Calibration of a High-Resolution Dynamic Model for Detailed Investigation of the Energy Flexibility of a Zero Emission Residential Building

John Clauß, Pierre Vogler-Finck and Laurent Georges

Abstract A detailed multi-zone building model of an existing zero emission residential building (ZEB) has been created using the software IDA Indoor Climate and Energy (IDA ICE). The model will later be used for investigating control strategies for the heating system to activate the building energy flexibility. The main purpose of this paper is to show how reliable the model reproduces the short-term thermal dynamics and the temperature zoning of the building. This is of particular interest for the control of heating, ventilation and air conditioning (HVAC) systems in order to provide meaningful insights of active demand response (ADR) measures. The model has been validated using data sets from seven experiments. Two dimensionless indicators, the normalized mean bias error (NMBE) and the coefficient of variation of the root mean square error (CVRMSE) were applied in order to evaluate the trend of the average indoor temperatures. The first approach considered standard operating conditions, where the measured indoor air temperature was used as input for the control of the electrical radiator and the total electricity use of the radiator as an output. Excitation sequences have been used in the second approach, where the electric power of the radiator has been imposed and the operative temperature taken as the output. The model shows good agreement between the temperature profiles from the measurements and the simulations based on the NMBE and CVRMSE remaining below 5% for most cases.

Keywords Detailed building model · Model validation · Zero emission building
Energy flexibility · Active demand response

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1 Introduction

1.1 Context of the Work

Calibration of a building model is an essential step to ensure simulation accuracy and thus to increase confidence in simulation results. Calibration can be achieved using monitoring data from the respective building [1]. This is of particular interest for ZEBs which contain advanced technologies that can be challenging to simulate. Model calibration often has, among others, two limitations: model complexity (use of single-zone models) and the use of hourly aggregated data of the energy consumption for space heating [1]. The ASHRAE 14 guideline defines acceptance criteria based on the energy consumption, whereas no standards exist that determine acceptance criteria for model calibration based on indoor temperatures [2, 3]. Nevertheless, several studies use a threshold for the CVRMSE of 5% when calibrating a building model with respect to hourly indoor temperatures [2, 4–6].

A detailed multi-zone numerical model of an existing residential ZEB, the Living Laboratory in Trondheim (Norway) [7], has been created using the software IDA ICE. The calibrated model will later be used to investigate the influence of different control strategies for space heating to activate the energy flexibility using structural energy storage. Knowing the short-term thermal dynamics and thermal zoning of the building envelope as a response to time-varying space heating set-point temperatures is of importance for active demand response measures as well as for the development of resulting control strategies for heat pumps. During structural energy storage, the indoor temperatures should fluctuate within the thermal comfort levels. Therefore, this study aims at investigating the indoor air temperature and operative temperature in different zones of the building.

1.2 Contribution

A multi-zone approach is used to evaluate the differences of the thermal environment between the bedrooms and the living spaces. Monitoring of the indoor thermal environment has been carried out during two periods, in February/March 2017 and April/May 2017. During the experiments in April and May 2017 the dynamics of the indoor thermal environment have been measured as a response to an excitation using a specified pre-defined heating sequence (with sub-hourly resolution). A first qualitative validation of the building model is carried out by a direct visual comparison of the measured building thermal behavior with the predictions from simulations in IDA ICE using identical boundary conditions. In a second step, a quantitative validation against experimental data is conveyed. Two dimensionless indicators, the NMBE and CVRMSE are used to evaluate the accuracy of the calibration based on the average indoor air temperature and operative temperature.

2 The Living Laboratory—A Residential ZEB in Norway

2.1 Short Description of the Building

The case study building (Fig. 2a) is a Norwegian residential zero emission building [7] which is located at the Gløshaugen Campus of the Norwegian University of Science and Technology (NTNU) in Trondheim, Norway.

The on-site electricity generation from the photovoltaic panels is designed to compensate for the building CO_{2eq} emissions from the operational phase as well as for embodied emissions over the lifetime of the building. The floor area is approximately 105 m^2 [8] and the specifications for the building envelope follow the requirements from the Norwegian standard for residential passive houses NS3700. The building has a highly-insulated envelope with a lightweight wooden construction [7] as well as energy efficient windows with low emissivity. Furthermore, it contains 90 m^2 of phase change material (PCM) in the roof construction. The PCM is active between 18 and 26 °C [9] and thus mitigates indoor temperature fluctuations in the building. The Living Laboratory consists of five heated zones (see Fig. 1): two bedrooms, one bathroom, one working room and one large room combining a kitchen, a living room and an entrance.

A single heat emitter is placed between the two living rooms, since such a passive house can theoretically be heated using a single heat emitter [10]. The other rooms are without active heating, except for the bathroom equipped with floor heating. Temperature differences between the rooms are thus expected.

2.2 Building Model in IDA ICE

The building simulation is done in IDA ICE 4.7.1 which is a dynamic multi-zone simulation software. The software applies equation-based modelling [11] and enables the user to evaluate the energy use and the indoor thermal climate of a building. A sketch of the 3-D virtual model is presented in Fig. 2b. The roof

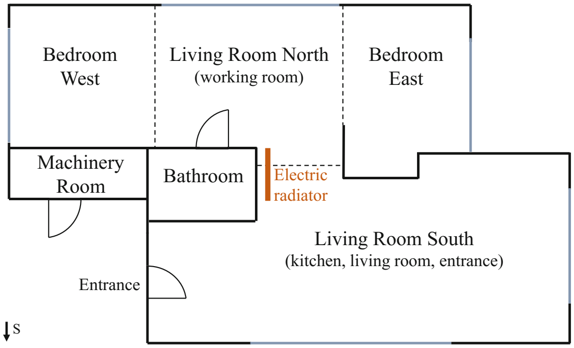

Fig. 1 Floor plan of the ZEB living laboratory (dashed lines show borderlines of the zones; moving doors between bedrooms and Living Room North can be opened)

overhang at the entrance of the real building was not considered in the building model, as this was originally done to increase the roof area for PV installation. It does not affect the heating needs nor the indoor temperatures of the building because this part of the building is not heated up.

3 Experiments

The building model is validated on the basis of two sets of experiments where the first four experiments were conducted between the 16th of February 2017 and the 24th of March 2017, whereas three other experiments were carried out from the 18th of April 2017 to the 15th of May 2017. During the second set of experiments, the indoor air temperatures and operative temperatures (at 0.7 m from the floor) were measured every 5 min in all heated zones, whereas during the first set of experiments the indoor temperatures were measured every minute. The air temperature was measured by Pt100 sensors, whereas the operative temperature was measured using Pt100 sensors enclosed in black globes. Vertical stratification of the air temperature was measured in the two living rooms. The bathroom door was always closed and the building was not occupied, although dummies with incandescent lamps were placed to mimic internal gains according to NS3031 using predefined on/off schedules for the first set of experiments.

3.1 Experiments 1 to 4 from February and March 2017

The aim of these measurements was the investigation of the temperature zoning by closing and opening the bedroom doors and to analyze the thermal dynamics of the Living Lab. An overview of the settings for these four experiments is given in Table 1.

The electricity use of the 1.6 kW electric radiator (with thermostatic on/off control) was logged every 30 s. The constant air volume (CAV) ventilation system continuously supplied air with a temperature of ca. 19 °C. All windows were

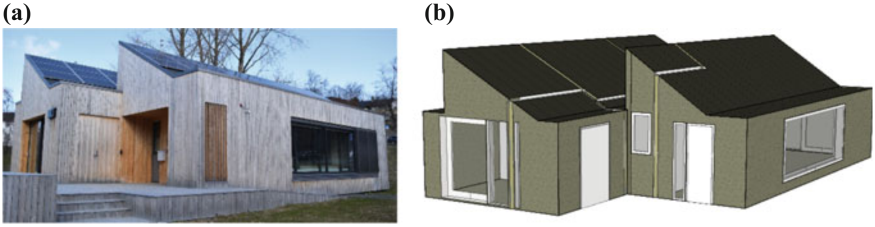

Fig. 2 **a** Photo of the living laboratory at the Gløshaugen campus at NTNU and **b** sketch of the modelled building

Table 1 Overview of the test settings for experiments 1 to 7 (E1–E7) where "Night setback" means that no electric heating is allowed between 23:00–07:00

Experiment	Time period	Bedroom doors	Night setback	Indoor Temperature variation (°C)	Sky condition
E1	17.2. 00:00–20.2. 00:00	Closed	No	15.7–19.9	Overcast
E2	20.2. 09:00–25.2. 00:00	Open	No	17.6–20.1	Clear on 21.2.
E3	16.3. 00:00–20.3. 12:00	Open	Yes	16.9–20.7	Clear on 19.3.
E4	20.3. 12:00–24.3. 12:00	Closed	Yes	14.5–21.6	Clear on 21.3.
E5	18.4. 20:00–24.4. 20:00	Open	No	16.8–24.5	Mostly clear
E6	29.4. 00:00–08.5. 09:00	Closed	No	15.9–26.8	Mostly clear
E7	09.5. 00:00–15.5. 06:00	Open	No	19.0–28.0	Mostly clear

always fully blinded to limit the influence of solar radiation. Weather data was taken from [12], which uses data from major weather stations close to a respective location as well as satellite data to construct the weather conditions with a grid size of 11 × 11 km [13].

3.2 Experiments 5 to 7 from April and May 2017

Electrical radiators with on/off control and a capacity of 0.8 kW (Experiment 7) and 1 kW (Experiment 5 and 6) were operated according to a pseudo random binary sequence (PRBS) [14, 15] in order to investigate the thermal dynamics of the building over a wide range of frequencies. This excitation sequence is typically applied for inverse modelling. A PRBS does not necessarily ensure comfortable thermal conditions inside a building. A more detailed description of these experiments can be found in [16], whereas an overview of the test settings is provided in Table 1.

The ventilation supply air temperature was set to 30 °C for the first experiment (E5) and changed to 18 °C in the beginning of the second experiment (E6). Ventilation heating was deactivated for the last days of Experiment 7. Windows were not blinded. Weather data was measured using the building embedded weather station. The Skartveit-Olsen method has been used to split the global horizontal radiation data (measured on-site) into direct horizontal and diffuse radiation [17].

4 Validation Results

The calibration of the building model was done based on the data set of Experiment 6 and with respect to the operative temperature aiming for a high correlation between the modelled and the measured temperatures. The model parameters (Table 2) were adjusted manually in an iterative manner, starting from their design values. The calibrated model has been validated using the data sets of six other experiments.

Two approaches have been applied to carry out the validation. For Experiments 1–4, the space-average of the measured indoor air temperature of the Living Room North and the Living Room South has been used as a set point for the electric radiator and the time-averaged measured electric power of the radiator was compared to the simulation results ("closed-loop" approach). In Experiments 5–7, the operative temperature of the rooms has been measured as a response to a pre-defined heating schedule ("open-loop" approach).

4.1 Dimensionless Indicators for Model Calibration

Two indicators for evaluating the model accuracy are the NMBE and the CVRMSE. The NMBE gives an indication of the total difference (percent error) between the measured and the predicted value from the simulations [18] and is calculated by

$$MBE = \frac{\sum_{i=1}^{n} (y_i - \hat{y}_i)}{n} \tag{1}$$

$$NMBE = \frac{MBE}{\bar{y}} \cdot 100 \tag{2}$$

where y_i and $\hat{y}_i$ are the measured and simulated value at instance i, $\bar{y}$ is the average of the measured data and n is the number of instances used in the calibration.

Table 2 Overview of tuned model parameters during calibration

Parameter	Starting value	Final tuned value	Range
U-value of external walls [W/(K m^2)]	0.1	0.1591	0.1–0.1591
g-value of windows (–)	0.2	0.3	0.1–0.5
Solar transmittance (–)	0.17	0.24	0.17–0.47
Internal emissivity of windows (–)	0.837	0.6	0.5–0.9
External emissivity of windows (–)	0.837	0.05	0.03–0.837
Thermal bridges [W/(K•m^{2}floor area)]	0.03	0.045	0.025–0.06
Infiltration rates (ACH)	0.3	0.7	0.3, 0.7
C_d flow coefficient for internal openings (–)	0.65	0.80	0.6–0.8

The CVRMSE is a measure for the goodness-of-fit of a model showing the variability between simulated and monitored data [1]. It is calculated by

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(y_i - \hat{y}_i)^2}{n}} \tag{3}$$

$$CVRMSE = \frac{RMSE}{\bar{y}} \cdot 100 \tag{4}$$

The model is considered calibrated with NMBE <10% and CVRMSE <30%, if the model is calibrated with respect to hourly energy use for space heating [19]. Since there is no approved guideline that determines acceptance criteria for model calibration with respect to indoor temperatures, the same thresholds were applied in this study, even though the calibration was aiming for a NMBE and CVRMSE <5%. A threshold of 5% has also been applied in other studies [2, 4–6] and is thus used as a benchmark.

4.2 Calibration Data Set: Experiment 6 (Closed Bedroom Doors)

During that experiment, the ambient temperature varied between –2.9 and 17.2 °C, whereas the global solar radiation varied between 0 and 834 W/m^2. An on/off-controlled electric radiator was operated according to a specified PRBS signal (Fig. 3). The bedroom doors were closed during this experiment.

Figure 4 shows the trend of the operative temperature for Living Room South and Bedroom West at the end of the calibration. It can be seen that the model is reliable for predicting the temperature trend for cases with intermittent heating. If the electric radiator is turned off for a longer time (such as in the end of this experiment), the model predicts a faster temperature drop.

The overall UA-value of the building model is 83 W/K and is thus in the range of the values (70–100 W/K) identified during experiments conducted by Vogler-Finck et al. using inverse modelling [20]. If the UA-value of the model was

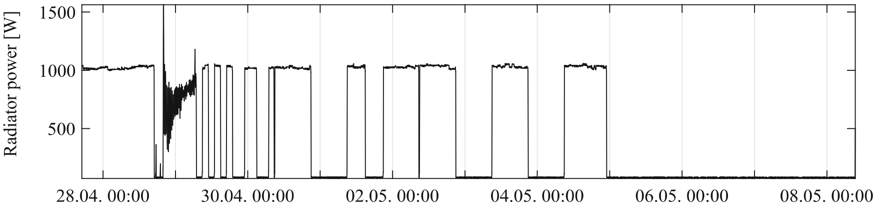

Fig. 3 Power supplied to the radiator during Experiment 6

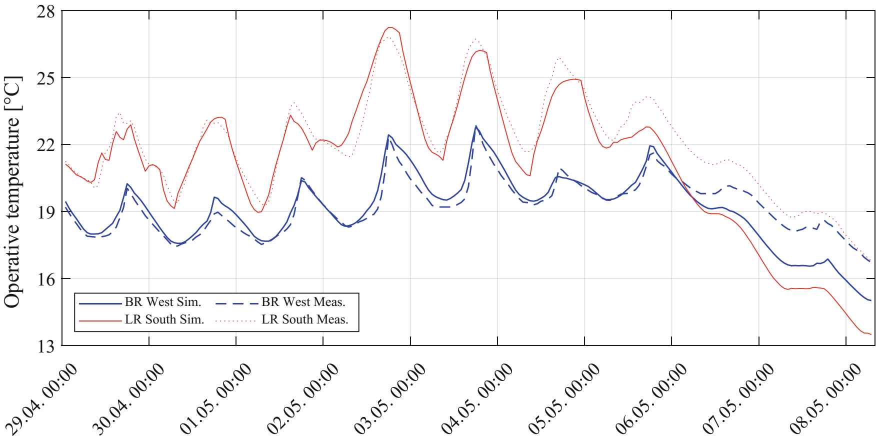

Fig. 4 Operative temperature trend in the Living Room South and Bedroom West at the end of the calibration

increased, the predicted temperature fluctuations would be even larger. The temperature fit for periods without any heating can be improved by considering the thermal mass of technical equipment (white goods) and by adjusting the properties of the PCM. Both will be investigated in further studies. The final NMBE and CVRMSE of Experiment 6 are shown in Table 3.

4.3 Example of a Validation Case: Experiment 7 (Open Bedroom Doors)

The model is also reliable for predicting the thermal dynamics of the building, if bedroom doors are opened. Figure 5 shows the trend of the operative temperatures in Living Room South and Bedroom West for the validation of Experiment 7. The temperature trend is similar for both Living Rooms as well as for both Bedrooms.

The model predicts the temperature fluctuations well for both rooms up to a temperature of 25 °C. It seems to slightly overpredict the maximum room temperature. This can be improved by tuning the thermal properties of the PCM. A summary of the results of all validation cases is given in Table 3.

The calibrated model predicts the temperature trend for all studied cases reliably, based on the NMBE and CVRMSE. Both indicators are below 8% for all studied cases, for most of the cases even below 5%. These results are in good agreement with other validation studies on residential buildings, where the building model was

Table 3 Summary of the NMBE and CVRMSE (for indoor air temperatures and operative temperatures) for all validation cases

Experiment	Room	NMBE (%)	MBE (°C)	CVRMSE (%)	RMSE (°C)	Energy use (kWh)	
						Measurement	Simulation
E1	BR East	5.57	0.94	6.05	1.02	51	42
	BR West	5.95	1.04	6.34	1.11		
	LR North	0.00	0.00	0.18	0.04		
	LR South	−0.56	−0.11	0.62	0.12		
E2	BR East	3.49	0.65	3.67	0.68	112	124
	BR West	2.56	0.47	2.72	0.50		
	LR North	−0.39	−0.07	0.75	0.14		
	LR South	0.74	0.14	1.26	0.24		
E3	BR East	3.47	0.64	3.92	0.72	65	73
	BR West	4.87	0.91	5.16	0.97		
	LR North	1.67	0.31	2.57	0.48		
	LR South	1.93	0.36	3.32	0.62		
E4	BR East	3.10	0.51	3.71	0.61	51	51
	BR West	6.76	1.20	7.00	1.24		
	LR North	1.11	0.21	2.67	0.51		
	LR South	1.60	0.30	2.99	0.57		
E5	BR East	−1.06	−0.22	3.61	0.74	PRBS signal given as model input and thus identical radiator power	
	BR West	0.14	0.03	3.23	0.67		
	LR North	−2.31	−0.47	4.59	0.93		
	LR South	−0.74	−0.15	5.23	1.07		
E6 (used for calibration)	BR East	−0.20	−0.04	3.82	0.71	PRBS signal given as model input and thus identical radiator power	
	BR West	0.80	0.15	4.17	0.80		
	LR North	3.54	0.77	6.46	1.40		
	LR South	4.56	1.01	7.61	1.68		
E7	BR East	−0.85	−0.19	3.71	0.83	PRBS signal given as model input and thus identical radiator power	
	BR West	−0.96	−0.21	3.81	0.84		
	LR North	−3.33	−0.74	4.49	0.99		
	LR South	−1.66	−0.38	3.47	0.79		

calibrated with respect to indoor temperatures [5, 6]. For experiments E2 and E3, the model predicts a slightly higher electricity use for keeping the indoor air temperature.

Only for Experiment 1, the model uses less electricity to keep the temperature set-point in the two living rooms. This discrepancy will be investigated in further studies.

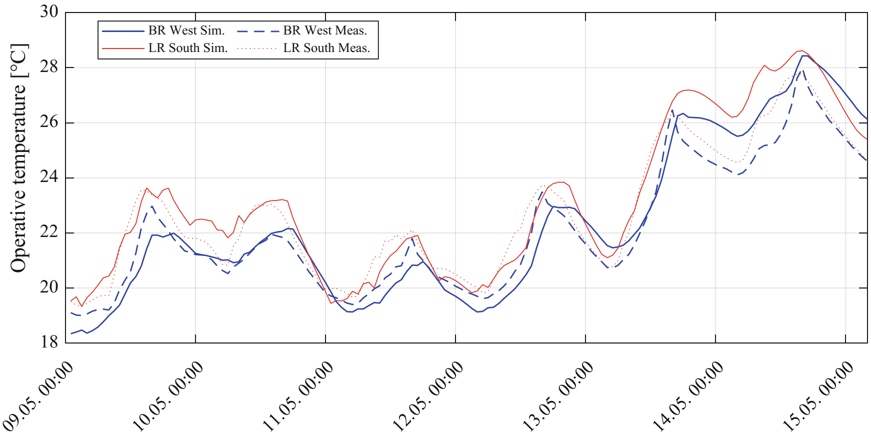

Fig. 5 Operative temperature trend in the Living Room South and the Bedroom West during experiment 7

5 Conclusion

The aim of this study was the calibration of a dynamic multi-zone building model of a super-insulated residential building located in Trondheim, Norway. Seven experiments have been used for the validation of the building envelope model (one for calibration and six for validation). The building model was calibrated on measurement results of a 9-day long experiment with respect to the operative temperature trend in different rooms. An on/off-controlled electric radiator with a capacity of 1 kW heated the building according to a pre-determined excitation sequence.

The calibrated model was validated against measurement data from six other experiments, where the validation was based on the NMBE and CVRMSE, revealing that both indicators are below 8% for all seven cases. The temperature trend of the calibrated model has been studied for cases with opened as well as closed internal doors. The model predicts the temperature trend for the different rooms reliably. The NMBE ranges between −3.33% (MBE is −0.74 °C) and 6.76% (MBE is 1.20 °C), whereas the CVRMSE is in a range of 0.18% (RMSE is 0.04 °C) to 7.61% (RMSE is 1.68 °C). Both indicators are 5% or lower for cases with open bedroom doors (E2, E3, E5, E7), which is in good agreement with other studies on calibrations with respect to indoor temperatures [2, 5, 6].

Compared to the measurements, the model predicts a faster temperature decrease, if the building is not heated (Fig. 4) even though the overall UA-value of the building model (83 W/K) is within the range of 70–100 W/K, which has been determined by Vogler-Finck et al. [20].

Therefore, further work will investigate the impact of additional thermal mass inside the building as well as the influence of the PCM on the indoor temperature trend. Furthermore, the impact of solar radiation on the indoor temperatures will be studied. A similar temperature trend for model predictions and measurements as response to intermittent heating will be important for the evaluation of ADR measures in future studies. The calibrated model will be used for testing different heating control strategies with regards to the energy flexibility potential that residential buildings can provide to the electricity grid.

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