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Observational study of the indoor environment and energy use in office buildings in tropical Asia

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Abstract. In recent years, the design for office buildings in tropical Asia have been affected by the American principals. In terms of energy conservation in the building sector, it is necessary to reveal the actual conditions in each region and the requirements of the standards, which are based on American building standards. This study thus investigated the indoor and outdoor thermal environments, the thermal sensation of the occupants, and energy consumption in office buildings in tropical Asia. This study simulated two models for a comparative analysis of real conditions and standards of American Society of Heating, Refrigeration and Air-Conditioning Engineers standard 90.1-2010. The simulation analysis showed that the electric power consumption of the actual models in Bangkok and Singapore were large because of the selection of a low temperature setting. Furthermore, in several cases investigated, the internal thermal loads, such as lighting and electrical equipment, were lower than the reference value. From the analysis, this paper presents the differences between reference values used in the Western and American standards, and the actual situation in tropical areas.

1. Introduction

The global energy consumption trend is increasing. The International Energy Agency predicts that the world energy consumption will increase by 30% by 2040 [1]. According to the data, the rate of energy consumption of economically developing Organization for Economic Co-operation and Development countries is decreasing. Conversely, the rate of energy consumption in regions where urbanization and economic development are progressing, such as India and Southeast Asia, is increasing. In areas where it is predicted that energy consumption will increase, the goal becomes to reduce energy consumption without hindering economic development.

Therefore, in the field of architecture, the governments of these countries are promoting environmentally friendly construction in an effort to reduce energy consumption. In order to reduce energy consumption throughout the building's lifecycle, countries have been promoting the development of building environmental performance evaluation systems for developments such as new constructions, operations, and refurbishments. Different evaluation criteria have been developed by each country, but many of them have been prepared with reference to international building environmental performance evaluation indices, including Leadership in Energy and Environmental Design (LEED) [2]. The international environmental performance evaluation systems are standards that reflect regional characteristics, such as weather conditions, but decide the evaluation items and methods with an emphasis on ease of dissemination and appropriateness for environmental load reduction. However, this approach can lead to inaccuracy when employed as standards.



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In particular, as far as LEED is concerned, an evaluation was performed using energy simulation to model the Energy & Atmosphere (EA) index, evaluated using the Performance Rating Method described in the ASHRAE Standard 90.1-2010 [3] [4]. the evaluation indicated that it achieved the highest score among the standards and proved to be an indispensable item for achieving a high performance level. However, according to Mark Frankel & Cathy Turner's survey, even in American buildings, the gap between operation and simulation was large. Furthermore, according to the current standards, there are few conditions that reflect the characteristics of each region. There is a concern about the deviation between calculation and actual conditions in tropical Asia, which has different lifestyle and thermal sensation preferences to America and other Western countries. Reliable measurement data is indispensable for preparing environmental performance evaluation systems in terms of reflecting the local characteristics of each region, but data is insufficient in tropical Asia.

Therefore, office buildings were the focus of this survey. Bangkok, Singapore, Hanoi, Taipei, and Taiwan were investigated, all located in tropical Asia. Two objectives were pursued as follows:

- Analysis of the thermal environment in the office space, the usage of office buildings, energy consumption and thermal sensation of occupants, along with clarifying the trends in environmental performance for each office building.
- Evaluation of the building using the ASHRAE Standard 90.1-2010 Performance Rating method, which is an important item of energy performance evaluation in LEEDv4, and grasping the divergence between current standards and actual conditions.

2. Method

This study analyzed the data obtained from indoor thermal measurements, an occupant sensation survey, building specification survey, and energy consumption measurements that were obtained during 2015 and 2018 in the summer.

After analyzing this data, the building was evaluated using a Performance Rating Method with EnergyPlus, a building heat load and heating ventilation and air-conditioning simulation software package. The Baseline model was then analyzed to identify whether it was appropriate for the city by comparing the Baseline model, described in the ASHRAE Standard 90.1-2010, with the model, based on the data of the actual survey results.

2.1. Target office buildings

Table 1 and 2 show an overview of the 19 target offices. Each was a typical office present in high-rise building, having a total floor area of greater than 5,000 m² or approximately 10 stories above ground level. Almost all of the offices made use of mechanical HVAC systems and were built within 20 years in terms of the LEED analysis. All buildings were constructed in Hanoi, Taipei, Hong Kong, Bangkok, and Singapore. SG-1 was in university buildings and their operation may differ from the other offices. Although TP-2(NE) and TP-2(NW) were both in the same building, the office was divided into Northeast and Northwest, which were operationally different. Separate analyses were thus conducted for these entities. BK-1 in Bangkok was investigated twice, once in 2017 and once in 2018. Analysis was performed on each data set.

2.2. Measurement of indoor thermal environment

The thermal environment was measured to identify its characteristics and those of the A/C operation for comparison with the occupant survey. Measurement points were set in a dispersed pattern and air temperature, air relative humidity, globe temperature, and desktop illuminance were measured.

Representative measurement points were arranged 1100 mm above floor level both inside and around each zone. Measurements were automatically collected using small devices and the measurement interval was 5 minutes in Hanoi and 1 minute in all other cities.

Outdoor environmental conditions were measured using automatic devices. The data collected included air temperature, relative humidity, air velocity, air direction, amount of precipitation, air pressure, solar illuminance, and solar radiation.

Table 1. Target building overview 1.

	HA-1	HA-2	HA-3	HA-4	HA-5	TP-1	TP-2 (NE)	TP-2 (NW)	HG-1
Date of investigation (mmm-yy)	May-15	May-15	May-15	May-15	May-15	Sep-16	Jun-18	Jun-18	May-18
Construction year	2010	2009	2002	2013	2009	-	2014	2014	2010
Location	Hanoi	Hanoi	Hanoi	Hanoi	Hanoi	Taipei	Taipei	Taipei	Hong Kong
Number of floors	23	27	19	25	27	12	23	23	-
Typical floor area(m ²)	1487	834	1225	2090	1520	-	3262	3263	484
Target area (m ²)	1265	436	403.2	1684	840	545	968	1063	-
Core Type	Central	Eccentric	Eccentric	Central	Central	Eccentric	Eccentric	Eccentric	Central
Window to wall ratio	0.75	0.49	0.61	0.89	0.46	0.59	0.53	0.53	0.8
A/C system Type	Individual	Central	Central	Central	Individual	Individual	Individual	Individual	Central
Investigated floor/s	22nd & 23rd	5th	12th & 14th	22nd & 24th	7th	10th	17th	17 th	19th
Number of occupants	36	40	54	152	35	62	60	61	41

Table 2. Target building overview 2.

	BK-1 (17)	BK-2	BK-3	BK-1 (18)	BK-4	SG-1	SG-2	SG-3	SG-4	SG-5
Date of investigation (mmm-yy)	Mar-17	Mar-17	Jul-17	Sep-18	Sep-18	Nov-17	Nov-17	Mar-18	Mar-18	May-18
Construction year	2014	1992	2011	2014	2016	-	1985	2014	2003	2015
Location	Bangkok	Bangkok	Bangkok	Bangkok	Chonburi	Singapore	Singapore	Singapore	Singapore	Singapore
Number of floors	22	31	41	22	5	9	42	5	5	6
Typical floor area(m ²)	1320	-	2485	1320	1330	963	1938	426	2287	919
Target area (m ²)	778	411	1090	778	892	520	879	360	1060	565
Core Type	Central	Eccentric	Central	Central	Eccentric	Eccentric	Central	Distributed	Eccentric	Eccentric
Window to wall ratio	0.38	0.4	0.56	0.38	0.4	0.7	0.6	0.54	0.4	0.4
A/C system Type	Central	Central	Central	Central	Central	Central	Central	Central	Individual	Central
Investigated floor/s	17th	28th	36th	17th	4th	4th	31st	3rd	2nd	5th
Number of occupants	85	53	142	85	109	31	88	22	92	51

2.3. Thermal comfort questionnaire survey

The questionnaire regarding occupant sensation of the thermal environment was designed to assess levels of comfort in the workplace. The questionnaire comprised three parts. The first part recorded necessary personal data such as age, height, weight, health condition, clothing, and home HVAC system. The second part recorded perceived thermal sensation, humidity, perceived thermal comfort, acceptance, and preferred temperature adjustment. The third part recorded symptoms. Table 3 shows each category and the associated available choices. The questionnaire was circulated to all office occupants who were present when the researcher visited in Hanoi, and in other cities, was circulated to all office occupants before work, and collected after work. Table 4 shows the survey schedule. The questionnaire was originally written in English and later translated into the official language of each city before being distributed. The layout was improved over time.

Table 3. Questionnaire overview.

Thermal sensation (until Mar-17)		Thermal sensation (from Jul-17)		Thermal comfort	
3	hot	4	very hot		
2	warm	3	hot	2	comfortable
1	slightly warm	2	warm	1	slightly comfortable
0	neutral	1	slightly warm	0	moderate
-1	slightly cool	0	neutral	-1	slightly uncomfortable
-2	cool	-1	slightly cool	-2	uncomfortable
-3	cold	-2	cool		
		-3	cold		
		-4	very cold		

Table 4. Daily schedule of manual measuring day.

	8:00	9:00	10:00	11:00	12:00	13:00	14:00	15:00	16:00	17:00
Occupants		Answer Q1		Answer Q2	Lunch			Answer Q3		Answer Q4
Automatic Measurement *1		Check Battery								Collect Data
Voting machine *2		Distribute machine								
Manual Measurement *3		Prepare	1 2 3 4 5 6		1 2 3 4 5 6			1 2 3 4 5 6		
Questionnaire *4		Q1		Q2				Q3		Answer Q4 Collect

2.4. Energy consumption survey

The energy consumption was monitored to measure the energy conservation performance and working activities of the target building. The energy consumption of the target office was measured in three parts: lighting, outlet power supply, and air conditioner power. The data was collected by the building management system (BMS) of the target buildings when present. In the absence of a BMS system, the data was collected by small, local devices. In cases involving complicated building wiring, that prevented the installation of the measuring devices, the readings from the electricity meter were confirmed visually.

It was difficult to accurately measure the electricity data for each system because of the complexity of the electrical building wiring. In some tenant buildings that use centralized air conditioning, it was difficult to measure the power consumption of the heat source system (chiller, pump, etc.), so there were many cases where this data was unavailable. The data therefore contains values estimated from other information, such as the power consumption of each lighting and ratio of each line in the distribution board. Also, in some target buildings that possess a central chiller system, it was difficult to measure the energy consumption of the heat source system (chiller, pump, etc.). There are thus many cases where there was no available data in this regard.

3. Results of observational survey on indoor environment

3.1. Outdoor thermal conditions

Figures 1 and 2 show the outdoor temperature and absolute humidity during the observational survey period. It was a hot and humid environment in all cities, typical of the characteristics of tropical Asia.

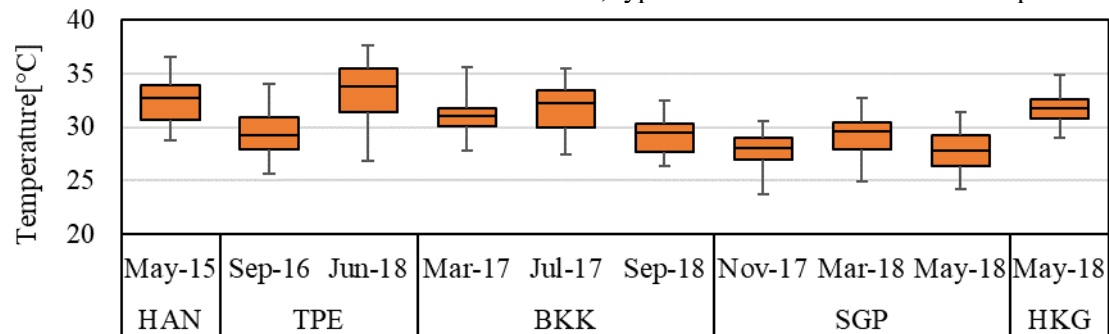


Figure 1. Outdoor air temperature.

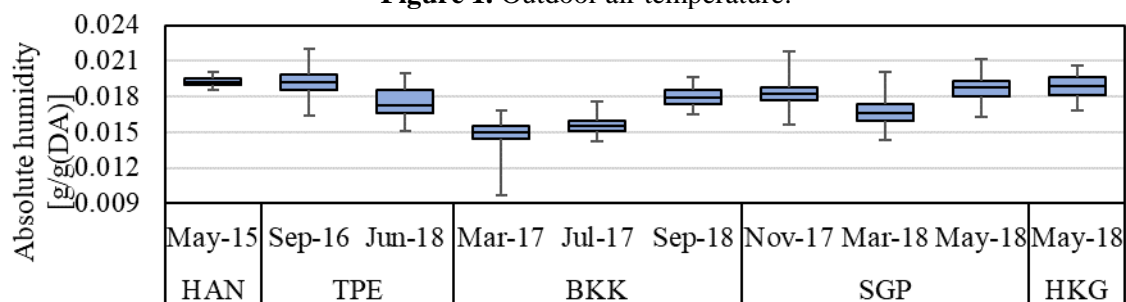


Figure 2. Outdoor air absolute humidity.

3.2. Indoor environment

Figures 3 and 4 show the operating temperature and predicted mean value (PMV) in the office spaces during office hours for each case [6]. The metabolic rate was set at 1.1 met due to the seated working state of the participants. The cloth insulation value was set at 0.5 clo as recommended by ISO9920 and as confirmed by questionnaire results [7].

The indoor operative temperature in the offices of Bangkok and Singapore were approximately 23 °C lower than in other cities. This value was 25 °C to 26 °C in Taipei and Hong Kong, 26 °C to 29 °C in Hanoi, significantly higher than in other cities. The PMV was approximately neutral in Taipei and Hongkong. In Bangkok and Singapore there were many cases of an environment that was colder than the comfortable range of ± 0.5 . In Hanoi, the median value was larger than 0, and there are many examples of environments where it was hotter than the comfortable range.

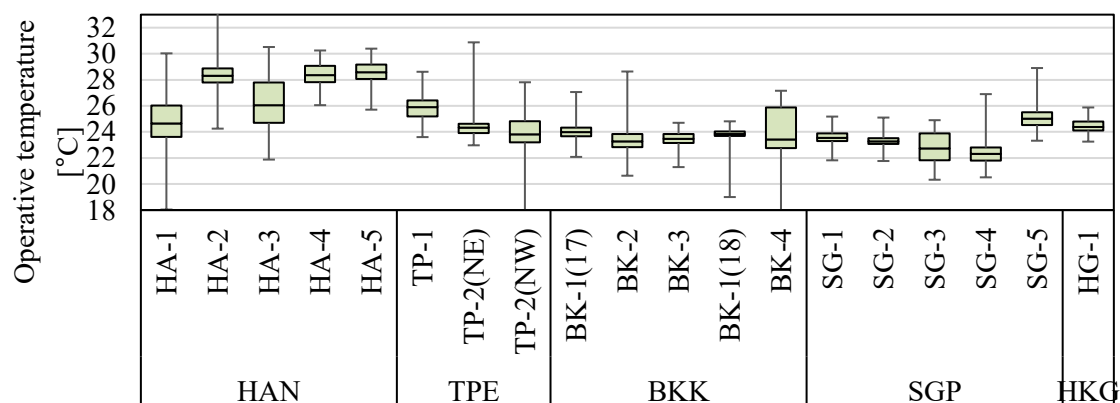


Figure 3. Indoor operative temperature during working hours.

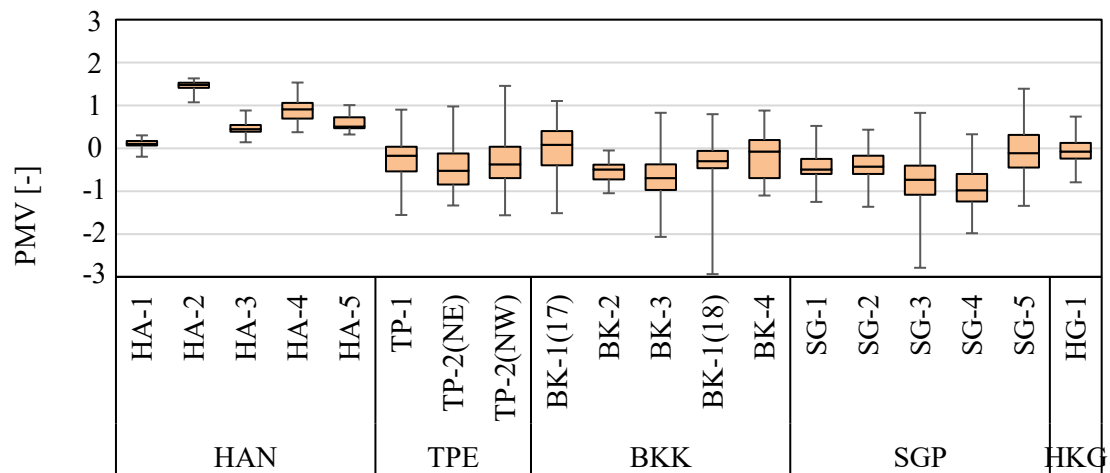


Figure 4. PMV during working hours.
(cloth-factor = 0.5, metabolic rate = 1.1).

3.3. Questionnaire survey results

Figure 4 shows the result of the thermal sensation questionnaire. In Hanoi, Bangkok, and Singapore approximately 40% of the occupants felt cool regardless of the difference in PMV. Approximately 40% of the occupants felt warm in Hong Kong. In Taipei, there were large differences between the offices. Figure 5 shows the result of thermal comfort questionnaire. In almost all the target offices, the comfortable and slightly comfortable states were more commonly chosen than the uncomfortable and slightly uncomfortable states. However, in some offices in Taipei and BK-1 in Bangkok, many occupants indicated that they were uncomfortable. BK-1 is a building with high environmental performance, so there is a possibility that the office workers were more conscious of the environmental conditions. Also, despite the number of occupants who felt cold or cool at SG-4, the number of occupants who indicated that they were uncomfortable was low.

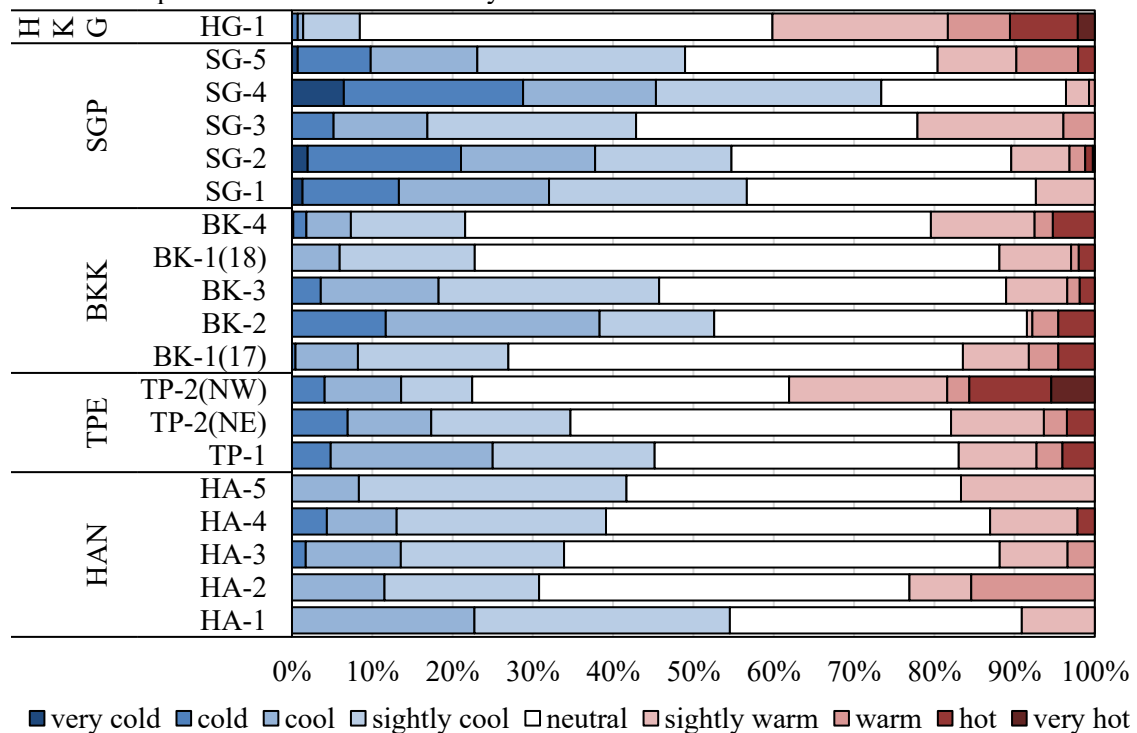


Figure 5. Thermal sensation questionnaire results.

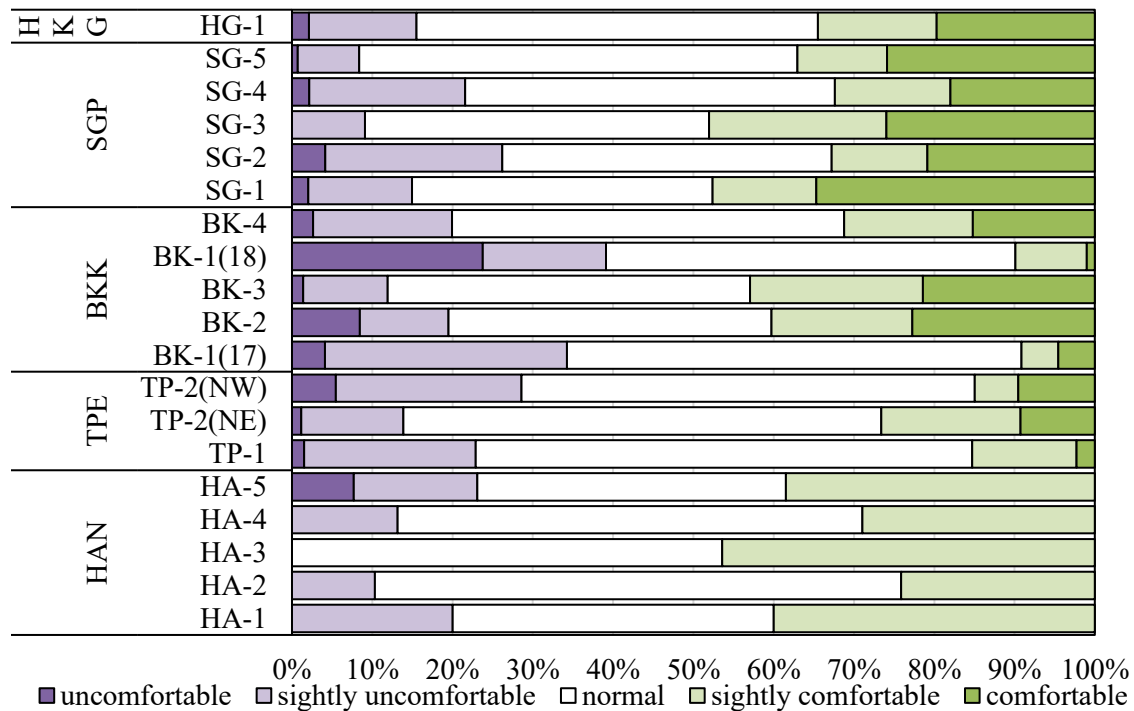


Figure 6. Thermal comfort questionnaire results.

4. Energy consumption results

Figure 7 shows the average daily electrical power consumption on the day of the survey. In the cases marked with an asterisk, the energy of the heat source machinery could not be measured, so the HVAC energy results were not shown. Also, since this survey was conducted over a short period of time, seasonal differences were not considered. Overtime work resulted in a large electrical power consumption. In SG-4, variable refrigerant volume was used after office hours, but registered lower than the actual value because only the package air conditioning, typically used only during office hours, could be measured. As a result, the power consumption of the air conditioning plant in Bangkok was large, while in Hanoi, it was low.

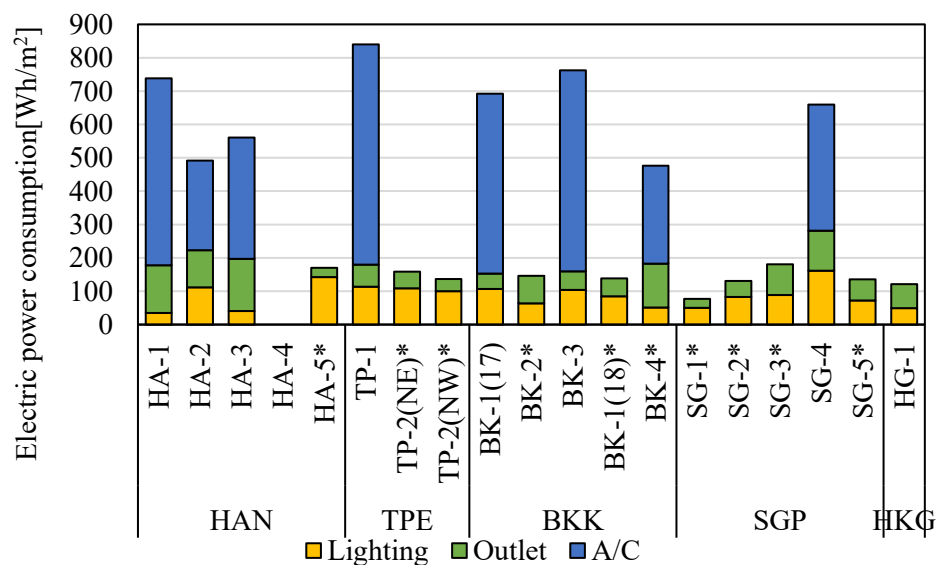


Figure 7. The average daily electrical power consumption on working days.

5. Regional property evaluation of the Performance Rating Method

In this study, the target offices were evaluated based on the Performance Rating Method presented in the ASHRAE standard 90.1-2010, which is an important Energy and Atmosphere item within LEEDv4. The simulation software package, EnergyPlus Version 8.8, developed by DOE of the United States, was used in this study. International Weather for Energy Calculation data for each city was used to provide weather data [8].

5.1. Analysis method

In this simulation analysis, the following two models were created and compared. This comparison evaluates the appropriateness of the Baseline model in these cities.

- B Model - This model was created according to the essentials of the Baseline model from the Performance Rating Method of the ASHRAE Standard 90.1-2010.
- A Model - This model incorporated the survey results, such as internal load, set point temperature, and window to wall ratio, into the B model.

Table 5 shows the conditions used as inputs into the B Model and A Model. Table 6 and Table 7 show the input parameters provided by the observational results. Most data were incorporated from the essentials of the Baseline model in Performance Rating Method of ASHRAE Standard 90.1-2010, ComNET appendix B and ComNET appendix C [9] [10]. Other data, noted as “Based on survey” in Table 5, were finalized using the results of the observational survey.

Table 5. Input parameters of A Model and B Model.

Country	HAN, BKK, SGP		TPE, HKG	
Input parameter	B Model	A Model	B Model	A Model
Window U-value	6.81(W/mK)	6.81(W/mK)	4.26(W/mK)	4.26(W/mK)
Window SHGC	0.25	0.25	0.25	0.25
Wall U-value	0.705(W/mK)	0.705(W/mK)	0.705(W/mK)	0.705(W/mK)
WWR	0.4	Based on survey	0.4	Based on survey
Outdoor shade	-	Based on survey	-	Based on survey
Setpoint temperature	26-22 °C	Based on survey	26-22 °C	Based on survey
Lighting electric power	9.68(W/m ²)	Based on survey	9.68(W/m ²)	Based on survey
Equipment electric power	9.68 (W/m ²)	Based on survey	9.68 (W/m ²)	Based on survey
Number of occupants	Based on survey		Based on survey	
Ciller COP	5.2		5.2	
Ventilation volume	2.5 (L/s/people), 0.3(L/s/m2)		2.5 (L/s/people), 0.3(L/s/m2)	

Table 6. Input parameters based on the observational survey.

Office	HA-1	HA-2	HA-3	HA-5	TP-1	TP-2 (NE)	TP-2 (NW)	BK-1 (17)	BK-2
City (Weather data)	HAI	HAI	HAI	HAI	TPE	TPE	TPE	BKK	BKK
Horizontal shade length (m)	0.7	0	0	0	0	0	0	1.5	0
Window to wall ratio	0.66	0.48	0.61	0.46	0.59	0.53	0.53	0.38	0.6
Lighting electric power (W/m ²)	3.08	10.29	3.77	13.48	7.56	12.71	11.16	7.23	2.99
Equipment electric power (W/m ²)	11.88	12.00	12.68	2.86	4.77	7.64	3.51	4.70	5.61
Number of occupants(people/m ²)	0.15	0.08	0.13	0.04	0.14	0.06	0.06	0.11	0.13
Actual air temperature (°C)	25.9	25.6	26.3	26.7	25.9	24.9	24.4	23.8	22.9

Table 7. Input parameters based on the observational survey.

Office	BK-3	BK-1	BK-4	SG-1	SG-2	SG-3	SG-4	SG-5	HG-1
	(18)								
City (Weather data)	BKK	BKK	BKK	SGP	SGP	SGP	SGP	SGP	HKG
Horizontal shade length (m)	0	1.5	0	0	0	0	0	0	0.5
Window to wall ratio	0.56	0.38	0.4	0.74	0.63	0.54	0.4	0.4	0.8
Lighting electric power (W/m ²)	7.78	8.47	4.56	3.65	6.03	6.64	10.50	6.35	4.71
Equipment electric power (W/m ²)	5.56	5.34	9.06	1.53	3.71	7.33	8.51	4.51	6.30
Number of occupants (people/m ²)	0.09	0.11	0.12	0.09	0.11	0.06	0.09	0.09	0.08
Actual air temperature (°C)	23.6	24.0	25.1	23.7	23.3	22.9	22.4	25.3	24.6

5.2. Results

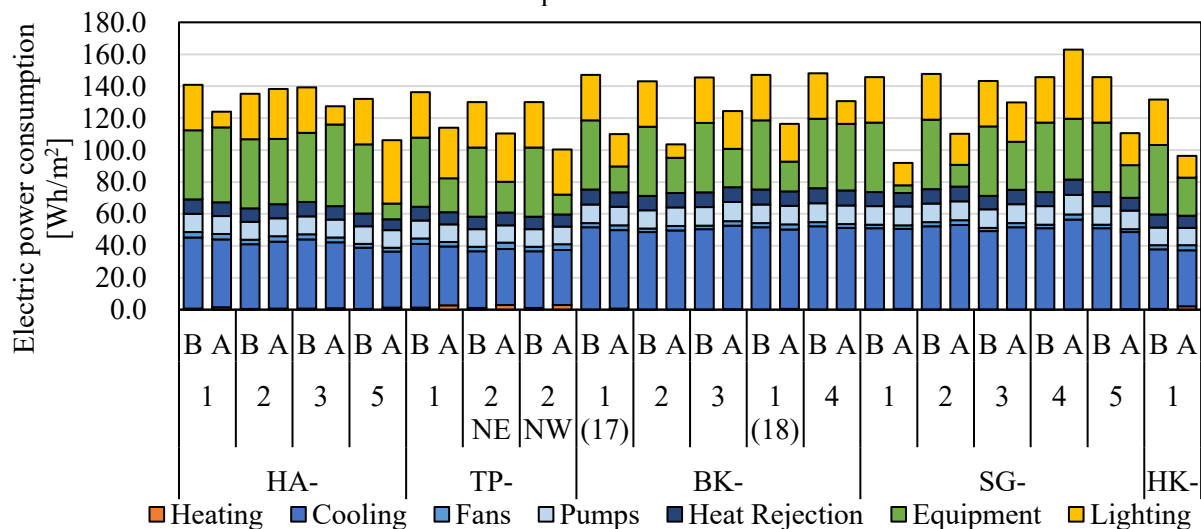
Figure 8 shows the simulation results of the annual electrical power consumption in each case. Because of the hot and humid climate, the energy consumption for heating was small in every model. The electrical power consumption of the OA equipment and lighting for the A Model were smaller than those of the B Model. It was shown that the reference value decided by Commercial Building Energy Consumption Survey (CBECS) was larger than the actual condition's value [11]. Regarding the cooling energy, there were many cases where the A model value was larger than the B model value in Bangkok and Singapore because of the low setpoint temperatures and large window to wall ratios.

Figure 9 shows the correlation between the energy performance, a value obtained by dividing the A Model's simulation result by the B Model's simulation result, along with the average value of the operative temperature in the office space during office hours. The target offices with outdoor overhang shading generally demonstrated superior energy performances. The lower the operative temperature, the poorer the energy efficiency of the office because the cooling load grew larger. Hanoi's office had a large internal load and the energy performance was comparable to offices in Bangkok and Singapore with low operating temperatures.

6. Discussion

6.1. Observational survey

The results showed that there were more occupants who felt cool than felt warm in all cities.

**Figure 8.** The simulation result of annual electrical power consumption

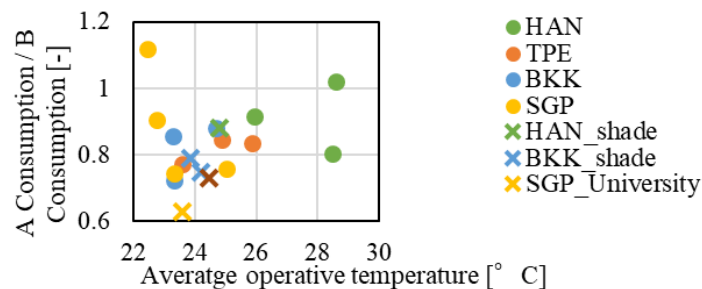


Figure 9. Correlation between energy performance and working temperature.

However, there was a big difference in the indoor environment for each city, and it was possible to confirm the differences in the preferences of each office along with differences in the service personnel's perception of warmth. The differences in room temperatures were large for each city, it was thus necessary to investigate the actual air conditioning operations more closely.

6.2. Energy simulation

In all cities except Hanoi, it was noted that the standard value of the indoor load was considerably larger than the actual load. In those areas where heating loads hardly ever occurred, the effect of the difference in indoor load on overall energy consumption was larger than in other areas. It is proposed that building performance can be more appropriately evaluated by setting reference values and schedules based on survey results for each country.

7. Conclusion

There were differences between the indoor environments of each of the office buildings. The operative temperature of Hanoi's offices was high, while it of the offices in Singapore and Bangkok was low. The operative temperature for Hong Kong and Taipei offices was lower than Hanoi's and higher than Bangkok's and Singapore's. There were no large differences in the thermal sensation and thermal comfort results. In all cities except Hong Kong, the number of cool sensation results was greater than the warm sensation results. Also, in all cities, the number of occupants who reported that they were comfortable was greater than the number of occupants who reported that they were uncomfortable. In the energy simulation, it was shown that the effect of the eaves on the annual power consumption was large and the reference value for the internal load was higher than the actual load.

8. Acknowledgments

This research was conducted by Tokyo Metropolitan Government Platform collaborative research grant (representative: Asso. Prof. Masayuki Ichinose). All of the kind for support for the case study is gratefully acknowledged.

9. References

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