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A Framework for Estimating the Energy-saving Potential of Occupant Behaviour Improvement

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Abstract:

Energy-related occupant behaviour in buildings has demonstrated considerable energy-saving potential. However, the current modelling method of occupant behaviour does not give sufficient considerations on the implementation difficulty of behaviour and provide a holistic map from survey data to various behaviour models.This article proposes a holistic survey-and-simulation-based framework for estimating the energy-saving potential of occupant behaviour improvement. In the framework, seven typical categories of occupant behaviour models are identified based on the survey results. According to the implementation difficulty, the models are integrated into four behaviour styles (baseline, wasteful, moderate and austere) to represent different levels of energy-saving consciousness of occupants. Based on a case study with a nationwide survey in Singapore, there are remarkable energy savings potential if occupant behaviour is improved; the building energy consumption can be reduced by up to 9.5% with the moderate behaviour improvement, and up to 21.0% with the aggressive behaviour improvement. The simulation results accord well with the measured results within a reasonable range of deviation. The framework can be applied to estimate the energy-saving potential of occupant behaviour improvement in a building with affordable cost, and the findings can inform a behaviour improvement program with effective and efficient measures.

Keywords: occupant behaviour; energy-saving potential; implementation difficulty; tropical region; building performance simulation

1. Introduction

Buildings are responsible for more than one-third of the world's energy consumption [1]. In tropical regions, the building energy consumption is more intensive than other climate zones due to the high outdoor temperature, humidity and significant dependence on air conditioning. Even with considerable efforts on building energy conservation, the annual electricity consumption of buildings still reports a 25% growth in Singapore from 2008 to 2017 [2] and is predicted to double in 2050 [3]. Therefore, the unabated growth in building energy consumption has become a critical challenge to curbing the energy demand in buildings.

Technological energy conservation measures (ECMs) have long been the primary approaches to improving building energy efficiency [4]. According to the Building Energy Efficiency (BEE) R&D Roadmap published by the Building Construction Authority (BCA), Singapore [5], building energy consumption is expected to be cut by up to 40% by moderate adoption of technological ECMs and up to 60% by aggressive adoption by 2030. However, even with substantial investment in technology innovations and improvements, it is hard to obtain the desired reduction of energy consumption if occupants do not perform the expected behaviour reactions to these technologies. This phenomenon has been evidenced by a field investigation in a green-certified office building in Putrajaya, Malaysia, of Alam and Shari [6]. They found that, even though the automatic light control was installed in the office, the occupant preferred to keep the blinds closed to prevent the automatic control system from switching off lights when there was adequate daylight. Besides, the cost of technology-related ECMs grows increasingly higher when no- and low-cost measures run out, and developers have to implement high-cost measures [7]. Due to these limitations of technological innovations and improvements, it is critical to adopt behaviour-related ECMs in order to yield further energy savings.

Energy-related occupant behaviour can impact building energy consumption in various ways. Occupants actively interact with building components, such as internal shading devices, windows, lights, thermostats, HVAC systems and plug-in equipment, to achieve environmental satisfaction. These behaviours can directly influence building energy use. Moreover, other occupant behaviours, like water drinking, changes in human metabolic rate, physiological and psychological changes, can affect the comfort and behaviour pattern of occupants, causing changes in energy use [8]. However, the impact of occupant behaviour on building energy consumption has not been generally identified in the practice of building performance simulation (BPS). In the conventional simulation method, occupant behaviours are modelled as several representative, static and homogeneous schedules, which ignore the dynamic, stochastic and diverse nature of occupant behaviour [9]. To evaluate this uncertainty caused by occupant behaviour, Eguaras-Martínez et al. [10] compared the energy predictions of building energy consumption including and excluding occupant behaviour modelling. The energy predictions were reported to have up to 30% discrepancies. Moreover, a study by Turner and Frankel [11] observed that the predicted building energy consumptions by

BPS showed more than 25% errors from the actual consumptions by on-site measurements. These findings indicated the uncertainty caused by occupant behaviour in BPS to be one of the most significant barriers to accurate energy predictions of BPS [12].

To address the uncertainty caused by occupant behaviour, occupant behaviour modelling has been introduced for simulation.For systematic occupant behaviour modelling, Hong et al. [13] outlined an ontology to formulate energy-related occupant behaviour in buildings in a DNAs framework. Moreover, a more recent advancement in the classification and selection of occupant behaviour models was achieved by the IEA EBC Annex 66 [14], which comprehensively summarised occupant behaviour models and modelling techniques. However, the data collection process of occupant behaviour modelling is normally costly when a substantial amount of measured data is required to determine the model parameters. In this context, some studies chose to use existing models to avoid the costly measurement [15]. However, this approach accounts for huge decision risks. Bahaj and James [16] compared the electricity consumption of nine identical houses and observed differences of up to 600% in certain months of a year. The significant impact of individuals' diversity on building energy consumption was also claimed by Haldi and Robinson [17]. They found that the cooling energy demand of the most wasteful individual in an identical building was about six times that of the most austere individual. When building type and location (e.g., climate, culture and energy conservation consciousness) change, occupant behaviour can be even more diverse, and the model parameters have to be tuned to fit the new cases. Therefore, many studies tried a cost-effective data collection approach, namely survey, for occupant behaviour modelling. The most recent attempt was conducted by Pioppi et al [18]. They used a survey-and-simulation-based framework to predict the energy saving potential of occupant behaviour improvement. However, they merely discussed the occupant behaviours specific to their case and over-simplified some models (especially the appliance use model) thus limiting the applicability of their method to other cases and the accuracy of estimation results. Unfortunately, there has not been a holistic framework based on survey results, which can provide a complete map of occupant behaviour modelling.

Another challenge in occupant behaviour research is the estimation of energy-saving potential of occupant behaviour improvement. Although some previous simulation-based studies have attempted to address this problem, the methods did not perform well when compared with actual measurements. Hong and Lin [19] evaluated how different behaviour styles (austerity, standard and wasteful) impact the energy use of private offices by simulation, reporting up to half of the energy consumption could be cut by promoting an energy-saving work style. Similarly, the framework proposed by Sun and Hong [15] demonstrated that building energy consumption was reduced by 27.9% to 41.0% by improving occupant behaviour in four representative climate regions of America. However, these anticipated energy savings are not observed in actual measurements. Two practical studies showed that energy consumption decreased by only 5% to 12% by promoting a culture of energy conservation among occupants in the two commercial buildings [20], that seriously deviates from the simulation predictions. As can be seen, the energy saving of occupant behaviour improvement varies widely from study to study and from simulation to practice. An important reason for the differences is that these simulation-based studies did not give thorough considerations to the actual implementation difficulty of behaviour. Most studies tended to use an extremely austere behaviour style which is almost unpractical as the boundary scenario of energy saver. This manner limits the meaningfulness of such comparisons between simulation and reality and is the current weakness in the field [21]. Thus, when estimating energy savings of occupant behaviour improvement, it is necessary to distinguish the occupant behaviour in terms of their implementation difficulty levels.

To address the above challenges, this study proposes a holistic survey-and-simulation-based framework for estimating the energy-saving potential of occupant behaviour improvement through building energy modeling. Regarding data collection, while many studies adopted costly measurement [20] or simply employed existing models [15], this framework adopts a cost-effective mixed approach by survey in combination with the existing data for behaviour modelling. On the basis, this study comprehensively reviews previous behaviour models and selects the most appropriate models for a survey-based methodology. A map from survey results and existing data to these behaviour models is given as well. Regarding scenario setup, while most studies tended to use extreme boundary scenarios [15], this framework introduces the concept of implementation difficulty of occupant behaviour, where a comfort-and-convenience-driven style (moderate) is added to the three commonly-used styles (baseline, austere, wasteful), thus presenting an important watershed in the implementation difficulty. Moreover, this framework identifies seven typical categories of occupant behaviour models which can well represent most of normal energy-related behaviours in buildings. In the case study, the framework is applied to a tropical large office buildings in Singapore, aiming to reveal the typical occupant behaviours and energy-saving potential of occupant behaviour improvement there.

The framework is described in Section 2. A case study is presented in this section as well. Section 3 presents the main results and findings in the case study. The key findings and conclusions are given in Section 4. Limitations of this study and recommendations for future studies are given in Section 5.

2. Methodology

2.1 Framework overview

The main application scenario of the framework is defined as follows. Before a behaviour improvement programme is going to be conducted in a building, the investigator wants to know how much the energy-saving potential of occupant behaviour improvement in the building is so as to draw up a plan with effective and efficient measures.

The proposed framework (see Figure 1) includes five steps: (i) collecting the data about the design, systems and occupant behaviour of the reference building, (ii) developing a baseline model based on the collected data, (iii) assuming occupant behaviour models of wasteful, moderate and austere behaviour styles and applying them to the reference building to create three alternative models, (iv) running simulations and calculating the energy consumptions of the models, and (v) comparing the results and deriving the energy-saving potential of occupant behaviour improvement in the reference building.

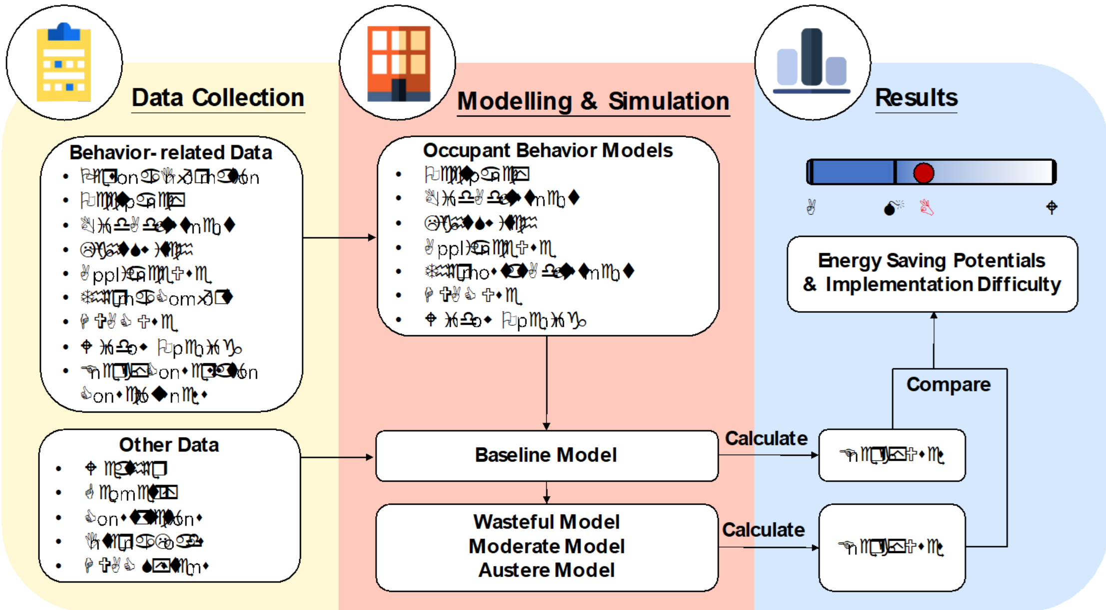

Figure 1. Diagram of the proposed framework for estimating the energy-saving potential of occupant behaviour improvement in buildings.

2.2 Data collection

Data collection is essential to settle a baseline occupant behaviour and assume improved behaviours. To determine a data collection plan, researchers need to make trade-offs between the potential options, considering the technical feasibility, data quality and solution economy.

On-site or laboratory measurement is a popular data collection approach which can provide long-duration, accurate and dynamic data records. It is widely used in the research on occupant behaviour modelling. The disadvantages of measurement are obvious. First, measurement is costly because it requires a large amount of money, time and manpower to buy, set up, test instruments and collect data. This limits the general application of measurement in an industrial project. Second, it is hard to totally avoid the Hawthorne effect, a type of reactivity in which individuals modify their behaviour in response to their awareness of being observed [23]. Last but importantly, ethics, participant recruitment and informed consent are also significant barriers to the application of this approach [24]. This is typically hard for the occupant behaviour research which could involve many occupants in the building and their privacy.

A cost-effective solution for data collection is survey. Usually, survey is taken as a complementary approach of measurement due to its ability to reveal the occupants' sensation and logic behind behaviour [25]. Nevertheless, survey shows its limitation to collect some data, such as the indoor illuminance and glare preference, which are hard to be directly acquired from occupants. Moreover, the data quality of surveys is vulnerable to psychological biases and misunderstanding of participants. Despite these, this study attempts to develop a survey-based method for occupant behaviour modelling to relieve the data collection cost and ensure an acceptable accuracy. The data unable to be acquired by survey would be taken from the existing studies (i.e., reports, standards and datasets).

A nationwide survey on the occupant behaviour was conducted in Singapore to identify the general behaviours in large office buildings. Table 1 lists the nine aspects of occupant behaviour needed and the survey results of this study. These nine aspects of occupant behaviour are: (i) personal information, (ii) occupancy (movement and presence), (iii) blind adjustment, (iv) light switch, (v) appliance use, (vi) thermal comfort, (vii) HVAC use, (viii) window opening, and (ix) energy conservation consciousness. Note that personal information includes more aspects than these listed in Table 1, which can help to group occupants. However, some personal information is too sensitive to be generally collected (e.g. income level and education level), not easy to be modelled in the simulation-based method and indirect to building energy consumption. Thus, this study focuses on those aspects directly related to energy usage. Since the general behaviour is anticipated and convergence exists in the behavioural patterns of occupants in the same building, this survey gathered replies from more different buildings instead of a large number of participants. In addition, besides the baseline behaviour style, three alternative styles were also required in this framework. Having the replies in different buildings would help to evaluate the implementation difficulty of occupant behaviour because the sensation and behaviour in different indoor conditions can be observed. Totally 168 replies that cover 30 large office buildings were randomly collected in 3 large business districts of Singapore (i.e. the Orchard Road, Suntec City and Marina Bay). Four sample buildings are shown in Figure 2. Note that if a study concerns one specific building (which is the normal case for the application of this framework), the survey should be taken in the building solely, of which the survey work could be much relieved.

To reduce the psychological biases and avoid the misunderstanding of questions, four measures are taken as follows. (i) Clear explanations, figures and examples were given along with the questions. For example, a question is "will you switch off the lights when temporarily leaving your office if you are the last person? (E.g. to have a short meeting or go to lunch)". Concrete descriptions, "temporarily", "your office" and "the last person", are given to specify the leaving scenario, and an example case is given. The options were also noted with specific frequency ranges. (ii) The entire survey was conducted on site and face-to-face to provide additional clarification to participants if necessary. (iii) The replies were reviewed to examine whether any contradictions or mistakes present, and the problematic replies were removed from the results. For example, the fractions of time staying in zones should be summed as one; if a participant answers he/she hardly controls the lights, he/she would not control usually switch off the lights when there is enough daylighting. (iv) For some answers, the investigators would attempt to verify the answers through interview or observation if possible. For example, for some buildings, the investigators contacted the facilities management officers to verify the HVAC operating schedules and thermostat setpoints; in most buildings, the security guards or receptionists were interviewed to verify the work profile information.

However, it is difficult to fully avoid the survey biases, which is a major limitation of the survey method. The social desirability bias, i.e., the tendency of survey respondents to answer questions in a manner that will be viewed favorably by others, is one of the most common biases that exist in the survey [26]. This is especially common for the questions with an obviously favorable answer, namely, the questions 4, 9, 12, 13, 14, 20 and 21 in Table 1. Regarding question 4, people might be reluctant to reveal that they always come to the office late or leave the office early if the local corporate work culture is very strict. Regarding question 9, 12, 13, 14, 20 and 21, they might prefer to describe themselves as an energy saver if they know which options are beneficial to energy saving. Though avoiding using the obviously guiding statements (e.g. “save energy”) in the questionnaire and the above-mentioned measures (iii) and (iv) can help to reduce some biases and their impact on the results, it should be noted that the psychological biases are still a major limitation of the survey method.

Figure 2. Four sample large office buildings surveyed in this study.

Table 1. Nine aspects of occupant behaviour needed to be surveyed and survey results of this study.

Aspects	No.	Variables/Behaviours	Key Results	Notes
Personal Information	1	Age	Not used in this study	Age and gender are related to the occupant behaviour, like thermal and visual comfort, but it is not used in this study. Post is used in occupant grouping.
	2	Gender	Not used in this study	
	3	Post	See Table 4	
Occupancy	4	Work profile	Office hour: 7:00-19:00 (weekdays); lunch break: 12:00-14:00 (see Table 4 for details)	Work schedule, break time, meeting frequency and duration, time staying in each kind of zones (own office, other office, meeting room, auxiliary room, outdoor).
	5	Office size and occupant number	Large office room (10+ occupants): 38%; middle office room (5-10 occupants): 38%; small office room (1-4 occupants): 24%	Profile of office size is used to developed the representative building model. The occupant group would be allocated in the respective zone accordingly.
Blind Adjustment	6	Access to blind control	Yes: 20%; yes, but hardly: 51%; no: 29%	In this study, only 20% participants actively adjust the blinds. If the adjustment is active, the probability of blind adjustment in different visual conditions should be investigated.
	7	Blind type	Mainly interior roller blinds (manual control)	
	8	Purposes for blind adjustment	See Table 5	
	9	Blind state	See Figure 6	
Light Switch	10	Access to light control	Yes: 79%; yes, but hardly: 10%; no: 11%	In this study, participants don't actively switch off lights when there is enough daylight. If the response to daylight is active, the probability of light switch in different daylighting levels should be investigated.
	11	Light type	Mainly ceiling mounted single-stepped lights (manual control)	
	12	Light state when occupied	(See Table 6)	
	13	Light state when unoccupied	Averagely 52.4% probability switch off lights when leaving Usually/always switch off (80%-100%): 8% Often switch off (60%-90%): 27% Sometimes switch off (40%-60%): 40% Occasionally switch off (20%-40%): 19% Seldom switch off (0%-20%): 6%	
Appliance Use	14	Appliance state when not engaged	Fully on: 39%; display off: 6%; standby mode: 54%; off: 2%	
Thermal Comfort	15	Access to thermostat control	Yes: 17%; yes, but hardly: 5%; no: 78%	The thermostats and HVAC systems are controlled by the facilities management offices in most large office buildings in Singapore. Occupants should call the facilities management offices for changes.
	16	Setpoint of thermostat	Averagely 22.6 ℃ (see Figure 8)	
	17	Thermal comfort sensation	2% think it is too cold (see Figure 8)	
HVAC Use	18	Access to HVAC control	Yes: 17%; yes, but hardly: 3%; no: 80%	
Window Opening	19	Access to window control	Windows of most large office buildings cannot open	Most large office buildings don't allow window opening.
Energy Conservation Consciousness	20	Self-evaluation of energy conservation consciousness	Strong: 15%; moderate: 56%; weak: 29%	
	21	Willingness to take training and change behaviour	98% are willing to take training and change behaviour	

2.3 Reference building model

To obtain realistic results of building energy consumption, a detailed building model (see Figure 3) with the zoning was developed as a reference building. While most simplified building models only keep the building outlines and roughly zones in bulk, the detailed building model provided detailed partitions of zones. The reference building had twelve above-ground floors and one underground floor with a total building area of 46,320 square meters. Table 2 presents the details of building constructions, HVAC systems, internal loads and the weather file. Figure 4 shows the plan of a representative above-ground floor. According to the occupancy characteristics, zone functions can be classified into five types, namely, (i) small office, (ii) large office, (iii) meeting room: classroom, conference room and dining room, (vi) auxiliary room: corridor, stair, lobby, electrical and mechanical room and storage, and (v) other zones: food court, carpark and elevator chamber.

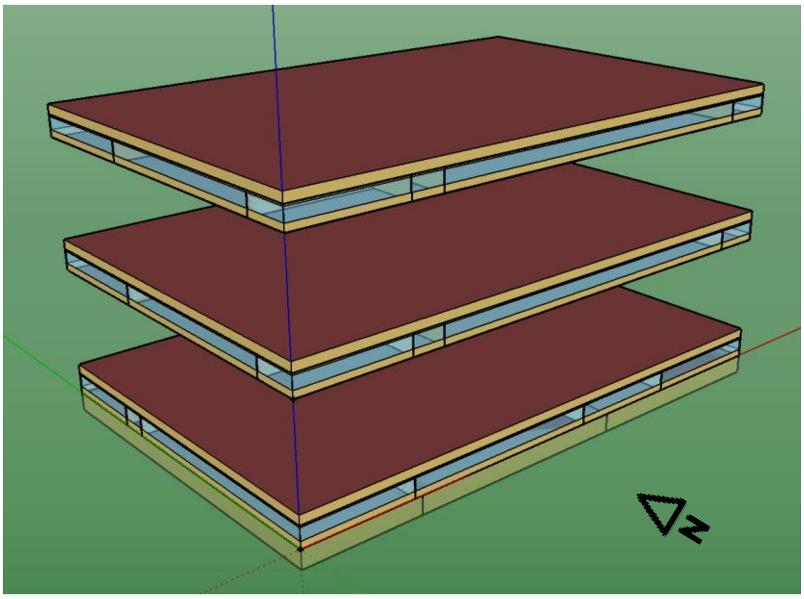

Figure 3. 3D view of the baseline building model.

Table 2. Details of the baseline building model.

Dimensions	Outline: 73.1 m × 48.7 m; Floor to floor height: 2.75 m; Floor to ceiling height: 3.95 m.
Envelopes	Window to wall ratio: 0.4; Window: Low-E spec sel tint 6 mm + air 13 mm + clear 6 mm, U-value = 1.63 W/m^{2}K SHGC = 0.29 Exterior wall: 25 mm stucco + 200 mm concrete + 13 mm gypsum, U-value = 2.38 W/m^{2}K Roof: 10 mm roof membrane + insulation (R=2.60 m^{2}K/W) + metal roof surface, U-value = 0.36 W/m^{2}K Floor: CP02 carpet pad + 100mm concrete
HVAC system	Outdoor air: 0.000254 m^3/s/m^2 System: Single-duct VAV system without reheat Chiller COP: 4.5
Internal Loads	Refer to [27] and [28]
Weather file	IWEC Singapore

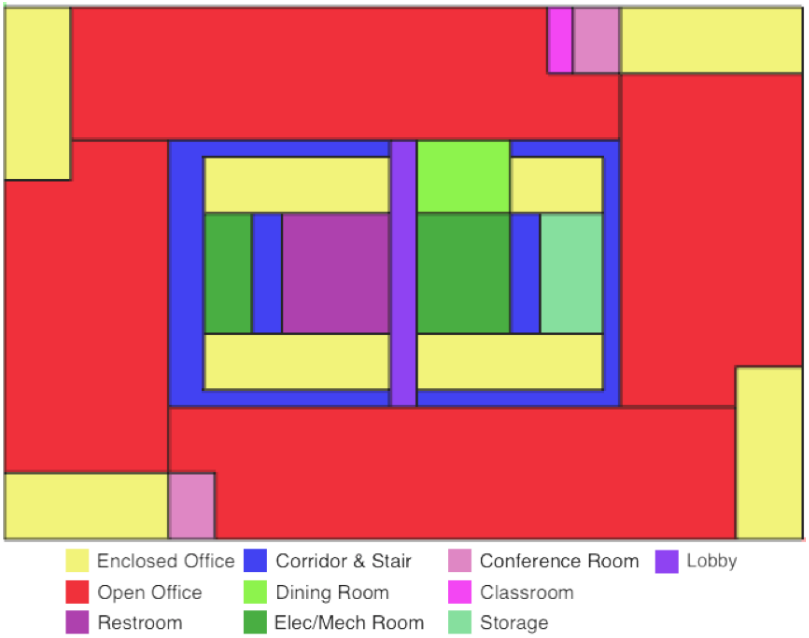

Figure 4. Plan of a representative above-ground floor.

To enable the glare and daylighting controls of blinds and lights, glare reference points (see G1 and G2 in Figure 5) and daylighting reference points (see D1 and D2 in Figure 5) were located in all perimeter zones. Each glare reference point was located at 1.5 meters from the corresponding window, which is the typical width of an aisle. The view direction of glare reference point was parallel to the window plane. On the other hand, according to the Input Output Reference of EnergyPlus [29], two daylighting reference points were located at the first and third quartiles of zone depth in each perimeter zone. Each daylighting reference point controlled half of the lights in the zone. All glare and daylighting reference points were located at 0.8 meters above the floor, which is the typical height of a desk.

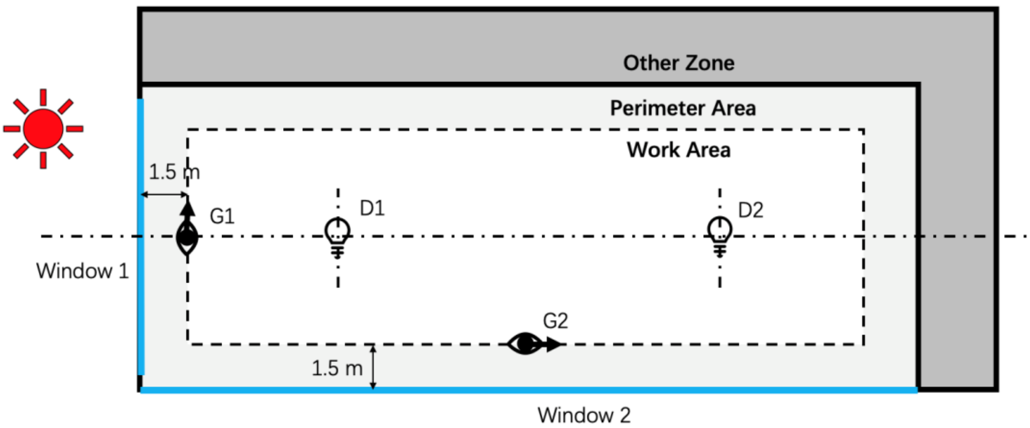

Figure 5. Glare and daylighting reference points in a perimeter zone with two windows.

2.4 Behaviour style and implementation difficulty

In this framework, four behaviour styles were defined to represent the diversity of occupant behaviour and different levels of energy-saving consciousness of occupants: baseline, wasteful, moderate and austere behaviour styles. While the wasteful and austere behaviour styles were normally identified in previous studies [15], the novel moderate behaviour style is first proposed by this study. The baseline behaviour style represents the present condition of occupant behaviour in the building. It can be taken as the average of investigated results of present behaviours, including the minimum daylighting level, maximum glare index, standby mode power fraction of appliance, thermostat setpoint and other model parameters. The wasteful, moderate and austere styles are hypothetical. Therein, the wasteful and austere behaviour styles represent the boundary conditions of energy spenders and savers, respectively; and the moderate behaviour style represents the comfort-and-convenience-driven conditions where the occupant is willing to take energy-saving behaviours without severe sacrifices of comfort and convenience.

The four-behaviour-style method helps to qualitatively distinguish the implementation difficulty. Assuming there is a ruler of behaviour style, the baseline style is like the present reading, and the hypothetical styles are the scales on the ruler to be compared with the reading. The moderate behaviour style is like a watershed demonstrating the largest degree of energy saving in acceptable ranges of the habitual comfort and convenience in current condition without building retrofit or other relief measures. When targeted behaviours overstep the moderate behaviour style, the implementation difficulty will rise increasingly as occupants' comfort and convenience degrades. Thus, if the improvement target is too ambitious, occupants may have to bear the relatively terrible discomfort and inconvenience, or reject the appeal for behaviour improvement. However, previous studies tended to focus on energy-saving potential of the extreme behaviour style, which explains why the previous studies overestimated the energy-saving potential of occupant behaviour improvement.

As is mentioned above, the implementation difficulty in this framework is a qualitative measure which consists of the concepts of comfort and convenience. It can be further decomposed to some quantitative indices for comfort and convenience to clearly identify the occupant behaviour models of three hypothetical styles.

Regarding comfort, the research is relatively mature. The commonly-used comfort indices are predicted mean vote (PMV) [30] for thermal comfort, light level (illumination) [31] and daylight glare index (DGI) [32] for visual comfort. Normally, the acceptable and recommended range are given along with these indices as well where the acceptable range is normally larger than the recommended range. Thus, the wasteful and austere styles would use the maximum and minimum of the acceptable range. The moderate style would adopt the recommended value. If the recommended value is a range, the moderate style would use the extremum which can save the most energy. The moderate style should also refer to the survey results, which should not depart from the real sensation of occupants. In this study, it was found that the survey results are generally coincident with the recommended ranges provided by previous studies. This truth validates the above statement that the research on comfort is relatively mature.

Regarding convenience, it can be evaluated by the operation frequency for non-durative behaviour (e.g. light switch, blind adjustment and thermostat adjustment) and operating time for durative behaviours (e.g. appliance switch). While the comfort preference of occupants is difficult to change, occupants normally have a higher tolerance for inconvenience, and the automatic control system can help to relieve this inconvenience. Thus, no limit is given to convenience indices. The wasteful and austere styles would mainly consider the energy-saving potential. The moderate style would mainly consider whether the occupants are willing to take the behaviour without additional automatic control system. If more than half of the occupants can accept an improved behaviour, it would be taken as the moderate style. Moreover, when a behaviour involves both comfort and convenience, the comfort should be given priority in consideration. Next section will give the detailed process to identify the occupant behaviour models.

2.5 Occupant behaviour models

Seven typical categories of occupant behaviours were identified in this study, including occupancy, blind adjustment, light switch, appliance use, thermal comfort, HVAC use and window opening. For each occupant behaviour, four models were identified for each behaviour to represent different behaviour styles as the criteria mentioned before. Table 3 lists models of four behaviour styles in this study.

Table 3. Models of four behaviour styles in this study.

	Baseline	Wasteful	Moderate	Austere
Occupancy Models	Occupancy Simulator (see Table 4 for details)			
Blind Adjustment Models	Always open	Always closed	Close if DGI > 22 when occupied	Always open
Light Switch Models	On when occupied; 50% probability of switching off upon leaving	Always on during office hours	Off if daylighting level > 500 lux when occupied; off when unoccupied	Off if daylighting level > 300 lux when occupied; off when unoccupied
Appliance Use Models	70%-100% linearly related to occupancy fraction during office hours	100% during office hours	50%-100% linearly related to occupancy fraction during office hours	25%-100% linearly related to occupancy fraction during office hours
Thermostat Adjustment Models	23 °C	20 °C	24 °C	26 °C
HVAC Use Models	On during 5 AM-7 PM (open 2 hours prior to office hours)			
Window Opening Models	Always closed			
Schedules of zones whose loads are not directly controlled by occupants, like food court and carpark, are static.				

2.5.1 Occupancy model

Occupancy refers to the occupant's movement between zones and presence in a specific zone of the building, which determines the real-time location of each occupant. However, representative, static and homogeneous occupancy schedules by the conventional modelling method fail to reflect the spatial and temporal variations of the occupant count. For example, when the schedule of a 5-person enclosed office is 0.1 at 7 AM by the conventional method, it is unrealistic for the office to have 0.5 persons at this time. The actual situation could be one person in two 5-person offices or 1 person staying in the office for 30 minutes of the hour. Without the realistic occupancy schedules, it is impossible to model the occupancy controls of the building systems because there is not a deterministic answer for whether the zone is occupied and how many occupants are in the zone. Thus, generating the realistic occupancy schedules of zones is the foundation of occupant behaviour modelling. In this study, the Occupancy Simulator [33], a web-based program developed by Lawrence Berkeley National Laboratory (LBNL), was employed to simulate movement and presence of occupants and generate the realistic occupancy schedules of zones. The Occupancy Simulator is developed based on a stochastic Markov Chain model, which takes occupant movement as probabilistic according to occupant's work profiles. Luo et al. [34] validated the performance of the program by measurements, showing that the generated occupant schedules by Occupancy Simulator accurately represent the realistic temporal and spatial variations of occupancy.

The inputs for occupancy simulation were from the survey results of the occupants' work profile and shown in Table 4. The generic office hours of Singapore's large office buildings are from 7 AM to 7 PM on weekdays. To generate schedules closer to the actual occupancy in buildings, the occupants were grouped into three groups according to the post: staff, manager and administrator. For each post group, the occupants were further grouped into several representative sub-groups to differentiate the work profiles of individuals (according to the first arrival and final departure time). The other variables are taken as the average values of the sub-group members. The overall distributions of work profile variables of the groups roughly matched with that of the survey results. If the work profiles are too diverse to be simply grouped as mentioned above, the k-mean clustering is recommended to generate the groups instead. The generated occupancy schedules were used in all behaviour styles to keep the consistency.

Table 4. Occupant groups and inputs of Occupancy Simulator.

	Staff				Manager		Administrator	
	S1	S2	S3	S4	M1	M2	A1	A2
Proportion	6%	36%	13%	10%	10%	5%	10%	10%
First arrival time	07:30	08:30	09:00	08:00	08:30	09:00	08:00	08:30
Variation [min]	30	30	30	30	30	60	30	30
Last departure time	17:30	18:00	19:00	18:30	18:00	18:00	18:00	18:00
Variation [min]	30	30	30	30	60	60	30	30
Lunch time	12:30	12:00	12:30	12:00	12:00	12:00	12:00	12:00
Variation [min]	30	30	30	30	30	30	30	30
Duration (lunch) [min]	75	75	60	90	75	90	75	90
Variation [min]	15	15	15	30	15	30	15	30
Percentage (own office)	35%	65%	65%	75%	40%	45%	75%	60%
Duration (own office) [min]	60	60	60	60	60	60	60	60
Percentage (other office)	0%	5%	5%	5%	5%	15%	0%	0%
Duration (other office) [min]	20	20	20	20	20	30	20	20
Percentage (meeting room)	10%	20%	20%	15%	45%	30%	15%	30%
Duration (meeting room) [min]	60	60	60	60	60	60	60	60
Percentage (auxiliary room)	5%	5%	5%	5%	5%	5%	5%	5%
Duration (auxiliary room) [min]	10	10	10	10	10	10	10	10
Percentage (outdoor)	50%	5%	5%	0%	5%	5%	5%	5%
Duration (outdoor) [min]	60	20	20	20	20	20	20	20

2.5.2 Blind adjustment model

Manually-controlled interior blinds are the most common type of blinds in Singapore's large office buildings, which stand out for its low cost, easy installation, maintenance and operation. However, unlike exterior blinds, interior blinds have little ability to diminish the solar heat gain and cooling load of the room. Overuse of blinds would impact the indoor illumination during the daytime, and then increase the use of artificial lights. According to the survey (see Table 5), the primary motivations for occupants to adjust interior blinds are (i) to reduce heat from the sun, (ii) to reduce glare or brightness from daylight, (iii) to have an outside view and (iv) to increase the daylighting level. Considering that the solar heat, glare and daylight have strong relations to each other, the blind adjustment is assumed to be driven by the glare condition for simplification in this study. Thus, the stronger glare occupants can bear, the more daylight can be utilized, and the more lighting energy can be saved.

Table 5. Main motivations of blind adjustment behaviour in Singapore.

Blind closing	
To reduce heat from the sun	76.9%
To reduce glare or brightness from daylight	46.2%
To reduce visual stimulus	1.9%
To increase privacy	0%
Blind opening	
To have an outside view	40.4%
To increase daylighting level	38.5%
To increase visual spaciousness	15.4%
To feel the warmth of the sun	5.8%

As recommended by the EnergyPlus Input Output Reference [29], the acceptable DGI for office is lower than 22. Because the DGI is related to (i) the internal obstruction, (ii) position and (iii) orientation of observer and glare source, the glare condition still may be acceptable when the DGI at the reference point is larger than 22 if the occupant's position and orientation are different from the reference point and proper obstructions are used. Thus, in this study, the wasteful style of blind adjustment model stood for the case that occupants keep the blinds fully closed (i.e. keep minimal DGI) and rely on artificial lights for illumination. The austere style of blind adjustment model stood for the case that occupants keep the blinds fully open (i.e. keep maximal DGI) for maximum utilisation of daylight. The moderate style of blind adjustment model stood for the case that occupants close the blinds when they are in the zone (occupant count > 0) and feel strong glare (DGI > 22), and open blinds during other time.

Actually, blind adjustment is not active in Singapore. 80% of participants in the survey reported they cannot or seldom adjust the blinds in their offices (see Table 1). On the one hand, the commercial buildings in Singapore should meet the mandatory requirement of the maximum Envelope Thermal Transfer Value (ETTV) [35] which normally requires well-insulated glazing units, like double low-E/reflective glazing. These glazing units can satisfying indoor visual conditions during the major part of the year. On the other hand, it was observed that occupants prefer to keep the blinds in a certain status rather than to adjust blinds actively. The survey results of the normal status of blinds are shown in Figure 6. The average opening rate of blinds is 70%. Since it is not able to model partly-open blinds in EnergyPlus, blinds were assumed to be always fully open in the baseline model in this study.

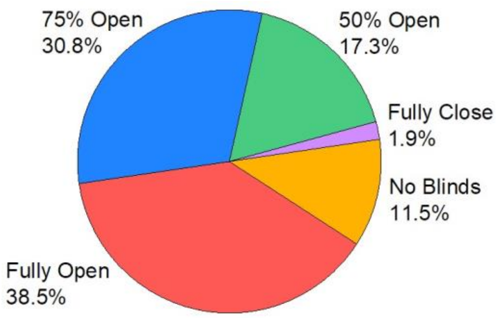

Figure 6. Normal status of blinds.

Besides blind adjustment models, other similar models may be included in some cases, like dynamic glazing adjustment models and shading adjustment models. These models follow the similar control logic of blinds. They are not discussed in this study since the dynamic glazing and adjustable shading are not common in Singapore.

2.5.3 Light switch model

Occupants use artificial lights to maintain favourable indoor illuminance for work and life. The control logic of artificial lights varies with the types of lights, such as automatic and manually-controlled lights, dimmable and stepped lights. According to the survey, manually-controlled single-stepped light is found to be the most common type of light in Singapore's large office buildings.

Two scenarios of light switch behaviours were considered in this study: (i) occupants switch on the lights upon arrival and switch off lights upon leaving; and (ii) occupants switch on the lights when they feel that it is dark; they switch off the lights when they are in the zone and feel that it is bright enough with daylighting. For the first scenario, the average probability of switching off upon leaving was calculated at 52.4% based on the results in Table 1. For the second scenario, only 19.2% of participants in the survey reported they usually switch off lights when there is enough daylight for them (see Table 6). A possible explanation is that the switch-off behaviour mainly happens in small office rooms while occupants in shared large office rooms seldom do this because they don't want to disturb others in the room. Thus, the baseline behaviour style of light switch model in this study stood for the case that lights are always on when the zone is occupied; and occupants have a 50% probability of switching off when they are the last person leaving the zone. According to previous studies by Fernandes et al. [36] and Zhou et al. [37], part of lighting power cannot be off during night and weekends. This power consists of standby power, emergency and security light power, which accounts for about 5%-30% of the design lighting loads. Thus, in this study, 10% of the design lighting load was always on no matter the status of lights.

Table 6. Light switch behaviour when occupants are in their office.

I usually keep the lights on no matter whether there is enough daylight.	57.7%
I usually switch off the lights when there is enough daylight.	19.2%
I don't/can't operate the lights in my office.	15.4%
Others	7.7%

For light level control, the recommended indoor light level (or called illumination) varies with standard, room type and task. Several literature, including the IESNA Lighting Handbook [31], European Standard EN 12464-1 [38] and Singapore Standard SS 531 [39], were reviewed to determine the recommended/acceptable minimum light level. It was found the light level for office work should be larger than 300 lux, and 500 lux is a recommended value for normal office work with writing, typing and reading. Thus, in this study, the wasteful style of light switch model stood for the case that the lights are always on (i.e. maximal light level) during office hours. The moderate style of light switch model stood for the case that occupants switch off lights when they are the last person leaving the zone or when they are in the zone, and the daylighting level reaches 500 lux (i.e. recommended light level). In the austere behaviour style of light switch model kept the same manner as the moderate style, but the threshold of the daylighting control was changed to the lowest acceptable value, 300 lux (i.e. minimal acceptable light level).

During the unoccupied time, the wasteful style assumed occupants would keep lights on for convenience. The moderate and austere styles assumed occupants would always switch off lights upon leaving. This is based on the truth that 94% of participants in the survey reported they would like to do so though they may forget in practice.

2.5.4 Appliance use models

Occupants have access to control the plug-in appliances, like laptops, desktop computers, chargers and other plug-in equipment. Lamano et al. [40] metered ten offices in Singapore, finding the offices consume about 20%-30% electricity of the peak plug load during night time and weekend. Thus, in this study, 25% of the design plug load is always on during night time and weekend. The rest plug load is strongly influenced by the occupant count in the zone and status of appliances when they are not engaged (namely standby status). According to previous studies by Mahdavi et al. [41] and Wang et al. [42], the plug load shows a linear relationship to the occupancy fraction. Thus, in this study, the plug load fraction of a zone is determined by the linear function of the occupancy fraction as illustrated in Figure 7. The plug load fractions when the zone is unoccupied (namely unoccupied plug load fraction) during office hours were determined by the following formulation:

$$Unoccupied\ \ plug\ \ load\ \ fraction = 25\% + 75\% \times \sum_{i=1}^{n}(P_i \ \times \ r_i)$$

where, P_i is the power fraction of appliance in standby status i and r_i is the proportion of occupants who normally use standby status i. By substituting the survey results of standby status (see Table 7) into the formulation, the unoccupied plug load fraction of the baseline model was about 70%.

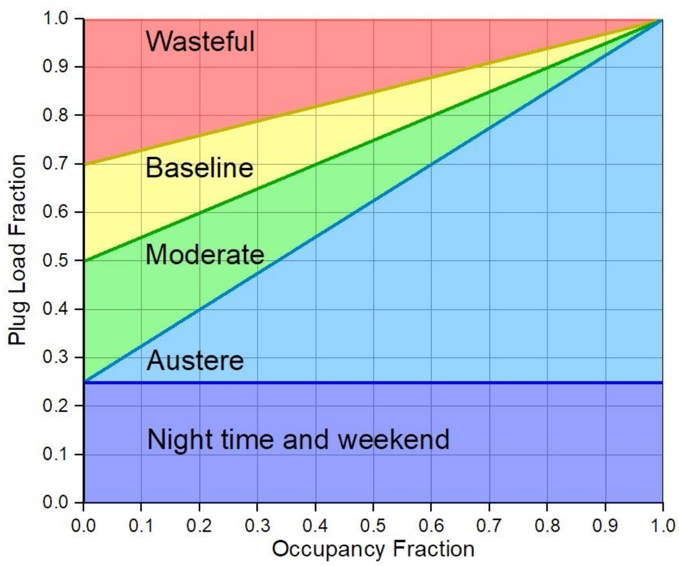

Figure 7. Relationship between the plug load fraction and occupancy fraction.

Table 7. Normal appliance standby status.

Appliance standby status	Representative power fraction *	Survey results
Fully on	100%	38.5%
Partly off (e.g., display off)	85%	5.8%
Standby mode	33%	53.8%
Fully off	0%	1.9%

* The representative power fraction refers to the general power fraction of desktop/laptop computer [43].

Normally, the more energy-saving the standby status is, the more time occupant needs to wait, and the more operation occupant needs to conduct to switch off or restart the appliance. This factor impact the convenience of appliance use. For example, if an occupant fully switches off the PC upon leaving, more time and operation is required for closing programs, shutting down system, restarting system and reopening programs to complete the intervention. In this study, the wasteful, moderate and austere behaviour styles of appliance use models stood for the cases that occupants put appliances in fully-on, standby and fully off modes, respectively, when they don't use the appliances. Therefore, their unoccupied plug load fractions were 100%, 50% and 25%, respectively. The reason why the moderate style adopted standby mode is that more than 50% participants in the survey have already used standby mode when they do not use the appliances. This implies that they would like to accept the degree of inconvenience caused by the standby mode.

2.5.5 Thermostat adjustment models

The thermal comfort sensation is impacted by indoor thermal condition, clothing, thermal comfort preference, physiological or psychological changes [44]. The survey results of thermostat setpoint and thermal comfort sensation are shown in Figure 8. The average thermostat setpoint was about 23 ℃ (see Table 1), which was taken as the baseline. Moreover, the thermostat setpoint was kept constant because occupants were not able to directly control the thermostats and HVAC systems. This is consistent with the fact that occupants have to ask the facility management offices to make changes of thermostat setpoints in most Singapore's large office buildings (see Table 1).

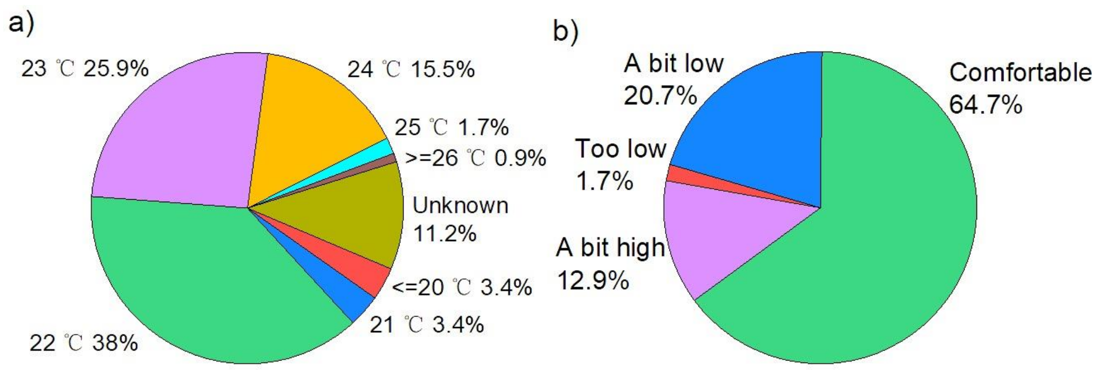

Figure 8. a) Thermostat setpoint, b) thermal comfort sensation.

ASHRAE Standard 55 [30] proposed the PMV index to evaluate the indoor thermal comfort. The standard recommends PMV between -0.5 and +0.5. Standard EN 16798 [45] further specifies the category I with PMV between -0.2 and +0.2 as most comfortable. Thus, the wasteful, moderate and austere styles respectively referred to the case with PMV at -0.5, +0.2 and +0.5. Taking the mean radiant temperature at 27 ℃ (the average mean radiant temperature of the perimeter zones), air speed at 0.1 m/s, relative humidity at 60%, metabolic rate at 1.1, clothing level at 0.6, the respective indoor temperatures are 20 ℃, 24 ℃, 26 ℃.

2.5.6 HVAC use models

For HVAC systems with zonal control, occupants can turn on or off the HVAC systems in the zone individually. However, most large office buildings in Singapore use central air conditioning systems and keep the air-conditioning systems running during office hours. This is because of the tremendous cooling demand in tropical regions to guarantee high work efficiency throughout the years. In this study, the HVAC system was kept on from 5 AM (2 hours prior to office hours to bring the space temperature down and remove the accumulated air contaminants in advance) to 7 PM for all behaviour styles.

2.5.7 Window opening models

Opening windows could increase the air exchange rate of the zone and decrease the cooling load at a proper time. But Singapore’s large office buildings generally do not allow window opening for climate, safety and design reasons. Therefore, in this study, windows were kept closed for all behaviour styles.

2.6 Simulation

There are five approaches to integrating occupant behaviour models in BPS programs [19], namely, (i) user-defined profiles: users directly input schedules in simulation tools; (ii) user-customised code: users write custom code or overwrite existing code without re-compiling the simulation tools; (iii) embedded occupant behaviour modules: users directly adopt the predefined functions the simulation programs to model occupant behaviour; (vi) user-modified source code: users insert new code or edit existing code in the simulation tools; (v) co-simulation: occupant behaviour tools exchange data with the simulation tools in real-time to run the simulation. In this study, the first and fifth approaches were used. The outputs of Occupancy Simulator were directly input as schedules into EnergyPlus simulation program. Other occupant behaviour models were firstly coded in Matlab and then incorporated into the simulation program for co-simulation.

After simulation, the building energy consumption can be obtained. The energy use intensity (EUI) is taken as the indicator of building energy consumption, which can be calculated as follow:

$$EUI = \frac{annual\ total\ energy\ consumption\ of\ building}{total\ floor\ area\ of\ building\ \times\ 1\ year}$$

By comparing the EUI of the baseline model with the EUI of three alternative models, the energy-saving potential of occupant behaviour improvement can be derived.

3. Results and discussion

3.1 Results of the occupancy simulations

Occupancy characteristic is an important factor which can influence the energy consumption of a zone because there is a considerable energy-saving potential by avoiding energy waste when occupants are leaving during office hours. Figure 9 displays the hourly variations and occupant count profiles of four representative zones. The figure shows that the results of occupancy models well reflect the dynamic, stochastic and diverse nature of occupant movements in the building.

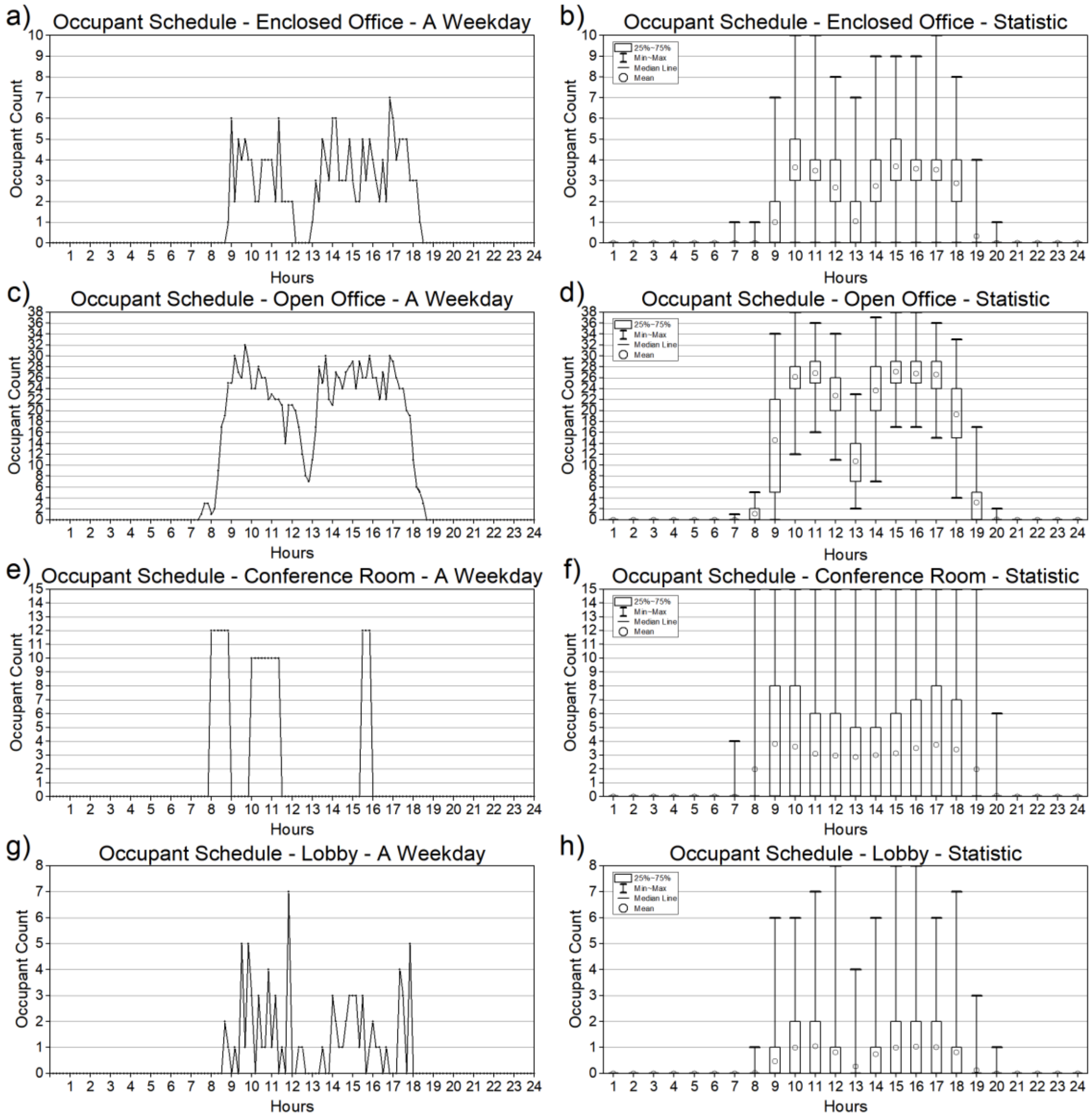

Figure 9. Hourly variations and profiles of occupant counts in four representative zones.

3.2 Total energy consumption

Figure 10 shows the breakdown of the energy consumption of the baseline model. The EUI of the baseline model is 189 kWh/m^2/yr, which is very close to the median EUI of large office buildings in Singapore (193 kWh/m^2/yr [2]). This demonstrates that the reference building model are fairly representative. The energy consumption can be classified into four categories in descending order of importance: HVAC system (42.0% which includes the energy consumption for cooling and ventilation), interior equipment (25.3%), interior lighting (18.2%), and others (14.5% which includes the energy consumption of food court, elevator and carpark lighting). Among the four categories, the energy consumptions of the former three can be influenced by occupant behaviour.

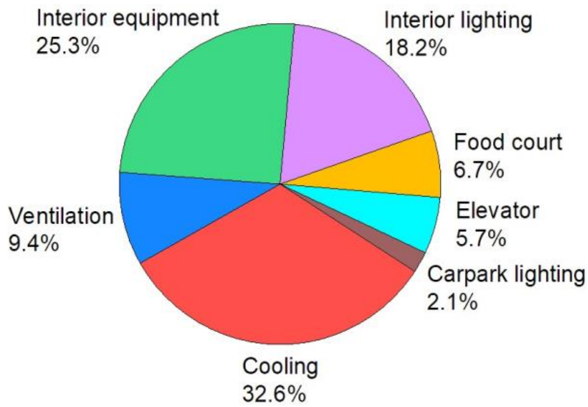

Figure 10. Breakdown of the energy consumption of the baseline model.

Figure 11 compares the energy consumptions of four behaviour style models. On the whole, compared with the EUI of the baseline model, the EUI increases by 13.4% by implementing the wasteful behaviour style; the EUI reduces by 9.5% by implementing the moderate behaviour style; the EUI reduces by 21.0% by implementing the austere behaviour style. Thus, it can be found that occupant behaviour has a strong impact on the building energy consumption, which accounts for 34.4% relative change of the reference building. In addition, by applying the austere behaviour style, the EUI drops from 189 kWh/m^2/yr to 149 kWh/m^2/yr, i.e., approximately from the median to the top quartile of the EUI of large office buildings in Singapore [2]. From this perspective, there are remarkable energy savings by improving occupant behaviour.

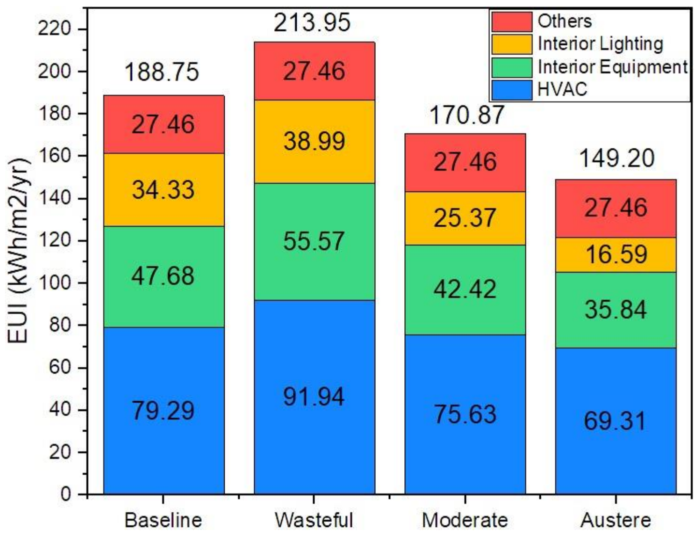

Figure 11. Energy uses of four behaviour styles.

For the perspective of energy saving, the largest energy saving presents in the interior lighting energy, which is 26.1% reduction by implementing the moderate behaviour style and 51.7% reduction by implementing the austere behaviour style; the second-largest energy saving presents in the interior equipment energy, which is 11.0% reduction by implementing the moderate behaviour style and 24.8% reduction by implementing the austere behaviour style; the third-largest energy saving presents in the HVAC energy, which is 4.6% reduction by implementing the moderate behaviour style and 12.6% reduction by implementing the austere behaviour style.

The reductions in different types of energy consumptions can help to figure out the priority of improvement measures because each behaviour has its particular impact on the building energy consumption. Specifically, the consumption of interior lighting energy is mainly influenced by the blind adjustment behaviour and the light switch behaviour; the consumption of interior equipment energy is mainly influenced by the appliance use behaviour; because the lighting and equipment energy would eventually become part of cooling load of the HVAC system, the consumption of HVAC energy is influenced together by the blind adjustment behaviour, light switch behaviour, appliance use behaviour and thermostat adjustment behaviour. In combination with the rank of the reductions in different energy consumptions, the priority of occupant behaviour improvement in the whole building scale hence could be gotten: (i) improving the light switch behaviour in combination with appropriate blind adjustment behaviour; (ii) improving the appliance use behaviour; (iii) improving the thermostat adjustment behaviour. These findings can be used to guide the planning of a behaviour improvement program with effective and efficient measures.

Figure 12 is drawn to give an integrated view on the energy-saving potential and implementation difficulty, which incorporates the energy consumption and implementation difficulty in one bar plot. In the plot, EUIs of the austere and wasteful behaviour styles are normalised to two ends of the bar, and the deeper colour of the bar represents greater implementation difficulty.

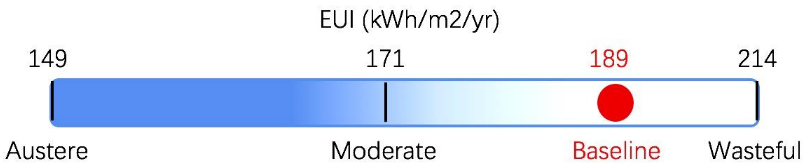

Figure 12. Bar plot showing the energy consumption and implementation difficulty of occupant behaviour.

3.3 Comparison with field measurements

Technically, it is improper to validate results by horizontal comparisons between different buildings in different regions, because many unexpected factors can influence the energy-saving potential of behaviour improvement, such as the system efficiency, building design and climate. However, the horizontal comparisons can still help to roughly evaluate whether the proposed framework can derive results in reasonable ranges. The simulated results in this study were compared with some results of previous field measurements which adopted behaviour improvement measures at similar implementation difficulty in similar room (see Table 8). It can be found that the case study results accord well with the previous measured results within a reasonable range of deviation. Slight deviations are acceptable due to the diversity of baseline occupant behaviours, climate and buildings, especially for the lighting energy savings which are significantly influenced by weather conditions, building design, visual comfort preference, occupancy characteristic, light type and control logic. Note that HVAC energy savings are not included in the comparisons since the climate and thermal comfort preference in tropical regions is quite different from other regions.

Table 8. Comparison between the simulated results and measurements.

Compared parameter	Baseline	Improvement measure	Savings reported	Corresponding improvement in this study	Simulated result	Reference
Total energy	Ordinary case	Non-technological measures to encourage the practice energy-saving behaviours	5%-12%	Baseline to moderate	9.7%	[20] (Canada)
Equipment energy	Ordinary control	Advanced control systems for plug load	21%-28%	Baseline to austere	24.8%	[22] (US)
Lighting energy (lecture rooms)	Ordinary manual control	Automated light systems with occupancy and daylighting control (threshold = 500 lux)	40%-65%	Baseline to moderate (meeting rooms)	48.6%	[46] (Italy)

4. Summary and conclusions

This study proposed a holistic survey-and-simulation-based framework for estimating the energy-saving potential of occupant behaviour improvement. In the framework, seven categories of occupant behaviour models were identified in tropical regions, and four clearly defined behaviour styles (baseline, wasteful, moderate and austere) were defined to distinguish the model's implementation difficulty. These behaviour models and styles could extend the understanding on the occupant behaviour in buildings and significantly relieve the modelling work of future research on occupant behaviour. To validate the framework, the framework was applied to a case study in Singapore, and the simulated results were compared with the previous measured results. It was found that the case study results accorded well with the measured results within a reasonable range of deviation. This indicated that considering the implementation difficulty of occupant behaviour improvement could reduce the significant deviations between the predictions of energy savings and the actual measurements. It hence would be reasonable to state that the framework develops a reliable link between the simulation and engineering practice on occupant behaviour improvement. Hence, the results derived by the proposed framework can be used to guide the planning of a behaviour improvement program with effective and efficient measures.

In the case study in Singapore, a nationwide survey on occupant behaviours in Singapore was conducted, which helped to identify the appropriate behaviour models specifically for tropics. Eventually, the energy-saving potential of occupant behaviour improvement in Singapore was quantified using the proposed framework. It was found that the building energy consumption of the reference building can be cut by up to 9.5% by the moderate behaviour improvement measures, and up to 21.0% by the aggressive behaviour improvement measures. Moreover, the first, second and third largest energy savings presented in the interior lighting energy, interior equipment energy, and HVAC energy of the reference office building, respectively. As seen, there are remarkable energy savings potential by improving occupant behaviour in buildings. Compared to technological innovations and improvements for building energy conservation, behaviour-related energy conservation measures cost nothing or much less and can be applied throughout the lifetime of a building to make continuous energy-efficient improvement. Though it should be noted that occupant behaviour is sometimes difficult to change, the results of this study show that the occupant behaviour improvement still can be a promising approach to reduce the energy consumption of tropical office buildings. This study sheds some light on the future research effort and energy-saving practice from the perspective of occupant behaviour, which is as important as technological measures in achieving global energy and environmental goals.

5. Limitations and future studies

It should be noted that there are a number of critical problems to be solved in this field. To further extend the understanding of occupant behaviour, some future research directions are recommended:

(i) Though the proposed framework was applied to the tropical large office building in the case study, investigations on other populations, buildings and cities should be conducted to explore the general performance of the framework.

(ii) The co-simulation method used in this study requires considerable effort on the programming and time for data exchange between programs, which is too costly for the industrial practice of occupant behaviour modelling. Hence, a simple and reliable tool to assist the behaviour modelling and simulation is needed.

(iii) This study provides a method to estimate the energy-saving potential of occupant behaviour improvementp, but it does not discuss how to achieve energy-efficient occupant behaviour with actual behavioural interventions. Thus, it is critical to figure out innovative and effective measures to encourage the practice of energy-saving behaviours from aspects of design, policy, technology, education and sociology. This is what the authors are currently working on.

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