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Paliouras, P.; Matzaflaras, N.; Peuhkuri, Ruut Hannele; Kolarik, Jakob

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Using measured indoor environment parameters for calibration of building simulation model- a passive house case study

P. Paliouras^a, N. Matzaflaras^a, R. H. Peuhkuri^{a,*} and J. Kolarik^b

^aDepartment of Civil Engineering, Technical University of Denmark, Nils Koppels Allé Building 402, Kgs. Lyngby 2800, Denmark

^bDepartment of Civil Engineering, Technical University of Denmark, Brovej Building 118, Kgs. Lyngby 2800, Denmark

Abstract

Simulation-aided commissioning is being increasingly used to address discrepancies between predicted and actual energy consumption in modern buildings. Calibration of building model, developed using Building Energy Performance Simulation (BEPS), represents a crucial part of the commissioning process. Most of current calibration methodologies focus on matching of measured and simulated energy consumption. The objective of the present study was to perform a calibration of a building model of a passive house located in Næstved, Denmark, using measured data for operative temperature (T_{op}), relative humidity (RH) and concentration of carbon dioxide (CO_2). Continuous monitoring of indoor environmental parameters was conducted in all zones for 30 days. The Coefficient of Variation of the Root Mean Square Error (CV(RMSE)) was used to evaluate agreement between simulated and measured data. CV(RMSE) did not demonstrate a continuous improvement along each iteration, however after all the required adjustments in the model, the initial limits were satisfied. A calibrated state was obtained after 10 significant iterations with respect to regulation of ventilation system, window opening and solar shading devices. Lowest value of CV(RMSE) was achieved in the southwest bedroom and was equal to 3 % for T_{op} , 11.3 % for CO_2 and 5.2 % for RH.

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Keywords: Building energy model; calibrated model; simulation-aided commissioning; indoor climate; energy consumption

* Corresponding author. Tel.: +45 45255036.

E-mail address: rpeu@byg.dtu.dk

1. Introduction

Nowadays, use of Building Energy Performance Simulation (BEPS) tools has become common during building design. However, they are still rarely used for operational diagnostics and on-going commissioning where comparison of measured data with results of simulation enables detection of potential failures and performance optimization [1, 2]. This helps to reduce both actual energy use [3] and the gap between predicted and actual energy use [4, 5, 6]. A BEPS model of building needs to be calibrated according to measured data to ensure usability of suggested optimization strategies. Current approaches to model calibration rely on i) manual iterative methods (adjustment of inputs on a trial-and-error basis), ii) graphical representations and comparative displays and iii) automated methods based on mathematic models [7]. Examples of different attempts to model calibration can be seen in work of Bertagnolio [8], Kaplan [9], Lunneberg [10], Cohen [11] and many others, however, the majority of relevant studies lack detailed analysis of indoor environment [12]. As occupant comfort should not be compromised for the sake of energy savings this article presents a building-calibration approach that primarily uses indoor environmental parameters to evaluate agreement between simulations and measurements.

2. Methodology

2.1. Description of calibration methodology

The proposed methodology encompasses the analysis of the actual and theoretical building model (TBMO) performance, in terms of indoor climate and energy consumption (see Fig. 1a). Data about actual performance were collected both quantitatively (field measurements) and qualitatively (occupant interviews). “As designed” model was created and calibrated using measured data. The model was considered calibrated when discrepancy between measured and simulated data, expressed by variation of root mean square error CV(RMSE) [1], was less than 5 % for operative temperature (T_{op}), 20 % for relative humidity (RH) and CO₂ concentration and 10 % for energy consumption. In case of a noteworthy deviation, the model was re-examined by modifying the appropriate input in the software and afterwards the updated model was simulated again. This process is presented and analysed in detail step-by-step, as it was implemented and validated in a real case study.

2.2. Description of case-study building

The examined house was a new-built single-storey family house, situated in Næstved of Denmark. It was built according to the Passive House standard [13], covers 188 m² of internal floor area and the main facade is oriented to southwest. The structure is highly insulated and thermal bridge free with an overall thermal transmittance of 0.11 W/m²K. Infiltration rate is equal to 0.5 1/h⁻¹ at 50 Pa. Two different types of triple glazing windows were installed with different characteristics, depending on the orientation of the façade: U = 0.59 and 0.44 W/m²K and g= 0.47 and 0.62 for windows facing north and south respectively. The south oriented sides are equipped by external movable roller sun-blinds with black fabric and by roof overhangs to minimize direct solar gains and avoid excessive overheating. A natural gas condensing boiler (maximum power 14 kW, efficiency 109 %) serves both for heating (floor heating system) and domestic hot water purposes. Temperature in each zone is controlled by thermostat. Apart from natural ventilation, the building has balanced mechanical ventilation with heat recovery. Outdoor air is preheated up to 6 °C in winter and pre-cooled down to 9 °C in summer in an earth tube buried in the ground outside the house. Mechanical ventilation is constant air volume (CAV) with manually adjusted ventilation rates (four levels). Air handling unit (AHU) [14] provides maximum air flow 300 m³/h, heat recovery efficiency is equal 93 % at 200 m³/h and the specific fan power (SFP) for both supply and exhaust fans is 0.8 kW/(m³/s).

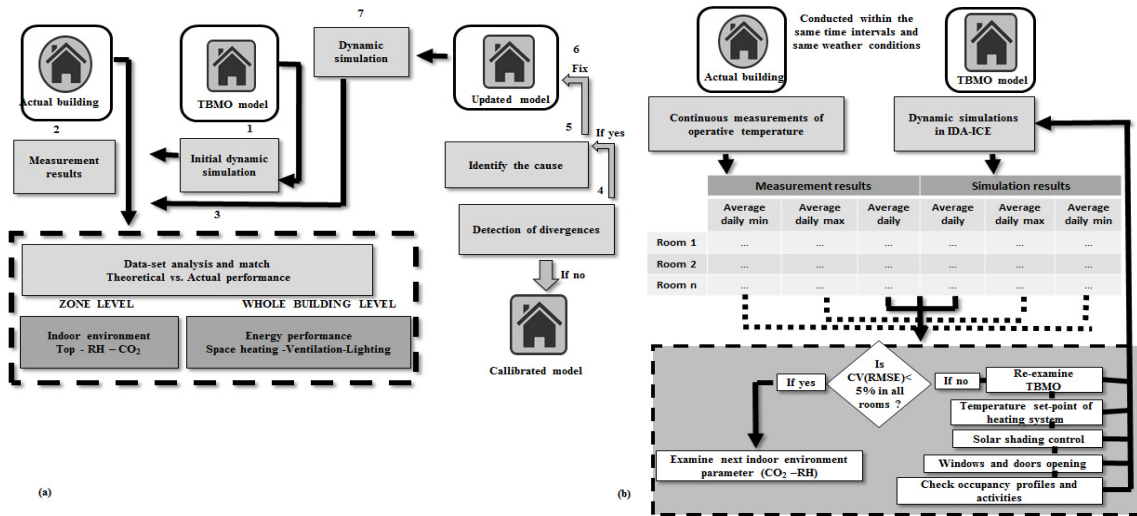


Fig. 1. (a) Description of methodology steps; (b) Required steps for the comparison of measured and simulated datasets of T_{op}

2.3. Building model simulations – “as designed” state of the house

The building was modelled in IDA-Indoor Climate and Energy software [15]. Building geometry was derived from AutoCAD drawings, while the building envelope components and construction details were designed as in reality. There were 11 thermal zones in the model, one for every room. Hourly weather data (external temperature and humidity, wind speed, direct and diffuse solar radiation) were retrieved from two adjacent weather stations and compared with the actual climate conditions in the exact same time-period. It was assumed that occupants open windows when T_{op} exceeded 25 °C, while at the same time outdoor air temperature was lower than temperature indoors. Concerning the control of solar shading devices, they were considered completely open during winter to minimize heating requirement. The ventilation system was modelled to operate up to its full capacity, aiming to keep the CO₂ concentration below 1000 ppm during occupied periods. In addition, an electric heating coil was used to simulate the earth tube heat exchanger. Heating set-point of all zones was $T_{op} = 21$ °C. Concerning occupancy and activity profiles for the 5 person family, it was impractical to create separate profiles for each day of the examining period; therefore, typical family schedules were established in the software. During weekdays, master bedroom and child rooms were assumed to be fully occupied between 00.00 a.m.–06.00 a.m. and 19.00 p.m.–07.00 a.m. respectively, while living room was occupied by 2 persons from 21.00 p.m. till 23.00 p.m. Kitchen was assumed fully occupied for one hour every day, while the office was occupied by 2 persons two hours per day. Occupants’ activity level was assumed to be 1.2 met. The generated gains from electrical appliances were applied in the software, based on reasonable hourly use predictions for a family. The peak emitted heat from equipment in the kitchen (oven, fridge, dishwasher, exhaust hood) was 2378 W during simultaneous operation, while 80 W when only a refrigerator was operating. The living room was equipped with a projector of 300 W that was operating three times per week from 21.00 p.m. to 23.00 p.m. and the office with a laptop of 30 W that was operating according to occupancy in this room.

2.4. Field measurements – “as operated” state of the house

Continuous in-situ measurements were carried out to obtain data about so called “as operated state” of the house. Eleven loggers were placed in particular zones. T_{op} , CO₂ and RH were recorded in 10 minute intervals for 30 consecutive days during March 2014. Regarding energy consumption of the house, the indications of the gas boiler were used, while the hourly consumption of electricity was acquired from electricity provider. Furthermore, detailed interviews were conducted with the occupants to pursue insight about their daily habits, activities and behavioural patterns. This information assisted in determining the existing control strategies of technical equipment, window opening and solar shading devices. Besides, these interviews provided information about occupants’ perception of indoor environment and indications of specific problems that were not detected by measurements.

2.5. Comparison of simulated and measured datasets, calibration procedure

A detailed investigation of the indoor environment parameters was done on zone level, while the energy use was determined for the building as a whole. Simulated and measured parameters were compared within the same time-interval. Fig. 1b serves as an illustrative example for the comparison process between measured and simulated values of T_{op} . For accuracy reasons, the examined period was not considered single and uniform, but the comparison was performed on hourly basis. Unlike other calibration methodologies, the minimum, maximum and average values of T_{op} were analysed in each day, aiming to acquire a holistic view of thermal conditions. The precision of this comparison was evaluated and expressed through two separate statistical indices. The first was the Root Mean Square Error (RMSE) [1] that is defined as the deviation between predicted (X_{pred}) and observed values (X_{obs}) in each day (n) of the calibration period (1). The second index, was the coefficient of variation of RMSE (CV(RMSE)) [1] and expresses the dispersion of data points around the mean of a data series (2). A CV(RMSE) value above 5 % was an indication that the model was not sufficiently calibrated and thus the input parameters of the model needed to be revised.

$$RMSE = \sqrt{\frac{\sum_{i=1}^n (X_{obs,i} - X_{pred,i})^2}{n}} \quad (1)$$

$$CV(RMSE) = \frac{RMSE}{\bar{X}_{obs}} \quad (2)$$

3. Results

3.1. Simulations and measurements

As it can be seen from Table 1, measured T_{op} was ranging within the permissible range of 21-25 °C for a Category I building according to European standard EN 15 251 [16] in all zones, except from child bedroom 1. RH was also acceptable (Mean±SD = 35.4 % ± 0.93), whereas CO₂ reached 1286 ppm in the master bedroom that was occupied by two persons. Simulations of the initial TBMO indicated a slight underestimation of peak T_{op} in most of the zones and noticeably lower electricity consumption. As regards CO₂, simulated CO₂ concentrations did not exceed the limit of 1000 ppm.

Table 1. Observed (Meas.) and predicted (Sim.) daily average values of indoor climate and energy use (from 02/03/2014 to 01/04/2014)

| | Min. T_{op} [°C] | | Max. T_{op} [°C] | | Mean RH [%] | | Max. CO ₂ [ppm] | | Heating [kWh] | | Electricity [kWh] | |
|--------------|--------------------|------|--------------------|------|-------------|------|----------------------------|------|---------------|------|-------------------|------|
| | Meas. | Sim. | Meas. | Sim. | Meas. | Sim. | Meas. | Sim. | Meas. | Sim. | Meas. | Sim. |
| Kitchen | 22.1 | 22.7 | 24.7 | 25.3 | 36.0 | 32.1 | 1050 | 983 | | | | |
| Office | 22.1 | 22.3 | 24.5 | 24.3 | 35.9 | 34.3 | 961 | 1000 | | | | |
| Child Room 1 | 22.1 | 22.0 | 25.2 | 24.3 | 34.0 | 34.2 | 926 | 1000 | 34.7 | 44 | 58.5 | 39 |
| Bedroom | 22.1 | 21.3 | 23.6 | 22.5 | 35.8 | 35.0 | 1286 | 1000 | | | | |

3.2. Iterative adjustment of the building model

In total 10 separate iterations in the TBMO were needed to calibrate the model, the first 6 modifications were related to disagreement between measured and simulated data regarding T_{op} , the next 3 modifications were related to CO₂ concentration and the last to energy consumption data. The iterative process of calibration was performed manually and the results of each iteration were used as input for the following iteration, until each examined parameter matched closely the measured values. All these modifications were justified based on the answers from interviews with occupants and reflect the way that technical equipment operates in reality. Table 2 illustrates all the input variations in the model and the outcome of each applied alteration.

Table 2. Summary of modifications in building model (“s” indicates simulations and “m” measurements)

| Reason | Adjustments in TBMO | Outcome after each alteration |
|--|--|---|
| 1 Max. $T_{op}(s) < \text{Max. } T_{op}(m)$ | Set internal doors to be always open | Amplification of heat diffusion between zones |
| 2 Max. $T_{op}(s) < \text{Max. } T_{op}(m)$ | Adjust room thermostat set-point to 21.5 °C | CV(RMSE) of $T_{op} > 5\%$ |
| 3 Outcome from interview | Set windows and external doors to be always closed | Overheating ($T_{op}(s)$ almost 28.5 °C in the kitchen) |
| 4 Overheating in all zones | Activate shading devices in case of excessive solar radiation | Acceptable CV(RMSE) in most zones, apart from guest-room |
| 5 $T_{op}(s) > T_{op}(m)$ in guest room | Adjust occupancy profile in this zone (room is mostly empty) | Satisfying consistency for T_{op} |
| 6 $CO_2(s) < CO_2(m)$ in bedrooms | Decrease supplied air flow of ventilation system to 160 m ³ /h | CV(RMSE) still not permissible |
| 7 $CO_2(s) > 1000$ ppm | Set min. & max. CO_2 set point in AHU to 850 ppm. Airflow was 160 m ³ /h in occupied hours and 75 m ³ /h in rest | CV(RMSE) < 20 % except from two zones |
| 8 Ventilation was not operating all day | Set temperature set-point of the ventilation system to 21 °C | Perfect matching of predicted and measured CO_2 values in all zones |
| 9 $T_{op}(s) > T_{op}(m)$ in kitchen, adjacent zones | Adjust heat output of electrical devices and activity profiles | Average CV(RMSE) < 5% in all zones |
| 10 High predicted heating use | Turn off gas boiler on 11th of March (outcome of interview) | CV(RMSE) for heating = 7.4 % |

After the completion of iterations, analysis of results showed satisfying consistency between calculations and measurements, with CV(RMSE) values below the predefined tolerance range in all zones and for each examined parameter. The final congruity of the results is also depicted graphically, once the calibrated state was achieved. Fig. 2a displays the disparity of monitored and simulated T_{op} in the kitchen for the entire calibration period of 30 days, while Fig. 2b shows the matching of CO_2 concentration in the master bedroom on a random day (03/03/2014). The final simulated heating demand for the 30 day period was calculated to be 32.3 kWh, the electricity for ventilation 45.9 kWh and 14.4 kWh for lighting and electrical appliances, thus they fitted well the measured values (Table 1).

4. Discussion and conclusions

Systematic manual iterative procedure presented in the paper resulted in a calibrated model of the case study house for a noteworthy period of 1 month. The novelty of the presented approach is that both predicted indoor climate parameters and energy use reproduced measurements in each zone of the house. This study differs in three substantial aspects from existing calibration methods. Firstly, required iterations were applied on the model only when there was adequate evidence to support them (interviews, logbooks) and were not only random adjustments.

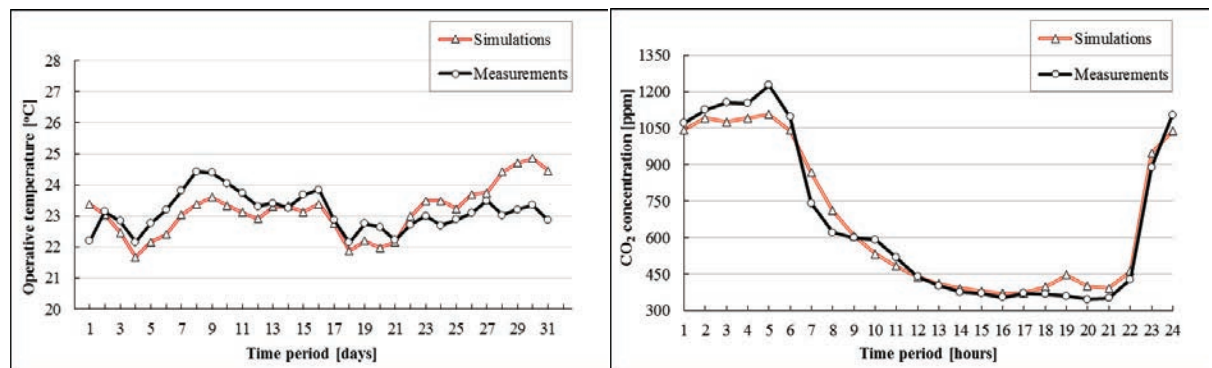


Fig. 2. (a) Daily simulated versus measured values of T_{op} (kitchen); (b) Hourly simulated versus measured values of CO_2 (masterbedroom)

Secondly, real weather data were acquired from a weather station in proximity of building, instead of using historical data for the area. The third main advantage was that simulated indoor climate data were statistically evaluated based on minimum, maximum and hourly mean values in each day of the calibration period. In contrary, similar techniques use just one indicative value of CV(RMSE) metric for every day, therefore such a generalized method may hide inaccuracies. These factors as well as the proper configuration of model inputs, contributed in a CV(RMSE) equal to 7.4 % for heating load, 7.0 % for ventilation and 8.3 % for electrical equipment, which are below the maximum allowable uncertainty of 15 % recommended by [17].

It should be mentioned that occupant behaviour could be considered as the most decisive source of uncertainty during calibration performed in the present study. In reality occupants interact with the built environment and climate conditioning systems (i.e. use of shading devices, windows, artificial lighting etc.) in highly stochastic manner. Hence, a deterministic modelling of their behaviour is not feasible with sufficient precision. In particular, shading devices were activated when solar radiation exceeded the threshold of 200 W/m² in the interior part of the glazing. A sensitivity analysis on this parameter indicated that this was the optimal limit to emulate the actual control of sun-blinds. Nevertheless, despite the complexity and limitations of representing precisely multi-dimensional parameters such as occupant behaviour, BEPS can also be utilized to determine and quantify energy conservation measures in an extended period. The development of this model calibration method to an automated software interface would simplify the whole process and minimize the likelihood of errors done by the consulting engineer. Lastly, the embedding of probabilistic methods for modelling human behaviour into BEPS may greatly enhance accuracy of model output.

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