BUILDING MODEL CALIBRATION METHODS FOR BUILDING OPERATION APPLICATIONS

F. Hengel[1], D. Jähnig[1], P. Nageler[2], R. Pertschy[1] and T. Weiss[1]
[1]AEE Intec, Gleisdorf, Austria
[2]EQUA Solutions AG, Zug, Switzerland

ABSTRACT

In order to make use of a dynamic simulation model even in the operational phase of a building, building model calibration is of great importance. This paper presents a first study in direction of such a building calibration for efficient use in practice: 1) key parameters were defined and a sensitivity analysis was carried out to identify the effects of parameter variations, and 2) different calibration methods were compared. The application of the methods at a Test-Box showed that key parameters can be used to calibrate a building model far more accurate than the requirements of the ASHRAE 14 guideline.

INTRODUCTION

In current practice building performance simulation is still almost exclusively used for design. However, it is expected that in the near future dynamic building models will support a more proactive building energy management during the whole operational phase.

First, discrepancies between simulated and measured values occur due to incomplete knowledge of the building or model assumptions (Heo, 2011). Such models need to be calibrated in an efficient way in order to identify the building's behavior properly. A simulation model can – if well calibrated – be applied to evaluate retrofit or usage behavior scenarios or operational changes of the heating systems.

Second, the simulation model – also called *digital twin* – can be coupled with the physical building in real time. Such a coupling opens up several possibilities:

- Specified goals can be controlled with the present boundary conditions and, if necessary, measures can be taken to achieve the target.
- Advanced control strategies such as model predictive control can be applied to minimize the real energy demand.
- In comparison to classical building monitoring, the simulation model offers much more extensive possibilities to record the condition of the building. These virtual sensors can be used to replace real sensors or to record quantities that are difficult or costly to measure such as operative room temperature, other comfort values, heat fluxes or the exposure of the solar radiation to the workplace.
- The digital twin in building operation can also be used for operational diagnostics. Malfunctions of the system and energy wasting user behavior can be detected by comparing the measured values with the simulation results.
- The comfort conditions for users in conjunction with energy demand optimization can be improved by user interaction with the digital twin. For example, a person can be contacted that the lights can be turned off or the room air temperature will get too hot unless there is a certain user reaction. Subsequently, real thermal comfort can be increased or real energy consumption can be decreased.

The calibration process plays an import part in the establishment of a digital twin in building operation. Reddy et al. (2007) and Fabrizio (2015) classified the calibration process in four categories:

- First, the calibration can be performed *manually* in an iterative process.
- In addition to the manual calibration, the calibration results are displayed *graphically* in comparative diagrams.
- Calibration based on *analytical* and *test* procedures: In this method, in situ inspections as well as test, e.g. blower door tests, are applied.
- *Automated* calibration techniques

In this study, only automated calibration techniques are considered in order to minimize the calibration time. In the literature, several automated calibration studies exist. Monetti et al. (2015) proposed a method to calibrate a building model by varying the material properties as well as infiltration rate and internal gains

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by means of the single objective optimization tool GenOpt (Wetter, 2001). Other studies (Delgarm et al. 2016) use multi-objective optimization algorithms in order to calibrate building energy performance.

The discrepancies between measured and simulated values are explained by Heo (2011) with four uncertainty categories:

- Uncertainties about the external environment such as the weather conditions and the building usage (occupancy) are referred to *scenario uncertainty.*
- The second category concerns about uncertainties in the building modelling called as the *building physics/operational uncertainty*. These uncertainties refer to the thermal-physical properties of the building envelope, the HVAC system as well as the internal gains and operation and control settings.
- *Model inadequacies* occur due to modelling assumptions, simplifications and ignored phenomena.
- Finally, *observation error* occurs due to data quality of the metered data.

The effects of the uncertainties can be evaluated in uncertainty and sensitivity studies (Saltelli et al., 1998). In external uncertainty methods, parameters are altered and the effects of their variation on the outputs are measured. In such studies, the largest influencing variables among the input data can be identified. This can help to deal with data gaps in the building modelling process. The parameters can be varied *one at a time* or *simultaneously.*

The discrepancy between the simulation results and the measurement data can be validated by means of metrics. The ASHRAE guideline 14 (2002) is commonly used to check if a simulation model is sufficiently accurate. This standard suggests that the hourly coefficient of variation of the root mean square error (CVRMSE) value for energy models must be less than 30% and the mean bias error (MBE) must be within ±10%. Other standards such as the IPMVP (2003) recommend lower threshold values for the CVRMSE with 20% and the MBE with ±5%. Other metrices such as the RMSE or the square error can also be used for calibration, but for these metrices no standard thresholds where found.

The sensitivity index can be used to screen the most influential parameters to the model output (Fabrizio & Monetti, 2015).

PAPER OBJECTIVES

The aim of this paper is to develop an adequate calibration method for the simulation model of a digital twin in building operation. The requirements for such a calibration method can be described as follows:

- The calibration process has to be automated in order to be efficient enough for practice.
- The calibrated model must accurate enough in order to reproduce the measured data within its uncertainties.
- The digital twin must react flexibly if the boundary conditions change. This means that the model must be able to recalibrate itself during operation.
- The digital twin has to be able to detect occupancy behavior properly.

This paper addresses the first and second requirement.

In the first section of the paper, the investigated calibration methods are explained. In these methods, input parameters for a thermal zone are identified as calibration key parameters and varied: Solar heat gain factor without shading, solar heat gain factor with shading, thermal inertia and thermal heat loss factor. The parameters are calibrated in order to find the values that lead to the smallest difference between measured and simulated air temperature.

In the second section, the calibration method is applied to a case study, in which measurement data of a Test-Box with three conditioned rooms were used. A sensitivity analysis was carried out in the detailed building simulation tool IDA ICE (EQUA, 2020) in order to identify the effects of key parameter variation. Different calibration methods with varying key parameters were compared. The calibration results are evaluated according to the ASHRAE guideline 14 and the square error.

CALIBRATION METHOD

The number of parameters will become very large when calibrating an entire building. To simplify first experiments, the calibration method is developed for a single thermal zone. Each thermal zone could later on be calibrated separately, or findings from one zone can be transferred to others. The building simulation environment IDA ICE is used in the calibration process, because it is a detailed validated simulation model that can be used at any level of detail for large-scale systems (Nageler, 2018). The variable timestep of the IDA solver speeds up the simulation by increasing the timestep during periods with little activity and shortens it for foreseeable events. This means that even short events such as window ventilation can be recorded accurately. Furthermore, the tool's integrated features such as *Parametric Runs*

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for parameter studies, or *Graphical scripting* as an easy way of graphically supported automated modelling technique allow an automated calibration, that is made even more efficient through parallelization techniques. *Parametric Runs* supports parameter studies, in which the parameters can be varied either *one at a time* for sensitivity analysis or *simultaneously* for automatic optimization. For this study, the single objective optimization tool GenOpt (Wetter, 2001) was used.

Physical phenomena

A digital twin in building operation is particularly suitable for new buildings or for fundamentally renovated buildings. Usually there is little time between the completion of the construction work and the people moving in. This means that short periods for calibration must be sufficient in which all essential physical phenomena should be covered. Such periods in which no arbitrary user influence is present are essential for calibration in order to obtain a basic model, which takes the following physical phenomena into account:

- Any *heat transport* between zones as well as towards environment. This includes both heat conduction, thermal bridges as well as infiltration.
- Any *thermal inertia* of a zone. This means that the thermal mass of the system (zone air, furniture as well as internal and external constructions) influence the temperature change in the room.
- *Any heat gain by solar radiation*. Here it is relevant to distinguish between the solar gains with and without shading elements. In case of multiple and separately controlled shading elements, such a calibration needs to be repeated per window instead of per zone.
- Furthermore, local heating and cooling units and natural or mechanical ventilation affect state variables in a room.

Based on a model that is calibrated for periods without occupancy, one can try to detect any user behavior with algorithms. This can be supported with CO_2 sensors or by evaluating the temperature gradient in time. Such an algorithm is not part of this paper.

Key parameters

In order to keep the calibration method simple, the number of the calibrated parameters needs to be reduced. All parameters describing one of the physical phenomena mentioned above, are thus combined into one calibration parameter, called *key parameters*.

For the *calibration of the heat transport* from the room to adjacent rooms and to the environment, the physical material properties or the wall thickness can be varied. Varying thermal bridges or leaks to adjacent rooms and to the environment will have approximately the same effect. We will therefore combine all these parameters into one key parameter. In principle, there are two possible levels of details:

i. The first option is to calibrate *each individual wall*. With this procedure the number of parameters to be calibrated is greater. Consequently, more calibration runs are required, which takes longer. The time needed for a calibration is an essential factor, since the aim is to calibrate also large buildings with many individual rooms. Furthermore, recalibration should also be carried out during operation. The probability is also higher that no global optimum is found. The *thermal conductivity* of the individual walls can be used as a key factor for modeling heat transport. On the other hand, the *heat capacity* or *wall thickness* can be used as a key factor to calibrate the inertia of the system. In order to reduce the number of key parameters, it is sufficient to use one heat transfer factor for all external walls.

ii. The second option is to use one single heat transfer factor for the entire room. This shortens the time required for calibration enormously. However, the temperature conditions of the environment and the adjacent rooms have a significant influence on the calibration, since depending on the temperature, the heat flows can be reversed. Normally the heat transport to the environment has a much greater influence than the heat transport to adjacent rooms, because the temperature difference to the environment is much greater. This means that the heat flow to the environment can be calibrated with sufficient accuracy if the temperature conditions to the adjacent rooms remain similar. As soon as heat flows to adjacent rooms show a significantly higher contribution or the heat flows reverse, the simulation model will not fit anymore. If the deviation of the model to the reality is too large, the model must be recalibrated.

Instead of a total heat transfer coefficient that influences many input parameters, we use a simple *extra heat loss factor for thermal bridges* as our key parameter. In the same way, we use an *extra mass* as key parameter for the thermal inertia.

Which of the two levels of detail can be selected depends on the level of knowledge of the wall constructions. The wall constructions are often well known with materials and their layer thicknesses, but the far greater problem is often lack of information about thermal bridges and leaks. If the state of

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knowledge is good, variant ii) can be chosen, otherwise variant i).

Next, the heat gain by solar radiation entering the room must be calibrated. A constant *solar heat gain coefficient* can be used here as a key parameter for the entire zone instead of calibrating the spectral data of each window glass separately.

Furthermore, shading elements reduce the amount of solar radiation entering the room. In this case, the solar heat gain coefficient is reduced by a *solar shading multiplier*.

Modelling method of the thermal zone

This paper describes a method in which each individual room is calibrated separately. The measured room air temperature of the adjacent thermal zone is set as boundary conditions. For this purpose, the convective heat transfer coefficient of the adjacent zone from the air to the wall can be set approximately constant. Omitting adjacent zones speeds up the simulation.

Calibration process

In this paper the tool GenOpt (Wetter, 2001) is used to support calibration. GenOpt is an open source tool, which provides single or multi parameter optimization by minimizing a single objective function. Other tools such as MOBO (Palonen et al., 2013) offer optimizations based on more objective functions, but this is not necessary in this case. Any metric (Ljung, 1998) that can evaluate the deviation between the simulated and measured values can be used as an objective function. Usually only the room air temperature is measured, sometimes in combination with the air humidity and the CO_2 concentration. Therefore, the room air temperature will be used to determine the state of calibration. For example, the square error or the CVRMSE and MBE recommended by ASHRAE can be used as metrics. The square error or the CVRMSE alone provides a good evaluation of the simulation model. The MBE alone is not sufficient to evaluate the simulation model, because it only determines a systematic deviation. A combination of the MBE with the CVRMSE can thus be used, where the respective metrics are added and/or weighted in an objective function.

The calibration can be carried out with a different number of calibration steps. The key parameters can be calibrated separately, several at once or all simultaneously. At least all parameters that belong to a certain physical phenomenon should be calibrated simultaneously, otherwise no global optimum can be determined. For stepwise calibration, a period in which each individual physical phenomenon is considered in isolation is crucial. If this is successful, a stepwise calibration is more accurate but slower. The effects of different calibration steps are shown in the chapter “Results and Discussion”.

EXPERIMENTAL SETUP

Test-Box

The Test-Box is located at AEE INTEC in Gleisdorf, Austria (15.709 East, 47.107 North), see Figure 1. The facility consists of two experiment rooms and a technical room hosting the air exchange system and the central PLC.

This research relied on measurement data from Room 2 (see R1, in Figure 1) only, which was used for the calibration study. External shading of the terrain and other facilities was taken into account. The façade with the embedded window faces south. The window is equipped with controllable venetian blinds between the glass planes. A door is installed in the north wall (towards the technical room). Ventilation of the Test-Box is assured by means of an air-handling unit, which can be operated either in supply air or exhaust air mode. In addition, heat can be supplied to the room by an electric radiator. Table 1 shows the thermal construction properties of Room 2 of the Test-Box.

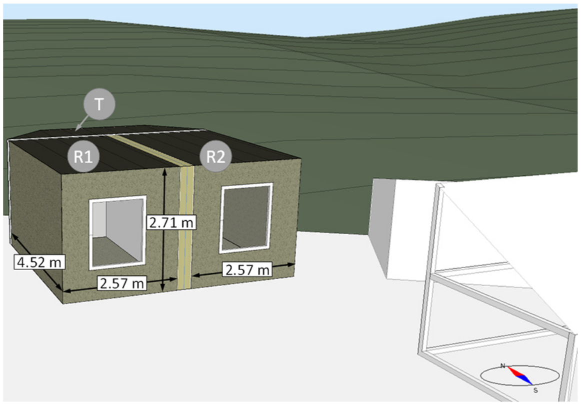

Figure 1: Model of the Test-Box with inner dimensions.

Table 1: Construction overview of the Test-Box

	Thickness	Area	Mass	Mean conductivity	Heat capacity	U-value
	m	m^2	kg	$W (m K)^{-1}$	$kJ K^{-1}$	$W m^{-2} K^{-1}$
Ext. ceiling	0.448	11.62	1122	0.0508	1741	0.111
Ext. floor	0.533	11.62	1497	0.0548	2361	0.101
Ext. south wall	0.276	5.06	202	0.0400	327	0.141
Ext. east wall	0.405	12.25	942	0.0477	1470	0.115
Int. north wall	0.223	5.37	422	0.0670	714	0.284
Int . west wall	0.334	12.25	502	0.0399	749	0.117
Int. door	0.040	1.60	17	0.0940	29	1.617
Ext. window	-	1.90	0	-	-	0.960
Total	**-**	**61.67**	**4703**	**-**	**7391**	**-**

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Measurement system and weather data

The Test-Box is equipped with numerous sensors that measures the temperature of the surfaces, the room air at 4 different heights and the operative room temperature. Temperatures are measured with Pt1000 sensors. Furthermore, the CO_2 concentration and the relative humidity are measured. The measurement data is available from 29.10.2019 to 7.1.2020. Figure 2 shows the measured room air temperature of the three rooms in the Test-Box.

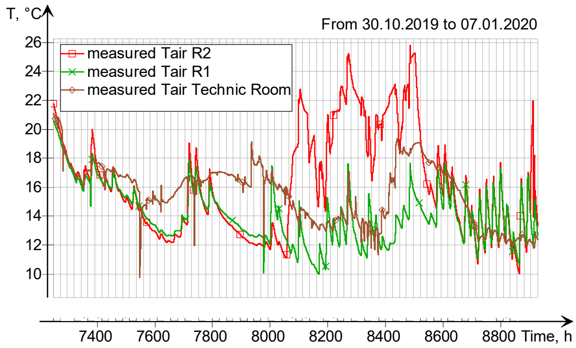

Figure 2: Measured room air temperature.

A weather station located next to the Test-Box and maintained by the AEE INTEC provides highly accurate weather data. The weather station measures the air pressure, the ambient air temperature, the relative humidity and the direct and diffuse solar radiation.

SIMULATION SCENARIOS

The scenarios are split into two parts. In all scenarios, Room 2 is modelled with one thermal zone, in which the temperatures of the neighboring rooms are set as boundary conditions. The actual wall constructions were converted into an equivalent wall layer regarding the thermal properties in order to reduce the number of calibration parameters. The constructions of the ceiling and floor are not calibrated, as the heat flows to the surroundings can as well be calibrated with the other two outer walls. First, a sensitivity analysis is performed, in which the influence of the key parameters are investigated. Second, the proposed calibration methods are tested based on the Test-Box facility. The evaluation interval is from 4.11.2019 to 7.1.2020. Ahead of the evaluation interval, lies a 6 days settling period. Figure 3 shows an overview of the Test-Box operation, in which a value 1 indicates that the action is executed. The solar radiation is also displayed. 0.4 means that the direct solar radiation exceeds 100 W per m^2.

Sensitivity analysis

In the sensitivity analysis, the thermal building model is based on the best knowledge of the modeler out of construction plans. Afterwards, the key parameters were varied +-50% in order to see the effects of each key parameter.

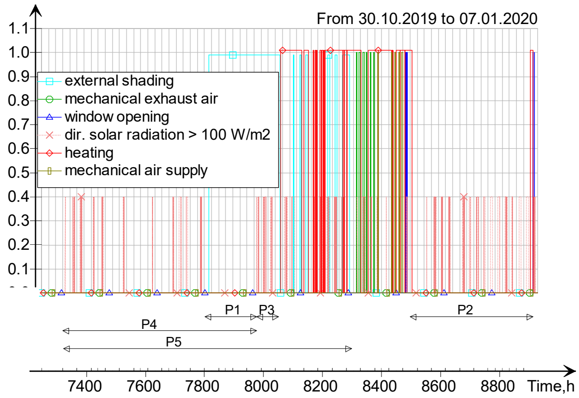

Figure 3: Overview Test-Box operation; direct solar radiation; calibration periods P1-6.

Calibration scenarios

Table 2:
Scenarios overview with selected key parameters and calibration periods.

Scenarios			Key parameters					
Id	Description	Calib. step	Each int. wall λ	Each int. wall c_p	Extra heat loss	Air mass	g	g_s
1	Slow calib. V1	1	P1	P1	P1	P1		
		2					P2	
		3						P3
2	Intermediate calib. V1	1	P4	P4	P4	P4	P4	
		2						P3
3	Simultaneous calib. V1	1	P5	P5	P5	P5	P5	P5
4	Slow calib. V2	1			P1	P1		
		2					P2	
		3						P3
5	Intermediate calib. V2	1			P4	P4	P4	
		2						P3
6	Simultaneous calib. V2	1			P5	P5	P5	P5

The calibration periods are shown in Figure 3 with P1-6. Table 2 shows six examined scenarios, in which a general distinction is made between the calibration of each internal wall (thermal conductivity λ; specific heat capacity cp) and an extra heat loss parameter to model the heat loss to ambient (V1 with Id`s 1-3) and an overall heat loss parameter (V2 with Id`s 4-6) in order to adjust the heat transfer with the ambient and the adjacent rooms. Furthermore, calibrations with a different number of calibration steps are examined and referred as *slow intermediate* and *fast*.

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RESULTS AND DISCUSSION

Sensitivity analysis

Figure 4 shows the results of the sensitivity analysis in a parallel coordinate diagram. The figure shows four sub plots a-d), each showing the effects of one separate parameter on the error as color codes. The diagrams show that the variation of the g-value from the window has the greatest effect on the results, followed by the extra heat loss. Here, the recalibration of the g-value due to dirty windows during operation of the digital twin can be particularly useful. The variation of the air mass and the integrated shading, on the other hand, have little influence on the results.

Calibration scenarios

Table 3 gives an overview of the results of the scenarios. The table also shows the progress after each calibration step. Before the calibration starts the model has a square error of 6786, the CVRMSE of 9.399 % and the MBE of -10.02 %. In all scenarios the accuracy required by the ASHRAE standard can be achieved. The calibration of the g-value of the windows has the greatest influence on the accuracy. The two most effective methods are the simultaneous calibration with (3) or without (6) calibration of the internal walls. The results of these two scenarios are highlighted in grey. Due to the higher accuracy and the faster calibration, since only one step is necessary, a simultaneous calibration is preferred, but one must be aware that a different choice of calibration periods can lead to improved results in stepwise calibration. Furthermore, the higher accuracy can be explained on the one hand by the longer calibration period and on the other hand by the fact that not all physical phenomena can be considered in isolation in the individual calibration steps. For example, there are rarely long periods without solar radiation during which only heat transport can be calibrated. Furthermore, the inertia of the thermal zone must be taken into account already during the calibration of the heat transport to the environment, but the largest dynamics occur only with solar irradiation. This indicates a more accurate calibration if all key factors are calibrated together. The additional calibration of the heat transport over the internal walls by means of conductivity and specific heat capacity does not show a significant improvement of the results even with large temperature differences between the rooms (see Figure 2). The reason for this is that in the selected calibration period P5 in V1 the heat transport to adjacent rooms cannot be calibrated with sufficient accuracy because the temperature difference between the rooms was too small and was covered by other physical phenomena. During the evaluation period, there were deviations between simulation and measurement because a significant heat flow between the rooms occurred. This temperature difference between the rooms, in order to achieve a better calibration result, could also be artificially induced by targeted heating.

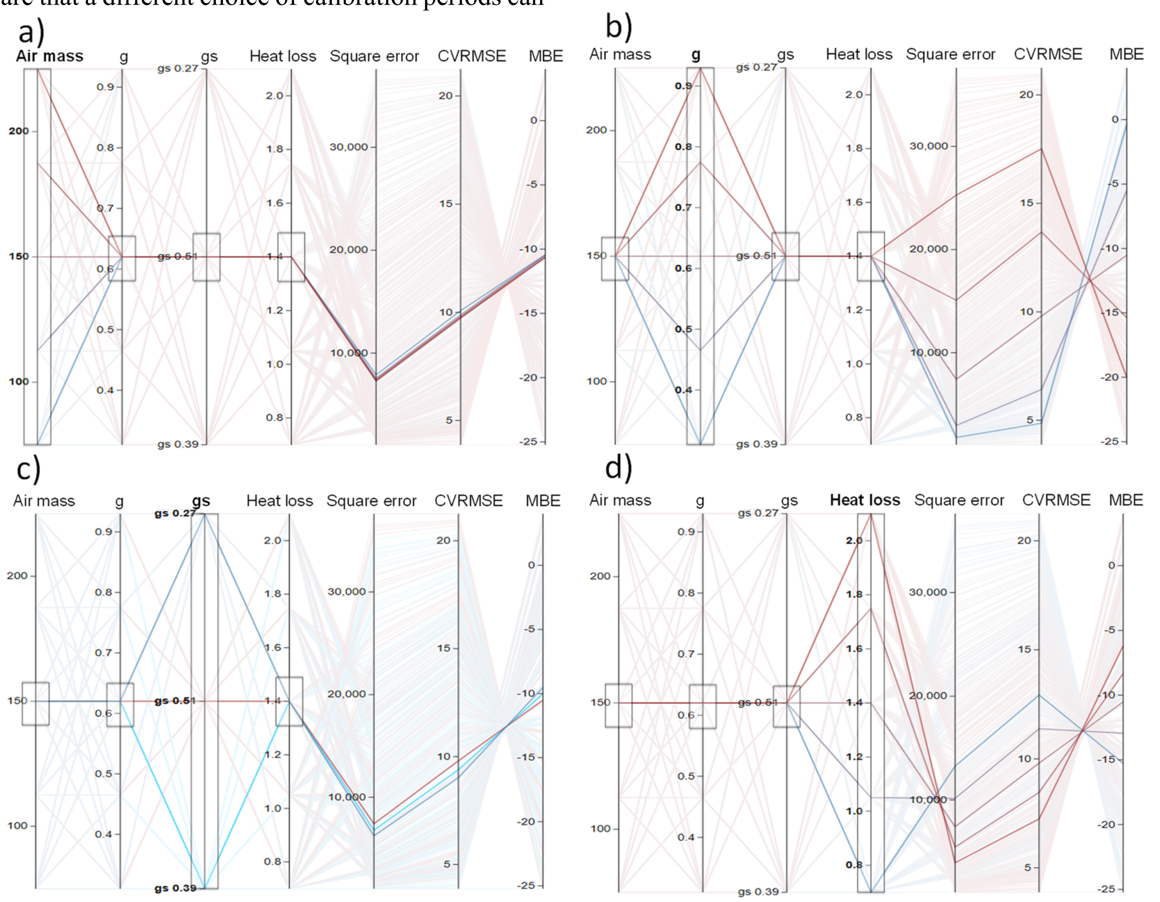

Figure 4: Results of the sensitivity analysis; each subplot shows the effects of the highlighted key parameter as color codes

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Table 3:
Overview simulation results.

Scenarios			Results		
Id	Description	Calib. step	Square error	CVRMSE(%)	MBE(%)
1	Slow calib. V1	1	4006	7.38	-8.57
		2	723	1.57	-0.23
		3	646	3.20	-1.82
2	Intermediate calib. V1	1	924	3.90	-4.12
		2	801	3.66	-3.95
3	Simultaneous calib. V1	1	306	2.18	-0.93
4	Slow calib. V2	1	1524	4.69	-4.74
		2	424	2.35	-0.10
		3	414	2.24	0.18
5	Intermediate calib. V2	1	438	2.61	-1.37
		2	395	2.42	-1.06
6	Simultaneous calib. V2	1	316	2.21	-0.78

The calibration progress of the two most accurate and effective methods with Scenario 3 and 6, in which all key parameters are varied simultaneously, are shown in Figure 5. The results show that the calibration algorithm finds a solution close to the optimum with about 100 runs relatively quickly and needs approximately another 100 runs to find the optimum and then aborts the algorithm. The optimum can be found comparably quickly in both variants. However, the results in Scenario 3 are insignificantly more accurate, as the heat transport via internal walls is calibrated.

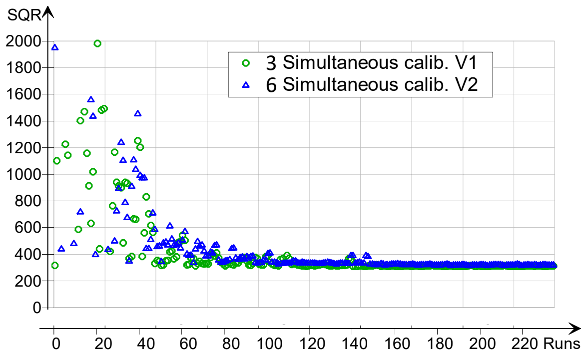

Figure 5: GenOpt calibration of scenarios 3 and 6: Number of runs vs. square error SQR.

Figure 6 shows the results out of the calibration process in GenOpt. The figure shows the square error of scenario 6 as a function of the extra heat loss on the x-axis, the air mass as area, the integrated window shading as shape and the solar heat gain coefficient g as color code.

In Figure 7 the effects of the g-value variation on the results can be seen more clearly by showing the g-value on the x-axis and the extra heat loss as a color code.

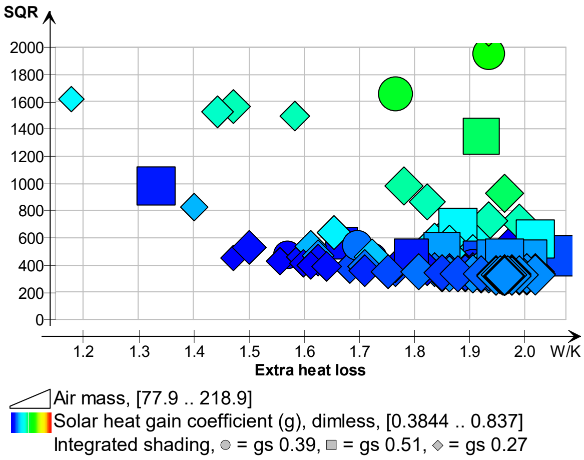

Figure 6: GenOpt calibration of scenario 6: Square error SQR in dependence of the key parameters.

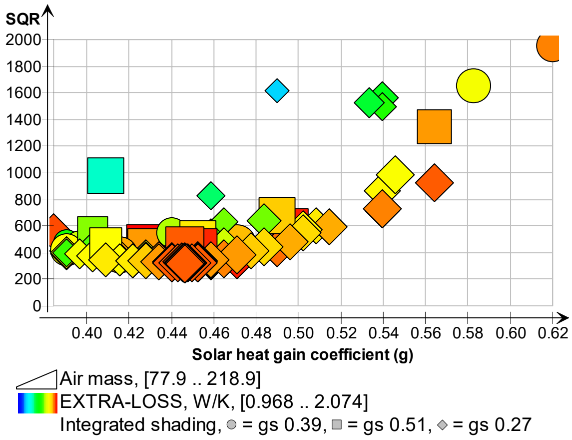

Figure 7: GenOpt calibration of scenario 6: Square error SQR in dependence of the g-value.

Figure 8 shows the comparison of the measured and simulated room air temperature of Room 2 of simulation scenario 3. The simulation results show a good agreement compared with the measurement data, especially if no mechanical airflow is present, in which the leak for ventilation is open, see Figure 3. The solar irradiation can also be modelled very well, see P2 in Figure 3.

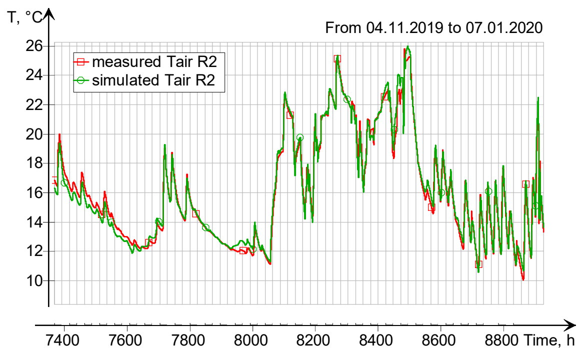

Figure 8: 3 Simultaneous calib. V1: Measured and simulated room air temperature.

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CONCLUSION

This paper presents and discusses several calibration methods, which can be applied to a digital twin in building operation. Key parameters are thus defined, which can be used to calibrate the thermal heat transfer with the ambient and the surrounding rooms, the thermal inertia of the room, the solar irradiation, the integrated shading device and the natural ventilation. The results show that the best key parameter combination is to use an overall extra heat loss and the air mass to model the heat exchange and the thermal inertia, the g-value and a multiplier for the shading device for the solar irradiation. The choice of calibration periods has a significant influence on the result. With an improved choice of calibration methods, the result could be further improved. If it is possible to define periods in which each physical phenomenon can be considered in isolation, a stepwise calibration is probably more accurate but slower. Such calibration scenarios were implemented in the simulation environment IDA ICE, which provides optimization using the integrated features *Graphical script* and *Parametric Runs* coupled to GenOpt. IDA ICE also uses a pressure-driven calculation method of the air flows through windows that is important to capture the occupancy behavior. The results show an excellent agreement of the measurement data and the simulation results.

OUTLOOK

The calibration methods and key parameters presented in this paper can be used and applied to a digital twin for building operation applications. The next step is the calibration of whole buildings. Therefore, it is essential to the detect the occupancy by means of artificial intelligence based on CO_2 concentrations and user patterns. Furthermore, it is necessary to define the applications for the digital in building operation and develop its interfaces to the users such as building users and facility managers. The real time measurement and set point data exchange is already implemented in IDA ICE.

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