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Development of a model for generating air-conditioner operation schedules in Malaysia

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Abstract

Accurate estimations of the stochastic natures of energy demand for air-conditioner (A/C) use, which are affected by the diverse occupant behaviour, are needed, for the design and operation of residential cogeneration systems and distributed generation systems coupled with renewable energy sources and supply-demand management technologies. However past studies have mainly focused on developed countries, and knowledge of tropical regions, including many emerging countries with large populations, remains limited. We conducted field measurements of occupants' A/C usage behaviour in 38 dwellings in Kuala Lumpur, Malaysia. Measured data were considered as a function of start and end times, duration, and frequency of A/C usage in each dwelling. Analysis showed that A/C events were rare during daytime; however, there was a drastic increase in the frequency of A/C usage at night. Based on this, a simple algorithm to synthesize stochastic time patterns of A/C operation schedules was developed. The validity of the model was demonstrated through comparison with observational data.

Keywords: stochastic model, occupant behaviour, field measurement, air-conditioner usage, dwellings

1. Introduction

It has become increasingly important to implement energy saving and CO₂ emission reduction measures to counteract global warming. The residential sector is one of the main energy consumers, accounting for about 30% of global energy demand [1]; therefore, improving the energy efficiency of residential heating, ventilation, and air-conditioning (A/C) equipment (HVAC) is essential. Renewable energy sources are expected to contribute positively towards a low carbon society; however, due to the dependence of several renewable energy sources (e.g., photovoltaics) on weather conditions, their power generation over time is generally unstable and may not coincide with the pattern of electricity demand, resulting in the need for expensive storage batteries. Accurate estimation of time-series demand for electricity, gas, hot water, and air-conditioning load all of which are strongly influenced by occupant behaviour is important to achieve optimum design at affordable cost.

Over the past decade, there has been substantial research into the characteristics of occupant adaptation behaviours that affect A/C load and energy consumption. For example, [Fritsch et al.](#) [2]

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proposed a stochastic model expressed by Markov chains for determining window opening angle based on occupant reactions to ambient temperatures, following field observations in four office rooms. Nicol and Humphreys [3] conducted a survey of occupant adaptation behaviour with respect to window opening, closing of window blinds, and use of lighting, heaters, and fans, finding that these behaviours vary with outdoor temperature and that their probabilities can be modelled by logit functions. Haldi and Robinson [4] also performed a field survey on the behaviour and adaptation of office occupants. They used the logistic regression model to predict the probability of occupant behaviour in term of adapting both personal (e.g., clothing, activity, drinking) and environmental (e.g., windows, doors, fans, blinds) factors. Haldi and Robinson [5] later developed a stochastic model of usage behaviour on window opening and closing determined by logistic probability distributions, Markov chains, and continuous-time random processes. Herkel et al. [6] proposed a user model based on a field survey in 21 offices to forecast window opening status in office buildings, taking into consideration outdoor temperature and occupancy. Tanimoto and Hagishima [7] performed a field survey of A/C use in residences, finding that stochastic switching-on/off actions can be modelled using state transition probability functions. Tanimoto et al. [8] developed an algorithm using the Monte Carlo technique to estimate cooling demand in residences based on a database of occupant A/C on/off behaviour in previous studies. Based on a field survey, Rijal et al. [9] proposed a building energy simulation coupled with a logistic model of window opening behaviour. Ren et al. [10] conducted a detailed analysis based on a field survey of three dwellings in China, classifying factors triggering A/C on/off actions into two groups: environmental triggers and event triggers. The latter include behavioural actions (e.g., sleeping, waking up, leaving a room, and dining). Finally, based on a field survey in Japan, Habara [11] suggested that A/C turning off behaviour is affected by occupant lifestyle.

Knowledge of stochastic occupant behaviour has been utilized in various building energy simulations to forecast realistic time-series energy demand and A/C load. The Total Utility Demand Prediction System (TUD-PS), developed and gradually improved by the authors for over a decade (e.g., [12]), is one such attempt at predicting household energy demand. The TUD-PS is a dynamic building energy simulation coupled with a stochastic model for reproducing stochastically time-varying electricity demands and the time schedule of A/C operation. Shimoda et al. [13] also conducted a numerical simulation of total utility demand at the city scale. Recently, Ranjbar [14, 15] conducted measurement

over a short period of household total and A/C electricity consumption in Malaysia; the results showed no correlation between outdoor temperature and electricity consumption.

Despite this research, most studies to date have been conducted in developed countries located in mid to high latitudes; research targeting developing countries is limited. Since many emerging countries located in tropical or subtropical climate zones (such as Association of Southeast Asian Nations [ASEAN] countries) are expected to face huge infrastructural demands in response to their rapid economic growth and expanding middle class populations, urban development might provide opportunities for introducing various low-carbon smart city technologies, which could include energy management for supply and demand. This would be comparatively easier in such emerging economies than in developed countries, which already have mature energy grids. Against this background, it is particularly important to study energy consumption-related behaviour in such developing regions.

To address the above, we performed a series of field observations of occupant space cooling behaviour in 38 dwellings in Kuala Lumpur, Malaysia. The on/off schedule of A/Cs in target dwellings was observed, and both room air and A/C outlet temperatures were measured. Since, Malaysia is located on the equator and is categorized as tropical, seasonal variations in outdoor air temperature and humidity would be expected to have little effect on A/C usage, as compared to countries with distinct seasons. Observed results were compared to those obtained by the authors in previous research conducted in Fukuoka, Japan [16]. Section 2 presents details of the field survey. Section 3 outlines the characteristics and stochastic nature of occupant A/C usage behaviour. Based on analysis results, we developed a model for generating the A/C operation schedule of Malaysians; rather than considering a dataset of occupant lifestyles based on large-scale statistical investigation, this is based on the stochastic nature of A/C usage behaviour (measurements in section 4). Finally, the accuracy of the simulation was tested, based on comparisons with field survey data.

2. Outline of field survey

2.1 Site description

Observations were conducted in 38 dwellings from two different housing complexes located in Kuala Lumpur (3°08'N, 101°42'E) from September 2013 to November 2015. Fig. 1 shows the exterior view and plan layout of the two residential buildings. All dwellings were located in one of two residential buildings constructed out of reinforced concrete a 19-storey building (MY1) with a floor area of 60.4 m² and a complex of 13- and 4-storey buildings (MY2) with floor areas of 55.4 m² and 73.9 m², respectively.

Both are located in a public low-cost housing complex. Table 1 provides a detailed description of the investigated buildings. Fig. 2 shows the number of occupants in target dwellings, with the value ranging from one to eight.

Table 1

Description of investigated buildings

Building code	Floor Area	Building material	Shading Devices	Type of Glazing	Ratio (%)
MY1	60.4 m ²	Reinforced concrete	Internal curtain	Single	Façade 1: 14.4
				clear	Façade 2: 18.8
				glazing	Façade 3: 14.1
					Façade 4: 18.4
MY2	55.4 m ² or 73.9 m ²	Reinforced concrete	Internal curtain	Single	Façade 1: 22.0
				clear	Façade 2: 0
				glazing	Façade 3: 22.0
					Façade 4: 0

(b)
(a)



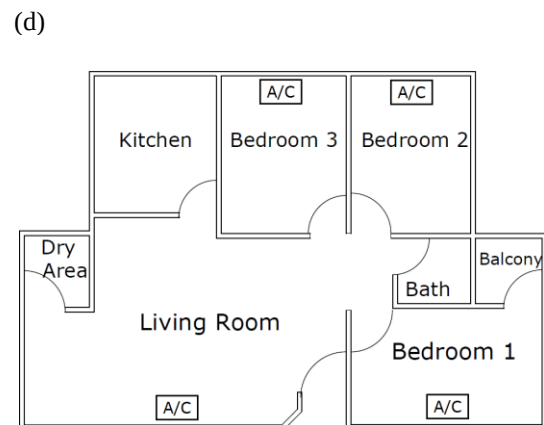


Fig. 1. Investigated buildings: (a) exterior view of 19 storey residential building; (b) interior plan of 19 storey residential building; (c) exterior view of 13 storey residential building; (d) interior plan of 13 storey residential building.

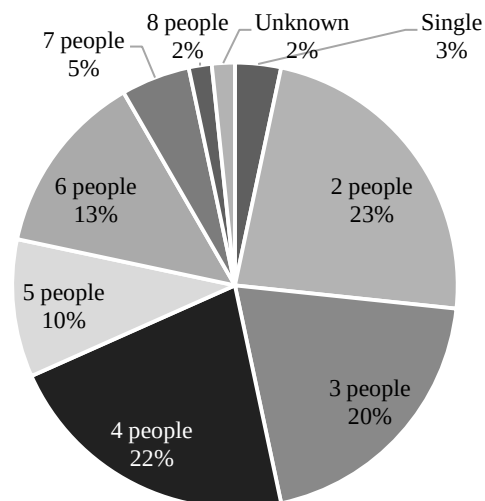


Fig. 2. Number of people living in target dwellings.

2.2 Outdoor climate

Fig. 3 shows annual variations in outdoor air temperature, as measured on the rooftop of the MJIT building of Universiti Teknologi Malaysia (UTM), Kuala Lumpur Campus, from March 2014 until February 2015; the Campus is within 0.6–2.0 km of the target dwellings. As shown, there was almost no seasonal variation and air temperature was 20–28 °C year-round. On this basis, we assumed that space cooling requirements did not differ seasonally and measurements were taken in each target dwelling arbitrarily over periods of 13–66 days (depending on occupant convenience) from September 2013 to November 2015. Hagishima et al. [16] conducted a similar analysis during summer in Fukuoka, Japan. Fig. 3 also shows data measured over one year in Fukuoka, Japan (March 2014 to February 2015). Despite the different climate zones, outdoor air temperatures in Japan during the period of measurement were nearly the same as those in Kuala Lumpur.

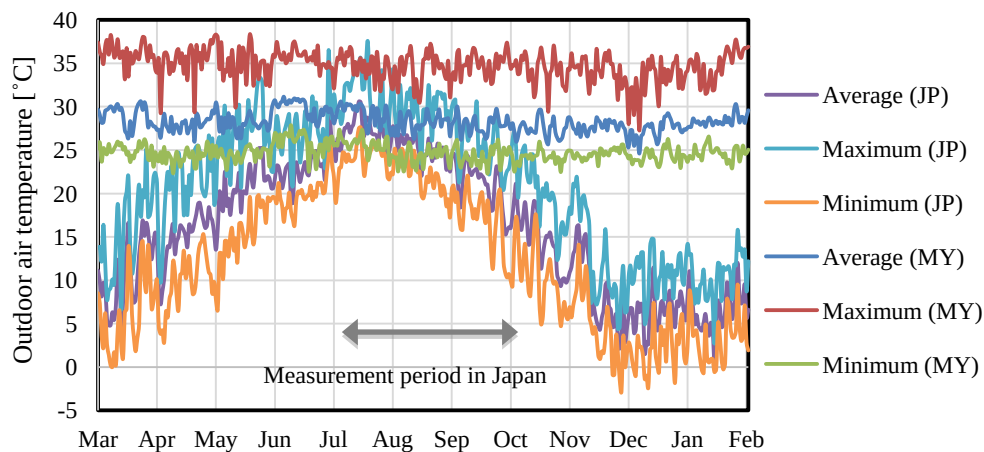


Fig. 3. Annual variations in daily outdoor temperature in Malaysia from March 2014 until February 2015. ‘MY’ refers to data measured on the rooftop of the Malaysia-Japan International Institute of Technology building at the Universiti Teknologi Malaysia, Kuala Lumpur Campus, Malaysia. Data measured at the Dazaifu weather station in Fukuoka, Japan, are included for reference purposes and denoted by the letters ‘JP’.

2.3 Measurement setup

We measured variations in the air temperature of a living room (Fig. 4a) and of an A/C outlet (Fig. 4b) installed in the living room in each dwelling at 15 min intervals throughout the survey period, using thermos-hygrometers consisting of a platinum resistance temperature detector. Table 2 provides details of each instrument. Measured data were used to determine the times at which occupants turned on and off their A/Cs. For most dwellings, the criterion for this was a temperature difference of 1.5 °C between room air and A/C outlet air, with this threshold varying slightly depending on the particular situation of each household. Based on the estimated schedule of A/C usage, we extracted A/C events, defined as periods extending from when occupants turned on the A/C to when they turned it off. Relevant data included number of events, and start time and duration of each.

Table 2.

Measurement instrument specifications

Instrument	Manufacturer, Country	Measured variable	Resolution	Accuracy and tolerance
Thermos-hygrometers, TR-52i	T&D, Japan	Air temperature	0.1 °C	± 0.3 °C [at -20 °C to 80 °C]
Thermos-hygrometers, TR-77Ui	T&D, Japan	Air temperature	0.1 °C	±0.5 °C
		Relative humidity	0.1% RH	±2.5% RH [at 25 °C and 10% to 85% RH]

(a)



(b)



Fig. 4 Location of the thermos-hygrometers: (a) air-conditioner outlet, (b) centre of the room.

3. Field survey results

3.1 Daily air-conditioner usage in each dwelling

Fig. 5 shows the relationship between averaged total duration of A/C usage and the number of A/C events in a day, for all 38 dwellings. Summer data for 20 dwellings in Fukuoka, Japan [16] are included for comparative purposes. In Malaysia, the average total duration of A/C usage varied widely (0–15 h); plots with longer total durations typically had more frequent A/C events, resulting in a positive correlation between these two factors. This can be explained by the reasonable assumption that a family that uses its A/C for more time daily tends to turn this on and off more frequently, compared to families with a shorter total period of A/C usage. The results for the two regions (Malaysia and Japan) are surprisingly similar, indicating limited influence of climate zone on frequency of A/C usage (provided that the comparison covers a period of similar outdoor air temperature conditions).

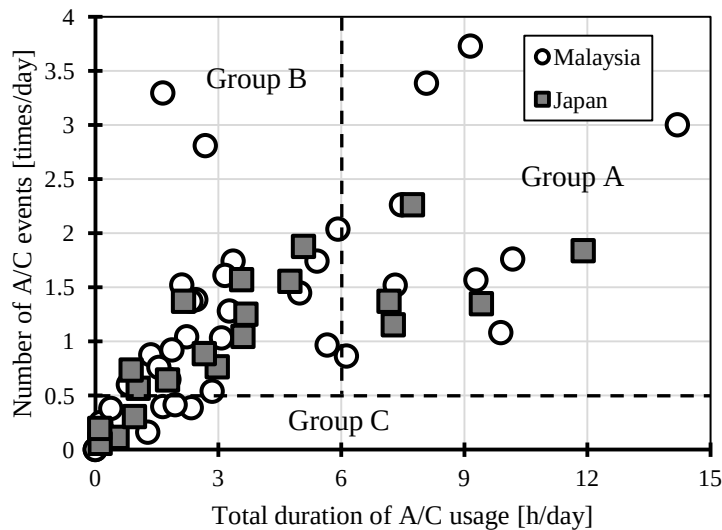


Fig. 5. Relationship between the number of air-conditioner usage events [times per day] and total duration of air-conditioner usage in a day [h per day] for each observed dwelling.

We classified the 38 dwellings into three groups according to frequency of A/C usage: Group A (10 families) with very frequent A/C usage, Group B (19 families) with moderate A/C usage, and Group C (9 families) with infrequent A/C usage. Classification criteria were the same as those in Hagishima et al. [16], as follows: Group A—number of events per day > 0.5 and total event duration > 6 h, Group

B—number of events per day > 0.5 and total event duration < 6 h, Group C—number of events per day < 0.5 .

3.2 Relationship between air-conditioner usage and outdoor temperature

Fig. 6 shows the relationship between daily hours of A/C usage and daily averaged outdoor air temperature, both for the present study in Kuala Lumpur and for Fukuoka [15]; this provides an indication of how occupants' space cooling behaviour is correlated with the outdoor thermal environment. The plots of Japanese dwellings show clear positive relationships, indicating that people use A/C units more frequently under hotter outdoor conditions. In contrast, plots for Malaysian dwellings suggest that outdoor thermal conditions had a much lower influence on frequency of A/C usage, although deviations from daily average outdoor air temperature were smaller in Malaysia than in Japan.

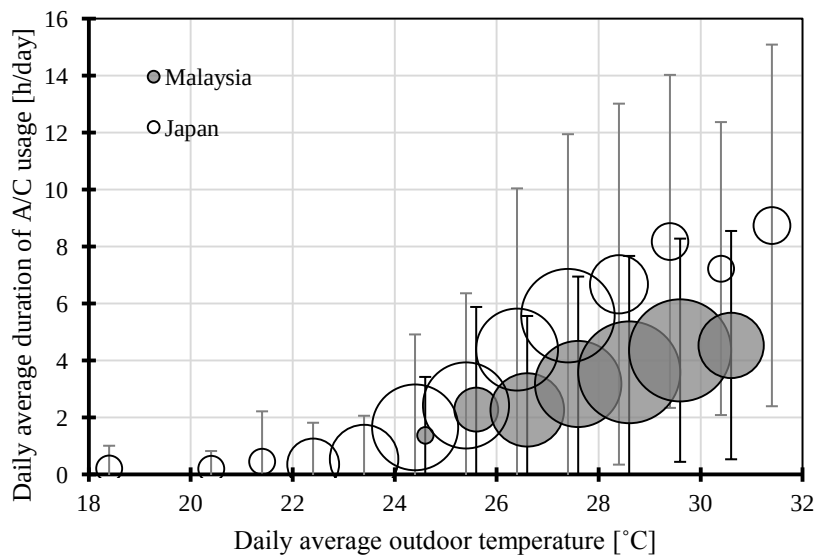


Fig. 6. Relationship between daily hours of A/C usage and daily averaged outdoor air temperature. The size of the circles corresponds to the number of samples; error bars indicate standard deviation.

3.3 Stochastic nature of air-conditioner usage

Fig. 7 shows variations in the number of A/C events per day over the measurement period. Each plot indicates the average probability density of Groups A (high frequency A/C users) and B (moderate users). The probability that an event occurs once a day is relatively largest for both Groups A and B, and decreases with an increase in the number of events per day for both groups. Additionally, Group A frequencies were higher than those of Group B, with A/C events occurring $>$ twice a day in dwellings of frequent A/C users. In the case of Group B families, the probability that the A/C is not used at all in one

day is 0.2 times higher than for Group A, with a probability of approximately 0.67 that the number of events is ≤ 1 . The corresponding probability for Group A is 0.41. On the other hand, the probability densities of zero-A/C events in a day were approximately 0.08 and 0.27 for groups A and B, respectively; frequent and moderate A/C users operated their A/Cs over 92% and 73% of the measurement period, using their A/Cs at least once a day.

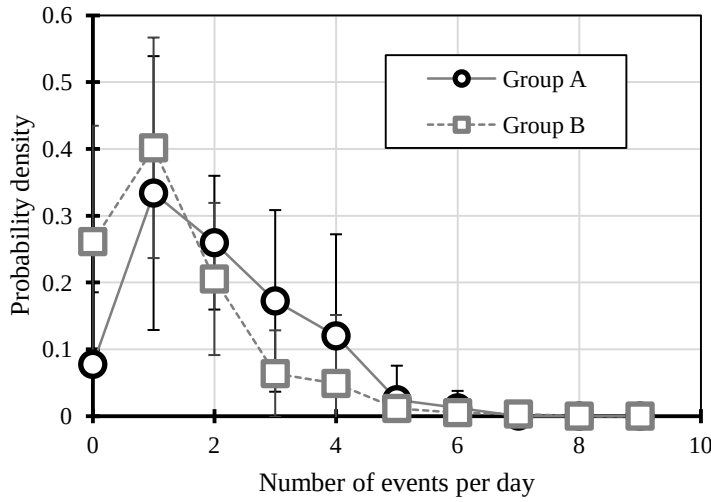
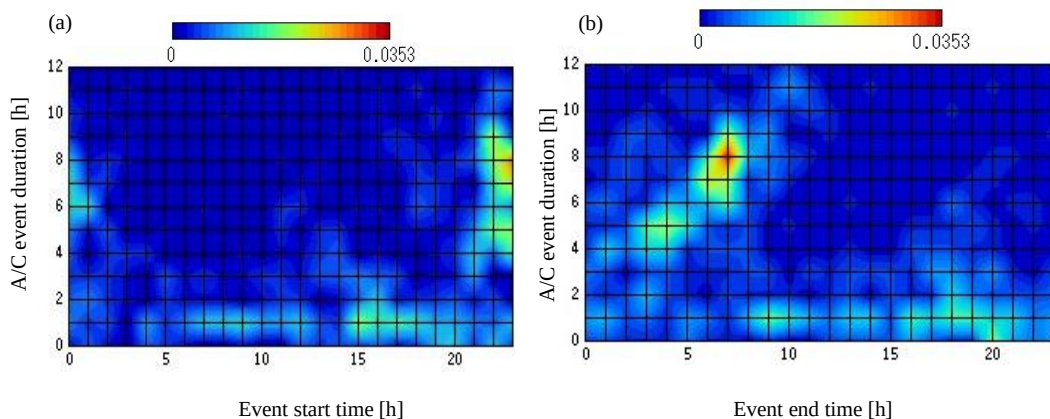
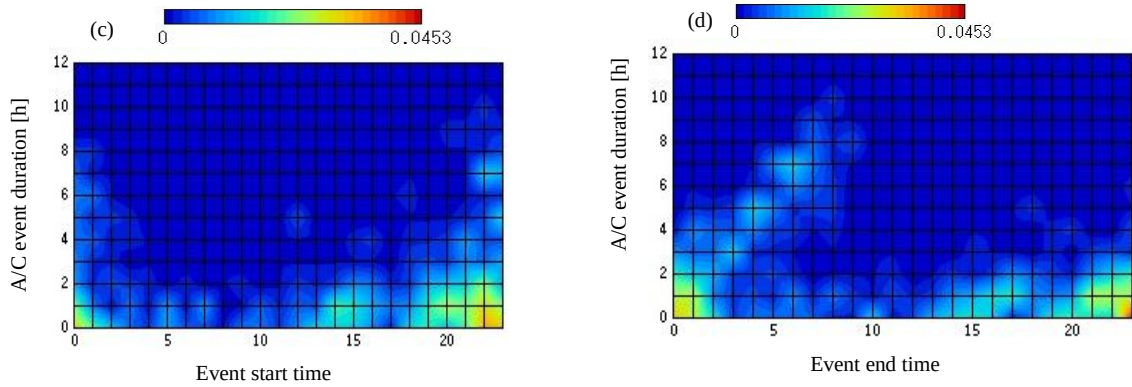


Fig. 7. Probability distributions for number of A/C events in a day.

Fig. 8 shows joint probability distributions for groups A and B of A/C events in terms of event duration, start time, and end time. Data for Group A exhibit a positive peak for an end time between 6 am and 7 am and duration from 7–9 h (Fig. 8a). This peak is correlated with the diagonal toward the upper right at night time in Fig. 8b. In Fig. 8d, the peak event of Group B occurred for an end time between 11 pm and 12 am, with duration of 0.5 h. Both groups A and B had almost zero probability of starting A/C operation during daytime, with A/C operation likely coinciding with sleeping periods (night time). Kubota et al. [17] reported similar results; on the basis of a questionnaire survey of dwellings in Johor Bahru, Malaysia, the authors found that only 10% of families operate A/Cs during daytime. In contrast, the peak value is approximately 80% during night time.





1

Fig. 8. Joint probability distributions: (a)–(b) Group A for A/C events–event duration, event start, and end times; (c)–(d) Group B for A/C events–event duration, event start, and end times.

These results indicate that the stochastic nature of number of events and event duration differed between groups A and B, although event start time was almost identical. In addition, the A/C usage pattern differed significantly between daytime and night time. A/C usage behaviours may therefore be influenced not by outdoor air temperature, which is constant year-round, but by occupants' schedules or habitual behaviours.

4. Model for generating A/C operation schedule

4.1 Algorithm

Given the above, the model for generating A/C operation schedule had to take into account the stochastic nature of A/C usage behaviour as depending on different occupant schedules, rather than environmental factors. Measurement results also indicated that A/C usage behaviour in Malaysia varied between daytime and night time. The characteristics of these two time slots therefore had to be considered, with daytime defined as the period between 3 am and 3 pm and night time as the period between 3 pm and 3 am.

Fig. 9 outlines the calculation scheme of the developed model. The number of target-simulated dwellings was 300, with on/off A/C generation every 15 min over a year (365 days) at each simulated dwelling. Dwelling type was determined stochastically based on A/C frequency usage groups (Fig. 5), with the proportion of dwellings as follows: Group A—26.3%, Group B—50.0%, and Group C—23.7%. A daily A/C on/off schedule was subsequently generated.

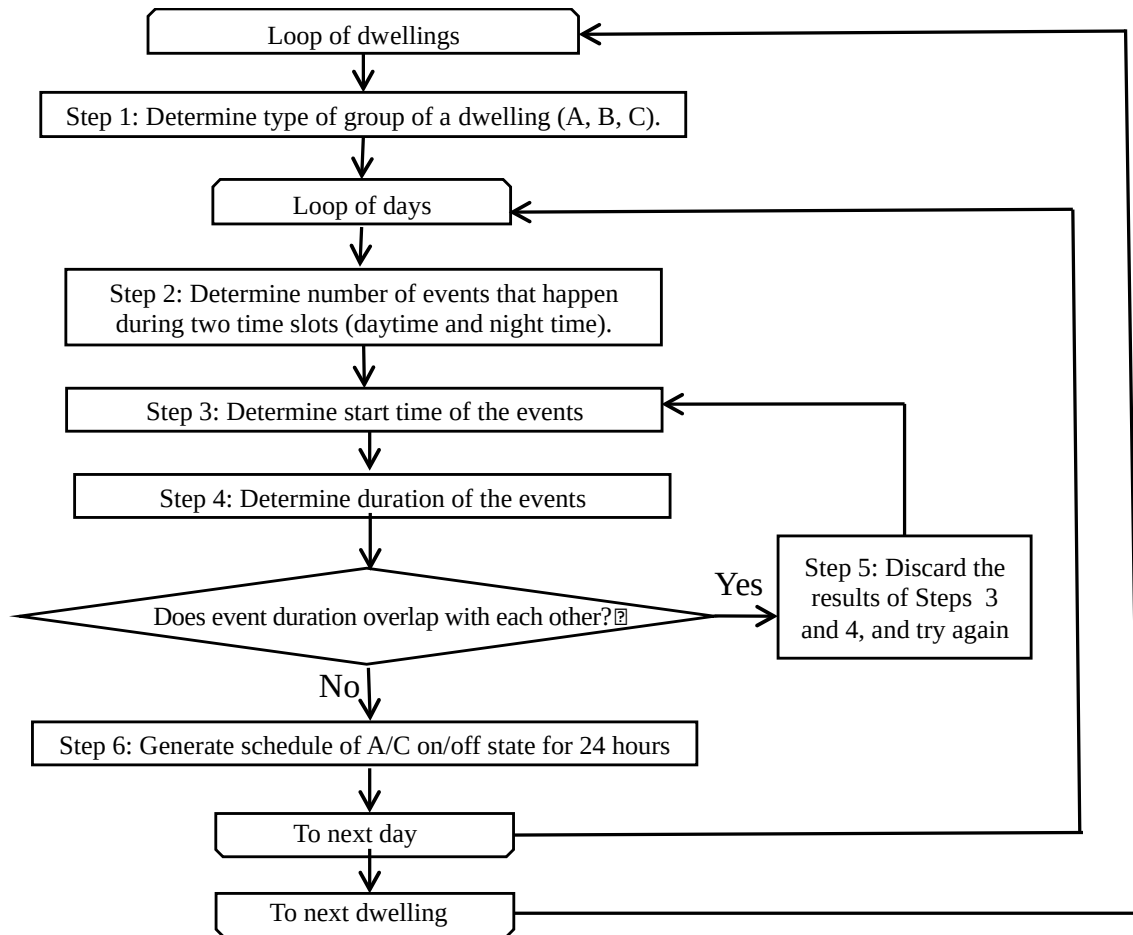


Fig. 9. Calculation scheme of the model for generating A/C operation schedule.

In daily loop calculations, the number of events, event duration, and event start time were determined stochastically based on the cumulative probability of these three variables occurring during daytime and night time, derived from measurement results shown in Fig. 10 and Fig. 11. Solid circles refer to data of certain dwellings in groups A and B for each observed dwelling for both daytime and night time during the measurement period. Rectangles refer to the average of all dwellings in Groups A and B. These results were applied in stochastic decision-making of the number of events, event duration, and event start time.

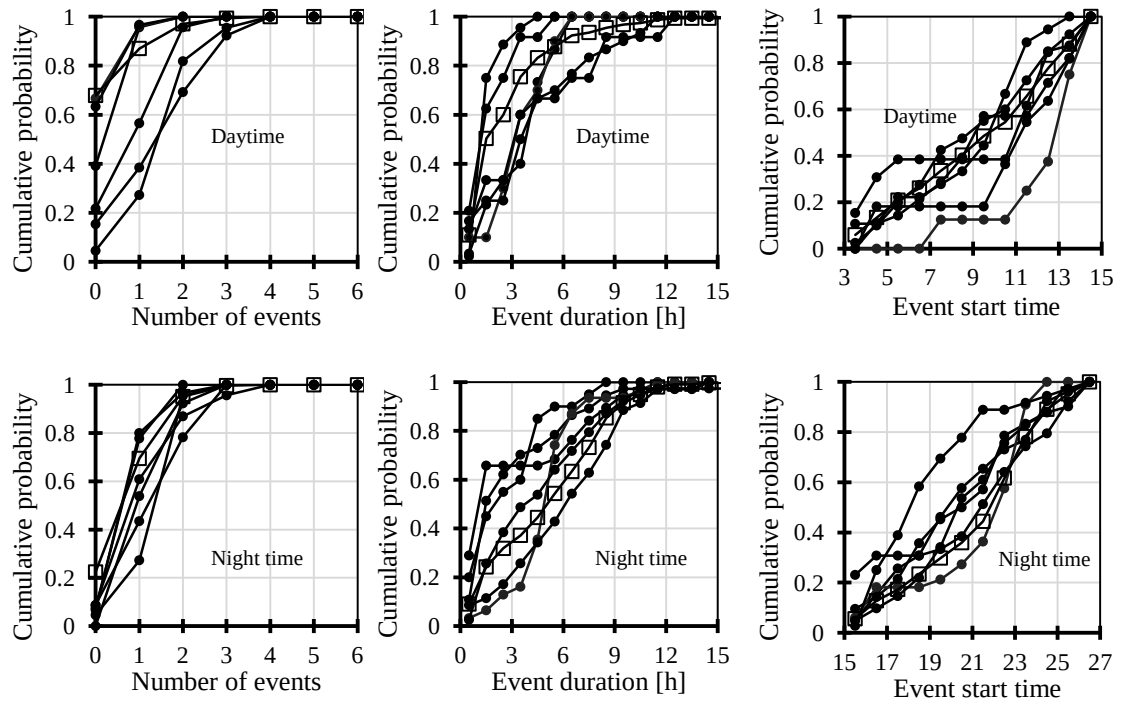


Fig. 10. Cumulative probability of number of events, event duration, and event start time for daytime and night time for each Group A dwelling. Solid circles refer to data of certain dwellings in Group A. Rectangles refers to the average of all dwellings in Group A.

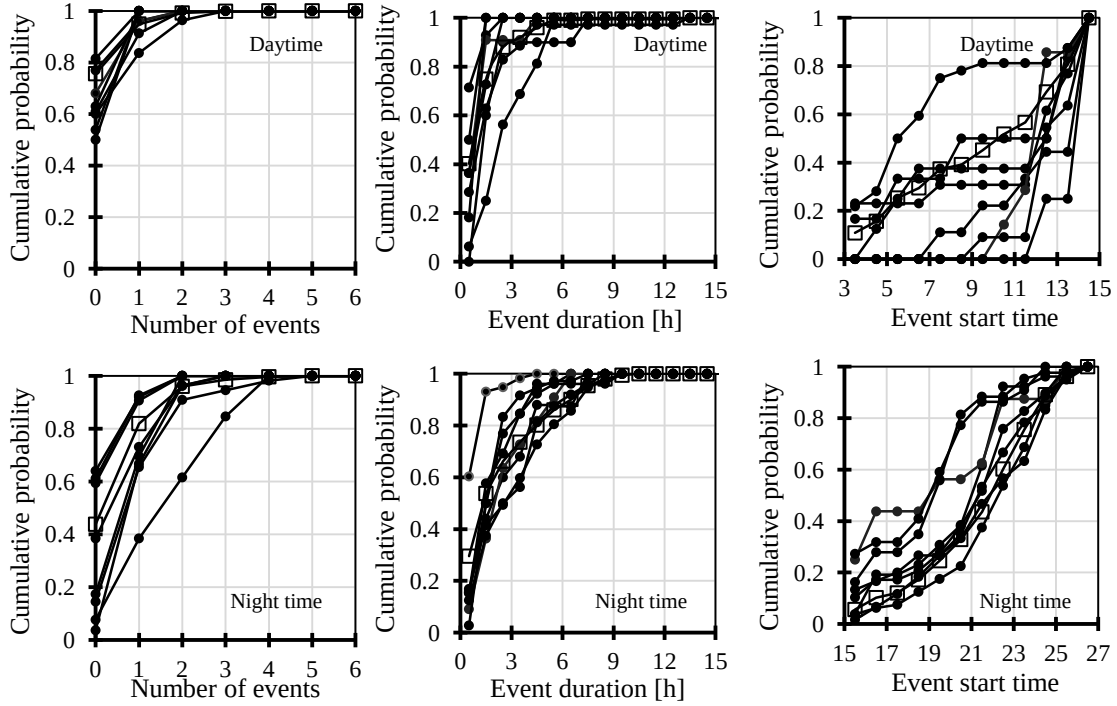


Fig. 11. Cumulative probability of number of events, event duration and event start time for daytime and night time for each Group B dwelling. Solid circles refer to data of certain dwellings in Group B. Rectangles refers to the average of all dwellings in Group B.

In daily loop calculations, the number of daytime and night time events per day was stochastically determined for classified dwellings (groups A and B). The stochastic rule applied to Group C was a 10% probability of one daytime event and a 30% probability of one night time event. The start time and duration of an event are stochastically decided based on cumulative probabilities determined by Fig. 12 and Fig. 13 according to the time slots (either daytime or night time). This process is repeated until the number of events reaches the value determined by step 2 (Fig. 9). In addition, the event start time of Group C was stochastically determined based on the cumulative probability of event start time during daytime and night time derived from all 38 observed dwellings, as shown in Fig. 12. Moreover, the stochastic rule applied to Group C assumed 40% probability of a 0.5 h event, 30% probability of a 1.5 h event, and 30% probability of a 2.5 h event. Finally, the daily A/C operation schedule was generated as binary code, with A/C on-state as '1' and A/C off-state as '0'.

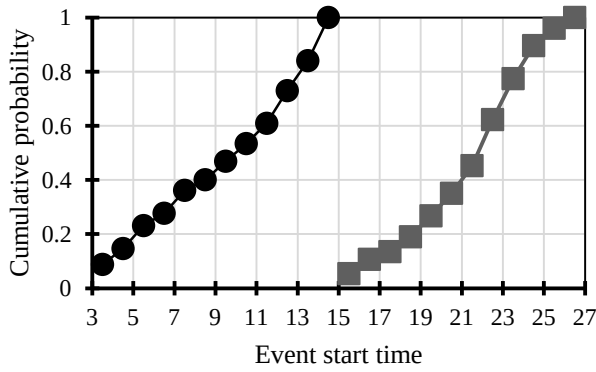


Fig. 12. Cumulative probability of event start time for all 38 dwellings during daytime and night time.

4.2 Calculation results

In order to test the developed model, we performed a calculation to artificially reproduce occupants' space cooling behaviour. The observed data were compared with the model-calculated averages, taking into account the number of events per day, event duration, and daily total duration of A/C usage (Fig. 13). The plots indicate averages across dwellings and the error bars represent standard deviation. The calculated results of the model were similar to observations, although the model slightly underestimated the daily number of events and daily total duration of A/C usage. Additionally, the length of simulated standard deviation for daily numbers of events was shorter than in the case of observed data, possibly due to the calculation scheme of the model, including repeated event overlaps with a previous temporal A/C on-state in daily loop calculations. In other words, several events in daily loop calculations were aggregated into one event.

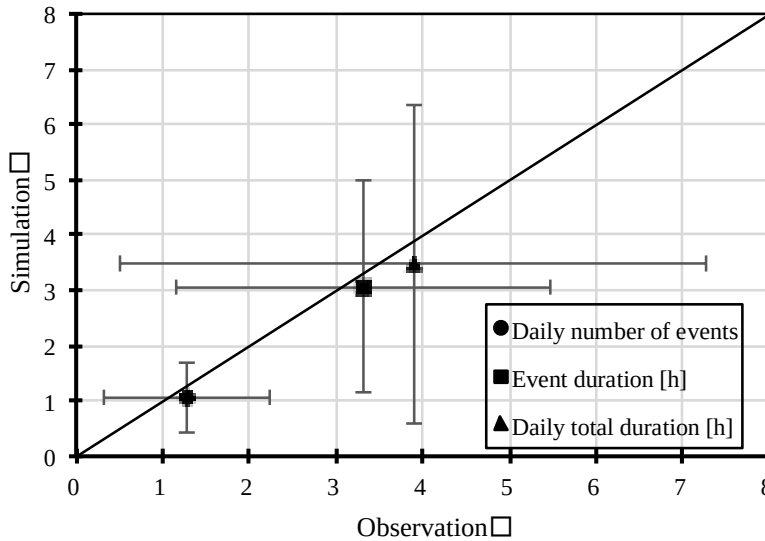


Fig. 13. Statistical comparison between simulations and observations. Data include daily number of events, event duration, and daily total duration of A/C usage.

Fig. 14 shows the relationship between number of events and daily total duration of A/C usage for each simulated dwelling. The extensive scatter represents dwelling data, indicating that the model for generating A/C operation schedule can express the diversity of occupant behaviours.

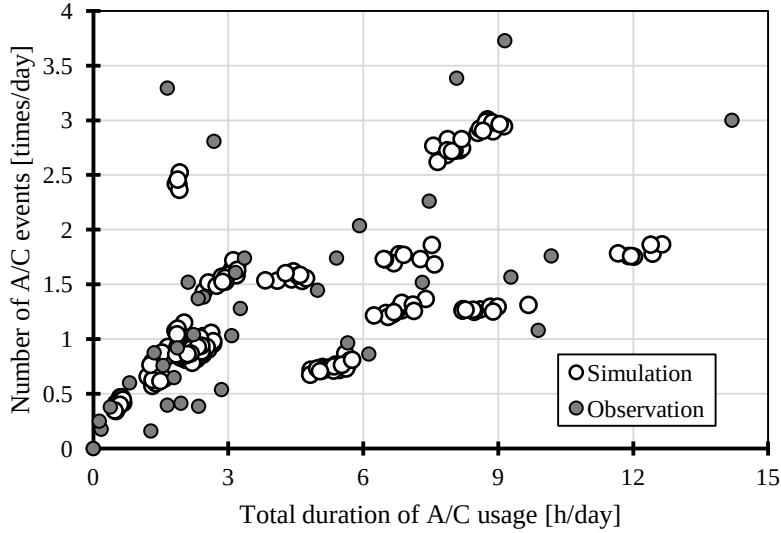


Fig. 14. Relationship between number of air-conditioner usage events [times per day] and total duration of air-conditioner usage in a day [h per day] for each simulated dwelling.

Fig. 15 compares the probability density distributions of daily number of events, event duration, and event start time for simulated and observed data; it shows that simulation results were similar to observations in all three cases. On this basis, it appears that the model for generating A/C operation schedule can recreate the stochastic nature of A/C usage behaviour.

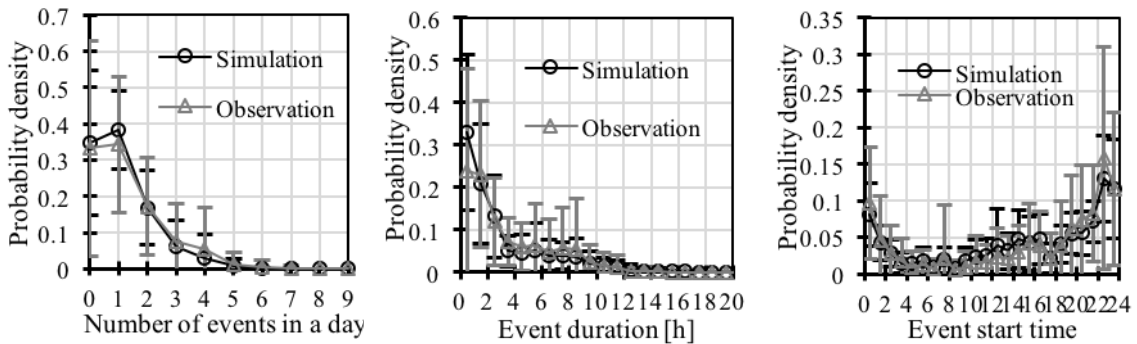


Fig. 15. Probability density distributions of number of A/C events in a day, event duration, and event start time obtained by model and the field survey.

We also compared variations in the ratio of dwellings using A/C to those that do not, for both observed and simulated results (Fig. 16). The model was able to reproduce the ratio distribution trend, in particular between 8 am and 8 pm. However, it underestimated usage during night time (9 pm–7 am). This could be due to the stochastic information used in the model (e.g. the cumulative probability of event duration during daytime and night time for groups A and B) not being adequate. Owing to the limited sample size, stochastic information on time patterns was encapsulated in the statistics for only two time slots (daytime and night time) due to sample size limitations. It is presumed that model performance would be improved by increasing the sample number and employing higher time resolution.

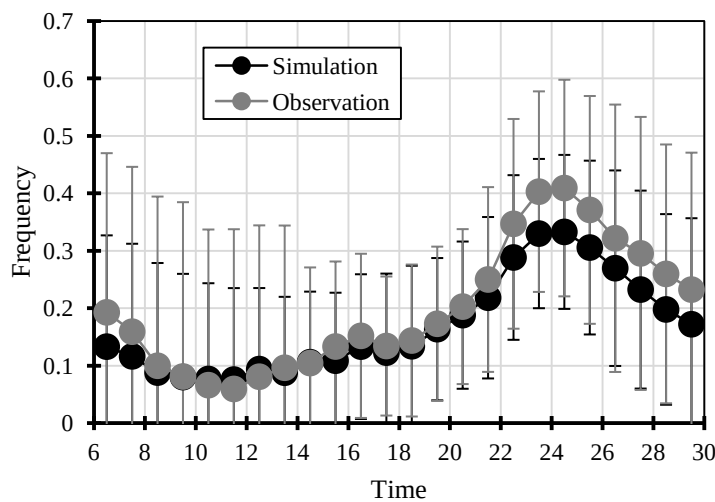


Fig. 16. Variations in ratio of dwellings using air-conditioning, as calculated by model and measured through the field survey.

5. Conclusions

A field survey of occupants' A/C usage behaviour was conducted in residential buildings in Kuala Lumpur, Malaysia. The 38 target dwellings were classified into three groups based on frequency of A/C usage, and the stochastic behaviour of each group was thoroughly examined. The findings of our research can be summarised as follows:

- 1) Malaysian A/C usage behaviour differs between day and night time, with hardly any A/C events during the day, but a rapid increase in frequency of A/C usage at night.
- 2) Indoor air temperatures in Malaysian dwellings are approximately 22–31 °C. Poor insulation performance and a desire to reduce electricity bills could explain results for occupants of dwellings with temperature data that exceeded indoor thermal comfort criteria.

3) A simple model for synthesizing artificial time patterns of rating A/C operation was developed, based on stochastic A/C event numbers per day and the probability of event start time, classified using two time slots and three user groups (based on A/C usage frequency level). The model generated schedules of A/C operation; it had good performance and was able to reproduce observation data.

It is of note that the proposed model has both advantages and limitations.

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