VOL. 19, NO. 13, JULY 2024 ISSN 1819-6608
ARPN Journal of Engineering and Applied Sciences

www.arpnjournals.com

THE EFFECTIVENESS OF DUTY CYCLING TECHNIQUE ON AIR CONDITIONING SYSTEM DURING BREAK PERIOD FOR COMFORT, ENERGY AND COST SAVINGS: A REAL CASE STUDY IN HEALTH CENTER

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ABSTRACT

This paper investigates the potential of duty cycling techniques for air conditioning (AC) systems in producing energy and cost savings and the impact on the indoor thermal environment, air quality, and environmental sustainability. The real case study concentrated on energy consumption practice during the break period between 13:00 to 14:00 in a lobby area of a Health Center. Site data measurements of electrical input power, energy, indoor air temperature and humidity, and indoor carbon dioxide (CO_2) concentration were conducted. Two zero-cost strategies were studied and results were compared to baseline conditions. In general, the results show that all strategies can meet the indoor thermal environment and air quality requirements, except room temperature for Strategy 2 which ranges on average between 26.71 to 26.82°C. In addition to the instant payback period (0 years), the results also indicate that as compared to baseline condition, Strategies 1 and 2 led to annual energy and cost savings of around 759.2 kWh (USD 64.40) and 1250.6 kWh (USD 106.08), respectively. In terms of environmental sustainability, Strategies 1 and 2 can avoid environmental CO_2 emissions by 444.13 and 731.60 kg of CO_2 per year, respectively. Due to these reasons and if the sensitivity of occupant comfort to room temperature during the break period can be tolerated, it is proposed that Strategy 2 is the best option for the AC system operation during the break period. Considering other buildings also adopted the same strategy, this small action can lead to a high impact, not only on energy and cost savings but also on environmental sustainability in the future.

Keywords: duty cycling technique, zero cost measure, air conditioning system, energy saving, cost saving.

Manuscript Received 07 May 2024; Revised 26 July 2024; Published 20 September 2024

INTRODUCTION

Air conditioning (AC) systems are well-known as major energy consumers of a typical commercial building estimated around 50-60% of total building energy consumption (Sukri *et al*, 2012). Due to this reason, small improvements in the AC system will lead to significant energy and cost savings. In the scenario of Malaysia, energy generation depends on non-renewable sources of around 85.2% (Energy Commission, 2020). As shown in Figure-1, major energy sources in 2019 for electricity generation came from coal (42.8%) and gas (40.2%). Consequently, significant improvement in energy consumption due to the operation of AC systems will also create a great impact on carbon dioxide (CO_2) emission reduction, which later drives environmental sustainability. Malaysian Green Technology Corporation analyzed that in 2017, each 1 kWh of electrical energy consumption in Peninsular Malaysia contributed to 585 g of CO_2 greenhouse gas emission to the environment (Malaysian Green Technology Corporation Center, 2019).

Figure-1. Energy generation mix in Malaysia (Energy Commission, 2020).

The majority of the AC systems used for commercial and residential buildings are based on the vapor compression refrigeration cycle (VCRC). In general, Sukri *et al.* (2015) pointed out two ways in which energy efficiency of AC systems utilizing VCRC could be achieved; component optimization and effective operational management and control strategy. Recently, a lot of research related to component optimization has been done in the past, i.e. using a dedicated subcooler to produce a greater subcooling effect (Sumeru *et al*, 2021), using internal heat exchanger to produce both subcooling and superheating effects and utilizing waste condensate for compressor discharge cooler, condenser surface cooler, and pre-cooled of air face condenser (Sumeru *et al*, 2019; Sukri *et al*., 2020; Thiangchchanta *et al*., 2021; Yang *et al*., 2021). However, the drawbacks of these strategies are they require system modification thus leading to more complex systems, extra maintenance work, and investment costs. Therefore, the payback period of these strategies is not instant as compared to the second option of using effective operational management and control strategy with zero cost in investment such as the duty cycling technique.

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The duty cycling technique can be considered a conventional method; however, this technique is still relevant in today's modern world, especially to existing AC systems due to no modification required on the system with zero cost measure. As a result, the payback period is instant if the technique is successful. In addition, it is easy to recover and correct to initial setting if the technique does not properly work as planned. Figure-2 illustrates an energy pyramid with three categories of energy-saving measures; energy conservation, energy efficiency, and renewable energy. To perform best practices under a sustainable energy management system, activities related to energy conservation measures must be a top priority to be executed due to no cost required, followed by energy efficiency measures (low to medium cost measures) and finally investment in renewable energy generation (high-cost measure). As a zero-cost measure, the duty cycling technique should be among the first to be considered before other energy-saving measures with a commitment to investment cost are implemented.

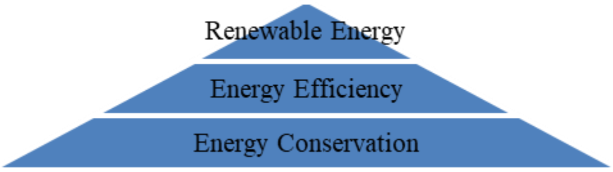


Figure-2. Energy pyramid under sustainable energy management system.

DUTY CYCLING TECHNIQUE

Haniff *et al*. (2013) classified the duty-cycling technique into three classes: basic techniques, conventional techniques, and advanced techniques. In the scope of the AC system, the basic scheduling technique involves only the manipulation of the ‘ON’ and ‘OFF’ states of the system. Meanwhile, the conventional scheduling technique focuses on the manipulation of the room set point temperatures of the AC system, and this is the most popular technique implemented in buildings (Haniff *et al*., 2013). Advanced scheduling is the improved technique that is based on the basic and the conventional scheduling techniques or combinations of both.

In the basic technique, to secure energy and cost savings, the AC system will be switched “ON” a bit late or/and “OFF” a bit early as compared to the standard operating schedule of the AC system. Meanwhile, in the conventional scheduling technique, the set point temperature will be set higher as compared to the current set point temperature as highlighted in Standard Operating Procedures. By doing so, the load of the AC system is significantly reduced, as well as energy consumption and cost.

In general, research on duty cycling techniques for AC systems has been done for the last few years. Yang *et al*. (1992) evaluated the effect of shifting peak cooling demand to off-peak hours for thermal storage-based AC systems. They found that successful load shifting can be achieved with around 20% of peak-cut with no significant indoor thermal comfort sacrifice. Garnier *et al*. (2015) investigated five non-predictive strategies, including four basic scheduling techniques, to highlight the benefits of the predictive approach developed for non-residential buildings equipped with multi-zone heating, ventilation, and air conditioning (HVAC) systems. They found that for all non-predictive strategies, energy consumption is significantly reduced and thermal comfort is improved, regardless of any operation mode (heating or cooling) and the year.

Due to the low energy efficiency of the AC system when operating under a low cooling load, Xue *et al*. (2020) proposed an operating strategy for the AC system based on the indoor occupancy rate, *R*. In this strategy, the start-stop of the AC system is adjusted according to *R*. An office building with an AC system was tested and a comparison to the same system operating under previous conditions was conducted. The test results show that the energy efficiency ratio of the AC system improved by 7.2%, thus led to 15% of the total energy consumption reduction while the indoor environment quality was also significantly improved. Meanwhile, Dorokhova *et al*. (2020) developed a rule-based scheduling algorithm for AC systems using occupancy forecasting with accuracies of 98.3% and 97.6% for supervised and unsupervised algorithms, respectively. Based on the developed algorithm, the authors predicted that a potential of 15.4% of energy savings for a mid-size (4000 m2) building could be achieved. Recently, Alazazmeh and Asif (2021) investigated the prospects of two duty cycling techniques; resetting the temperature set point from 24 to 26°C during summer and shutting down the HVAC system during unoccupied hours. The results show that resetting the temperature set point during summer and shutting down the HVAC system during unoccupied hours could produce annual energy savings of 1.5 and 22% as compared to the baseline condition, respectively.

Based on previous research, it was proven that the duty cycling technique significantly reduces energy consumption and cost, while at the same time maintaining human thermal comfort at the appropriate level. However, there is a possibility where human thermal comfort is not achieved especially when the space cooling load is high, which typically occurs around afternoon hours. On the other aspect, this technique can be superior and effective in producing energy and cost savings, especially when the space cooling load is low (as found by Xue *et al.* (2020), Dorokhova *et al.* (2020) and Alazazmeh and Asif (2021)) and the productivity is not significantly important, i.e. during break hours between 1.00 pm to 2.00 pm. During this period, the majority of occupants working in commercial buildings usually go out, search for lunch breaks, etc. The number of occupants is minimal in the building during this period and in general, there is no productive work being carried out. Therefore, human thermal comfort can be tolerated and/or sacrificed.

So far, there is no research investigating the effect of the duty cycling technique on energy consumption and indoor environmental quality during break periods for real buildings in operation with relation to the impact on environmental sustainability of CO_2 emission, at least to the authors' knowledge. Therefore, this paper intends to investigate the impact of two strategies in duty cycling technique on energy and cost savings, as well as on human thermal comfort, indoor environmental quality, and contribution to environmental sustainability during break hours between 1.00 pm to 2.00 pm. A Health Center with real daily operations has been selected as a building for this case study.

METHODOLOGY

Figure-3 shows a Health Center that was chosen as a building under study to identify the opportunity for energy and cost savings from the operation of the AC system during the break period (1.00 pm to 2.00 pm). Current practice shows that the AC system in the lobby area works as usual during working hours during the break period with a room set point temperature of 24°C. The lobby area consists of the patient's waiting area, pharmacy, and registration counters.

Figure-3. Front view of the Health Center.

Two strategies were proposed and the results were compared with the baseline conditions of current practice. The first strategy is a basic technique where the AC system is shut down/OFF during this break period. The second strategy is a conventional scheduling technique where during this break period, the room set point temperature was set at 2°C higher than the current practice, at 26°C. During the break period, for the lobby area, it is expected that some staff and patients will occupy the waiting area, pharmacy counter, and registration counter. Therefore, to justify human thermal comfort for each proposed strategy, electrical energy consumption, room temperature and humidity, and concentration of CO_2 were recorded at these 3 different points of points A (pharmacy counter), B (waiting area), and C (registration counter). Figure-4 shows the locations of points A, B, and C in the floor plan of the Health Center.

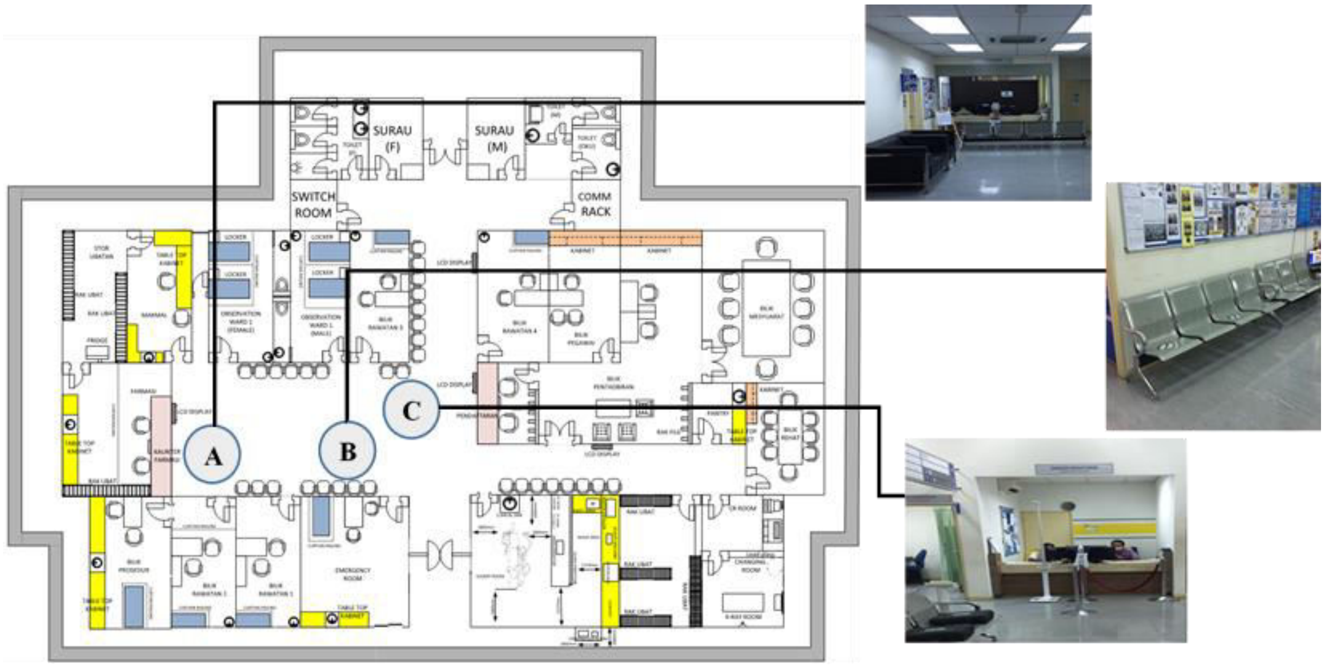


Figure-4. Floor plan of the Health Center and location of measuring points A, B, and C.

Data were recorded with a sampling time of 6 minutes. The outdoor temperature is not recorded but to gain a fair effect of the outdoor condition during comparative analysis, the site data measurements were conducted on sunny days only. Human thermal comfort for all strategies was justified using Malaysian Standard, MS 1525 (Department of Standard Malaysia, 2014). To ensure the higher accuracy of the data, a briefing to all staff and occupants before site data measurement was recorded was conducted to ensure daily operational parameters of the number of occupants, level of occupant activity, and intensity of electrical equipment being used were controlled as constant as possible throughout all data measurements.

Measurements of indoor temperature and humidity at three different locations (Figure-4) were done using an indoor air quality meter, model TSI Alnor IAQ-Calc 7545 (Figure-5a). The sensor was placed 1.5 m from the floor during measurement of the room air temperature and humidity. Electrical energy consumption was recorded with a minute sampling time using a digital power meter (Figure-5b), connected to the Smart Electrical Energy Monitoring (SEEM) System. Table-1 presents the accuracies of the measuring equipment.

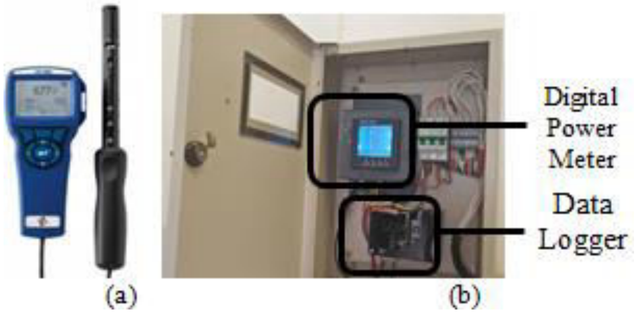


Figure-5. Measuring equipment. (a) TSI Alnor IAQ-Calc 7545 Indoor Air Quality Meter; (b) Digital Power Meter

The hardware of this SEEM System (Figure-5b) is installed in the Main Switch Board as in Figure-5b. The electrical energy consumption data is then downloaded from the web platform of the SEEM System. Therefore, energy consumption improvement for strategy x can be calculated by using equation (1), where:

$$E_{imp,x} = \frac{E_{base} - E_x}{E_{base}} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (1)$$

with

$E_{imp,x}$ = percentage of energy consumption improvement of strategy x, %
E_{base} = baseline energy consumption between 1:00 to 2.00 pm, kWh
E_x = energy consumption of strategy x between 1:00 to 2.00 pm, kWh

Table-1. Specification of measuring equipment.

System / Measuring Equipment	Model	Measured Parameters	Accuracy
Indoor Air Quality Meter	TSI Alnor IAQ-Calc 7545	Air temperature, CO_2 concentration, Air humidity	CO_2: ±3.0% of reading or ±50 ppm, whichever is greater. Temperature: ±0.5°C Humidity: ±3.0% RH
Smart Energy Monitoring System	Digital Power Meter: Mikro DPM380 Data Logger: Raspberry Pi 3 Model B+	Electrical power, Electrical energy (IEC62053-21:Class 1)	1%

In addition, with five working days per week, 52 weeks per year with 1 kWh costs RM 0.402 (Tenaga Nasional Berhad, 2022) and RM 1.00 equivalent to USD 0.211 (Forbes, 2022), annual energy cost savings of strategy *x*, $CS_{annual,x}$ in US dollars, and a simple payback period, SPP in years for any energy saving measure can be determined by using equations (2) and (3) where

$$CS_{annual,x} = (E_{base} - E_x) \times 5 \times 52 \times 0.402 \times 0.211 \quad \text{……..(2)}$$

$$SPP = \frac{IC}{CS_{annual}} \quad \text{……………………………………....(3)}$$

with

IC = investment cost for respective energy saving measure, USD

CS_{annual} = annual energy cost saving as compared to baseline condition, USD

RESULTS AND DISCUSSIONS

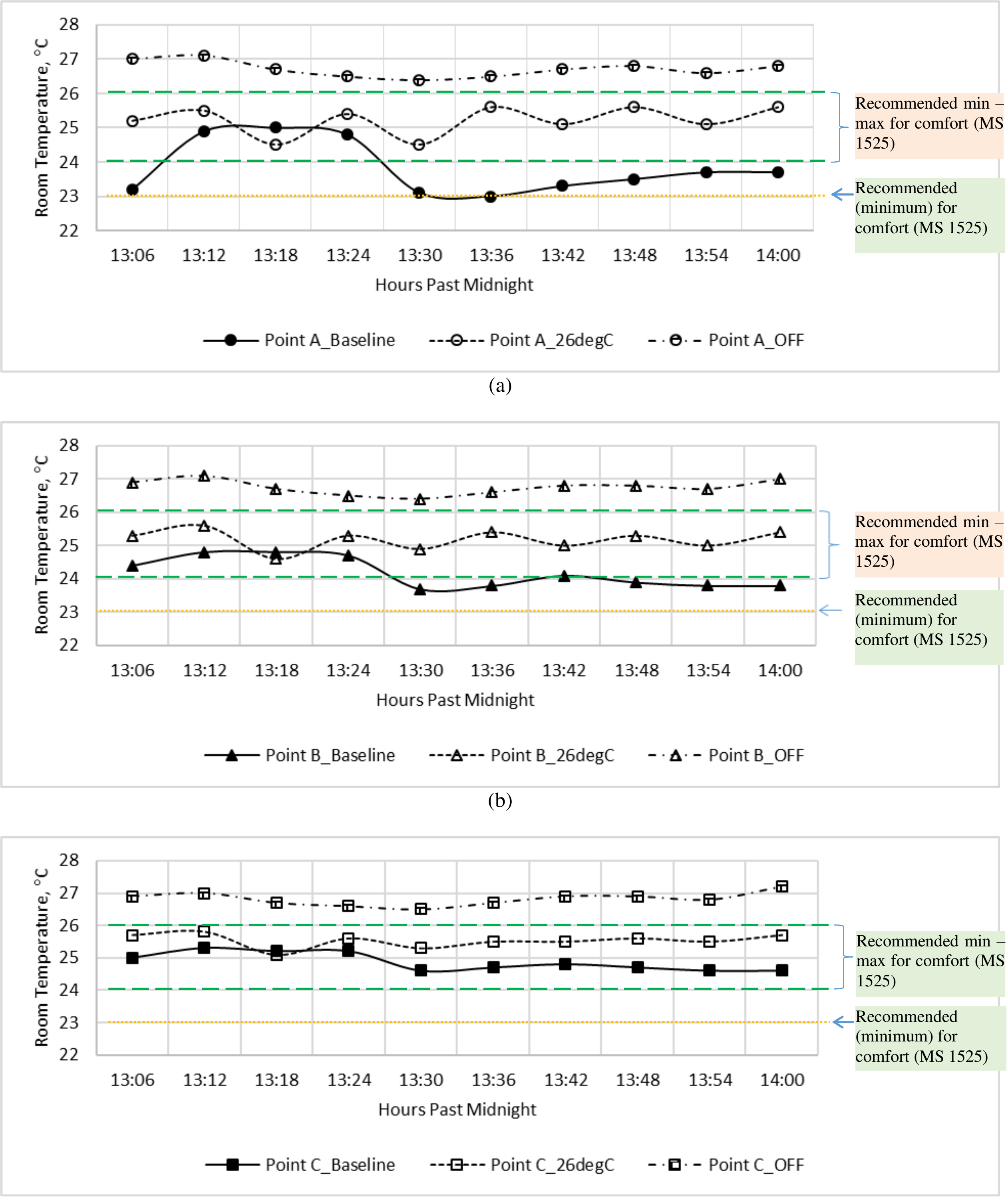
This section describes the impact of proposed strategies under the duty cycling technique on the room thermal comfort, indoor environmental quality, energy, and cost savings, and the impact on environmental sustainability (CO_2 emission). The room thermal comfort is accessed in the aspects of room air temperature, and room air relative humidity, while indoor environmental quality is evaluated in terms of indoor CO_2 concentration. Meanwhile, the energy and cost savings are justified by comparing the proposed strategies with the baseline condition of current practices. The data measurements for baseline, Strategy 1, and 2 were conducted on the 27th, 28th, and 29th of April 2022, respectively.

The Impact on Indoor Air Temperature

Figure-6 shows the variations of indoor air temperatures at three points A, B, and C, for three different operational conditions of the AC system. Site data measurement was conducted during the real operation of the Health Center on different days. As a result, data measurement is highly dependent on parameters that influence the daily operation of the Health Center on those respective days, before and during the measurement, i.e. level of occupancy and activity in the lobby area before 1.00 pm (13.00), intensity of electrical equipment being used, as well as variation of outdoor temperature and humidity. Outdoor temperature and humidity are not controlled, but during site data measurement the condition outdoors is observed as a sunny day, as explained in section 3.0.

In short, the indoor air temperature variation between these points is significantly related to air balancing and thermal equilibrium of the lobby area, influenced by how the AC system is being utilized. Real daily operational parameters of the Health Center; number of occupants, variation of outdoor air condition, level of occupant's activity, and intensity of electrical equipment being used were controlled to the best possible condition and therefore, these parameters were expected to contribute a small impact on the indoor air temperature variation.

In general, fig. clearly shows that temperature variations at any point can be maintained within the minimum and recommended temperature range for baseline condition and Strategy 1. Meanwhile, the operation of Strategy 2 (switching OFF the AC system during the break period) caused the room temperature to exceed the maximum recommended temperature for thermal comfort of 26°C. Implementation of Strategy 2 produced average temperatures at points A, B, and C within an hour (1.00 pm to 2.00 pm) of around 26.71, 26.75, and 26.82°C, respectively.



(a)

(b)

(c)

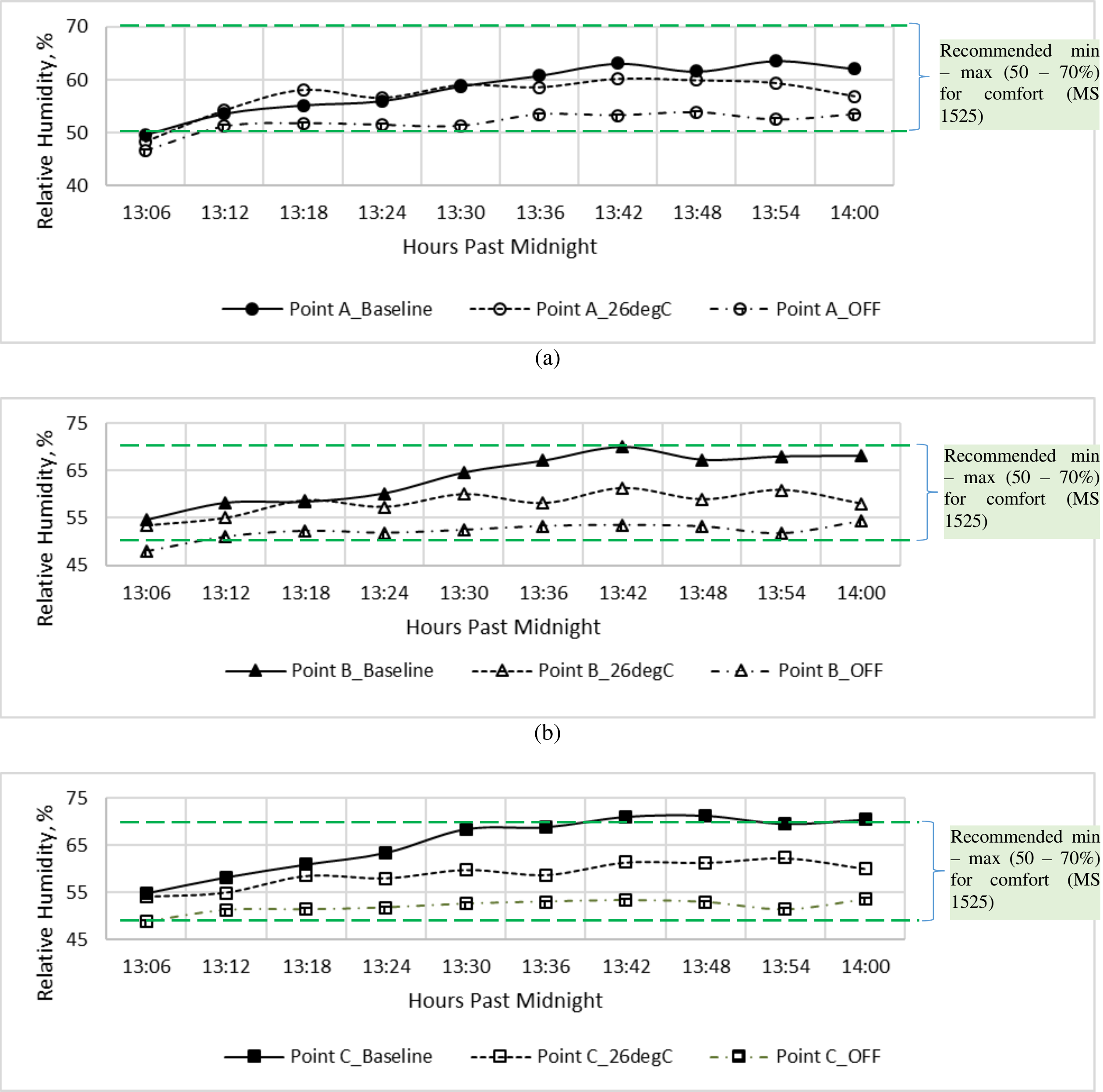
Figure-6. Variation of room air temperature for three conditions. (a) Point A, (b) point B, (c) point C.

From Figure-6, it can be seen that during the implementation of Strategy 2 where the AC system was turned off, room temperature at all points can be maintained at almost constant temperature, slightly above the maximum recommended temperature of 26°C. Although the AC system was turned off, no significant room temperature increment was observed. Therefore, since the room temperature did not increase drastically, it gives an advantage to thermal comfort when the AC operation resumes normal operation after break hour where the set point temperature, i.e. 24°C can be reached faster.

The Impact on Indoor Air Humidity

Figure-7 shows the variations of relative humidity at each point, A, B, and C. As observed during indoor air temperature measurement, the indoor air humidity measurement is also highly dependent on air balancing and thermal equilibrium of the current condition at each point influenced by how the AC system is being utilized and also due to real daily operational parameters of the Health Center before and during data measurement being conducted.

MS 1525 recommends design relative humidity between 50 - 70% for human indoor thermal comfort. In general, during an hour of measurement, all strategies were able to main the room's relative humidity within the recommended range, except for point C, at measurement number 7 (42nd minute) and onwards. However, the deviation from the maximum value of 70% is considered very minimal.



(a)

(b)

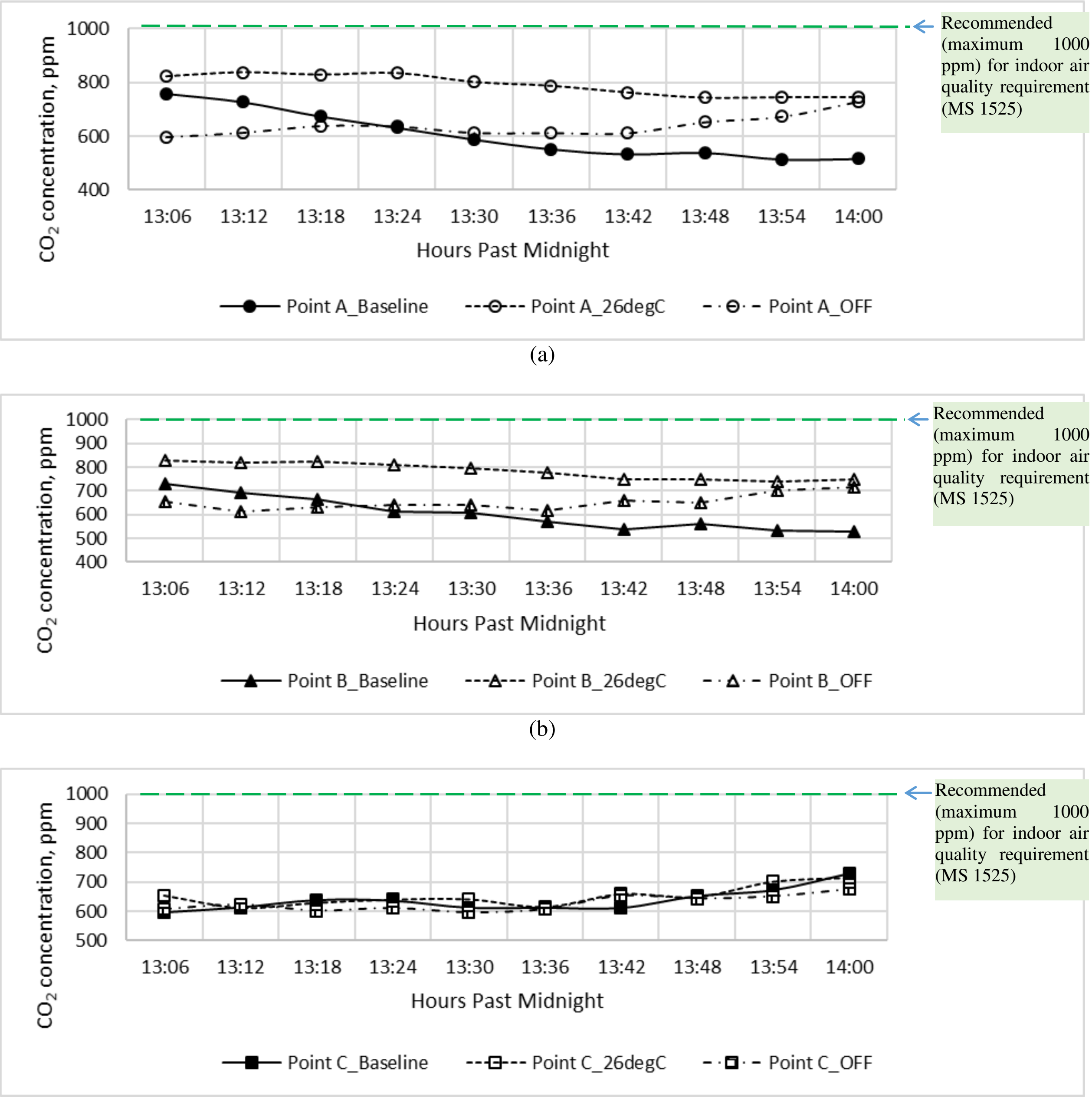
(c)

Figure-7. Variation of room air relative humidity for three conditions. (a) Point A, (b) point B, (c) point C.

The Impact on Indoor Concentration of Carbon Dioxide

During the break period between 1.00 pm to 2.00 pm, the number of occupants in the lobby area is very low leading to a low level of CO_2 concentration at all measuring points. Figure-8 summarizes that CO_2 concentration is less than the maximum value of 1000 ppm for indoor air quality requirements as highlighted by

MS1525 regardless of baseline condition or any strategy being implemented. Therefore, in the aspect of CO_2 concentration, implementation of Strategy 1 where the AC system is turned off is the best strategy due to complying with the indoor air quality standard while consuming no energy.



Recommended (maximum 1000 ppm) for indoor air quality requirement (MS 1525)

(a)

Recommended (maximum 1000 ppm) for indoor air quality requirement (MS 1525)

(b)

Recommended (maximum 1000 ppm) for indoor air quality requirement (MS 1525)

(c)

Figure-8. Variation of room air relative humidity for three conditions. (a) Point A, (b) point B, (c) point C.

The Impact on Power Demand

Figure-9 shows the power demand characteristic of baseline, Strategies 1 and 2 between the break period of 13:00 (1.00 pm) to 14.00 (2.00 pm). In general baseline condition requires the highest demand with an average of 4.05 kW, followed by Strategy 2 (3.07 kW) and Strategy 1 (2.89 kW). The baseline condition demands the highest power due to the significant power demand required by the AC system to maintain the room temperature at 24°C during that break period. In the other aspect, it is expected that Strategy 2 will demand the lowest power as compared to Strategy 1 because the AC system is turned off. However, real data measurement indicates that the average power demand for Strategy 2 is higher than Strategy 1 by 0.18 kW. Figure-8 is due to the higher power demand of Strategy 2 between 13.00 and 13.39 as compared to Strategy 1. Since data measurement was conducted on different days at real operational conditions, it is expected that other active electrical equipment was significantly used during that measurement period of Strategy 2 as compared to measurement during Strategy A. However, when this active electrical equipment was turned off around 13.39 (1.39 pm), a significant power reduction of Strategy 2 as compared to Strategy 1 can be observed.

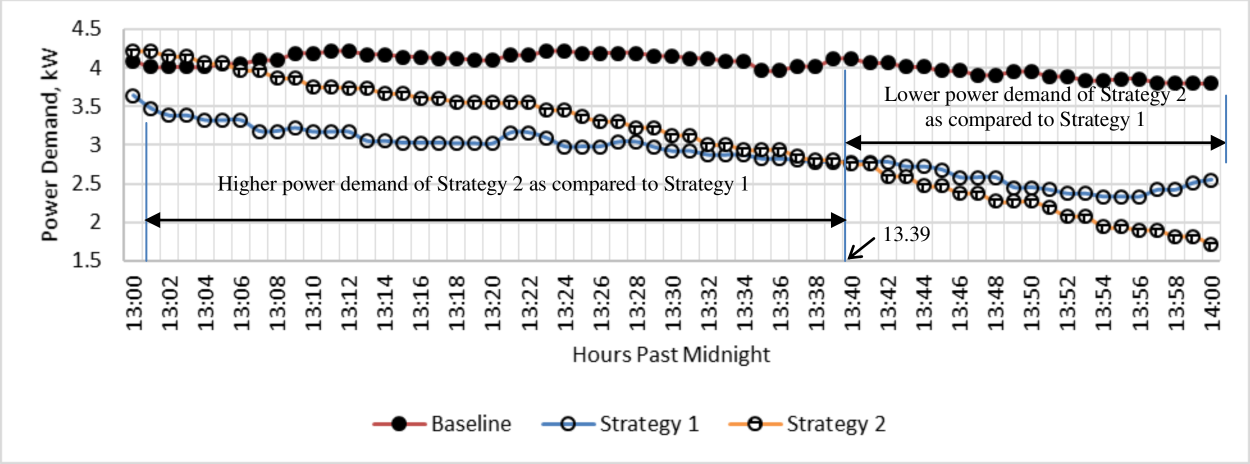


Figure-9. Power demand variation for baseline and all Strategies 1 and 2.

The Impact on Energy and Cost Savings

In the aspect of total energy consumption between 13:00 to 14.00, it is observed in Figure-10 that Strategy 2 consumes the lowest electrical energy (9.00 kWh), followed by Strategy 1 (10.89 kWh) and baseline condition (13.81 kWh). Although during Strategy 2 the AC system was turned off, electrical energy was still being consumed particularly by other electrical equipment and appliances such as medical freezers, lamps, computers, etc.

Utilizing equation (1), the percentage of energy saving per day for Strategies 1 and 2 as compared to baseline condition are calculated at 21.1% (2.92 kWh) and 34.8% (4.81 kWh), respectively. It is equivalent to annual energy savings of 759.2 kWh for Strategy 1, and 1250.6 kWh for Strategy 2. In terms of annual energy cost saving, by using equation (2), Strategies 1 and 2 are predicted to produce annual energy cost savings of around USD 64.40 (RM 305.20) and USD 106.08 (RM 502.74) respectively, as compared to the baseline condition.

In addition to potential energy and cost savings, all strategies are considered as zero cost measures where there is no investment cost required for all strategies. Therefore, the SPP for any Strategy 1 or 2 is instant (0 years) once the saving is gained. As a result, Strategies 1 and 2 are very low in terms of risk and could be implemented as soon as possible.

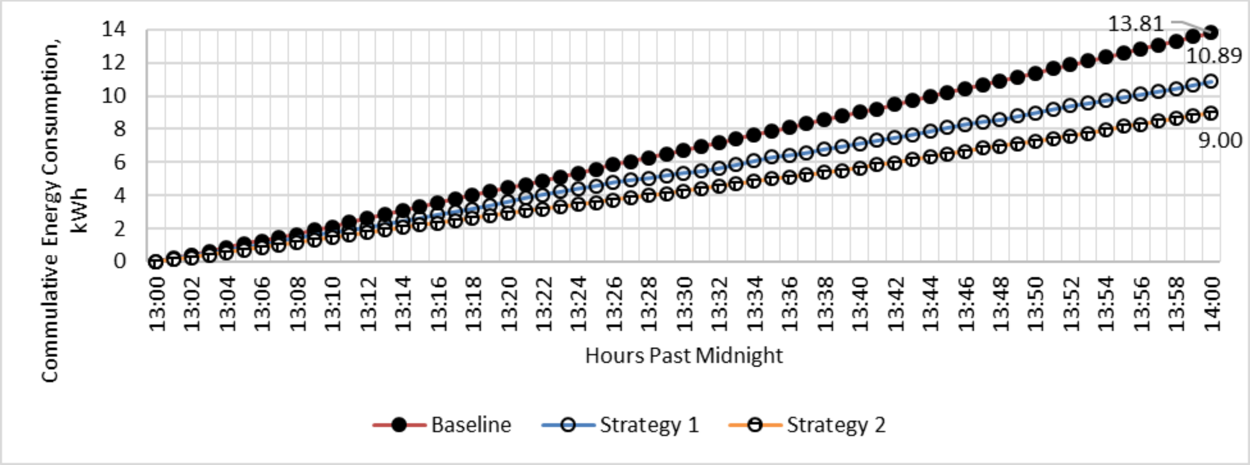


Figure-10. Power demand variation for baseline and all Strategies 1 and 2.

The Impact on Environmental Sustainability

The emission factor of CO_2 to the environment is strongly influenced by two main factors; how electricity is generated in the power plant and the advancement of technology being used in electricity generation, especially for non-renewable fuel-powered power plants. Today in Malaysia, due to improvements in electricity generation in terms of friendly policy to renewable energy and high technology applications for new coal-fired power plants, the CO_2 emission factor has improved from 760 g of CO_2 per kWh in 2010 to 585 g of CO_2 per kWh in 2017 (Malaysian Green Technology Corporation, 2019),

Based on the latest emission factor data available where 1 kWh of electrical consumption in Peninsular

Malaysia produces 585 g of CO_2 (Malaysian Green Technology Corporation, 2019), implementation of Strategies 1 and 2 can avoid contribution to world CO_2 emissions by 444.13 and 731.60 kg of CO_2 per year, respectively. Considering other buildings also adopted the same strategy, this small action can lead to a high impact, not only on energy and cost savings but also on environmental sustainability in the future.

Best strategy for Health Center

During the break period between 13:00 (1:00 pm) to 14:00 (2:00 pm), staff are normally at rest condition and the productivity of staff doing work can be tolerated or neglected. It is observed that Strategy 2 led to a room temperature slightly higher than the recommended maximum value of 26°C. However, the deviation from the recommended maximum value is less than 1°C and thus, considered small. In the other aspect of room relative humidity and CO_2 concentration, Strategy 2 can meet the standard. With the lowest energy consumption as compared to baseline and Strategy 1, and if the sensitivity of occupant comfort to room temperature during the break period can be tolerated, Strategy 2 was identified as the best strategy.

However, if room temperature within the recommended range is considered crucial during this break period, Strategy 1 can be adopted. This strategy can maintain the room temperature below 26°C while consuming a reasonable amount of energy as compared to baseline conditions.

CONCLUSIONS

The potential of duty cycling techniques for AC systems during break periods in producing energy and cost savings and the impact on the indoor thermal environment, air quality, and environmental sustainability have been investigated. A lobby of a Health Center was chosen for the case study and two strategies were proposed and investigated.

In addition to the instant payback period (0 years), the result shows that both strategies, 1 and 2 can meet the indoor thermal environment and air quality requirements, except for Strategy 2 where switching OFF the AC system led to higher room temperature of more than 26 (average between 26.71 to 26.82°C). In the aspect of energy and cost savings potential as compared to the baseline condition, annual savings of around 759.2 kWh (USD 64.40) and 1250.6 kWh (USD 106.08) are expected for Strategies 1 and 2, respectively. Consequently, these savings contribute to environmental CO_2 emission reduction by 444.13 kg of CO_2 per year (Strategy 1) and 731.60 kg of CO_2 per year (Strategy 2).

Due to these reasons and if the sensitivity of occupant comfort to room temperature during the break period can be tolerated or neglected, it is proposed that Strategy 2 is the best practice for the AC system operation during the break period. Adoption of this no-cost-energy saving measure into other suitable buildings/organizations can lead to a high impact, especially on the aspect of environmental sustainability in the future.

ACKNOWLEDGEMENTS

The authors are grateful for the support of the Universiti Teknikal Malaysia Melaka (UTeM) in providing a platform for research activities in terms of facilities and management support.

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