demonstrated the effects of workplace conditions on the working environment [5–7,18]. The comfort level in the workplace is influenced by different factors, such as the physical properties of building materials, ventilation, and space usage. Individuals or occupants play a critical role in building energy consumption. Occupants use different cooling or heating mechanisms to accomplish comfort. Kofoworola and Gheewala [19] indicated that the energy consumption rates are high during working hours. Fisk et al. [8] stated that every year 17 to 26 billion dollars in monetary benefits are achievable in office buildings by enhancing indoor thermal conditions in the United States.

Thermal comfort has been defined by Hensen [20] as "*a state in which there are no driving impulses to correct the environment by the behaviour*". The American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) [21] defined it as "*the condition of the mind in which satisfaction is expressed with the thermal environment*". As such, it is influenced by personal differences in mood [22], culture [23] and other individuals, and organizational and social factors [24]. Based on the above definitions, we can perceive comfort as a state of mind.

Comfort has a strong influence on occupant productivity. Occupants that reported complaints of thermal discomfort demonstrated low productivity [25–27]. Studies indicated that thermal condition is critical for occupant productivity. According to Vimalanathan and Babu [28], an office environment has a range of purposes, such as reading, typing, and learning activities. Air temperatures from 18 °C to 30 °C demonstrated a diverse response in occupant productivity. In an office environment, temperatures between 21 °C and 25 °C represent the optimum range to provide a sense of comfort. If the air temperature rises above 25 °C, an increase of 1 °C reported a 2% decrease in productivity up to 30 °C [16,29].

Most buildings in the tropics still rely on conventional energy sources, accounting for some 45% of carbon emissions. In addition, it has been estimated that 80% of new buildings to be occupied in 2050 have already been built [30]. Therefore, further efforts to enhance existing buildings based on NZCB should be considered in the tropics. Notwithstanding, providing a clear pathway to enable relevant stakeholders to effectively tackle the complex phenomenon and significantly reduce carbon emissions in the construction industry is lacking [31]. However, more efforts are needed to develop effective methods to reduce energy consumption while maintaining high levels of comfort and productivity. As a result, the adopted methods must be researched and perfected to quickly address existing buildings to mitigate climate change.

The aim of this research is to develop a method for lowering Building Energy Index (BEI) and maintaining acceptable indoor conditions while increasing productivity in Malaysian office buildings. The originality of this study lies in developing a triangulation method using Building Use Studies (BUS) for evaluating and benchmarking occupant satisfaction, physical measurements, and simulation modelling to configure the indoor environmental performance of an office building. The core of this study is maintaining (or increasing) staff's productivity while decreasing the Building Energy Index (BEI). In the tropics, this approach would help to achieve energy reduction without compromising staff satisfaction in office buildings.

2. Materials and Methods

A developed triangulation method using Building Use Studies (BUS) for evaluating occupant satisfaction, physical measurements, and simulation modelling was utilized to measure building performance. A case study building with standard performance was selected for an in-depth study through all its aspects as shown in Figure 1. The primary data were collected with the BUS survey, which is used to indicate the occupants' perception of indoor environmental conditions. Simultaneously, the actual indoor environments were physically measured by HOBOs data loggers (Onset Computer Corporation, Bourne, MA, USA) to acquire the indoor performance. Finally, IES-VE for education software (Integrated Environmental Solutions Limited, Glasgow, UK) was used in modelling the case study; this method was used for validation purposes to assess simulation outputs against measurement results.

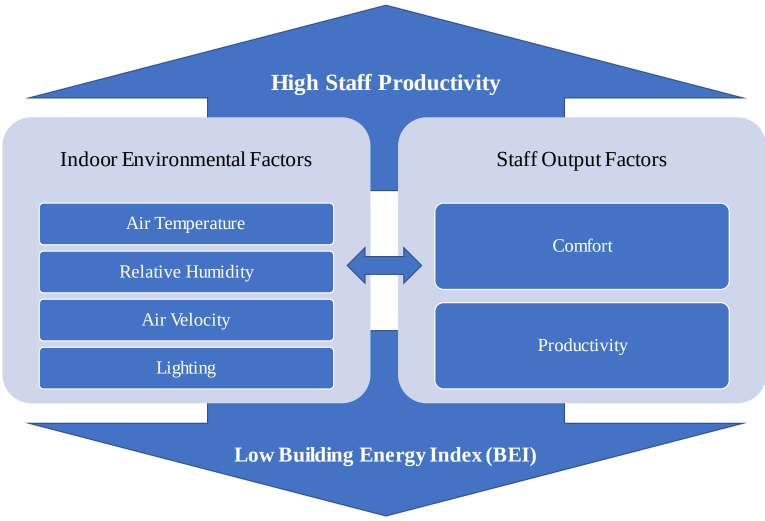

Figure 1. Theoretical Framework.

The primary data were analyzed using four different fundamental analyses. For the BUS survey variables, SPSS (IBM, Armonk, NY, USA) hierarchical multiple regression and BUS benchmarking were applied for analysis. At the same time, the physical measurements were evaluated using HOBOware graphing & analysis software (Onset Computer Corporation). For simulation, indoor environmental conditions were presented using descriptive statistics to quantitatively summarize the generated outputs. In addition, IES-VE was used to simulate several case scenarios with indoor environment enhancements following the variables indicated by the BUS survey to achieve the lowest BEI results without interfering with comfort and productivity, as shown in Figure 2.

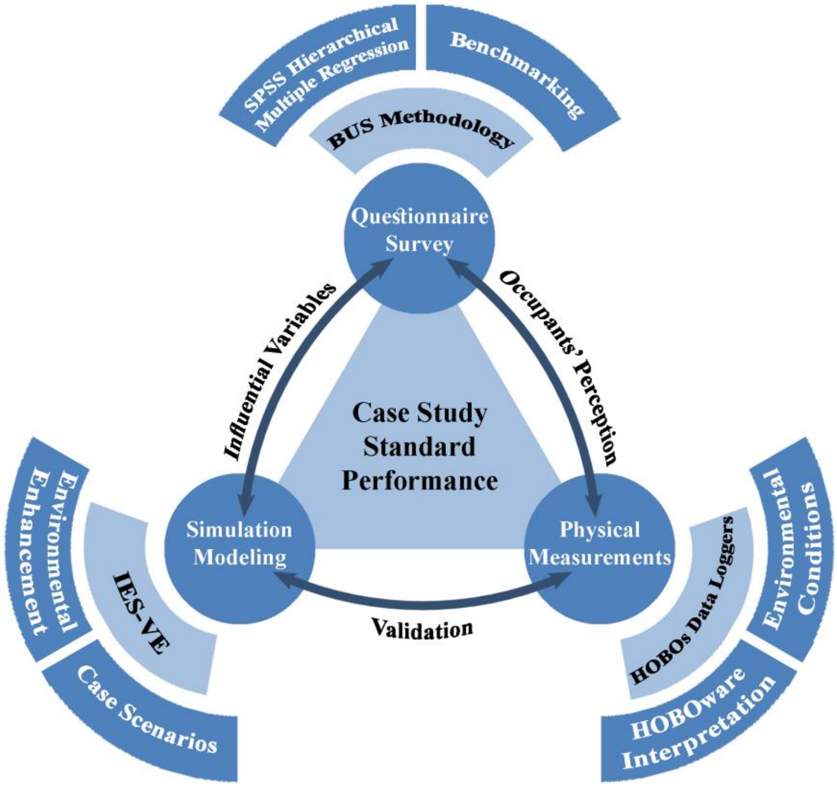

Figure 2. Developed triangulation method to assess indoor environmental conditions and staff productivity.

The research used a case study to prove and analyze the various phenomena that constitute a particular case [32]. According to Yin [33], the research could have a single case study if it is exploratory and involves more than one analysis unit. Thus, even though this research uses only one case study, different types of data and analyses were applied to fully cover this case study from different perspectives. The selected case study is the Universiti Malaya Chancellery Building in Kuala Lumpur, Malaysia. It is an office building in which different administrative divisions of 400 staff members are centralized. The building was completed in early 2011 and has been fully operational since mid-2011. The building represents the fusion of modern and traditional architecture, in which the designer mixed the use of curtain walling (modern element) and latticework with Islamic motifs (traditional) in the façade. In keeping with the popular "Malaysian Architecture" style of the 80s, the building was painted white and became the new icon for the university. Driving along the middle ring road of the campus, the building sits symbolically on the horizon of a lake as shown in Figure 3.

Figure 3. Universiti Malaya Chancellery Building.

This nine-floor building was initially designed using an open plan concept with central and side cores. Eventually, the open plan office layout evolved into a semi-open plan (closed plan) due to the specific needs of the administrative divisions. As one of the latest additions, the study building is expected to provide a comfortable indoor environment for its occupants with shading elements incorporated into the building façade design. The eleven-story building houses administrative offices, meeting and seminar rooms, an art gallery, and a sub-basement car park. Designed and built to take advantage of its location adjacent to Varsity Lake, the building was furnished with floor-to-ceiling glazing walls on its most prominent facades, allowing for a fantastic view of the lake and the old Chancellery.

This building is located in a greenery area with low building density and perfect north and south orientation. With the view, the glazing invites natural light, but also glare and heat from the morning and evening sun. The fully air-conditioned building was designed with a central core for lifts, risers for services, and emergency staircases, which prevent the use of natural ventilation. However, the toilets, pantry, air handling unit (AHU) rooms, and another set of emergency staircases were positioned on both shorter ends of the rectangular building where natural ventilation is possible and fully utilized. This building was chosen as a case study to demonstrate how an existing office can be evaluated for reducing energy consumption while maintaining an acceptable working environment.

Due to its administrative purpose, the usage of the building is entirely predictable. Activities are expected to generally commence at 8 am and subside at 6 pm from Monday to Friday. Minimal activity is expected during Saturday, Sunday, and public holidays. One hundred per cent of the energy consumed by the study building is in the form of electricity supplied by the national electricity provider. According to the monthly electricity use reports, the average total electricity usage for this building for three months was 180,500 kWh. Based on calculations, the yearly energy consumption for the building is about 2,166,000 kWh, which means the BEI is 114 kWh/m2/year. Table 1 summarizes the methodology applied in this research.

Table 1. Summary of Research Methodology.

Research Question	Research Objective	Method Approached		Purpose of Method	Type of Analysis
Q.1. What essential indoor comfort factors influence occupants' satisfaction and productivity?	1st Objective: To identify the critical indoor comfort factors influencing occupants' satisfaction and productivity.	Developed triangulation methodology to measure a case study performance	Structured questionnaire survey method (BUS survey)	To indicate the occupants' perception of the indoor comfort conditions and satisfaction	BUS benchmarking, SPSS hierarchical multiple regression
Q.2. How do indoor environmental conditions affect the operations of an office building in Malaysia?	2nd Objective: To evaluate the effects of indoor environmental conditions at an office building in Malaysia.		Physical measurements method (HOBOs data loggers)	To acquire the indoor conditions during the same period of the occupants' perception	HOBOware interpretation, descriptive analysis
Q.3. How to reduce the Building Energy Index (BEI) of an office building in Malaysia without interfering with the comfort and productivity of the staff?	3rd Objective: To develop a method for reducing the Building Energy Index (BEI) for office buildings in Malaysia with comfortable and productive staff.		Simulation modelling method (IES-VE software)	To obtain the lowest BEI results without interfering with the staff comfort and productivity	Simulate several case scenarios with indoor environment enhancements

The first method used in this study is the BUS technique, which is a global and large-scale study initiated in 1985 [34] to study building performances [35]. Besides providing a benchmark dataset for the study, BUS also provides a rapid and thorough analysis method for buildings studied. Another advantage of adopting this survey is that the BUS approach has developed a database of all studied buildings and created ‘benchmarks’ based on the most recent fifty buildings surveyed from 17 countries [36].

Measuring satisfaction and comfort is a subjective exercise. It has been argued that occupants’ satisfaction and comfort are subjective variables that can be misleading and biased if measured inappropriately and poorly supported by evidence [37]. Satisfaction may be defined differently from one respondent to another. Where an individual respondent may feel ‘satisfied’ when the building and its facilities are all in working condition, another may feel ‘satisfied’ only if he/she feels that they deliver more when working inside the building. Therefore, the questionnaire was constructed from many sub-measurements that describe ‘satisfaction’ and ‘comfort’ when aggregated.

The second approach in the developed triangulation method is the empirical measurements using HOBOs data loggers. These devices were used to collect data about the building’s internal conditions, including air temperature, relative humidity, and illuminance. The measurement took 7 days covering weekdays and weekends for each floor from the first week of December 2016 to the end of January 2017. Eight data loggers were installed on each of the selected six building floors, namely 2nd, 3rd, 6th, 7th, 8th, and 9th. The HOBOs were not installed on all the building floors as some floors were unoccupied during the study or used for different functions (e.g., gallery or car park), and other floors have temporary occupations such as the 4th floor, which include meeting rooms and a prayer room. The HOBOs were installed at 900 mm above the floor, within the average seating height in an office, carefully considering their locations in the office spaces and considering the existence of two AHUs on each floor. Typically, four data loggers were distributed under each section of the AHUs, as shown in Figure 4.

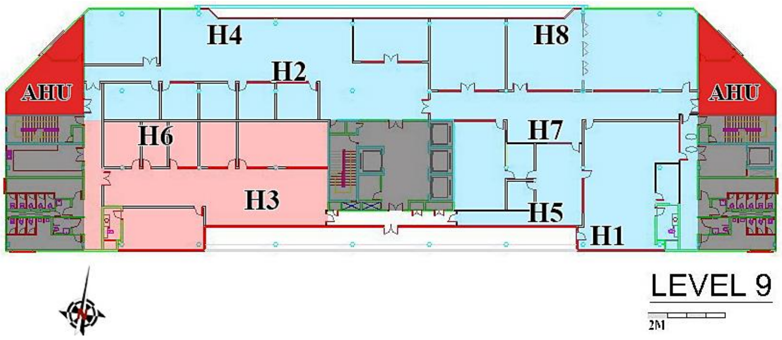

Figure 4. Typical floor (9th) of UM Chancellery Building and distribution of data loggers. There are two air-conditioned offices on this floor in light blue and pink. HOBO data loggers were located at H1–H8 (close to the curtain walls and deep inside the offices). AHU is the air-handling unit.

The third approach in the developed triangulation method is simulation modelling using the Integrated Environmental Solutions-Virtual Environment (IES-VE). IES-VE represents one of the most reliable simulation tools in energy-efficient design, particularly for building systems. IES-VE meets the requirements of ASHRAE Standard 140 and CIBSE AM11 [38]. The Green Building Index [39] and the Building Energy Efficiency Technical Guideline for Passive Design [40] recommend the simulation program for Malaysian conditions. Several studies have validated the accuracy of the selected software, and a procedure commonly referred to as calibration was performed on the simulation model. The findings of the simulations by Al-Tamimi and Syed Fadzil [41], Lim and Ahmad [42], and Al-Obaidi et al. [43] investigated the accuracy of IES-VE with field measurements. The results of IES-VE evaluation, including solar radiation (irradiance and irradiation), air temperature, and air humidity, showed a high-reliability level in the tropics.

This study is limited to measuring the indoor air temperature, relative humidity, air velocity, and lighting due to equipment availability, plus the ability to configure a comfortable indoor environmental condition without restricting the occupants' clothing. The clothing restriction issue stems from the need to adapt to the hot and humid tropical climatic conditions where the case study is located. Further, the clothing of occupants differs between genders and staff ranks. Thermal comfort was not conducted in the field and simulation analysis. Therefore, the satisfaction of indoor conditions was instead examined using the BUS survey instead of a PMV-PPD model. In addition, a comparison with the PMV-PPD was not made as the PMV method has low accuracy for air-conditioned buildings, which affects the accuracy of the PPD, as argued by Cheung et al. [44].

3. Results and Discussion

The total number of participants who answered the questionnaire survey was 208 out of 376 (56.7% response rate). The participants were from twenty different departments on nine floors within the building. The demographic characteristics of the respondents in the Chancellery building are summarized in Table 2. The respondents are categorized by age, gender, number of occupants in the working area, sitting next to a window or not, years worked in this building, years worked in the present working area, and floor. One hundred and fifty-two respondents (76.0%) are 30 years old or over and one hundred and forty respondents (71.1%) are females. One hundred and eighteen respondents (59.0%) share their working area with more than eight occupants and one hundred and seventeen respondents (56.5%) do not sit next to a window. One hundred and seventy-nine respondents (86.5%) have been working in the case study building for a year or more, while one hundred and sixty-six respondents (80.2%) have been working in the same work area for a year or more.

Table 2. Demographic characteristics of the respondents (all floors).

Demographic	Characteristics	Missing	Frequency	Valid Percentage
Age	Under 30 years	8	48	24.0%
	30 or over		152	76.0%
Gender	Male	11	57	28.9%
	Female		140	71.1%
Number of occupants in the working area	Alone	8	24	12.0%
	Shared with 1 other		8	4.0%
	With 2–4 others		22	11.0%
	With 5–8 others		28	14.0%
	With more than 8		118	59.0%
Setting next to a window	Yes	1	90	43.5%
	No		117	56.5%
Worked in this building	Less than a year	1	28	13.5%
	A year or more		179	86.5%
Worked in present work area	Less than a year	1	41	19.8%
	A year or more		166	80.2%
Floor	Ground floor (OS)	-	23	11.1%
	Second floor (OS)		33	15.9%
	Third floor (CS)		23	11.1%
	Fourth floor		4	1.9%
	Fifth floor		1	0.5%
	Sixth floor (OS)		41	19.7%
	Seventh floor (CS)		35	16.8%
	Eighth floor (CS)		23	11.1%
	Ninth floor (CS)		25	12.0%

The obtained results focused on measuring fifteen variables, divided into four main groups, as shown in Table 3. The first group covers temperature variables, namely temperature comfort (uncomfortable–comfortable), temperature range (too hot–too cold) and temperature stability (stable–varies during the day). In contrast, the second group contains air humidity and velocity variables that are air movement (still–draughty), air humidity (dry–humid), air freshness (fresh–stuffy), air smell (odorless–smelly), and air conditions overall (unsatisfactory–satisfactory). However, the third group consists of lighting variables, i.e., lighting overall satisfactory (unsatisfactory–satisfactory), natural light (too little–too much), glare from the sun and sky (none–too much), artificial light (too little–too much), and glare from lights (none–too much) were also measured.

Moreover, for the fourth group of variables, the respondents were asked to provide their general opinion about the overall comfort of their working conditions (unsatisfactory–satisfactory) and productivity at work (−40% or less to +40% or more) as essential variables. The benchmarking results indicated how well or poorly the conditions in the Chancellery Building the results compared with other buildings benchmarked by the BUS Methodology. For instance, the temperature is not suitable as it is colder than the benchmark (shown in red).

Table 3. The BUS survey results for all building floors.

Variable	Mean	Std. Error of Mean	Std. Deviation	Variance	Benchmarking Results
Temperature Variables					
Temperature: comfort overall	4.74	0.076	1.073	1.152	Green (above the benchmark—comfortable)
Range: hot/cold	4.84	0.079	1.111	1.235	Red (above the benchmark—too cold)
Stability: stable/varies	4.51	0.078	1.107	1.226	Red (above the benchmark—varies)
Air (Humidity & Velocity) Variables					
Air movement: still/draughty	4.05	0.079	1.109	1.230	Green (above the benchmark—acceptable)
Air humidity: dry/humid	4.12	0.068	0.953	0.908	Amber (no difference with the benchmark)
Air freshness: fresh/stuffy	4.11	0.074	1.046	1.094	Amber (no difference with the benchmark)
Air smell: odorless/smelly	3.91	0.080	1.126	1.267	Amber (no difference with the benchmark)
Air Conditions overall	4.76	0.062	0.886	0.784	Green (above the benchmark—satisfactory)
Lighting Variables					
Lighting: overall satisfactory	4.79	0.077	1.100	1.210	Amber (no difference with the benchmark)
Natural light: too little/too much	4.36	0.086	1.225	1.501	Red (above the benchmark—too much)
Glare from the sun: none/too much	3.98	0.105	1.490	2.220	Amber (no difference with the benchmark)
Artificial light: too little/too much	4.37	0.079	1.115	1.244	Red (above the benchmark—too much)
Glare from lights: none/too much	4.21	0.084	1.195	1.429	Red (above the benchmark—too much)
Other Essential Variables					
Comfort: overall satisfactory	4.87	0.058	0.829	0.687	Amber (no difference with the benchmark)
Productivity: −40% to +40%	6.55 +15.5%	0.100	1.388	1.925	Green (above the benchmark—increased)

The number of valid responses for this test was 169. The minimum sample size required is 69 for a significant hierarchical multiple regression test within two sets of variables: set A with six variables and set B with thirteen variables [45]. Accordingly, the influence of temperature, humidity, air velocity, and illuminance were analyzed on overall comfort. Control variables were considered in the analysis to ensure that overall comfort was not affected by other variables other than building conditions. The following variables were considered as control variables for comfort, namely, age (less than 30 or more than 30), gender (male or female), and the number of occupants of the office (working alone, shared with 1 person, shared with 2–4 others, shared with 5–8 others, or shared with more than 8 others). Other variables were sitting next to a window (yes or no), the duration of working in this building (less than a year or more than a year), and how long you have worked in your present work area (less than a year or more than a year). The results are presented for comfort as follows.

First, the results showed that the first block of control variables had no significant influence on comfort, as shown in Table 4. The building conditions significantly influenced comfort when control variables were considered (R^2 Change = 0.444). The result shows that building conditions have about 42% influence on staff level of comfort (Adjusted R^2= 0.418).

Table 4. Influence of temperature, air, and light on comfort (Model Summary).

Model	R	R^2	Adjusted R^2	Std. Error of the Estimate	Change Statistics					Durbin-Watson
					R^2 Change	F Change	df1	df2	Sig. F Change	
1	0.200 [a]	0.040	0.004	0.793	0.040	1.125	6	162	0.350	
2	0.695 [b]	0.484	0.418	0.606	0.444	9.842	13	149	0.000	1.963

[a]. Predictors: (Constant), How long have you worked in your present work area? Do you sit next to a window in your regular workspace? Is your office or work area? What is your sex? What is your age? How long have you worked in this building? [b]. Predictors: (Constant), How long have you worked in your present work area? Do you sit next to a window in your regular workspace? Is your office or work area? What is your sex? What is your age? How long have you worked in this building? Air smell, Temperature stable, Comfort conditions overall, Glare from lights, Air humidity, Natural light, Temperature (hot–cold), Temperature comfort, Lighting overall, Air movement, Artificial light, Glare from sun and sky, Air freshness.

Variables that have great influence on comfort were temperature range (Beta = 0.230), air conditions overall (Beta = 0.380), natural light (Beta = 0.227), glare from sun and sky (Beta = −0.224), artificial light (Beta = 0.180), and glare from lights (Beta = −0.197) as shown in the coefficient results (Table 5).

Table 5. Coefficient results of the influence of building conditions on comfort.

Model		Unstandardized Coefficients		Standardized Coefficients	Sig.	Collinearity Statistics	
		B	Std. Error	Beta		Tolerance	VIF
1	(Constant)	4.880	0.542		0.000		
	What is your age?	0.239	0.153	0.126	0.120	0.911	1.098
	What is your sex?	0.145	0.135	0.085	0.284	0.955	1.047
	Is your office or work area?	−0.012	0.045	−0.020	0.797	0.972	1.029
	Do you sit next to a window in your regular workspace?	0.038	0.124	0.024	0.758	0.988	1.012
	How long have you worked in this building?	−0.312	0.236	−0.130	0.187	0.616	1.624
	How long have you worked in your present work area?	−0.073	0.193	−0.037	0.704	0.637	1.571
2	(Constant)	1.988	0.635		0.002		
	What is your age?	0.072	0.124	0.038	0.560	0.811	1.234
	What is your sex?	0.221	0.109	0.129	0.045	0.855	1.169
	Is your office or work area?	−0.012	0.036	−0.020	0.745	0.915	1.093
	Do you sit next to a window in your regular workspace?	−0.083	0.106	−0.051	0.439	0.787	1.271
	How long have you worked in this building?	−0.269	0.185	−0.112	0.148	0.582	1.717
	How long have you worked in your present work area?	−0.029	0.154	−0.015	0.849	0.585	1.709
	Temperature comfort	0.046	0.058	0.061	0.431	0.590	1.696
	Temperature (hot-cold)	0.161	0.053	0.230	0.003	0.605	1.653
	Temperature stable	−0.010	0.056	−0.013	0.861	0.596	1.677
	Air movement	−0.058	0.058	−0.081	0.323	0.517	1.934
	Air humidity	0.039	0.078	0.045	0.616	0.440	2.272
	Air freshness	0.051	0.077	0.063	0.506	0.383	2.613
	Air smell	−0.093	0.058	−0.124	0.108	0.591	1.691
	Air conditions overall (Air)	0.352	0.067	0.380	0.000	0.665	1.503
	Lighting overall	0.103	0.061	0.138	0.095	0.517	1.935
	Natural light	0.156	0.062	0.227	0.013	0.424	2.359
	Glare from the sun and sky	−0.119	0.049	−0.224	0.016	0.411	2.435
	Artificial light	0.130	0.060	0.180	0.032	0.498	2.008
	Glare from lights	−0.136	0.054	−0.197	0.012	0.571	1.752

The number of valid responses for this test was 163. The minimum sample size required is 72 for a significant hierarchical multiple regression test within two sets of variables, set (A) six variables and set (B) fourteen variables [45]. Accordingly, productivity was analyzed on the influence of temperature, humidity, air velocity, light, and overall comfort. Control variables were considered in the analysis to ensure that productivity was not affected by other variables other than building conditions. The following variables were considered as control variables for productivity, namely, age (less than 30 or more than 30), gender (male or female), and the number of occupants of the office (working alone, shared with 1 person, shared with 2–4 others, shared with 5–8 others, or shared with more than 8 others). Other variables are, sitting next to a window (yes or no), the duration of working in this building (less than a year or more than a year), and how long you have worked in your present work area (less than a year or more than a year). The results for productivity are presented as follows.

First, the results show that the first block of control variables has no significant influence on productivity, as shown in Table 6. Building conditions and comfort significantly influence productivity when control variables are considered (R^2 Change = 0.160). The overall results indicated that building conditions have about 8% influence on staff productivity (Adjusted R^2 = 0.075).

Table 6. Influence of temperature, air, lighting, and comfort on productivity (Model Summary).

Model	R	R^2	Adjusted R^2	Std. Error of the Estimate	Change Statistics					Durbin-Watson
					R^2 Change	F Change	df1	df2	Sig. F Change	
1	0.173 [a]	0.030	−0.007	1.384	0.030	0.805	6	156	0.567	
2	0.435 [b]	0.190	0.075	1.326	0.160	1.998	14	142	0.022	2.170

[a]. Predictors: (Constant), How long have you worked in your present work area? Is your office or work area? Do you sit next to a window in your regular workspace? What is your sex? What is your age? How long have you worked in this building? [b]. Predictors: (Constant), How long have you worked in your present work area? Is your office or work area? Do you sit next to a window in your regular workspace? What is your sex? What is your age? How long have you worked in this building? Air smell, Temperature stable, Comfort conditions overall, Glare from lights, Air humidity, Natural light, Temperature (hot–cold), Temperature comfort, and Lighting overall. All things considered, how do you rate the overall comfort of the building environment? Air movement, Artificial light, Glare from sun and sky, Air freshness.

Table 7 demonstrates the variable that significantly influences productivity, the overall comfort is (Beta = 0.305) as shown in the coefficient results. Age has an almost significant influence on productivity but with small Beta value.

Table 7. Coefficient results of the influence of building conditions and comfort on productivity.

Model		Unstandardized Coefficients		Standardized Coefficients	Sig.	Collinearity Statistics	
		B	Std. Error	Beta		Tolerance	VIF
1	(Constant)	6.510	0.950		0.000		
	What is your age?	0.530	0.273	0.161	0.054	0.902	1.109
	What is your sex?	0.029	0.239	0.010	0.902	0.956	1.046
	Is your office or work area?	0.003	0.081	0.003	0.975	0.973	1.028
	Do you sit next to a window in your regular workspace?	0.045	0.221	0.016	0.838	0.982	1.019
	How long have you worked in this building?	−0.301	0.428	−0.072	0.482	0.597	1.674
	How long have you worked in your present work area?	−0.215	0.352	−0.061	0.543	0.630	1.587
2	(Constant)	4.819	1.468		0.001		
	What is your age?	0.236	0.278	0.072	0.399	0.793	1.261
	What is your sex?	0.121	0.247	0.041	0.624	0.821	1.217
	Is your office or work area?	0.013	0.081	0.013	0.875	0.897	1.115

Do you sit next to a window in your regular workspace?	0.076	0.242	0.027	0.756	0.752	1.330
How long have you worked in this building?	−0.262	0.425	−0.062	0.539	0.555	1.801
How long have you worked in your present work area?	−0.050	0.355	−0.014	0.889	0.570	1.756
Temperature comfort	−0.018	0.131	−0.014	0.893	0.568	1.761
Temperature (hot-cold)	−0.087	0.120	−0.072	0.472	0.566	1.767
Temperature stable	−0.061	0.129	−0.048	0.638	0.555	1.802
Air movement	−0.063	0.130	−0.052	0.625	0.504	1.984
Air humidity	−0.002	0.173	−0.001	0.990	0.441	2.265
Air freshness	0.122	0.171	0.087	0.477	0.380	2.628
Air smell	−0.147	0.129	−0.113	0.257	0.575	1.740
Air conditions overall	0.190	0.160	0.119	0.238	0.567	1.763
Lighting overall	−0.066	0.137	−0.051	0.631	0.514	1.945
Natural light	−0.081	0.139	−0.069	0.560	0.403	2.484
Glare from the sun and sky	0.066	0.110	0.073	0.550	0.389	2.571
Artificial light	0.120	0.134	0.098	0.372	0.479	2.086
Glare from lights	−0.218	0.120	−0.185	0.073	0.546	1.833
All things considered, how do you rate the overall comfort of the building environment?	0.531	0.183	0.305	0.004	0.518	1.930

The critical indoor comfort factors that influence occupants' comfort and productivity have been identified to meet the first objective of the study with both benchmarking and SPSS hierarchical multiple regression as follows:

Benchmarking results indicated how well or poorly the conditions in the Chancellery Building compared with other buildings benchmarked by the BUS Methodology. Benchmarking for the whole building generally indicated that most temperature variables are shown in red, which means they are worse than the benchmark. In comparison, most air variables are amber, meaning there is no difference from the benchmark. However, most lighting variables are red, which shows that the lighting in this case study is worse than the benchmark. Moreover, the overall comfort variable is amber, which states that comfort in this building is similar to the benchmark; furthermore, the productivity variable is green, indicating that staff productivity for the chancellery building is better than the benchmark.

The hierarchical multiple regression test indicated that six variables of building conditions, namely, temperature range, air conditions overall, natural light, glare from sun and sky, artificial light, and glare from lights have a significant influence on staff comfort. Changes to these variables can have a change of about 42% to staff comfort which is quite high. As staff productivity is mainly influenced by the overall comfort of the building environment, an increase in overall comfort conditions can increase staff productivity by about 8%.

The physical conditions of the indoor environments are presented in Table 8. This part investigated the second objective in terms of understanding the physical factors of the indoor environmental conditions that affected the operations of the case study. The results demonstrated average findings of air temperature, relative humidity, air velocity, and illuminance during work days. By examining the collected data against the criteria of comfort conditioning in ASHRAE [46], it was found that more than 87.50% of data loggers did not meet comfort perception which should be adjusted to deliver comfortable and productive environments for the staff in the case study. Figure 5 illustrates the locations of data loggers that provide comfort perception. The green shades demonstrate the locations with comfortable conditions while the red shades indicate the locations that need to be improved.

Table 8. Average readings of all physical measurements at all levels.

Floor	Data Logger	Temp °C	RH %	Vel. m/s	Illuminance Lux		
					9:00	12:00	15:00
Level 2	H1	21.69	73.36	0.170	157.68	212.86	208.93
	H2	21.88	65.44	0.055	108.40	143.90	112.35
	H3	22.70	74.10	1.152	100.48	122.20	124.18
	H4	25.41	53.93	1.070	2524.75	4964.78	4229.65
	H5	21.69	65.50	0.806	404.03	703.63	918.48
	H6	20.87	68.90	0.385	106.40	137.98	151.75
	H7	25.57	62.10	0.386	806.10	1395.43	1198.33
	H8	23.68	69.45	0.950	236.50	376.45	411.93
Level 6	H1	24.29	63.94	0.068	985.48	1326.45	812.03
	H2	22.67	75.74	0.165	114.30	124.18	130.08
	H3	22.41	72.17	1.186	171.48	203.00	191.20
	H4	21.97	73.29	0.549	92.65	90.70	92.65
	H5	25.18	65.03	0.759	788.38	1022.93	618.90
	H6	23.81	65.72	0.302	120.23	132.05	102.48
	H7	22.22	77.29	0.618	214.83	197.08	120.23
	H8	23.76	69.94	1.038	1046.55	1722.60	1409.23
Level 7	H1	23.23	72.19	0.055	1320.55	3244.18	2717.90
	H2	24.03	73.44	0.074	323.25	406.03	346.90
	H3	24.25	72.46	1.214	218.775	281.83	201.05
	H4	22.87	75.24	0.549	86.73	122.18	114.30
	H5	23.38	71.92	0.956	934.20	2244.90	1923.63
	H6	23.61	70.58	0.372	216.78	319.30	275.93
	H7	22.87	77.17	0.600	139.95	151.73	147.76
	H8	24.38	68.31	1.122	1241.70	2438.08	1509.75
Level 8	H1	22.92	75.39	0.089	1322.48	2497.23	1643.75
	H2	23.25	73.88	0.053	183.30	230.60	155.70
	H3	23.33	71.92	1.220	386.33	354.76	193.15
	H4	22.37	77.82	0.683	250.33	425.73	266.08
	H5	23.51	71.72	0.863	1805.38	1501.85	354.78
	H6	23.15	74.30	0.380	69.00	80.83	61.10
	H7	21.88	80.21	0.782	143.85	157.65	139.93
	H8	21.82	80.32	0.791	51.20	51.20	27.55

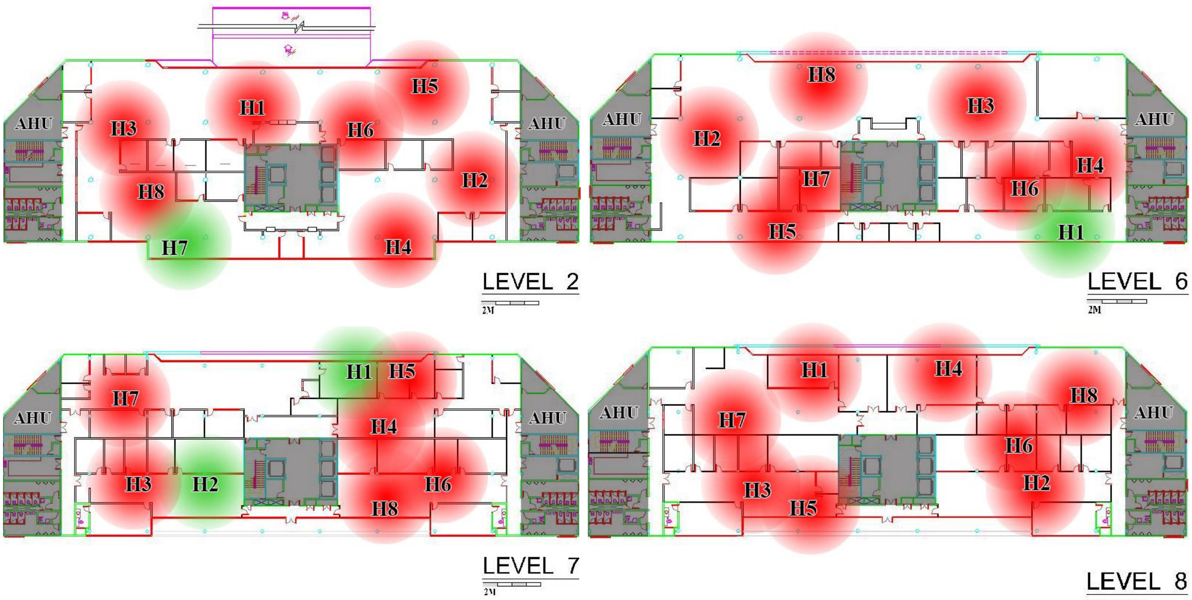

Figure 5. Locations of data loggers and perceived comfort in different floors. HOBO data loggers were located at H1–H8 (close to the curtain walls and deep inside the offices). AHU is the air-handling unit.

Furthermore, the third method using simulation modelling was used to investigate the physical factors of the indoor environments. As shown in Figure 6, physical measurements and IES-VE results are similar, indicating the simulation results' validity. The results showed that indoor comfort conditions are unstable during weekdays and even weekends. In short, the outdoor environmental condition quickly affects the Chancellery building envelope. The outdoor climate data used for simulation is the IES-VE Kuala Lumpur climate data file.

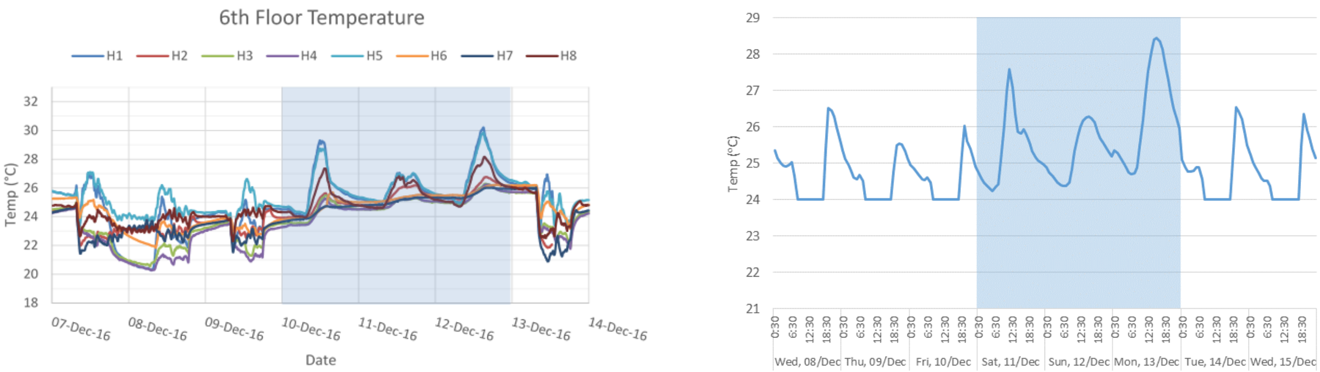

Figure 6. Indoor air temperature for 7 days in level 6 (field measurements on the **left** and simulation results on the **right**) [18].

As shown in Figure 7, the simulation results indicated a similar pattern in relative humidity readings. These results pointed to a problem with cooling systems that deliver high humidity levels and add more loads to indoor environmental conditions. In addition, the simulation results showed that the illuminance measurement was similar to the data loggers, as shown in Figure 8.

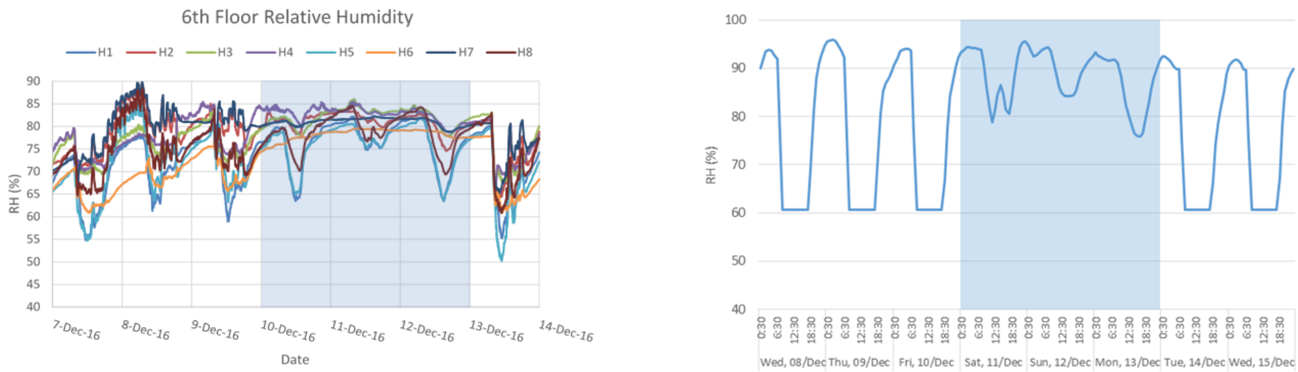

Figure 7. Readings of relative humidity for 7 days in level 6 (field measurements on the **left** and simulation results on the **right**) [18].

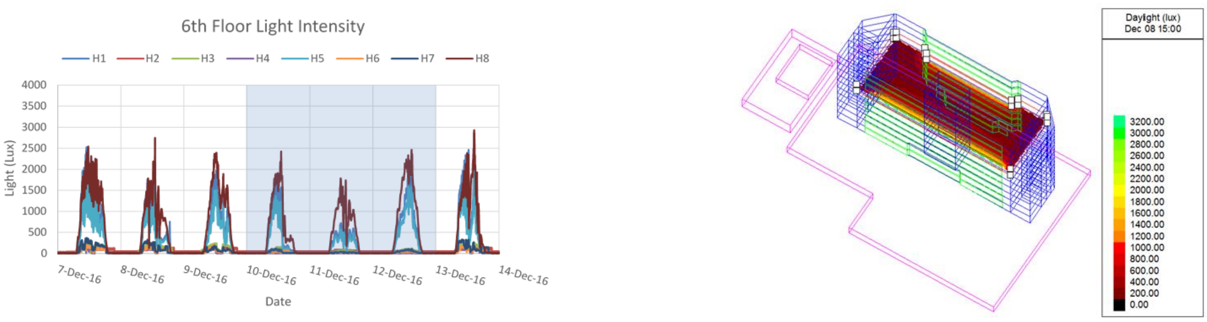

Figure 8. Readings of illuminance levels for 7 days in level 6 (field measurements on the **left** and simulation results on the **right**) [18].

Air conditions and temperature range are the most significant variables resulting in the multiple regression analysis; therefore, the simulation case scenarios have been based on changing the chillers' temperature and working hours. The simulation was categorized into six main groups according to the chillers' temperature case scenarios, namely, chillers set to 24 °C, 24.5 °C, 23.5 °C, 25 °C, 23 °C, and 25.5 °C. Each group is divided into 16 simulations. As a result, the total number of simulations was 96 case scenarios, including the chillers load outcomes calculated in MWh. All floors in the simulation analysis were adjusted into open plan offices as occupants' perception and physical measurements in open plan floors demonstrated improved results.

The current yearly energy consumption for the chancellery building is 2,166,000 kWh, which means its current Building Energy Index (BEI) is 114.00 kWh/m^2/year. Eighty-six out of ninety-six cases have less yearly energy consumption than the current situation. It is estimated that the reduction of 3 h in the air-conditioning operating hours resulted in 314,630 kWh of yearly energy consumption reduction. Thus, adjusting the working hours of the chillers from 0900 to 1600 with the same temperature, which is 24 °C, improves indoor thermal conditions inside the building and reduces the building's BEI to 97.44 kWh/m^2/year with an energy saving of 14.53%. Furthermore, it is possible to obtain the optimum results by reducing the air-conditioning operating hours by 3 h while increasing the temperature of the chillers by just 1.5 °C. Hence, adjusting the working hours of the chillers to 0900–1600 with a temperature of 25.5 °C maintained comfort inside the building. This adjustment also reduced the building's BEI to 89.48 kWh/m^2/year with an energy saving of 21.51%, as shown in Table 9.

Table 9. Simulation scenarios with various chiller temperatures to achieve energy efficiency.

No.	Case Scenarios Simulation		Yearly Energy Consumption (kWh)	BEI (kWh/m^2/year)	Energy Saving
	ON-OFF	Temp (°C)			
1	0900–1600	25.5	1,700,190	89.48	21.51%
2	0830–1600	25.5	1,741,860	91.68	19.58%
3	0900–1600	25.0	1,750,740	92.14	19.18%
4	0900–1630	25.5	1,773,410	93.34	18.12%
5	0800–1600	25.5	1,774,740	93.41	18.06%
6	0830–1600	25.0	1,794,430	94.44	17.16%
7	0730–1600	25.5	1,798,940	94.68	16.95%
8	0900–1600	24.5	1,801,130	94.80	16.84%
9	0830–1630	25.5	1,812,590	95.40	16.32%
10	0900–1630	25.0	1,826,030	96.11	15.69%
11	0800–1600	25.0	1,829,250	96.28	15.54%
12	0900–1700	25.5	1,841,640	96.93	14.97%
13	0800–1630	25.5	1,843,310	97.02	14.89%
14	0830–1600	24.5	1,846,850	97.20	14.74%
15	0900–1600	24.0	1,851,370	97.44	14.53%
16	0730–1600	25.0	1,855,300	97.65	14.34%
17	0730–1630	25.5	1,865,690	98.19	13.87%
18	0830–1630	25.0	1,867,150	98.27	13.80%
19	0900–1630	24.5	1,878,500	98.86	13.28%
20	0830–1700	25.5	1,878,560	98.87	13.27%
21	0800–1600	24.5	1,883,600	99.14	13.04%
22	0900–1730	25.5	1,893,110	99.64	12.60%
23	0900–1700	25.0	1,896,260	99.80	12.46%
24	0830–1600	24.0	1,899,100	99.95	12.32%
25	0800–1630	25.0	1,899,740	99.98	12.30%
26	0900–1600	23.5	1,901,440	100.08	12.21%
27	0800–1700	25.5	1,907,320	100.39	11.94%
28	0730–1600	24.5	1,911,500	100.61	11.75%
29	0830–1630	24.5	1,921,560	101.13	11.29%
30	0730–1630	25.0	1,923,880	101.26	11.18%
31	0730–1700	25.5	1,928,020	101.47	10.99%

32	0830–1730	25.5	1,928,190	101.48	10.98%
33	0900–1630	24.0	1,930,800	101.62	10.86%
34	0830–1700	25.0	1,935,040	101.84	10.67%
35	0800–1600	24.0	1,937,790	102.00	10.53%
36	0900–1730	25.0	1,949,650	102.61	10.00%
37	0900–1700	24.5	1,950,720	102.67	9.94%
38	0830–1600	23.5	1,951,200	102.69	9.92%
39	0900–1600	23.0	1,951,360	102.70	9.91%
40	0800–1730	25.5	1,955,380	102.91	9.73%
41	0800–1630	24.5	1,956,000	102.95	9.69%
42	0800–1700	25.0	1,965,580	103.45	9.25%
43	0730–1600	24.0	1,967,540	103.55	9.17%
44	0730–1730	25.5	1,974,760	103.93	8.83%
45	0830–1630	24.0	1,975,800	104.00	8.77%
46	0730–1630	24.5	1,981,910	104.31	8.50%
47	0900–1630	23.5	1,982,950	104.37	8.44%
48	0830–1730	25.0	1,986,510	104.55	8.29%
49	0730–1700	25.0	1,987,980	104.63	8.22%
50	0830–1700	24.5	1,991,350	104.81	8.06%
51	0800–1600	23.5	1,991,820	104.83	8.04%
52	0830–1600	23.0	2,003,130	105.43	7.52%
53	0900–1700	24.0	2,005,010	105.53	7.43%
54	0900–1730	24.5	2,006,030	105.58	7.39%
55	0800–1630	24.0	2,012,090	105.90	7.11%
56	0800–1730	25.0	2,015,410	106.07	6.96%
57	0730–1600	23.5	2,023,410	106.50	6.58%
58	0800–1700	24.5	2,023,680	106.51	6.57%
59	0830–1630	23.5	2,029,870	106.84	6.28%
60	0900–1630	23.0	2,034,930	107.10	6.05%
61	0730–1730	25.0	2,036,420	107.18	5.98%
62	0730–1630	24.0	2,039,780	107.36	5.82%
63	0830–1730	24.5	2,044,670	107.61	5.61%
64	0800–1600	23.0	2,045,680	107.67	5.55%
65	0830–1700	24.0	2,047,500	107.76	5.47%
66	0730–1700	24.5	2,047,780	107.78	5.46%
67	0900–1700	23.5	2,059,140	108.38	4.93%
68	0900–1730	24.0	2,062,250	108.54	4.79%
69	0800–1630	23.5	2,068,020	108.84	4.53%
70	0800–1730	24.5	2,075,280	109.23	4.18%
71	0730–1600	23.0	2,079,110	109.43	4.01%
72	0800–1700	24.0	2,081,600	109.56	3.89%
73	0830–1630	23.0	2,083,790	109.67	3.80%
74	0730–1630	23.5	2,097,470	110.39	3.17%
75	0730–1730	24.5	2,097,920	110.42	3.14%
76	0830–1730	24.0	2,102,660	110.67	2.92%
77	0830–1700	23.5	2,103,480	110.71	2.89%
78	0730–1700	24.0	2,107,400	110.92	2.70%
79	0900–1700	23.0	2,113,110	111.22	2.44%
80	0900–1730	23.5	2,118,290	111.49	2.20%
81	0800–1630	23.0	2,123,780	111.78	1.95%
82	0800–1730	24.0	2,134,980	112.37	1.43%
83	0800–1700	23.5	2,139,360	112.60	1.23%
84	0730–1630	23.0	2,155,000	113.42	0.51%
85	0730–1730	24.0	2,159,250	113.64	0.32%
86	0830–1700	23.0	2,159,300	113.65	0.31%
87	Existing		2,166,000	114.00	0.00%

4. Conclusions

By applying the developed triangulation method using Building Use Studies (BUS) for evaluating occupant satisfaction, physical measurements, and simulation modelling on the case study, energy consumption was reduced, and indoor environmental conditions and perceived productivity of staff were improved. This triangulation method provided a simple yet practical way to develop a greater understanding of building conditions and occupants' requirements. The method, through the simulation trials, enabled the development of recommendations to reduce energy and enhance indoor conditions, comfort, and productivity. The main findings from this research are summarized below:

- The general benchmarking results for the whole building indicate that most temperature variables are lower than the benchmark. However, most of the air variables have no difference from the benchmark. Moreover, the overall comfort variable was similar to the benchmark. Interestingly, the productivity variable was better than the benchmark.
- The results of physical measurements indicated that 87.50% of the studied areas/zones do not comply with comfort perception. Thus, the majority of office areas should be adjusted to provide comfortable and productive environments.
- The simulation analysis showed that a reduction of 3 h in the operating hours with an increase in chillers' temperature by just 1.5 °C managed to provide optimum results. The application was demonstrated by adjusting the working hours of the chillers to 0900–1600 with a temperature of 25.5 °C, maintaining indoor conditions and reducing the building's BEI to 89.48 kWh/m^2/year with an energy saving of 21.51%.
- This simple adjustment of chillers operation not only reduces the building's BEI, but also can enhance staff comfort and productivity. The result of the hierarchical multiple regression analysis showed the expected level of change based on Beta values (i.e., considering all other variables can lead to a 42% change to staff comfort and 8% change to productivity).

Finally, this study offers a new strategy in providing a method for lowering carbon emissions and energy consumption while improving the productivity of users in existing office buildings.

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