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*Applied Energy* 2016

DOI: http://dx.doi.org/10.1016/j.apenergy.2015.12.053



**DOI link to article:**

http://dx.doi.org/10.1016/j.apenergy.2015.12.053

**Date deposited:**

18/04/2016

**Embargo release date:**

02 January 2017

Office Building Cooling Load Reduction Using Thermal Analysis Method – A Case Study

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*Keywords: Sustainable building, Retrofit, Cooling system, Thermal analysis.*

**Abstract**

Buildings worldwide consume approximately 45% of primary energy sources, making it the single largest energy consumption sector. The importance of improving a building's energy performance was emphasized by the government with the enforcement of sustainable building policies. Article 9 of the Directive 2010/31/EU of the European Parliament and the Council (19$^{th}$ May 2010) on the energy performance of buildings states the importance of stimulating refurbishment of existing buildings into near zero-energy buildings. However, the effectiveness of the process depends on the basic building structure and the refurbishment designs. Hence, methods to find the effective strategies for retrofitting and modelling to predict energy reduction is vital. Unlike the previous studies, this paper presents a method for a deep building retrofit based on the whole building's thermal analysis specifically for cooling demand countries. This work set against recommended best practice office building energy benchmarks in Malaysia, and following a comprehensive building audit, a retrofit strategy was proposed based on target building's thermal analysis with cooling demand reduction in particular focus. It was found that 71% of the building's heat gain emanated from its lighting system and solar heat gain through windows. A 40.2% reduction in the building's cooling load is estimated to reduce 47% of the total energy consumption. A comparison of the actual and simulated energy results suggested that the simulation made under predicted the energy reduction by 4.3%.

*This paper was presented at the 7th International Conference on Applied Energy (ICAE2015), March 28-31, 2015, Abu Dhabi, UAE (Original paper title: " Methodologies to Reduce Cooling Load using Heat Balance Analysis: A Case Study in an Office Building in a Tropical Country" and Paper No.: 117).*

**Nomenclature**

| | |
|---|---|
| ACC | annual cooling system's energy consumption |
| AEC | annual energy consumption |
| AELC | annual electricity consumption |
| AHU | air handling unit |
| BEI | building energy index |
| BMS | building monitoring system |
| COP | coefficient of performance |
| $COP_{chiller}$ | coefficient of performance for the GDP's chiller |
| $CO_2$ | carbon dioxide |
| $C_p$ | the ratio of cooling system's electricity usage per total building's electricity usage |
| CV(RMSE) | coefficient of variation of the root mean square error |
| $CW_{(RTH)}$ | chilled water consumption in RTH |
| DOSH | Malaysia's Department of Safety and Health |
| EEMs | energy efficiency measurements |
| $El_{building(kWh)}$ | building's electricity consumption |
| $El_{CS(kWh)}$ | electricity consumption for the cooling system's equipment inside the building |
| $E_{CW\ (kWh)}$ | energy consumption by GDP's chiller in kWh |
| FA | conditioned building's floor area |
| G | solar irradiance |
| GEO | green energy office |
| GF | ground floor |
| GDP | gas district cooling plant |
| HVAC | heating, ventilation and air conditioning |
| kWh | kilowatt hour |
| LEO | low energy office |
| LOR | light output ratio |
| M | meter |
| MBE | mean bias error |
| MF | maintenance factor |
| $M_i$ | measured data at instantaneous *i* |

| | |
|---|---|
| $N_i$ | the count of the number of values used in the calculation |
| PL-C | Philips lamp (compact type) |
| PL-L | Philips lamp (L type) |
| $P_{sys}$ | power consumption by lighting system |
| $Q_i$ | instantaneous room's heat gain |
| RH | relative humidity |
| RTH | refrigeration tonne per hour |
| SHGC | solar heat gain coefficient |
| SHGW | solar heat gain through windows |
| $S_i$ | stimulated data at instantaneous *i* |
| T | temperature |
| Ta | outside ambient temperature |
| Tr | room temperature |
| U | lamp's utilization factor |
| $U_g$ | U-value (thermal transmittance) for glazing |
| VLT | visible light transmission |
| $\eta_{LS}$ | lighting system's efficiency |
| $\eta_L$ | lamp efficiency |
| $\eta_g$ | lamp's gear efficiency |
| $\phi$ | luminious flux at task area |

## 1.0 Introduction

Buildings account for a large share in global energy demand. They consumed 30% of the primary energy in South East Asia [1], 40% in International Energy Agency (IEA) countries [2], Europe [3][4] and 50% globally [5]. The figure is expected to increase in the future due to the growth in population, development, increasing demand for improved building's services and comfort levels and the rise in time spent in buildings [6]. This statement is supported by the building energy demand annual growth rate in several countries (Table 1) extracted from L. Perez-Lombard et al (2008) [6] and South East Asia Energy Outlook report by IEA (2013) [1].

Table 1: Buildings energy demand annual growth rate by country.

| Country | Buildings energy demand annual growth rate (%) | Sources |
|---|---|---|
| Europe | 1.50 | [6] |
| USA | 1.90 | [6] |
| UK | 0.50 | [6] |
| Malaysia | 3.10 | [1] |
| Spain | 4.20 | [6] |
| Indonesia | 1.00 | [1] |
| Thailand | 2.40 | [1] |
| Philippines | 2.00 | [1] |

The call for improvement in building energy efficiency was highlighted by changes in sustainable building policies, legislation and incentives. Due to high numbers of unsustainable existing buildings, great interest was paid on building refurbishment to increase energy efficiency [7]. In many cases this process is more economical and has a less environmental impact compared to a complete demolition and rebuild [7][8][9]. However, the effectiveness of the process depends on the basic building structure and the refurbishment designs [8][10]. Hence, methods to find effective strategies for retrofitting and modelling to predict energy reduction are vital [9][10]. General energy retrofit guides and energy efficient measures (EEMs) were published by various institutions including the US Department of Energy (US DOE) and ASHRAE (in collaboration with other institutes) [11][12][13] as a response to the increasing demand for building refurbishment. Nonetheless, retrofit measures may have different impacts on different buildings due to the variance in design and sub-systems, making the retrofit selection very complex [9].

In previous studies, buildings were audited to determine the area of concerns before applying EEMs [14][15][16][17][18][19] selected based on the multi-objective optimization methods [9][10][20][21][22] or cost-benefit analysis [23][24]. Mainly, the audit process concerns the end-use energy consumption to determine sector that requires retrofitting but not in depth holistic approach to define the building's parameters that contributing towards the large energy share from the sector. Whereas in early design phase, sensitivity analysis is widely adopted to determine parameters which significantly contributes towards the performance of the design solution [25]. Andarini et al [26] used a sensitivity analysis to obtain parameters that can significantly reduce cooling demand in a shophouse design for Indonesia climate. A sensitivity analysis was also performed by Yildiz et al [27] to define parameters in an apartment's design which greatly contributes towards heating and cooling load. While Heiselberg et al [25] studied a wider range of input parameters to determine their impact on the total energy performance of an office building design. Normally, heating and cooling load were assigned as the output variables for the sensitivity analysis as it is a significant energy performance indicator and the major building's energy consumer globally [6][25][26][27][28][29]. Whereas, in cooling-dominated countries, air conditioning dominated the building's energy share [15][27][30]. A study by S.Aun et al [31] concluded that Malaysia's office buildings used 64% of the total building's energy for air conditioning. Meanwhile other tropical countries such as Indonesia, Thailand and Singapore, spent 51% to 59% of the building's energy budget on air conditioning [15][26].

Against this background, this study proposed a retrofit methods based on a whole building thermal analysis to determine parameters contributes towards heat gain. It was developed to cater buildings in cooling dominated countries encompassing a building audit, simulation based whole building thermal analysis, devise energy saving options to reduce the heat gains and hence cooling loads while adhering to thermal comfort and stakeholder's requirement. It is hoped that the steps followed could provide assistance to stakeholders involved in building retrofits (focusing on buildings with cooling systems as its highest energy user) within high-density urban areas in climates similar to that of our case study building.

## 2.0 Methods

The proposed method consists of four steps as summarized in Figure 1. The process is further elaborated in section 2.1, 2.2, 2.3 and 2.4.

### *2.1 Building Energy Audit*

The Building Energy Index (BEI) was used as a benchmark to compare the current building energy performance with the low energy office (LEO) suggested by the Malaysian government [31][32]. BEI is calculated using equation (1) [15][30] while the annual energy consumption for the building is expressed by the equation (2). It is a sum of the building's annual electricity consumption and the estimated energy used for chilled water supplied to the building. The estimated energy used by the external Gas District Cooling Plant (GDP) chiller is shown in equation (3) [33][34]. The chilled water usage is recorded in RTH. Therefore, the values are converted to kWh (1 RTH is equivalent to 3.5 kWh). It is assumed that there are no energy losses while the chilled water travels from the GDP to the building.

$$BEI = \Sigma AEC / \Sigma FA \quad (1)$$

$$AEC = \Sigma El_{building(kWh)} + \Sigma E_{CW(kWh)} \quad (2)$$

$$E_{CW\,(kWh)} = (CW_{(RTH)} \times 3.5) / COP_{chiller} \quad (3)$$

The building's energy usage and the indoor environmental measurement (air temperature, humidity, carbon dioxide level and lux) were referred to the building audit report ([34]) and BMS. The equipment used for the measurement is listed in Table 2.

Table 2: List of equipment used for indoor environmental measurement.

| Equipment model | Usage | Accuracy |
|---|---|---|
| Testo 540 | Illuminance | All measurement: +/- 3% |
| pSENSE RH | $CO_2$ | For 0 to 2000 ppm measurement: +/- 5% |
| HT305 | Air temperature and humidity | RH measurement : +/- 3%<br>Air temperature measurement: -0.8°C |

*2.2 Building Modelling and Calibration.*

A model of the case study building was constructed using the Design Builder software version 4.2.0.034. It is the most comprehensive Graphical User Interface to the Energy Plus simulation engine (from US DOE) which has intensively used for building modelling in previous research [35][36][37][38][39][40]. It provides an intuitive interface and high-resolution data output on energy consumption, carbon emissions, occupant comfort, and daylight availability [41]. Modelling complex buildings involves inaccuracies and errors due to various input requirements and limitations [35][36]. Studies on building modelling presented ways of increasing the model's prediction accuracy [35][36] and ASHRAE Guide 14 [42] is an established method for measuring a model's accuracy [14][35][36][38]. It is suggested that with instances of monthly data, a building is considered accurate if the CV(RMSE) for monthly values is below ≤+15% and MBE of monthly values is within ±5% [42]. If these tolerances are met, EnergyPlus was demonstrated to be capable of predicting space air temperatures within zones of interest with an accuracy of ± 1.5°C for 99.5% of the time [35]. In this study, the input data listed below was collected by the help from building's facility management and onsite visits to ensure the model reflects the actual building in:

- Geometry: The building's floor plan, geometry and fabric (derived from architect's drawings. DXF files created from the architect's drawings (AutoCAD) to import into Design Builder [36].
- Equipment data: Power rating, operation's schedule, equipment quantity in every office floor.
- Lighting: lux measurement, operation's schedule, lamp and luminaire types.
- Occupancy in every floor: number of occupants, type of activities and schedule.
- Local weather data was collected from Malaysia Meteorological Department [43] and ASHRAE global weather repository.
- HVAC system: the building HVAC system schematic drawing, HVAC system and chiller's COP, the average zone's temperature measurement for every office floor and average chilled water temperature for every AHU's was extracted from the building audit report and prepared by facility management [33][34].

This software simulates the total energy for the cooling system as 'district cooling' while the building's chilled water was supplied by a district cooling plant. Hence, the actual energy consumption by the cooling system was calculated using equation (4) where the monthly electric consumption by the cooling system ($EL_{CS(kWh)}$) is calculated using Equation (5). Equation (6) calculates CV(RMSE) and equation (7) calculates MBE between the simulated and actual results [35]. Model parameter inputs were refined until the tolerance range was met.

$$ACC = EL_{CS(kWh)} + E_{CW\,(kWh)} \quad (4)$$

$$EL_{CS(kWh)} = Cp \times \Sigma AELC \quad (5)$$

$$CV(RMSE) = \frac{\sqrt{\sum_{i=1}^{N_i} [(M_i - S_i)^2 / N_i]}}{\frac{1}{N_i} \sum_{i=1}^{N_i} M_i} \quad (6)$$

$$MBE = \frac{\sum_{i=1}^{N_i} (M_i - S_i)}{\sum_{i=1}^{N_i} M_i} \quad (7)$$

*2.3 Building thermal analysis.*

Three steps of thermal analysis were used. Step 1 aimed to define the zones with the highest cooling load and cooling load intensity, step 2 aimed to discover the main heat sources in those zones and step 3 aimed to diagnose what causes these components to emit such a high amount of heat which contributes towards the retrofit strategies.

*2.4 Cooling load reduction strategies, cost analysis and actual implementation*

The strategies were proposed to the facility manager for implementation. The energy data after a year of implementation was analysed. The economic analysis is a comparison of the initial cost per 1 kWh annual energy reduction (equation (8)). The initial implementation costs are derived from Design Builder's cost analysis package.

Energy reduction cost (GBP/kWh) = Initial cost / annual energy reduction (8)

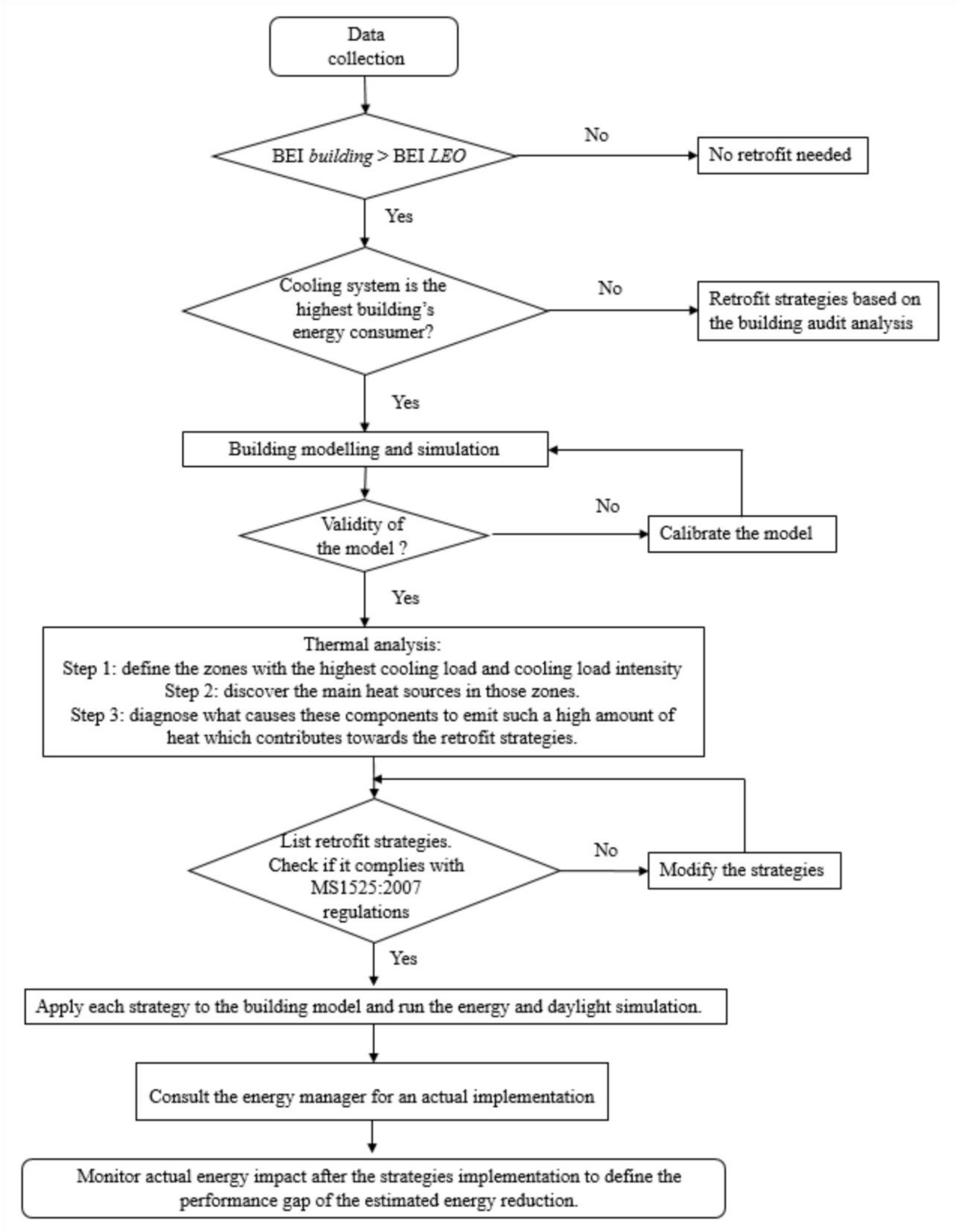


Figure 1: The retrofit method based on the thermal analysis.

## 3.0 Case-study building

Figure 2: An image of the case study building taken during a field visit.

An office building in Putrajaya, Malaysia, was taken as the building case study (shown in Figure 2) as it represents cooling-dominated nature of modern offices in Malaysia. The building data was gathered through personal interviews with the building's energy manager, site visits, online building consumption input system (BCiS) and the annual audit reports which were performed by a qualified energy consultant and the facility management company. The findings concerning the building specification are summarized in Table 3. Only the building's communal areas and offices in the North block were studied. It consists of two underground floors and a ground floor that connects the North and South building and seven office floors in the North building. The building's fabric and floor plan were derived from the architect drawings.

Table 3: Summary of the case study building specification gathered from [33] and architect's drawings.

| Component | Description |
|---|---|
| Weather | Hot and humid (tropical weather) |
| Conditioned Floor area | 36,750 m² |
| Occupants | 351 (peak time) |
| Major zones | Lobby, corridors, toilets, AHU rooms, janitor rooms, offices, IT rooms, pantries, parking areas, kitchen, cafeteria, cold room, auditorium, data center and communal hall. |
| External wall | Brick and cement construction. U-value : 2.898 W/m²K |
| Glazing | Green float glass (8mm). 85% glazed with local shades. |
| Lighting | Provided by 3119 lamps (84.4% of PL-L 36W recessed and surface mounted. Average lighting density in office zones is 4.85 W/m²). |

### *3.1 HVAC Services and Building Monitoring System (BMS)*

The air conditioning is provided by a unitary constant air volume system, AHU systems on every floor, fan coil air conditioning units for the lifts lounge and the chilled water was supplied by an external Gas District Cooling Plant (GDP) [33][34]. The building is equipped with a monitoring system (Circutor Power Studio Scada by Monitor Power Energy) that covers all small power, lighting, ventilation, auxiliary elements of electricity consumption, each zone temperature and chilled water temperature for every AHUs. Also, the cooling energy consumption is logged separately by the district provider since the chilled water is supplied by a GDP. A combined heat and power chiller is used by the GDP, and the chiller's coefficient of performance (COP) is 4.0 [33][34].

## 4.0 Results and discussion.

### *4.1 Energy and indoor environmental quality*

The average BEI over four years from 2009 to 2012 was 238.53 kWh/m²/year [33][34]. It is slightly lower than the typical BEI for Malaysian office buildings (250 kWh/m²/year) [30][44] and in range with the BEI of Malaysian public hospitals (234 kWh/m²/year) as studied by Saidur et al [15]. Interestingly, the BEI value is comparatively lower when compared to the average office's BEI in Europe (306 kWh/m²/year) [45]. The annual BEI values in 2009 to 2012 are listed in Table 4.

Table 4: The building annual energy index (BEI) over four years [33][34].

| Year | BEI (kWh/m²/year) |
|---|---|
| 2009 | 241.78 |
| 2010 | 241.12 |
| 2011 | 254.3 |
| 2012 | 216.9 |

In 2012, cooling was responsible for 58.9% of the building total energy consumption. The energy intensity from the cooling system was 127.89 kWh/m²/year that is higher than the BEI benchmark for LEO buildings (114 kWh/m²/year) [32] and passive buildings (120 kWh/m²/year) [2]. The building end-use energy intensity by sector is shown in Table 5. The building needed to reduce its total energy consumption by 46.9% to become a LEO building, and this was found to be possible primarily through cooling load reduction.

Table 5: End-use energy intensity by sectors in 2012 [33][34].

| | End-use Energy Consumption | |
|---|---|---|
| Sectors | Energy intensity (kWh/m²/year) | Percentage of total energy (%) |
| Cooling system | 128 | 58.9 |
| Lighting | 62 | 28.6 |
| General sockets | 15 | 6.9 |
| Data centre | 12 | 5.5 |

The building indoor environmental quality analysis (in office zones) was extracted from the building energy audit report and measured by a variety of sensors listed in Table 2. The results

(Table 6) shows that 6 out of 8 office spaces have lower than the minimum room temperature suggested by MS1525:2007 [46]. Average luminance in 5 out of 8 office spaces was lower than the minimum requirement. The relative air humidity (RH) and the carbon dioxide ($CO_2$) level were within the suggested range [47].

Table 6: Measured indoor environment's condition in office zones [34].

| Floor | Luminance (lux) | T (°C) | R.H (%) | $CO_2$ (ppm) |
|---|---|---|---|---|
| G | 315.2 | 23.3 | 57.5 | 671.2 |
| 1 | 201.2 | 23.3 | 62.6 | 645.8 |
| 2 | 347.7 | 22.5 | 64.2 | 678.2 |
| 3 | 363.2 | 22.3 | 60.7 | 802.0 |
| 4 | 244.5 | 21.8 | 63.9 | 583.8 |
| 5 | 237.0 | 22.1 | 66.8 | 639.0 |
| 6 | 256.0 | 22.6 | 67.0 | 609.8 |
| 7 | 259.0 | 22.2 | 66.9 | 539.6 |
| Recommended by MS1525:2007 and DOSH | 300 | 23-26 | 55-70 | <1000 |

*4.2 Building modelling*

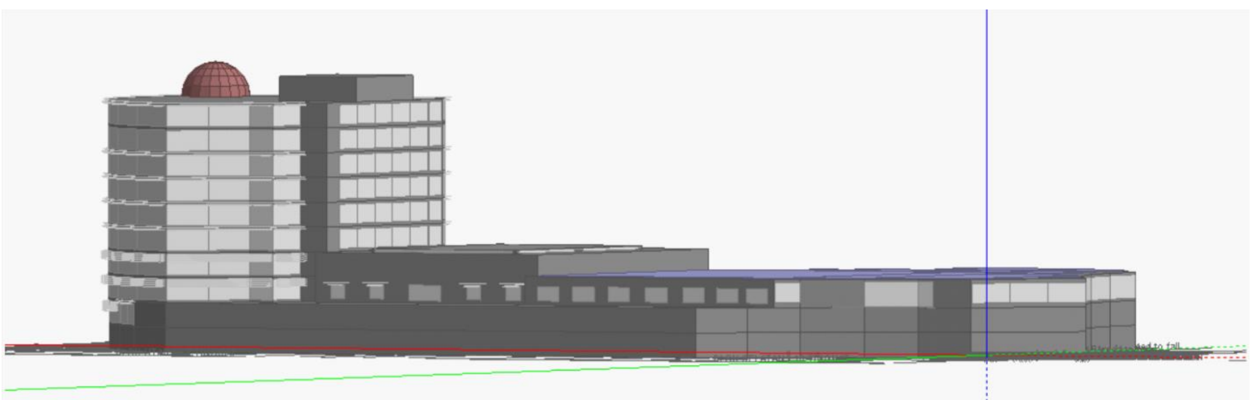

Figure 3: The building model built in Design Builder Software.

The comparison of actual energy usage and simulated energy usage using the ASHRAE Guide 14 shows the building model prediction to be within the acceptance range. The estimated MBE was +1.31% (acceptance criteria is ±5%), and the CV (RMSE) value was 8.33% (less than the 15% requirement). Total energy consumption in 2012 was 7.33 GWh while the simulation results predicted it to be 7.24 GWh. The comparison of monthly actual and estimated energy usage and its percentage deviation is shown in Figure 4. The average deviation was +1.31% with the highest deviation on August (over predicted by 18.1%). Greater uncertainty in occupancy levels during the celebration month leads to the over prediction.

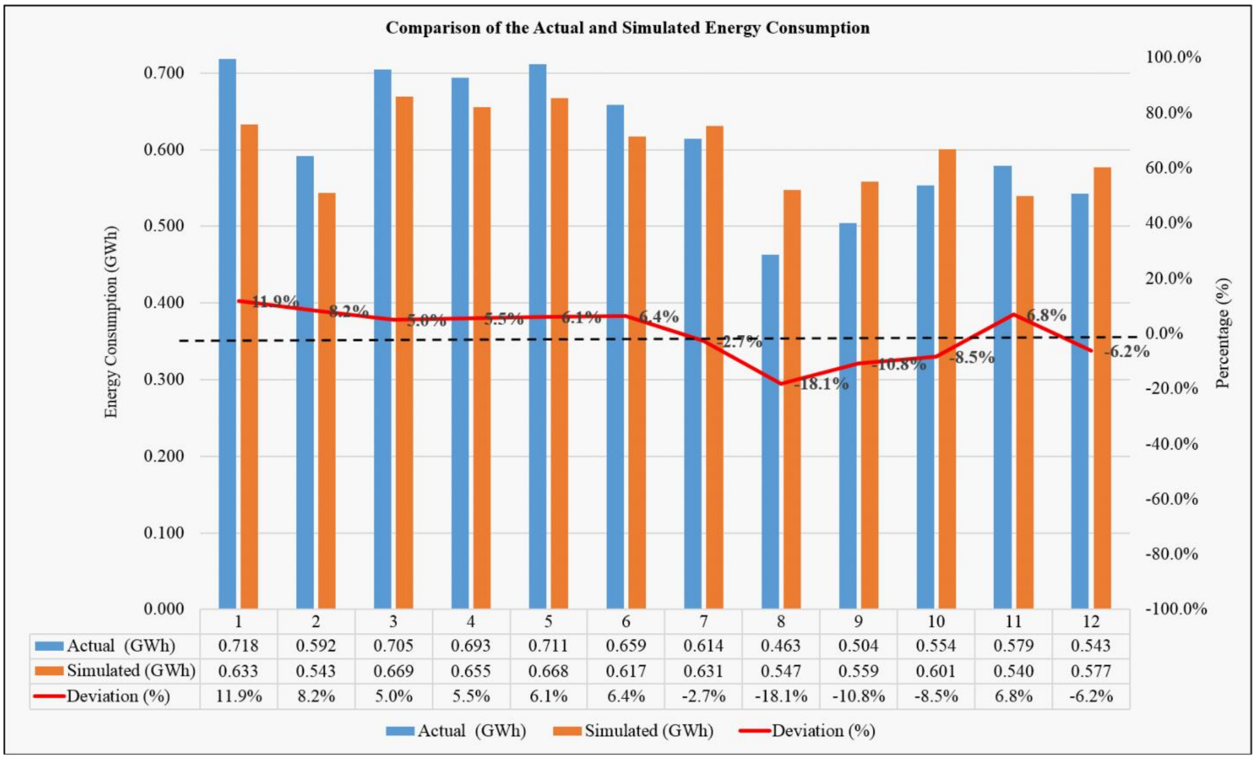

Figure 4: Comparison of the actual and simulated monthly energy consumption.

*4.3 Thermal analysis*

Zones with the highest overall cooling load and cooling load intensity were defined (shown in Table 7) for a further heat source analysis. It is found that zones with heavy duty equipment (data centre and IT rooms) were deemed to have the highest cooling load intensity (annual cooling load per zone's area) while total annual cooling loads are largest in bigger areas. Further analysis on the heat sources in the main cooling areas area shown in Table 8. It can be seen that heat distribution in every area varied depending on the zone's internal equipment type, architectural design (fenestration and area), type of activities and operational schedules. In this case study, four important components contributing to the heat gain were highlighted as the lighting system, windows, and equipment and operation settings. An in-depth holistic analysis was carried out and discussed in section 4.3.1, 4.3.2 and 4.3.3 to obtain the causes for the components' high heat emission rate.

Table 7: Annual cooling load in different cooling zones.

| Cooling zones | Annual cooling load (kWh) | Cooling load intensity (kWh/m²/year) |
|---|---|---|
| Offices | 2,666,685 | 193 |
| Data centre | 468,459 | 5545 |
| Corridors | 393,208 | 119 |
| Cafeteria | 201,989 | 348 |
| IT rooms | 78,812 | 938 |
| Hall and auditorium | 7,354 | 6 |
| Total | 4,082,655 | 10,848 |

Table 8: Heat gain distribution in different zones.

| | Annual heat gain distribution (%) | | | |
|---|---|---|---|---|
| Zones | SG | L | Eq | Occ |
| Office | 26 | 47 | 22 | 5 |
| Data centre | 0 | 23 | 76 | 1 |
| Corridors | 13 | 85 | 0 | 2 |

*Solar gain from external windows (SG), lighting (L), Equipment (Eq) and Occupancy (Occ)*

*4.3.1 Lighting system*

Despite the fact that the majority of the office zones received lower than the MS1525:2007 recommended light luminance level, the heat emitted and energy consumed by the lighting system was high. This finding highlighted the actual inefficiency of the lighting system and potential for improvement. An example of the luminance in office areas is shown in Figure 5. The actual lighting system efficiency was calculated using equation (9) which was derived from the equation (10) [45]. The results are listed in Table 9.

$\eta_{LS}$ = measured lumen/ total power used (9)

$\phi$ = (MF×U×LOR×$\eta_L$× $\eta_g$ ) × $P_{sys}$ (10)

Table 9: Measured efficiency of the lighting system.

| Office zones | $\eta_{LS}$ (%) | Power rating (W/m²) |
|---|---|---|
| Level 1 | 1.94 | 6 |
| Level 2 | 4.02 | 5 |
| Level 3 | 4.20 | 5 |
| Level 4 | 2.82 | 5 |
| Level 5 | 3.42 | 4 |
| Level 6 | 2.96 | 5 |
| Level 7 | 3.74 | 4 |

The low average lighting system efficiency in office areas explains the high heat gain as the lamp power losses are emitted into space as heat (radiation and convection) [39]. Previous studies (P Hanselear et al) [48] suggested that the light's utilization factor (utilance) is more important than the lighting output ration in reaching energy efficiency and it depends on:

a) the arrangement of the luminaires in the room concerning the position of the task area
b) the luminous intensity distribution of the luminaires and the spacing to height ratio
c) the reflectance of the surroundings, which determined the indirect contribution.

Therefore, besides lamp efficiency, their arrangement, maintenance, lamp's control gear efficiency, as well as the construction and space design play a major part in determining the efficiency of the whole lighting system in delivering the minimum required lumen to space. Most of the lamp types used were PL-L (36W) lamps 2008's version that has low lamp efficiency and used a recessed type configuration. Typical fluorescent lamps emit 21% of its input power to visible light, 37% radiant heat and 42% convective heat [39].

Figure 5: Lighting in a typical office and associated circulation areas taken during a field visit.

The curtain wall windows in corridors and office areas allowed high daylight luminance to light up the spaces without depending on the artificial light. The recommended luminance level for a corridor is 50 lux and 100 lux for lift lobbies [46] whereas the daylight luminance measurement in those areas (as listed in Table 10) were in the range of 502 lux to 25,001 lux. In practice, lightings in these areas were switched on 24 hours a day even though it could benefit from the high levels of daylight. A daylight linked installation could have eliminated the unnecessary energy usage and excessive internal heat gains.

Table 10: Daylight luminance measurement.

| Zone | Luminance (lux) |
|---|---|
| Corridor level 2 | 21,000 |
| Corridor level 3 | 25,001 |
| Corridor level 4 | 14,840 |
| Lift lobby level 2 | 502 |
| Lift lobby level 3 | 503 |
| Lift lobby level 4 | 396 |

*4.3.2 Windows*

For countries requiring high cooling demand, windows are an important element in ensuring the occupants' thermal comfort and in providing daylight illumination into the building. Malaysia receives an average of 4.67 kWh/m² average of daily solar radiation [31] where the incident solar radiation on a building's glazing is partially reflected and partially transmitted into the building depending on the glazing properties [49][50]. Despite a degree of overlap, the infrared component of the incoming daylight transmitted into the building materialises itself in the form of internal heat gain whereas the visible light spectrum (which in its lower bands overlaps with the near infra-red) increases daylight luminance. In a cooling-dominated country, glazing with high visible light transmittance, low U-value (heat loss value) and low SHGC is preferable to maximise daylight luminance and reduce heat gain. The instantaneous room heat gain is governed by the equation (11) [49].

$$Qi = U_g * (Ta - Tr) + (SHGC * G) \qquad (11)$$

Even though the building has an 85% window to wall ratio, it benefits from its architectural selection of window pane and shading designs that managed to offset a major fraction of the external solar heat gain. The building windows were made from single panel green float glass: 8 mm thick, SHGC value of 0.447, VLT 0.237 and U-value of 5.7 W/m². However, a further reduction of solar heat gain through windows is achievable by selectively adding a second pane to the existing window to create double panel windows with a lower SHGC and U-value while maintaining the VLT to maintain the daylight received.

### *4.3.3 Equipment and operation settings*

The heat gain analysis revealed that zones with heavy duty equipment (data centre and IT rooms) had the highest cooling load intensity (annual cooling load per zone area) that reached up to 5545 kWh/m²/year for the data centre and 938 kWh/m²/year for the IT rooms. The equipment high rating power and 24 hours operation released substantial amounts of heat into the surroundings which in turned requires the building manager to set the cooling set point temperature at 21°C at all times in these zones to avoid equipment overheating and ensure good operating conditions. In the office areas, equipment was responsible for 22% of the total annual heat gain. 529 pieces of office equipment were used in the building with mainly desktop computers (256 units) and small printers (137 units). Office pantries at each level used refrigerators that constantly operate and most of the desktop computers did not have Energy Star rating. Inefficient equipment increased heat gains, which in turn exacerbated the cooling load. The air conditioning in office areas was set to 22°C, which is 1°C to 4°C lower than the suggested value by MS1525:2007. While the cooling system and lighting were scheduled to turn on at 7.00 am that is an hour earlier than the office opening time.

## *4.4 Strategies to reduce cooling load.*

The retrofit plans suggested for this building are categorized into five different types that are the lighting system, glazing, equipment, operation settings and on-site renewable energy. Each modification is discussed below:

a) Lighting System: A lighting system that includes automatic daylight dimmer in corridors and office zones as well as replacing existing lamps with high-efficiency LEDs [39]. Luminance in the office zones were adjusted to 300 lux by the recommendations from previous studies [45] and MS1525:2007 [46]. Lighting operating schedule was proposed to accommodate the employees when the area is occupied (i.e. 0730 hours to 1800 hours).

b) Glazing: A 6mm thick low emissivity (Low-E) glass panel was added to the existing model as an internal layer to the existing green float glass with a 16mm air gap between them. The commonly used clear glass window panels were also examined for comparative studies. The impact of different glazing types on building solar heat gain is detailed in Table 11.

Table 11: The impact of different glazing types on the building solar heat gain through external windows.

| Glazing type | SHGC | U-value ($W/m^2$) | SHGW (kWh) |
|---|---|---|---|
| Single panel clear float glass (8mm) | 0.815 | 5.7 | 2,014,444 |
| Single panel green float glass (8mm) | 0.447 | 5.7 | 598,054 |
| Double panel (retrofit) | 0.325 | 1.8 | 274,900 |

c) Equipment: The office equipment in the model was changed so as to represent the latest generation of energy-efficient ICT devices. While the original HP desktop used 300W of power, a 216W Energy Star rated HP desktop computer was chosen as a replacement. Also, Aficio™ MP C2051 by RICOH multifunction printers (rated power 1680 kWh) were changed to HP Color LaserJet Pro MFP M476dw printers (rated power 640 kWh). Finally, the chest freezers in the kitchens were changed from band F energy rated to band A+.

d) Operation settings: 24 °C was chosen as the new set point temperature while the new operation schedule for the cooling system is shown in Figure 6 and lighting systems in office zones were set to 0730 to 1730 hours. This new set point temperature was chosen based on a discussion with the building energy manager concerning the occupants' thermal comfort. Previously, a series of trials were conducted by the building energy manager to appraise the sensitivity of the office workers to increases in internal office temperatures. The cooling temperature set points were adjusted within the suggested guideline by MS1525:2007 [46]. Based on the information provided by the building energy manager, 24 $^{O}$C was the maximum temperature set point for office areas that was voted acceptable in occupants' feedback trials (the building management increased cooling temperature set point to 24 $^{O}$C and 25 $^{O}$C to examine space thermal acceptability range). The employees launched complaints when the cooling set point was raised to 25 $^{O}$C, but interestingly no negative feedback was received when it was set to 24 $^{O}$C. Although this does not conclusively elucidate the neutral thermal point of the occupants, it demonstrates the possibility of raiding zone target temperatures while maintaining occupant satisfaction.

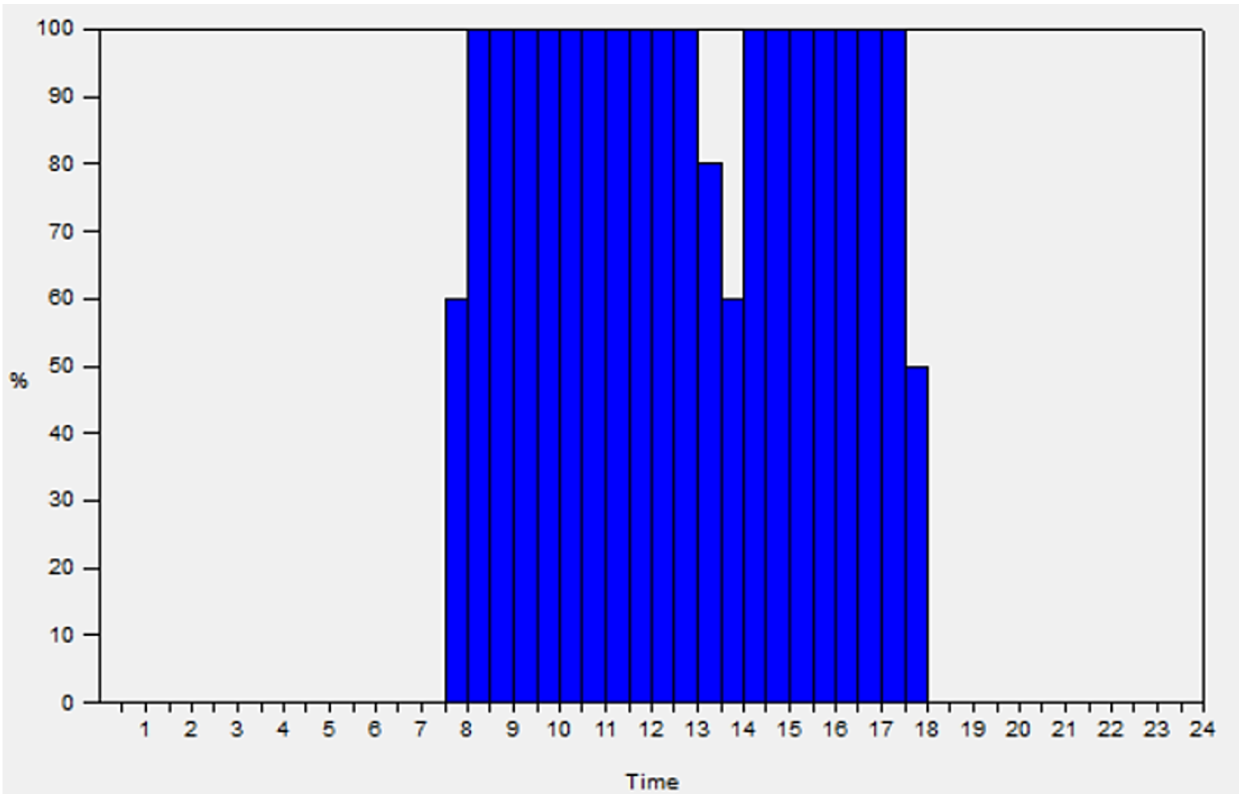


Figure 6: Modified cooling operation schedule for office zones from the Design Builder software.

e) Renewable Energy: Installation of solar panels (15% efficiency) on the South building roof utilising 3681 $m^2$ area to aid operational de-carbonization and limit building envelope heat gain.

### *4.5 Estimated Energy Reduction*

The cumulative effect of all the strategies was estimated to reduce 57% of the annual primary energy demand and 40.2% of the total cooling load. The energy performance and the initial cost for the suggested methods are summarised in Table 12, and the comparison of end-use energy consumption before and after retrofit is shown in Figure 7. Notably, besides having no cost implication, modification in operational regimes is estimated to be more effective in reducing cooling load compared to modification in glazing and equipment. While from the economic perspective, modification in operation settings and lighting system deemed to be the most economical compared to other strategies. The installation of solar PV panels is estimated to supply 12% of the total building annual energy demand besides reducing cooling load by 0.3%.

Table 12: The estimated energy performance and initial cost for the suggested methods.

| Method | Total energy consumption (kWh) | Renewable energy (kWh) | Total cooling load (kWh) | Energy reduction cost (GBP/kWh) | Primary energy reduction (kWh) | Primary energy reduction (%) | Cooling load reduction (%) |
|---|---|---|---|---|---|---|---|
| Initial | 7224042 | - | 4082655 | - | n/a | n/a | - |
| Operation | 6594767.09 | - | 3570735 | 0 | 629275 | 9% | 12.5% |
| Lighting | 4726123 | - | 3137779 | 0.96 | 2497919 | 35% | 23.1% |
| Glazing | 7095982 | - | 3954596 | 3.21 | 128059 | 2% | 3.1% |
| Equipment | 6855625 | - | 3941439 | n/a | 368417 | 5% | 3.5% |
| PV | 7210797 | 746703 | 4069411 | 2.91 | 759948 | 12% | 0.3% |
| Combine | 3830363 | 746703 | 2439678 | n/a | 4140382 | 57% | 40.2% |

By switching on only 60% of the cooling system at 0730 hours as pre-cooling, peak latent load that arises due to the high outside humidity at that hour [51] can be significantly reduced. These changes resulted in a significant reduction in peak cooling load that occurs in the morning. The comparison of hourly building's cooling load before and after retrofit is shown in Figure 8. While a comparison of the hourly measurement of indoor air temperature before and after the retrofit during work days in January (shown in Figure 9) suggested that 98.9% of instances of indoor air temperature (during office hours) measurements satisfies MS1525:2007 Guidelines.

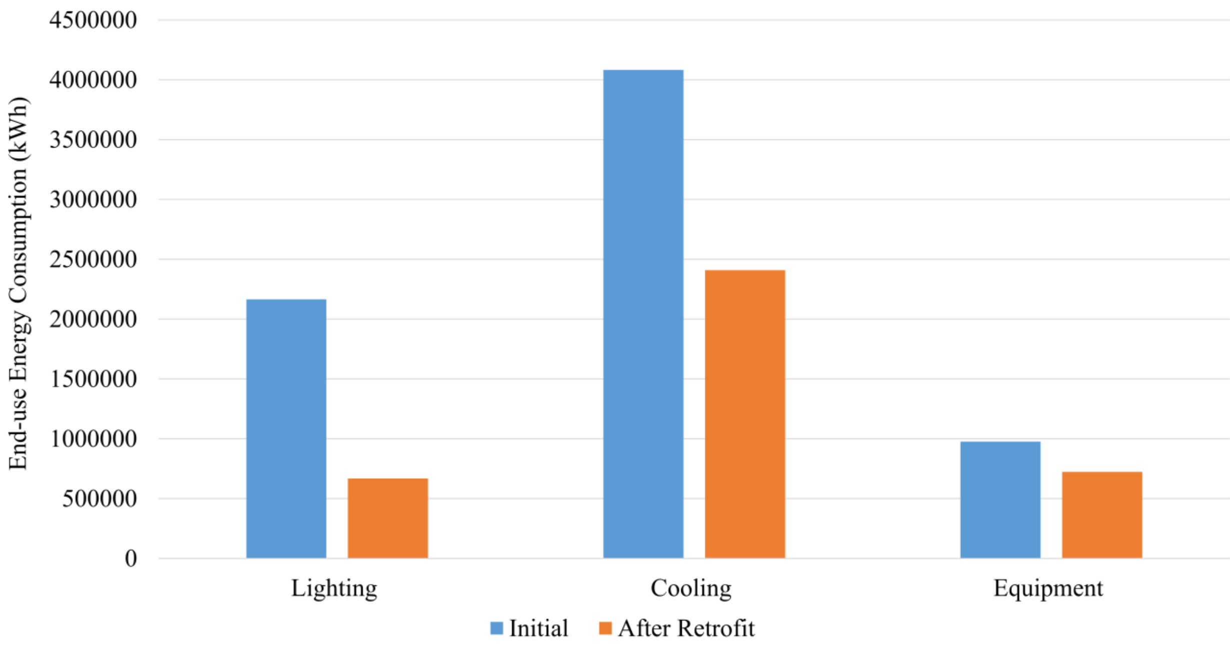


Figure 7: The comparison of end-use energy consumption for the initial and after the retrofit.

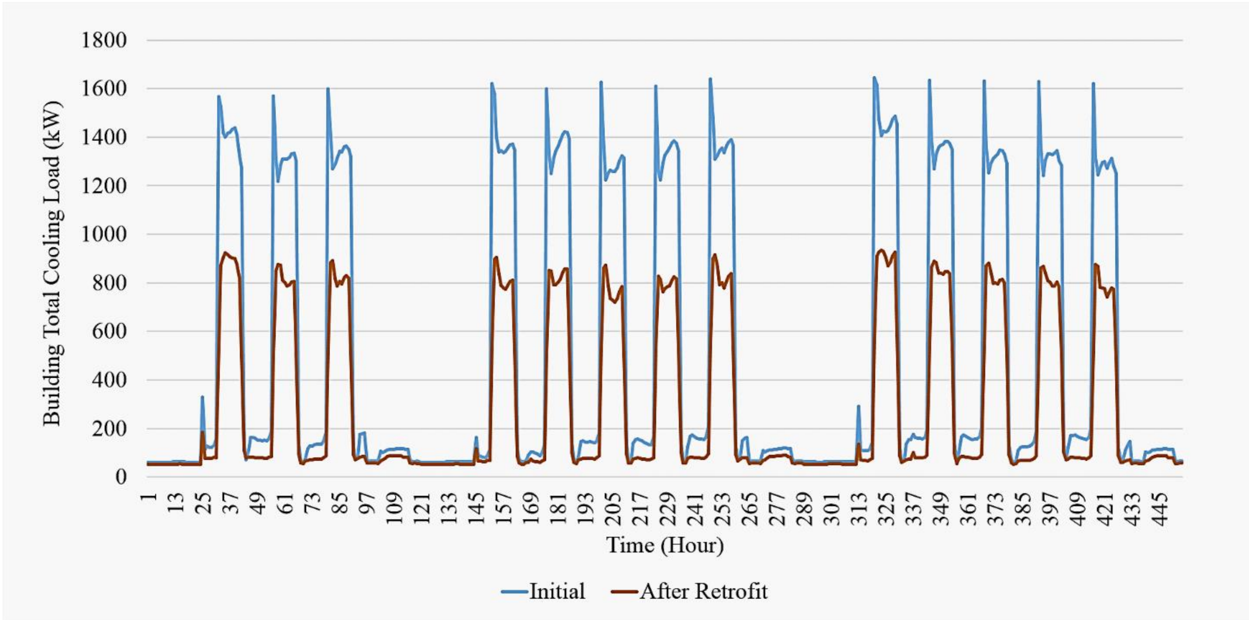


Figure 8: The simulated hourly building's cooling load before and after retrofit - 450 hours data (01/01 to 19/01)

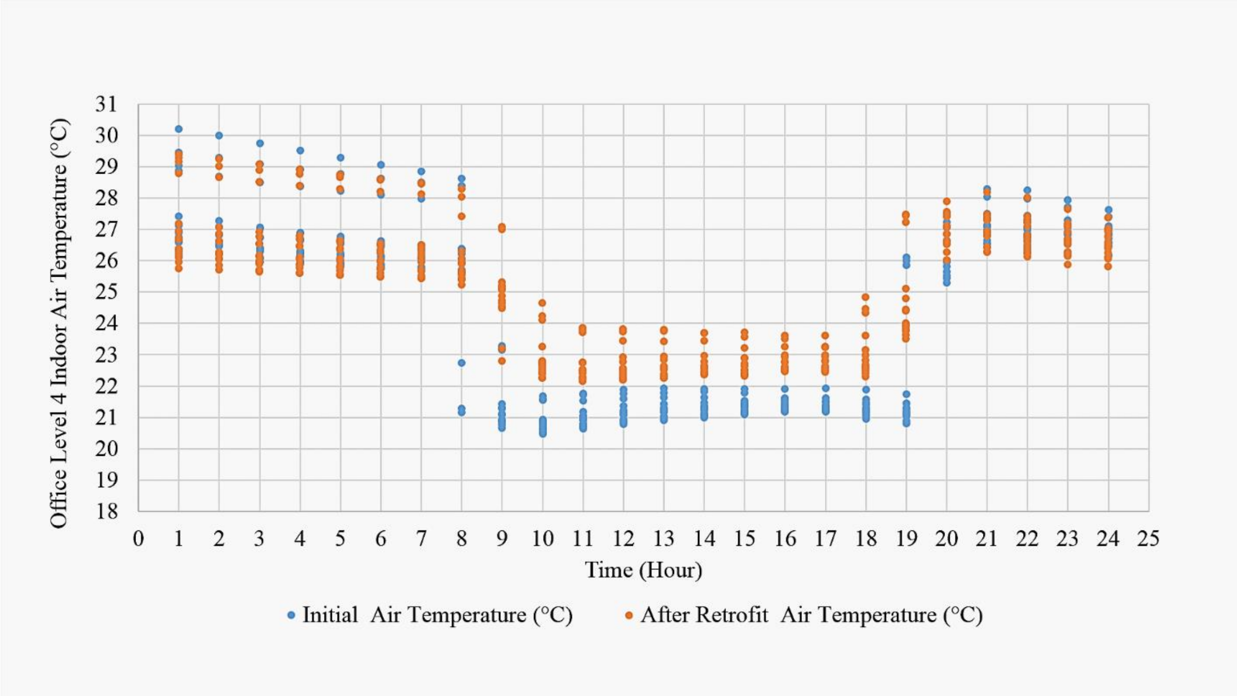


Figure 9: Hourly estimated indoor air temperature for an office zone on Level 4 during work days in January.

*4.6 Actual building implementation*

The simulation results were presented to the building energy manager for an actual application. The methods implemented by the building management in 2014 are listed below:

- Cooling set point temperature was increased to 24°C, and the cooling system was operated from 0800 to 1300 and 1330 to 1730 hours during work days.
- 56 fluorescent outdoor lamps were changed to LED lamps and office lighting was operated from 0730 to 1800 (unless requested by the employee for extension time).
- Promoted energy saving awareness.

These modifications resulted in an 18.8% energy reduction when compared to the energy consumption in 2012. The same methods used by the building were applied to the building model and yielded an estimation of 14.5% energy reduction. The simulation takes into account changes in hall and auditorium schedule usage in 2014 but could not predict the impact of energy saving awareness on occupants' reaction. Hence, the actual result showed a greater energy reduction compared to the simulated result. The comparison of actual and simulated results suggested the estimation made under predicted the energy reduction by 4.3% that is quite close to the mean bias value (+1.31%).

## 5.0 Conclusion

Reducing building cooling load and increasing the cooling systems efficiency is a major component in the de-carbonisation of buildings in tropical countries. Within this work, a building was audited and modelled using EnergyPlus where notably 58.9% of the total energy consumption were cooling-related. Sensible cooling load arises from the need to remove heat gain in a building as to maintain a comfortable thermal condition. Managing the heat sources and cooling system operation settings proved successful in reducing a significant amount of cooling load. The thermal analysis method proposed in this study enables heat gain components to be mapped, allowing the design of effective strategies to reduce the cooling load. This holistic approach results in 57% overall primary energy reduction and a reduction in peak cooling load while adhering to indoor comfort requirements (MS1525:2007). An actual implementation of selected strategies (operation settings, energy saving campaign and changes in outdoor lamps to LEDs) resulted in 18.8% energy reduction that was predicted by modelling analysis to be 14.5%. The simulated energy reduction was under-predicted by 4.3%. Though every building is unique, it is hoped that the proposed method will assist retrofit designers in selecting the most effective strategies, in particular with regards to energy reduction in cooling dominated countries.

Modern architecture has evolved towards typical office buildings with large fenestration to optimise daylight [49] findings in this study show that the lighting system could not benefit from this design without the application of automatic dimmers to adjust the artificial lamp luminance level. Another area of concern is the high cooling load intensity in the data centre and IT rooms due to equipment’s energy intensity. Most of the government buildings in Malaysia have a data centre and IT rooms to manage building’s energy, systems and indoor environmental quality. However, these rooms require a high cooling capacity to maintain their performance that results in high energy usage. Managing heat gain in these rooms (ventilation and improvement in the equipment efficiency) will be beneficial for the building sector. While, improvement strategies that relate to occupant behaviour (i.e. sensors based human occupancy detection) are not yet possible within whole building simulation software, limiting the number of strategies presented for this specific building case study. A specific study on building energy simulation using occupancy detection sensor deployment could be addressed in future research.

## 6.0 Acknowledgments

The authors would like to acknowledge Majlis Amanah Rakyat (MARA) for the research funding, KCJ Engineering Sdn Bhd and Pulau Reka Sdn Bhd (a cooling system and a facility management company in Malaysia) for their building's data contribution and Sir Joseph Swan Centre for Energy Research, Newcastle University for the support and facility provided.

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