VENTILATION PERFORMANCE AND ENERGY ASSESSMENT OF A HIGH-RISE RESIDENTIAL BUILDING - A CASE STUDY IN MALAYSIA

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ABSTRACT

Kuala Lumpur, Malaysia's capital, nestles the majority of high-rise buildings in the country, and nearly half are residential. Such buildings are designed predominantly to be naturally ventilated, yet occupants rely mostly on mechanical ventilation. This pilot study assessed ventilation strategies in oppositely oriented units of a high-rise residential building in Kuala Lumpur. The study combined experimental and simulation methods. The simulation analysis was performed using IES_VE simulation tool in two parts, commencing with a calibration procedure, followed by a ventilation strategies analysis. The result concluded that the indoor air temperature of field and simulated data compares well with a positive correlation coefficient. Further annual simulation validated mixed-mode ventilation as an optimal ventilation strategy to achieve potential energy savings without foregoing occupants' thermal comfort.

INTRODUCTION

The building sector is one of the most significant carbon emissions contributors in the world (IPCC, 2019). In Malaysia's case, the carbon emissions from this particular sector have been doubled in the last decades, representing now 25% of the total country's emissions (Lucon et al., 2014). Kuala Lumpur accommodates 81.5% of the total number of high-rise buildings in Malaysia, and half of these buildings are residential buildings (CTBUH, 2018). Given this statistic, measures to reduce cooling loads, as well as enhancing the indoor thermal performance, are proposed in the Malaysian Standard Energy Efficiency and Use of Renewable Energy (MS 2680:2017). The code of practice gives guidance on the design, selection of materials, and efficient use of energy in residential buildings.

Objective One: Base-line Model Calibration

According to the literature, Integrated Environmental Solution (IES_VE) software is a powerful commercial tool that shown its reliability and correspondence between collected field measurements and simulation results. Previous research stated that the calibration of site measurement data with the base-line model offers the possibility to introduce ultimate solutions for environmental studies concluding a positive correlation coefficient ranging between 70 and 90% (Liu, et al., 2018), (Christensen, et al., 2015), (Almhafdy, et al., 2013) and (Leng, et al., 2012).

Prior to the ventilation strategy analysis, a calibration procedure was performed to ensure the simulation results are valid. The discrepancy percentage between the field and simulation data was evaluated, concluding a correlation coefficient. In this study, the ambient air temperature parameter only was used to calibrate. To estimate the correlation between the investigated variable and the simulation results, a Pearson coefficient of correlation formula was used.

Objective Two: Optimal Ventilation Strategy

Various studies investigating different ventilation strategies' impact on the thermal or/and energy performance in high-rise residential buildings are summarized in Table 1.

Table 1:
Summary of previous ventilation performance studies

VENTILATION STRATEGY	INVESTIGATION METHOD	REF.
Natural	Simulation	Zhou, et al., 2014
Natural	Field measurement	Aflaki et al., 2016
Natural Mixed-mode	Simulation/Field measurement	Wong & Li, 2007
Natural Mixed-mode	Simulation/Field measurement	Omrani, et al., 2017
Natural Mechanical	Simulation	Prajongsan & Sharples, 2012
Natural Mechanical	Simulation	Priyadarsini et al., 2004
Mechanical	Simulation	Fahmi et al., 2018

It can be concluded that numerous past performance studies have investigated one or combined ventilation strategies. Quantitative research combining natural, mechanical, and mixed-mode strategies, utilizing both field measurements and simulation methods, is still scarce. This study combines both investigation methods while examining natural, mechanical, and mixed-mode ventilation strategies.

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Thermal comfort

MS 2680:2017 includes an adaptive thermal comfort equation (2) for naturally ventilated or non-air-conditioned residential buildings. The MS 2680:2017 equation seems to be adapted from ASHRAE Standard 55 (ASHRAE, 2010), however employing different constants.

$$Tc = 13.8 + 0.57 * To \tag{1}$$

$$Tc = 17.6 + 0.31 * To \tag{2}$$

Tc = Indoor temperature (°C); To = Mean monthly outdoor temperature (°C).

Humphreys (1976) and Nicol and Roaf (1996) proposed an earlier adaptive model, where the developed model regulates the comfort zone in the psychometric chart by determining neutrality temperature, using the equation **(2)**to indicate the center point for the comfort zone. Auliciems and de Dear revised the relations for predicting group neutralities based on mean indoor and outdoor temperatures and proposed the current equation applied by the ASHRAE Standard 55 (ASHRAE, 2010). The equation states that the indoor temperature for human thermal comfort (Tc) is dependent on the outdoor ambient (To). The adaptive thermal comfort desired indoor temperature ranges within ± 2 °C of the neutrality temperature (Tc) (Szokolay, 1991).

The practicality and applicability of the thermal adaptive equation mentioned in MS 2680:2017 code of practice were examined in the study and compared to the one in ASHRAE Standard 55.

Cooling Load

The MS 2680:2017 proposes a guide on the recommended capacity of air conditioners dependable on various room sizes. The practicality of applying the recommended cooling capacity of 110 w/m² was evaluated and compared with the provided air conditioning cooling capacity in the tested units.

The paper eventually explores different ventilation strategies with the aid of simulation models that prioritize efficient cooling load within an acceptable thermal comfort range.

METHODOLOGY

The chosen building for this pilot study is a high-rise residential building nestled in the city center of Kuala Lumpur, consisting of 500 units split over two towers, as shown in Figure 1. While the residence is built with means to maximize natural lighting and ventilation, yet it features a high window-to-wall ratio (WWR), which imposes the worst problems regarding thermal environments in the tropics. The development obtained as well a Green Building Index (GBI) Gold certification. Although being awarded a golden GBI certificate, this fact must be considered as available literature shows that outcome and drivers of most green building certifications are diverse (Scofield, 2009) and (Matisoff, et al., 2014). For instance, to enhance the marketability and profitability of the certified buildings.

Quantitative research methodology is the approach for this study as it is experimental and technical research—Figure 1 displays the methodology flow chart.

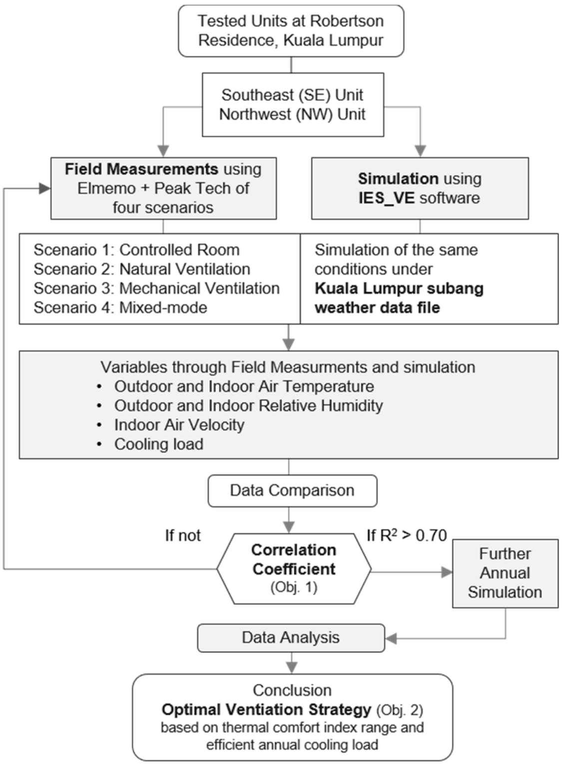

Figure 1: Methodology flowchart

A continuous measurement was undertaken in both units included ten minutes' intervals monitoring of the air temperature, relative humidity, and air velocity, using the data loggers, i.e., ELMEMO and PeakTech. The field investigations were performed in two oppositely oriented one-bedroom units (area: 64 m^2, floor-to-ceiling height: 3 m) located on the 19th floor (South tower: 38 floors and North tower: 36 floors), as shown in Figure 2.

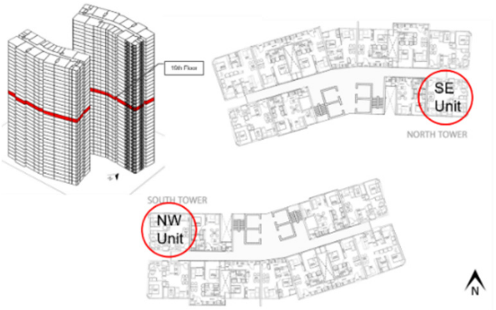

Figure 2: Selected experimental units and high-rise building layout plan

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The two corner units are facing respectively southeast (SE) and northwest (NW). The units' external walls feature 50% WWR with a glazing area of 11.8 m^2. The openable window area of 3.1 m^2 are awning windows, and the remaining are fixed windows.

Moreover, the units accommodate two single split air-conditioning units with a cooling capacity of 5.33 kW; hence, a total of 10.66 kW. Following the MS 2680:2017 code of practice, the guide, however, recommends a total cooling capacity of 6.05 kW.

The monitoring equipment indicated in Table 2 was installed accordingly to the guideline mentioned in the ASHRAE Standard 55. For the indoor investigation, air temperature sensor, humidity sensor, and air velocity anemometer were set up at 1.1 m above the floor in the center of each room, as indicated in Figure 3. For the outdoor investigation, an outdoor weather station was set up on an external sled to collect micro-climate data.

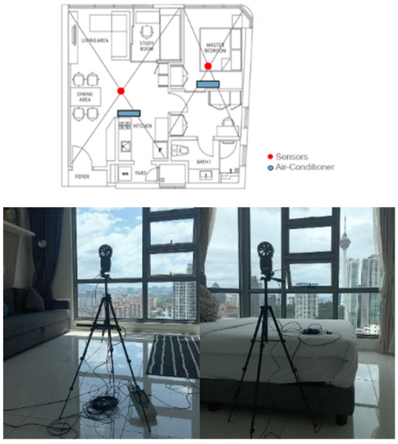

Figure 3: Installation of monitoring equipment in the experimental units

The investigation period was conducted between 10-19 February 2020. During the 24-hour investigation, the occupancy characteristic was defined under the following four scenarios:

- Scenario 1: 24-hour without ventilation, all windows closed. (Controlled room)
- Scenario 2: 24-hour with natural ventilation, all windows opened.
- Scenario 3: 12-hour (6:00 am to 6:00 pm) without ventilation (all windows closed). During the night-time (6:00 pm to 6:00 am) with an air conditioning system utilized.
- Scenario 4: 12-hour (6:00 am to 6:00 pm) with natural ventilation (all windows opened). During the night-time, 12-hour (6:00 pm to 6:00 am) with an air conditioning system utilized.

IES_VE simulation tool was chosen to simulate the units under the ASHRAE design weather file for Subang/Kuala Lumpur which is already linked to the software. The software assimilates various third-party application programs by integrated collection function. ModelIT was used for the preprocessing of the high-rise model, SunCast for solar shading analysis, and the APACHE component performs a thermal calculation based on the designated weather file. The construction materials indicated in Table 3 were applied to the model. In addition, internal gains of one occupant, appliances, lighting, and infiltration rate of 0.5 ACH were set to the simulation model.

Table 2:
Monitoring Equipment

PARAMETER	SPECIFICATION	ACCURACY/ RESOLUTION
AHLBORN + ELMEMO		
Temperature	Thermocouple NTC Typ N	-20…100°C: ±0.4K
Relative Humidity	Capacitive humidity sensor	0.5…98 % ±0.3k
PEAK TECH 5185		
Temperature	Thermocouple NTC Typ K	-40°C...125° C:±0.3K
Relative Humidity	Capacitive humidity sensor	0.0%...100% ±0.3k
Vane-Anemometer	Vane sensor	0.1...30.00 m/s; ±1.0%

Table 3:
Material properties of building element

ELEMENT	CONSTRUCTIONS	U-VALUE (W/m² K)
External wall	Shear concrete + Monocouche render	3.235
Internal wall	Cement brick wall	2.126
Glazing (Aluminum framing)	Single laminated Low-E (6.38-0.76-6.38mm) Including framing Total shading coefficient	3.834 4.541 0.38
Ceiling/ flooring	Porcelain tile finish + Reinforced concrete + suspended Plasterboard ceiling	1.036

The cooling profile was defined annually from January to December, taking 24-26 °C as setpoints, the cooling capacity of 5.33 kW, and per the occupancy schedule profile displayed in Figure 4.

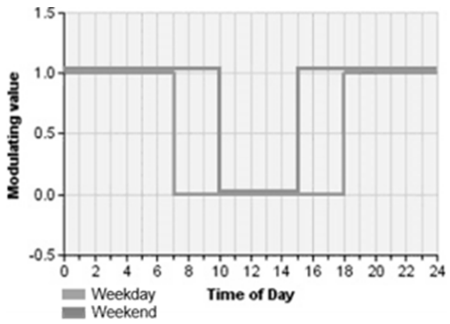

Figure 4: Occupancy Schedule Profile

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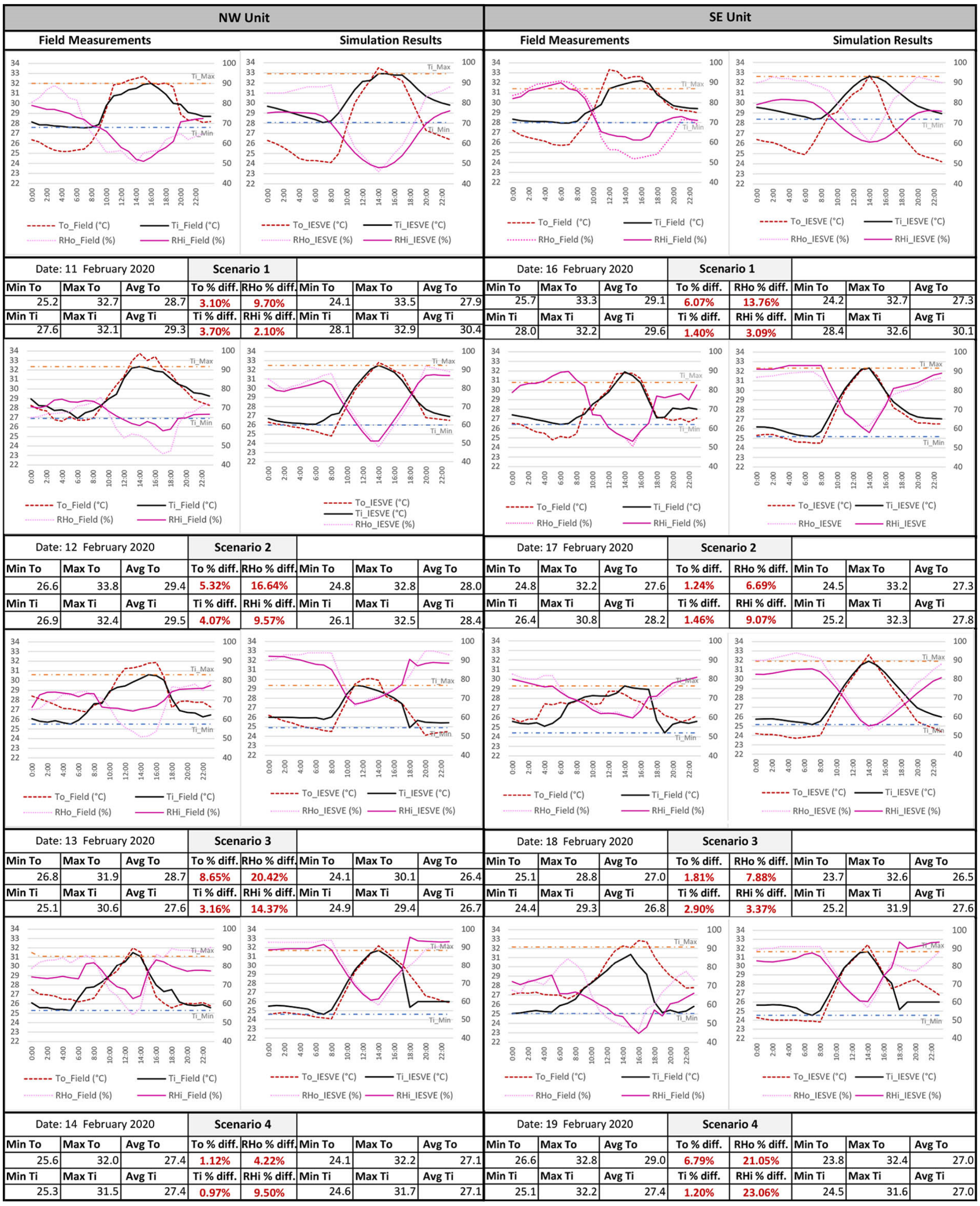
RESULTS AND DISCUSSION

Base-line Model Calibration

A comparative analysis between the field measurement readings and the simulation results for the varied scenarios as labeled is illustrated in Figure 5. In general, the results showed that the differences between field-measured indoor air temperature (AvgTi) and simulation results are satisfactory and mostly share similar patterns. In the case of AvgTi, the discrepancy percentage varied between 0.97-4.07%, respectively. While the percentage difference of the average outdoor temperature (AvgTo) tended to be higher, varying between 1.12-8.65%. This difference is because the IES_VE weather data for Subang/Kuala Lumpur was found to be slightly lower than that of the micro-climate data collected.

The relative humidity curve reflected a typical hot-humid climate condition whereby the RH gradually escalates towards night-time and drops during the day. The correlation, however, between the measured average outdoor relative humidity (RHo) and indoor relative humidity (RHi) with simulation results was relatively low, especially on 13 and 19 February. This may be attributed to the precipitation that occurred on the days of the field data collection.



Date: 11 February 2020			Scenario 1				
Min To	Max To	Avg To	To % diff.	RHo % diff.	Min To	Max To	Avg To
25.2	32.7	28.7	3.10%	9.70%	24.1	33.5	27.9
Min Ti	Max Ti	Avg Ti	Ti % diff.	RHi % diff.	Min Ti	Max Ti	Avg Ti
27.6	32.1	29.3	3.70%	2.10%	28.1	32.9	30.4

Date: 16 February 2020			Scenario 1				
Min To	Max To	Avg To	To % diff.	RHo % diff.	Min To	Max To	Avg To
25.7	33.3	29.1	6.07%	13.76%	24.2	32.7	27.3
Min Ti	Max Ti	Avg Ti	Ti % diff.	RHi % diff.	Min Ti	Max Ti	Avg Ti
28.0	32.2	29.6	1.40%	3.09%	28.4	32.6	30.1

Date: 12 February 2020			Scenario 2				
Min To	Max To	Avg To	To % diff.	RHo % diff.	Min To	Max To	Avg To
26.6	33.8	29.4	5.32%	16.64%	24.8	32.8	28.0
Min Ti	Max Ti	Avg Ti	Ti % diff.	RHi % diff.	Min Ti	Max Ti	Avg Ti
26.9	32.4	29.5	4.07%	9.57%	26.1	32.5	28.4

Date: 17 February 2020			Scenario 2				
Min To	Max To	Avg To	To % diff.	RHo % diff.	Min To	Max To	Avg To
24.8	32.2	27.6	1.24%	6.69%	24.5	33.2	27.3
Min Ti	Max Ti	Avg Ti	Ti % diff.	RHi % diff.	Min Ti	Max Ti	Avg Ti
26.4	30.8	28.2	1.46%	9.07%	25.2	32.3	27.8

Date: 13 February 2020			Scenario 3				
Min To	Max To	Avg To	To % diff.	RHo % diff.	Min To	Max To	Avg To
26.8	31.9	28.7	8.65%	20.42%	24.1	30.1	26.4
Min Ti	Max Ti	Avg Ti	Ti % diff.	RHi % diff.	Min Ti	Max Ti	Avg Ti
25.1	30.6	27.6	3.16%	14.37%	24.9	29.4	26.7

Date: 18 February 2020			Scenario 3				
Min To	Max To	Avg To	To % diff.	RHo % diff.	Min To	Max To	Avg To
25.1	28.8	27.0	1.81%	7.88%	23.7	32.6	26.5
Min Ti	Max Ti	Avg Ti	Ti % diff.	RHi % diff.	Min Ti	Max Ti	Avg Ti
24.4	29.3	26.8	2.90%	3.37%	25.2	31.9	27.6

Date: 14 February 2020			Scenario 4				
Min To	Max To	Avg To	To % diff.	RHo % diff.	Min To	Max To	Avg To
25.6	32.0	27.4	1.12%	4.22%	24.1	32.2	27.1
Min Ti	Max Ti	Avg Ti	Ti % diff.	RHi % diff.	Min Ti	Max Ti	Avg Ti
25.3	31.5	27.4	0.97%	9.50%	24.6	31.7	27.1

Date: 19 February 2020			Scenario 4				
Min To	Max To	Avg To	To % diff.	RHo % diff.	Min To	Max To	Avg To
26.6	32.8	29.0	6.79%	21.05%	23.8	32.4	27.0
Min Ti	Max Ti	Avg Ti	Ti % diff.	RHi % diff.	Min Ti	Max Ti	Avg Ti
25.1	32.2	27.4	1.20%	23.06%	24.5	31.6	27.0

Figure 5: Summary of field measurements and simulation results

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Figure 6 presents the relationship between the simulated indoor air temperature results and the collected field measurement as a scatter plot. As displayed, a positive correlation coefficient of (R^2=0.84) was observed when comparing the simulated indoor air temperature and field measurements. This attribute to the validity and reliability of IES_VE to generate further annual simulations models to conduct further analysis of the proposed ventilation strategies.

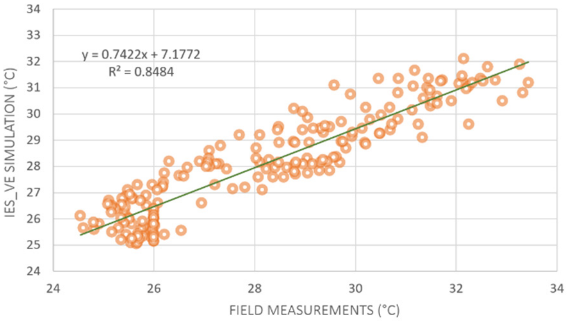

Figure 6: Scatter plot, the correlation coefficient between field-measured indoor air temperature and IES_VE simulation results

Moreover, Figure 7 displays the annual cooling load between the air conditioner provided cooling capacity and IES_VE simulation results. A percentage difference of 9% reflects the reliability of IES_VE software to be used for annual cooling simulations.

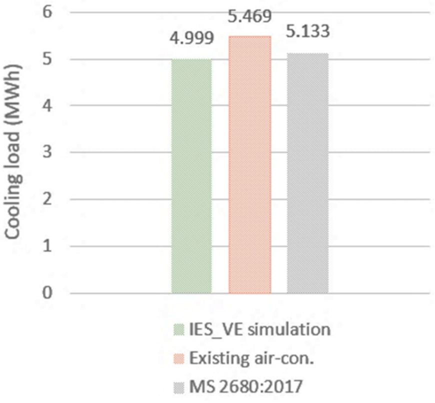

Figure 7: Annual cooling demand

Optimal Ventilation Strategy

Thermal Comfort

For a better understanding of the neutral temperature behavior, an hourly mean indoor and outdoor air temperature of the simulation results for February are aggregated in Figure 8. A comparative illustration of the MS 2680:2017 and ASHRAE adaptive thermal comfort equation curves is presented below. The indoor air temperature where natural ventilation is applied; scenarios 2 and 4 are notably out of the thermal comfort range of the MS:2680:2017 curve and slightly closer to the ASHRAE one, especially during the night-time. In contrast, during the day-time, especially between 10:00 and 16:00, the indoor air temperature tended to be closer to the MS 2680:2017 comfort zone; however, only for a range of six hours.

The illustrated evaluation demonstrates the inapplicability of the adaptive thermal comfort equation mentioned in the MS 2680:2017 in this study since the thermal comfort satisfactory range is limited to certain hours of the day.

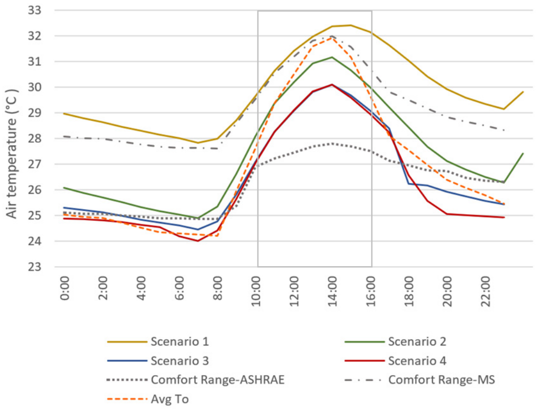

Figure 8: Mean indoor/outdoor air temperature and comfort zone range

Cooling load

As mentioned earlier, the MS:2680:2017 recommends a cooling capacity of 110 w/m^2. As shown in Figure 7, a reduced annual cooling demand of 5.133 MWh was observed when following the guideline of MS:2680:2017. Based on annual simulated thermal analysis, Table 4 shows the impact of recommended MS:2680:2017 and provided cooling capacities on the indoor air temperature in terms of hours in the range of 24-26 °C. The differences seemed to be trivial. However, the cooling capacity provided in the units, correspondingly, increase the annual cooling demand unnecessarily by 6%.

Table 4:

Annual indoor air temperature in hour ranges

COOLING CAPACITY (KWH)		AIR TEMPERATURE (°C) – HOURS IN RANGE
		>24.00 to <=26.00
MS Standard	3.025	2172
Existing air-con	5.33	2190

Furthermore, over the considered field measurement period, it is difficult to estimate an optimal ventilation strategy as the field measurement duration seems insufficient for a credible estimation. Annual ventilation analysis using simulation results was conducted. Indoor air temperatures between 24.8 °C and 28.0 °C were taken as a lower and upper limit of thermal comfort derived from the ASHRAE Standard 55 thermal adaptive equation. As shown in Figures 9-10, the 24-hour ventilation (scenario 2) resulted in

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longer hours of cooler conditions than those without ventilation exhibited in scenario 1.

Scenarios 1 and 3 experienced longer hours of high indoor air temperature. Thus, imposing the worst indoor air temperature conditions, namely because of the high solar heat gain and the lack of ventilation. Whereas, scenario 3 experienced slightly lower temperatures than Scenario 1. This was concluded, namely due to the overnight mechanical cooling.

In contrast, natural ventilation showed high effectiveness on the indoor air temperature reduction (scenarios 2 and 4). This was due to the heat loss occurred faster than the condition without natural ventilation. However, only 24-hour natural ventilation might not be able to provide a comfortable thermal environment; hence the relative humidity percentage tends to be higher, ranging between 70-80%, as presented in scenarios 2 and 4 in Figures 9-10.

The percentage of discomfort hours indicates when a natural ventilation system was utilized, the need for active cooling or mechanical ventilation is essential. Thus, scenario 4 (mixed-mode ventilation) is concluded to provide a balanced indoor thermal comfort in terms of both indoor air temperature and relative humidity percentage.

Figure 11 presents the simulated annual cooling loads of the tested units. As illustrated, the SE unit generally experiences higher annual cooling loads in both scenarios 3 and 4 than the NW unit. This was due to the amount of incident solar radiation projected on the south façade throughout the year.

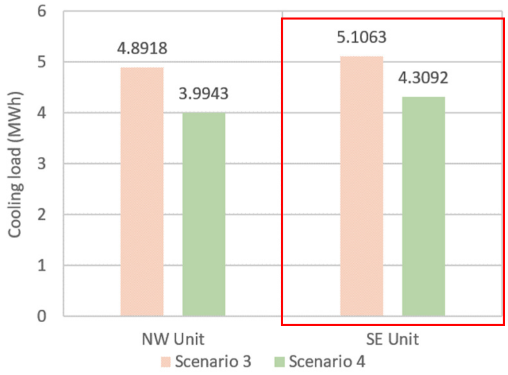

Figure 11: Orientation impact on the annual cooling load

Scenario 4, however, experienced lower cooling loads by 16-19% than scenario 3. This was highly caused by the natural heat loss occurring through natural ventilation and an increase of thermal energy absorbed in internal surfaces in the case without ventilation. Though, other load factors must be studied further for increased validity.

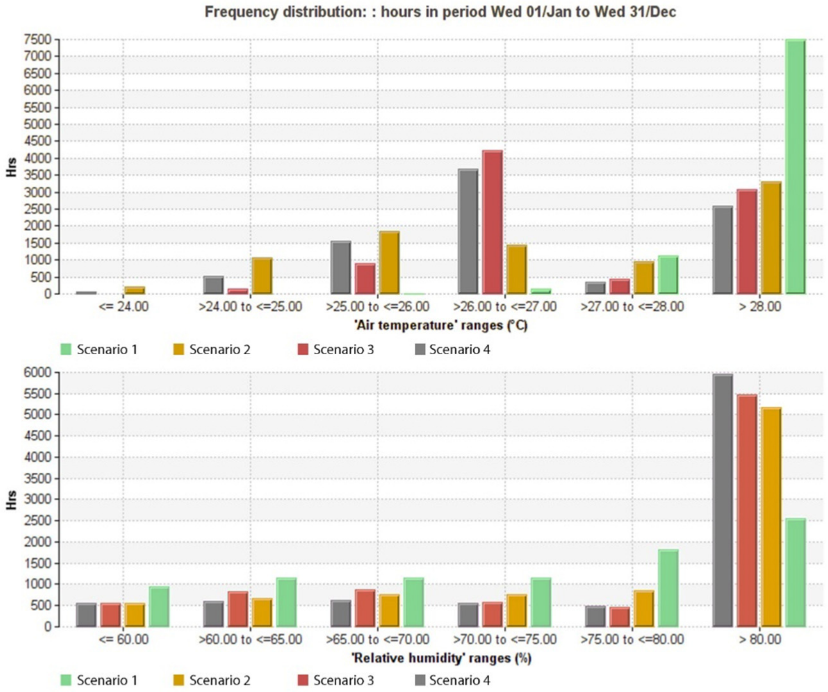

Figure 9: Simulated annual indoor air temperature and relative humidity in hour ranges of NW unit

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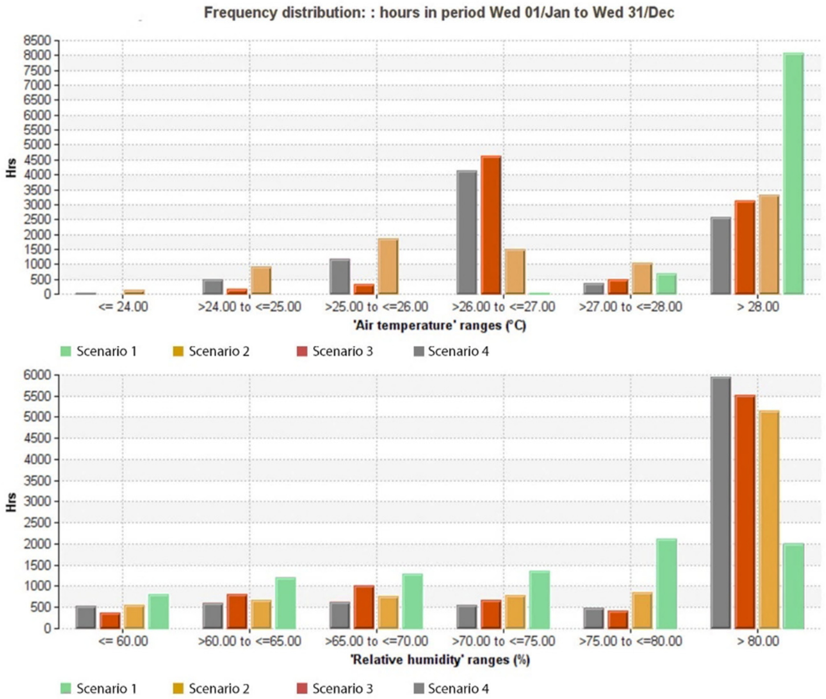

Figure 10: Simulated annual indoor air temperature and relative humidity in hour ranges of SE unit

CONCLUSION

Using a quantitative methodology approach, this paper combined experimental and technical research using IES_VE as a simulation tool. A calibration procedure was performed to compare the field measurements with the simulation results to validate the software. The comparison between the field measurements and simulation results showed a positive correlation coefficient of (R^2=0.84). Hence, indicating the potential of IES_VE simulation software as a useful tool to evaluate the environmental performance.

The study also aimed to analyze the thermal and energy performance of a high-rise residential building located in Kuala Lumpur, Malaysia. The unit conditions were chosen based on the occupancy characteristics towards the use of natural, mechanical, and mixed-mode ventilation. An annual simulation was carried out using IES_VE software, concluding mixed-mode ventilation (scenario 4) anticipated energy-saving potential reducing the cooling load between 15-19% (depending on the orientation) when compared with mechanical ventilation (scenario 3).

Designing energy-efficient buildings involves the use of effective thermal comfort models. Major international standards can be modified to incorporate specific climate regions for better applicability. The analysis presented draws upon the importance of revising the MS 2680:2017 adaptive thermal comfort equation. Consequently, this would result in better thermal and energy performance in the residential building sector.

Lastly, the significance of the results reported is limited as the results are based on the selected experimental model building configuration, and thus, it is difficult to generalize the conclusions. Nevertheless, the framework could be extended to similar climatic regions and potential high-rise residential buildings with similar settings and configurations.

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REFERENCES

Aflaki, A., Mahyuddin, N., & Baharum, M. R. 2016. "The influence of single-sided ventilation towards the indoor thermal performance of high-rise residential building: A field study." Energy and Buildings.

Almhafdy, Abdulbasit, Norhati Ibrahim, Sabarinah Sh Ahmad, and Josmin Yahya. 2013. "Courtyard Design Variants and Microclimate Performance." AMER AicQoL. Procedia and behavior sciences.

ASHRAE. 2010. American Society of Heating, Refrigerating and Air-conditioning Engineers standard 55 pp. 13-15.

Christensen, Jørgen Erik, Kleanthis Chasapis, Libor Gazovic, Jakub Kolarik, and Jakub Kolarik. 2015. "Indoor Environment and Energy Consumption Optimization Using Field Measurements and Building Energy Simulation." Energy Procedia.

CTBUH. 2018. The Skyscraper Center: The Global Tall Building Database, http://skyscrapercenter.com/compare-data

Fahmi, M. R., Defiana, I., & Antaryama, I. G. N. (2018). "Cross Ventilation in High-Rise Apartment Building : Effect of Ventilation Shaft Aperture Configuration on Air Velocity and Air Flow Distribution." IPTEK Journal of Perocedings Series.

Humphreys, MA. 1976. Comfortable indoor temperatures related to the outdoor air temperature. Building Service Engineer.

IPCC. 2019. IPCC Climate Change. United Nations.

Leng, P., bin Ahmad, M. H., Ossen, D. R., & Hamid, M. 2012. "Investigation of Integrated Environmental Solutions-Virtual Environment Software Accuracy for Air Temperature and Relative Humidity of the Test Room Simulations." The International Annual Symposium on Sustainability Science and Management.

Liu, Zhijian, Di Wu, Hancheng Yu, Wensheng Ma, and Guangya Jin. 2018. "Field measurement and numerical simulation of combined solar heating operation modes for domestic buildings based on the Qinghai–Tibetan plateau case." Energy & Buildings.

Lucon, O., D, et al. 2014. Buildings. In: Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the IPCC. Cambridge University Press.

Matisoff, D.C., D.S. Noonan, and A.M. Mazzolini. 2014. "Performance or marketing benefits? The case of LEED certification." Environmental Science Technology.

MS 2680. 2017. Malaysian Standard Energy efficiency and use of renewal energy for residential buildings (MS 2680:2017) – code of practice. Department of Standards Malaysia.

Newsham, G.R., S. Mancini, and B.J Birt. 2009. "Do LEED-certified buildings save energy? Yes, but." Energy & Buildings.

Nicol, F., and S. Roaf. 1996. Pioneering new indoor temperature standard: the Pakistan project. Energy and Buildings.

Omrani, S., Garcia-hansen, V., Capra, B., & Drogemuller, R. 2017. "On the effect of provision of balconies on natural ventilation and thermal comfort in high-rise residential buildings." Building and Environment.

Prajongsan, P., & Sharples, S. 2012. "Enhancing natural ventilation, thermal comfort and energy savings in high-rise residential buildings in Bangkok through the use of ventilation shafts." Building and Environment.

Priyadarsini, R., Cheong, K. W., & Wong, N. H. 2004. "Enhancement of natural ventilation in high-rise residential buildings using stack system." Energy and Buildings.

Scofield, J.H. 2009. "Do LEED-certified buildings save energy? Not really." Energy Build.

Szokolay, SV. 1991. Heating and cooling of buildings: Handbook of architectural technology. Van Nostrand Reinhold

Wong, N. H., & Li, S. 2007. "A study of the effectiveness of passive climate control in naturally ventilated residential buildings in Singapore." Building and Environment.

Zhou, C., et al. 2014. "Design optimization and field demonstration of natural ventilation for high-rise residential buildings." Energy & Buildings.

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