Using a calibrated multi-zone building model to analyse the impact of occupant behaviour on building performance

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Abstract. Building performance simulation has been commonly used for performance-based building design. However, the simulation accuracy is closely related to the model and input parameters regarding the building physics and occupant behaviour. To check and improve the accuracy of the simulation, the model usually needs to be calibrated using measured data. Uncertain parameters are adjusted in this process to reduce the discrepancy between simulation and measurement results. Although occupant behaviour has a significant impact on building performance, it has not been considered a key component of model calibration in previous studies. Model calibration using only indoor environmental and energy consumption data without considering occupant behaviour is unreliable. In this context, a step-by-step model calibration approach is proposed in this study to optimise the estimated parameters in typical operational scenarios where occupant behaviour can be conveniently determined. A case study shows that although the simulation results for apartment energy use are similar before and after model calibration, differences can be observed in the evaluation of indoor air quality and thermal environment. Simulation results using occupant behaviour based on design standards are significantly deviated from the measured values, compared to that using actual occupant behaviour.

1 Introduction

The building sectors are responsible for over one-third of global final energy consumption and nearly 40% of total CO2 emissions, while the energy demand for space cooling is continuously growing [1]. To address the unprecedented cooling demands in the building sector of the next decade, building performance must be improved with appropriate energy efficiency measures (EEM). In this context, Building Performance Simulation (BPS) is widely used as an effective tool for dynamic building behaviour prediction and building performance optimisation. BPS enables quantitative analysis of the effectiveness of EEMs to support decision making in building design and retrofitting. Although BPS is well developed nowadays, significant discrepancies between simulated and measured results can still occur due to the weather data gap, construction gap, occupant behaviour gap, and modelling gap [2]. Model calibration allows for the optimisation of uncertain parameters based on measurement data to reduce the impact of construction and modelling gap. However, occupant behaviour is often not given enough attention in modelling and simulation. For example, if only a constant air change rate is used when analysing a naturally ventilated building, the thermal and airflow behaviour cannot be accurately modelled. This increases the uncertainty when evaluating indoor air quality, thermal environment and energy performance. In addition, the use of deterministic occupant-related settings based on design standards can also lead to incorrect predictions [3, 4]. Since occupant behaviour has a significant impact on building simulation, it should also be considered in model calibration. However, some studies on model calibration either do not take occupant behaviour into account [5] or try to adjust the uncertain occupant behaviour to reduce the discrepancies between simulated and measured results, assuming that all other model settings are correct [6, 7]. However, these models can be limited in predicting the effectiveness of EEMs under near-actual conditions.

In this context, this study aims to develop an approach to calibrate the BPS model using indoor environmental data and occupant behaviour data to analyse the impact of occupant behaviour on building performance. This allows for a comprehensive evaluation of the effectiveness of EEMs under diverse occupant behaviours rather than just using deterministic behaviour.

2 Methodology

2.1 Model calibration workflow

The proposed model calibration approach in this study follows a clear evidence-based structure with statistical methods (see Fig.1). The basic idea of this approach is to calibrate the model step-by-step in several typical scenarios where occupant behaviour and

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building operation are known. The advantage of this approach is that the number of known parameters can be gradually increased as the calibration proceeds, while the number of uncertain parameters is gradually reduced.

![Diagram of Calibration Process](image)

**Fig. 1. Model calibration workflow**

Following this approach, uncertain parameters are first estimated according to the design standards, literature references and practical experience. An initial model is then built based on the available and estimated information. After that, this initial model is validated in a typical scenario to determine if the relevant parameters have been reasonably estimated. If the deviation of the key simulation results from the actual measurements exceeds the tolerance limits, then an iterative model improvement process is carried out in which the uncertain parameters are re-estimated based on other reliable reference sources. If it is not possible to avoid adjusting multiple parameters in the same calibration step (scenario), a sensitivity analysis can be used to determine those most influential parameters. Insignificant parameters will be ignored to reduce the calibration effort. These influential parameters will be further optimised during the parametric simulation and analysis. A detailed description of the calibration process is provided in Section 2.2 through a case study.

### 2.2 Case study

The studied object is a northwest-facing apartment unit on the 9th floor of a high-rise residential building constructed in 2012 in Hanoi, Vietnam. The apartment (AP) comprises a master bedroom (BR), a children's room, a study, a living room (LR) and a balcony with a total floor area of 88.6 m² (see Fig. 2). The balcony is connected to the living room by a French door. The master bedroom has four single-glazed top-hung windows with a maximum opening angle of 45°. Due to the hot and humid local climate, two split air conditioners are equipment in the living room and the master bedroom with a cooling capacity of 5 kW and 2.5 kW respectively. Air conditioners are mainly used for space cooling in the summer and rarely for heating in the winter. There are two adults and two children living in the apartment, because co-sleeping is a very common practice in Vietnam, the parents always share their bed in the master bedroom with their children.

![Apartment layout](image)

**Fig. 2. Apartment layout**

The ventilation behaviour of occupants in such naturally ventilated buildings affects not only indoor air quality but also cooling demand, therefore a multi-zone airflow model is needed to analyse in-depth the impact of occupant behaviour on building performance. The Transient System Simulation Tool (TRNSYS) was chosen for modelling and simulation in this study, as the add-on TRNFLOW enables airflow simulation in its thermal multi-zone building model Type56 [8]. This makes it possible to couple airflow between rooms and the natural ventilation will depend on wind pressure and temperature gradient rather than on predefined input values. In a previous study [9] detailed information on building characteristics and occupant characteristics, as well as indoor environmental data and weather data, was collected through building audits, occupant surveys and long-term measurements. This available information was used to build the initial model and set up the simulation inputs.

In this case study, the parameters related to the building airtightness, thermal performance of the building envelope and natural ventilation were calibrated step by step in 3 specified operational scenarios (see Table 1). The leakage rate of building components, material properties of walls, ceilings, floors and windows as well as discharge coefficient of large openings were optimised sequentially by comparing the relevant simulation results with the measured results. Root mean square error (RMSE), coefficient of variation of the RMSE (CV), and goodness-of-fit (GOF) between the key simulation results and measured data were used as indicators to evaluate the calibration. In the model validation process the CV less than 20% for CO₂ concentration [7], the RMSE less than 0.5 K for temperature and the RMSE less than 10 % for relative humidity (RH) [10] were used as criteria depending on the parameters to be calibrated. The initial estimated leakage rate in Scenario A needs to be further optimised due to the inadequate model calibration result. A more appropriate setting was determined through parametric simulation using the...
lowest RMSE as a criterion (GOF is used for the overall evaluation of the optimisation of parameters in multiple rooms). Because building material properties and discharge coefficient were reasonably estimated based on local design standards and literature references, the model in Scenario B and C met the validation criteria and therefore the parameter optimisation process was skipped.

| Table 1. Model calibration scenarios |
|-------------------------------------|
| A         | B          | C          |
| Typical period |            |            |
| some nights |             |            |
| Related Rooms |        |            |
| BR        | BR+LR     | BR+LR     |
| Occupancy status |            |            |
| occupied | unoccupied | day: unoccupied night: occupied |
| Window status |        |            |
| closed    | closed     | based on survey   |
| Internal door status |        |            |
| closed | open | based on survey |
| Optimised parameter |        |            |
| leakage rate | material properties | discharge coefficient |
| Key result |        |            |
| CO₂ | temperature | temperature |
| Tolerance |        |            |
| CV | <20 % | RMSE | <0.5 K |
| RMSE | <0.5 K | RMSE | <0.5 K |

2.3 Comparative analysis

To analyse the impact of occupant-related settings and model calibration on the building performance simulation, the measurements (5th June to 5th July 2020) were compared with the simulations using calibrated and uncalibrated (initial) models with consideration of two types of occupant-related settings, i.e. deterministic settings based on design standards and actual behaviour based on measurements and surveys (see Table 2).

| Table 2. Simulation variants |
|-------------------------------|
| Modell | V1 | V2 | V3 |
| Occupancy Schedule BR(LR) | Occupied: 22:00 – 06:30 (06:30 – 22:00) | measured | measured |
| AC schedule | full time (24 h) | measured | measured |
| Setpoints | 26 °C, 65% RH | measured | measured |
| Airflow rate BR(LR) | Occupied: 35(30) m³/(h*pers.) Unoccupied: 0.7 h⁻¹ (infiltration) | calculated with airflow model | calculated with airflow model |

Variant V1 and V2 used the uncalibrated initial model, while V3 used the calibrated model. In V2 and V3, the occupancy schedule, AC schedule and AC set points were set based on indoor measurements, while the air change rate was calculated by airflow model using window settings estimated from occupied surveys. The AC schedule, AC set points, and air change rate in V1 was extracted from the local design standard [11], while the specified infiltration rate is commonly used by local experts. The occupancy schedule in V1 was set according to a design standard [12] that provides occupancy rates for individual rooms.

3 Results and discussion

3.1 Cooling energy consumption

Table 3 presents the comparison of simulated (V1-V3) and measured (M) AC running time and electricity use for cooling from 5th June to 5th July 2022. The simulated cooling energy consumption is calculated based on the energy removal and AC performance data, while the measured energy consumption is derived from the energy bills. In simulation V1 a ‘full-time and full-space’ AC behaviour was used, which means that the temperature and humidity in all rooms are maintained constant during the cooling season. This leads to a significant overestimation of AC use. The simulated total AC running time and cooling energy consumption for one month are 1.7 times and 4 times higher than their measured results, respectively. On the other hand, simulations using inputs based on actual occupant behaviour are very close to the measured results.

| Table 3. Simulated and measured AC running time and cooling energy consumption (5th June to 5th July 2022) |
|-------------------------------------------------------------|
| Total AC running time [h] | V1 | V2 | V3 | M |
| AC energy consumption [kWh] | 632 | 117 | 122 | 126 |

3.2 Thermal environment

Fig.3 shows a part of the measured and simulated temperature profiles in the living room. The local people mainly use to turn on the AC in the bedroom when they sleep, but rarely in the living room, so the temperature in the living room is usually very high in summer. If standard-based AC-related inputs (as in V1) are used without validation, it can cause significant uncertainty in both model calibration and performance simulation. In addition, it is clear to see that the accuracy of the temperature simulation has improved with the calibrated model (V3) compared to the initial model (V2).

3.3 Indoor air quality

As shown in Fig. 4, differences in modelling methods and simulation settings of occupant ventilation...
behaviour can have a significant impact on the prediction of indoor air quality (IAQ) when using CO₂ concentration as an indicator. V1 uses pre-defined supply ventilation airflow rates as inputs, which makes the building behave as if it was mechanically ventilated. The CO₂ concentrations in BR are kept below 700 ppm at all times. However, the measurements show that room air quality is not always at such a good level and is closely dependent on the AC and ventilation behaviour of occupants. When occupants turn on the AC before going to bed, the door and windows of BR are often closed to cool the room quickly, which can cause CO₂ concentrations to reach around 2800 ppm on some nights. In other cases, the occupants open the BR door slightly when using the AC, which improves IAQ in BR due to the increased air exchange with LR. However, as Fig. 3 shows, the room temperature in LR is very high and the air exchange also increases the cooling load and additional cooling energy consumption in BR. Both V2 and V3, which use the airflow models, accurately reflect the impact of occupant behaviour on the IAQ. Measures need to be developed to avoid high CO₂ concentration (over 1000 ppm) in the room, especially when sleeping and using AC.

4 Conclusion

A step-by-step model calibration approach was proposed in this study to check and improve the simulation accuracy while considering the impact of actual occupant behaviour. This new approach was then tested and evaluated through a case study. An initial model was built based on available information collected from a typical residential apartment in Hanoi, Vietnam. Uncertain model parameters were first estimated according to the design standards, literature references and practical experience. The model was then calibrated step-by-step in several observed scenarios where occupant behaviour and building operation were known. Comparative analysis shows that calibrated models using actual occupant behaviour inputs have a high simulation accuracy, while occupant-related settings based on design standards introduce significant deviations. The model also accurately reflects the impact of occupant behaviour on building performance. However, to design calibration scenarios, detailed data on occupant behaviour is required, which in practice is often accompanied by limitations and has to be addressed in further research.

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