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Multi-Stage Multi-Level Calibration of a School Building Energy Model

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Abstract

The calibration of the building input parameters is the process aimed at minimizing the difference between actual and simulated performance. It is of paramount importance to implement a reliable model of an existing building, as this enables the study of its behaviour and the evaluation of improvement actions. However, when the number of unknown or uncertain parameters (such as thermo-physical properties of components and materials, infiltration and ventilation rates, internal thermal capacitances, system characteristics, etc.) is large, manual calibration methods require unacceptably long trial-and-error cycles and do not always ensure a significant improvement, as the complexity of the simulation increases. This paper explores the potential of calibrating an entire building simulation model by means of a stepwise approach and automated calibration of the model (optimization-based calibration). The approach is *multi-stage* since it considers different reference periods in order to calibrate different parameters, and *multi-level* as it starts from a room level, in order to apply the calibrated parameters to the entire building, and perform calibration to refine the estimation of the missing parameters. The described approach is shown to be effective in reducing the number of initial unknown inputs at each step as well as in validating the previous calibration results when moving to the multi-zone level. The application of the proposed calibration method to a case study aims at demonstrating the details of its implementation and its efficacy, using the available limited number of measurement sensors and short observation periods.

1. Introduction

In the last few decades, an increasing amount of research has focussed on the implementation and applications of building simulation procedures for the definition and optimization of retrofitting strategies, for building operation or for the application of predictive methods for building system control in existing buildings (Tahmasebi and Mahdavi, 2013). Energy diagnoses of buildings require accurate simulation models to allow a reliable representation of the building and energy systems behaviour. To implementing a reliable building model, expensive and long-term monitoring of some building performance variables (e.g. energy consumption, air temperature, etc.) is generally required. A calibration process, by changing uncertain input parameters until the output matches measured values is often adopted to improve the agreement. However, when the complexity of the building is high, the number of descriptive parameters is typically too high to rely on a calibration method based on an iterative manual procedure. Such a procedure requires a time-consuming trial-and-error process (Yang et al., 2015) and potentially leads to results which are still far from reflecting the real building data. To simplify the problem, the calibration process can be divided into different steps in order to limit the number of model parameters calibrated at each step, considering their different impact in different reference periods. In addition, the monitoring phase can be less expensive by choosing a small representative portion of building to monitor and calibrate the values of some specific quantities to be extended to the whole-building model, thus leaving fewer parameters to calibrate when the whole building model is considered. This paper explores the potential of calibrating an entire building simulation model by means of a multi-stage and multi-level approach based on an automated process. The calibration was applied in a case study, a school building located in the North-East of Italy, monitored from December 2012 to April 2014. The result is a multi-level calibration implemented through the automated discrepancy minimization of the simulated temperatures and the temperatures measured during short-term periods.

2. Methods

2.1 Calibration Method

The proposed calibration method is based on the monitoring of the air temperature of a limited part of a building, such as one or two reference rooms and all the surrounding rooms (i.e. monitored zones) in order to provide the required boundary conditions. The calibration phase is split into two main levels: (i) the calibration of a small part of the building (i.e. partial-building calibration) and (ii) the subsequent calibration of the whole-building model (i.e. whole-building calibration). To do this, a model of the reference rooms is set up to be calibrated. Inputs are not calibrated all together but the model is progressively calibrated during different periods of the year, adopting a multi-stage approach. These periods are chosen in order to avoid as much as possible any interference from different parameters and to be representative of different seasons and building operation in relation to people occupancy and the HVAC system mode (on/off). In each period, different sets of input parameters are consequently calibrated (e.g. physical characteristics of the building envelope and infiltration, heating system characteristics, shading level and ventilation rate due to occupants' presence and behaviour). The result is a multi-stage calibration of partial-building model. The calibrated parameters are extended to the whole-building model, and the remaining unknown quantities are calibrated, considering again the different periods already defined. The simulation output considered to calibrate the model is the air temperature of the reference rooms in the first level and the air temperature of all the monitored rooms in the second level. The calibration is performed according to an optimization-based approach (Tahmasebi et al., 2012; Tahmasebi and Mahdavi, 2013) aimed at the simultaneous minimization of the differences between the simulated and monitored indoor air temperatures of the selected reference rooms in partial-building calibration and of all the monitored rooms in the whole-building calibration. In order to represent the cumulative differences between measured and simulated air temperatures, the cost function of the optimization-based calibration is defined using two statistical indexes, namely the Coefficient of Variation of the Root Mean Square Difference CV(RMSD), and the regression coefficient R^2 (Equations 1 and 2):

$$CV(RMSD) = \frac{RMSD}{\overline{m}} \cdot 100 \quad (1)$$

with:

$$RMSD = \sqrt{\frac{\sum_{i=1}^{n}(m_i - s_i)^2}{n}} \quad (2)$$

where: $\boldsymbol{m_i}$ is the measured indoor air temperature; $\boldsymbol{s_i}$ is the simulated indoor air temperature; $\boldsymbol{n}$ is the number of the simulation time steps and $\overline{m}$ is the measured mean temperature. The determination coefficient R^2 (Equation 3) is used for describing the proportion of the variance in measured data according with the model (Moriasi et al., 2007):

$$R^2 = \left(\frac{n\sum_i m_i \cdot s_i - \sum_i m_i \cdot s_i}{\sqrt{(n\sum_i m_i^2 - (\sum_i m_i)^2 \cdot (n\sum_i s_i^2 - (\sum_i s_i)^2}} \right)^2 \quad (3)$$

For calibration purposes, the minimization of the CV (RMSD) was prioritised and different weighting factors were assigned to the statistical indexes. A cost function f (Equation 4) is defined for each monitored zone:

$$f = 0.7 \cdot CV(RMSD) + 0.3 \cdot (1 - R^2) \cdot (CV_{ini}(1 - R_{ini}^2)) \quad (4)$$

and the overall cost function f_{tot} is calculated as their summation. In Equation (4), CV_{ini} is the coefficient of variation of the RMSD of the initial model, and R^2_{ini} is the coefficient of determination of the initial model. The parameters calibrated in one period are also adopted for the periods following. In the same way, those calibrated on the partial-building model (e.g. reference rooms) are extended to other similar zones where they can reliably be expected to be the same. In order to test and illustrate the abov-mentioned methodology, a school building was calibrated in a case study. While the first level of this methodology (e.g. the partial calibration) has already been implemented and described in some previous works (Penna et al., 2015a and 2015b), this paper focuses on the implementation of the second level (whole-building calibration). Two periods of the year have been considered to date, both without occupants: Period 1, characterized by no occupancy and system off, and Period 2, characterized by no occupancy inside and system on (Fig. 1). In order to test their effectiveness, the calibrated models in Period 1 and Period 2 were validated in other periods with the same characteristics, respectively unoccupied building, passive mode and unoccupied building, heating system on.

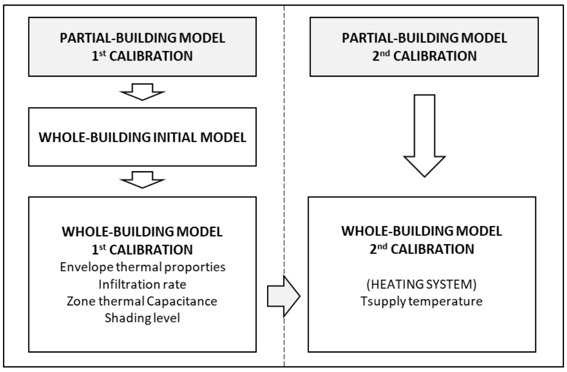

Fig. 1 – Scheme of the applied calibration procedure: from partial-building to the whole-building calibration. Period 1: non-occupied building, passive mode, Period 2: non-occupied building, system on

2.2 Monitoring of the Case Study

The building selected for testing the proposed method is a primary school located in Schio, a municipality in the North-East of Italy (Fig. 2). The building has three storeys: the basement and two upper floors, where the classrooms are. Two overlying classrooms located on the first (R1) and second floors (R2), were chosen as the reference rooms (Fig. 3) for the first level of the calibration, so the measuring instruments were located in those rooms and in the adjacent spaces (B1, B2, B3, B4, B5, B6 and B7) in order to also monitor the boundary conditions of the reference rooms. Measured air temperature was collected for 9 rooms in total (Fig. 3). The monitoring setup included data loggers to measure indoor air temperature (accuracy ±0.35°C) and supply and return radiator pipe temperatures at small intervals (10 minutes). In the first level of this approach (Penna et al., 2015a and 2015b), i.e. the partial-building calibration, also referred to as the 'two-zone calibration' in the following sections, the monitored temperatures of the spaces adjacent to the reference rooms had been used as boundary conditions. Moving to the second level, the so-called multi-zone or whole-building calibration, those boundary temperatures were used together with those of the reference rooms in the calibration process. A weather data file was created through the hourly weather recordings from the weather station of the municipality of Malo (10 km far away from school site).

2.3 Whole-Building Model Simulation and Calibration (Period 1)

The dynamic simulation model of the entire school was implemented with the simulation code TRNSYS v.17. A 3D geometrical model of the building was described using the TRNSYS plugin and Google Sketch-up v.8, while the building thermo-physical characteristics were set in TRNBuild. The model of the building was defined through the multi-zone building subroutine Type 56, using Simulation Studio, and ground temperature profile was modelled with the subroutine Type 77. A simulation time-step of 10 minutes was set.

Fig. 2 – Case study: San Benedetto Primary School (Italy)

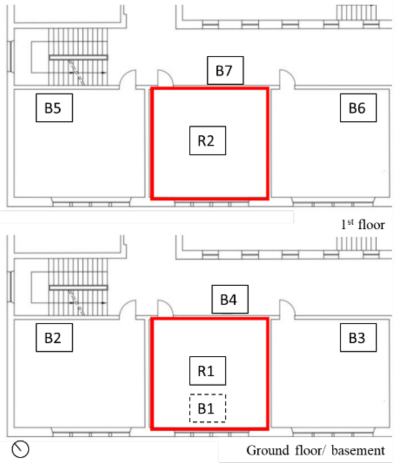

Fig. 3 – Monitoring of the case-study: sensors inside the 9 monitored rooms. Letters R and B before sensor numbering indicate respectively Reference room and Boundary room

Calibrated parameters from the partial-building (Table 1) model derived from the previous works (Penna et al., 2014, 2015a and 2015b) were used to construct the model of the entire school building. In detail, calibrated values of the thermal properties of the envelope (i), the infiltration rates (ii), the zone thermal capacitance, and the shading coefficients (iii) obtained from the two-zone calibration were extended to all the similar thermal zones (class-rooms on the ground and first levels) in order to construct the whole-building multi-zone initial model (Table 1). Moreover, the multi-zone model requires a certain number of additional data that were not calibrated in the first level, namely the frame conductance and the glazing thickness of the single-glazing windows, the infiltration rate of the basement and the corridors, the thickness of the ground floor hollow slab and the shading coefficients. For all these quantities, tentative values were set in order to build the whole-building initial model (Table 3) and were calibrated further. For all calibration parameters, a variation range of ±20% of the initial value was determined for the calibration process. The parameters calibrated during Period 1, were extended further to the model for the calibration of the heating system operation during Period 2. The calibration was validated (Table 6) by simulating the building model in the period 20th August–1st September (unoccupied building, passive mode).

2.4 Whole-Building Model Simulation and Calibration (Period 2)

Calibration in Period 2 has the aim of calibrating the heating system characteristics and operation.

Table 1 – Input calibrated in the partial-building level for Period 1 (from 5th to 19th August) and extended to the whole building

Parameters	**Calibrated value**
Envelope thermal properties	
External Wall Brick	
• *Conductivity λ [W/(m K)]*	**2.34**
• *Density ρ [kg/m3]*	**1540**
• *External Solar Absorpt.*	**0.34**
Internal Wall Brick	
• *Conductivity λ [W/(m K)]*	**2.484**
• *Density ρ [kg/m^3]*	**2140**
Internal floor Hollow Slab	
• *Conductivity λ [W/(m K)]*	**1.8216**
• *Density ρ [kg/m^3]*	**1101**
Roof Hollow Slab	
• *Conductivity λ [W/(m K)]*	**2.54**
• *Density ρ [kg/m^3]*	**1387**
• *External Solar Absorpt.*	**0.58**
Window 1	
• *Frame Conductance U [W/(m^2 K)]*	**4**
• *Transmittance * [W/(m^2 K)]*	**1.57**
Infiltration rate [ACH]	**0.21**
Air node thermal capacitance (mult. factor)*	**17.55**

The system was simulated through TRNSYS subroutines Types 869 and 362. The characteristics of the radiators calibrated during Period 2 in the two-zone calibration (Table 2), the heating system operation schedule and the radiators' supply temperature collected in the same period, were adopted for all radiators in the school in order to simulate the whole-building model. Two operation modes were determined: one during working days, based on a scheduled heating time and a climatic control of the water supply temperature, and a setback mode, when the building is unoccupied for a long period. During the scheduled heating time, the system is turned on from 6 am to 12 pm and a climatic adjustment of the radiator supply temperature, $T_{supply,0}$, is assumed as in the following equations:

$$\text{If}\quad T_{ext}<10°C;\quad T_{supply,\,0} = (a \cdot T_{ext} + b) \tag{5}$$

$$\text{If}\quad T_{ext}>10°C;\quad T_{supply,0} = c \tag{6}$$

where T_{ext} is the outdoor air temperature and a, b, c are the multiplying coefficients of the supply temperature of the radiators. Outside the scheduled heating time, the heating system is switched on only when the indoor temperature falls below 14°C. For this period the supply temperature $T_{supply,0}$ assumes a constant value, d

$$\text{if}\quad T_{indoor} < 14°C;\quad T_{supply,0} = d \tag{7}$$

Moreover, a decremental factor is applied to $T_{supply,0}$ to take into account the thermal losses due to the distribution system, as follows:

$$T_{supply,1}= T_{supply,0} - \Delta T_1 \cdot (20 - T_{ext}) \,/\, (20 - T_{ext,0}) \tag{8}$$

$$T_{supply,2}= T_{supply,0} - \Delta T_2 \cdot (20 - T_{ext}) \,/\, (20 - T_{ext,0}) \tag{9}$$

where ΔT_1 and ΔT_2 are respectively the thermal loss between the basement and ground floor and between the basement and the first floor, calculated at a design external temperature ($T_{ext,0}$) equal to -10°C. Firstly, the whole-building initial model was built using the multiplying coefficients of the radiators a, b, c and d calibrated during the partial calibration while ΔT_1 and ΔT_2 were set as tentative values (Table 7). Secondly, a, b, c and d together with ΔT_1 and ΔT_2 were calibrated. For all coefficients, a variation range of ±20% of the tentative values was determined. The calibration was validated (Table 10) by simulating the building model in the period 4th–7th January (unoccupied building, passive mode).

3. Results

3.1 Whole-Building Initial Model and Calibrated Model (Period 1)

Table 3–6 report the standardized statistical indices RMSE, CV(RMSE) and R^2 of the partial-building calibrated model, the initial whole-building model, the whole-building calibrated model and the whole-building validated model in Period 1. Comparing the results of the whole-building initial model and those of the partial-building calibrated model, it can be noticed that the air temperature of the two reference rooms is less accurately predicted by the whole-building model. The statistical indices of the two reference rooms (R1 and R2) are worse in the initial whole-building model: RMSD=+31%, CV(RMSD) = +29 %, with the same $R^2 = 0.99$ for R1 and RMSD =+22 %, CV(RMSD) = +20 %, $R^2 = -1$ % for R2). The same occurs comparing the partial-buildng calibrated model with the whole-building calibrated model RMSD=+30%, CV(RMSD)=+28%, R^2=-1% for R1 and RMSD=+21%, CV(RMSD)=+19%, R^2=-2% for R2), but globally, looking at the average values of the statistical indices calculated in all 9 monitored zones, the calibration leads to slight improvements in the initial whole-building model (RMSD_{avrg} = -11 %, CV(RMSD)_{avrg} = -11 % with the same R^2_{avrg}=0.99). During the first validation period (from 20th August to 1st September), the statistical indices are slightly worse than those of the calibrated period (RMSD_{avrg}= +21 %, CV(RMSD)_{avrg} = +31 %, R^2_{avrg} = -1 %). In Period 1 the CV(RMSD) related to the whole-building and the CV(RMSD) of the single rooms (Table 5–6) are inside the tolerance range of ±30% indicated by ASHRAE Guideline 14 (2002), in all the models (initial, calibrated and validated).

3.2 Whole-Building Model Simulation and Calibration (Period 2)

The standardized statistical indices RMSE, CV(RMSE) and R^2 of the partial-building calibration, the initial whole-building model, the calibrated model and the validated model in Period 2 are reported in (Table 7–10). Comparing the results of the whole-building initial model and those of the previous calibration of the partial-building model, it can be noticed that the air temperature of the two reference rooms is predicted with less accuracy by the whole-building model. The statistical indices of the two reference rooms (R1 and R2) are worse in the initial whole-building model (RMSD = +51 %, CV(RMSD) = +51 %, $R^2 = -6$ % in the case of room R1 and RMSD = +18 %, CV(RMSD) = +19 %, $R^2 = -38$ % for room R2). Calibration slightly improves the accuracy of the model when comparing the partial-building calibrated model with the whole-building calibrated model: it can be seen that the statistical indices of room R1 are worse in the whole-building calibrated model (RMSD = +45 %, CV(RMSD) = +45 %, R^2 = -9 %), while for room R2 they are slightly better in the whole-building calibrated model (RMSD = -8 % and, CV(RMSD) = -9 %), except for R^2 that is 22% worse.

Table 2 – Input calibrated during the partial-building model in Period 2: characteristics of the hydronic system set as constant in the whole-building model

Parameters	**Values**
Maximum Water Flow Rate [kg/h]	150
Nominal Power with ΔT = 60°C [W]	2592
Radiator exponent	1.358
Radiator Thermal Capacitance [kJ/K]	134.5
Radiative Fraction (Nominal Conditions	0.3

Table 3 –Input calibrated in the whole-building model during Period 1 (from 5th to 19th August)

Parameters	**Initial value**	**Range value**	**Calibrated value**
Basement floor Hollow • *Slab thickness [m]*	0.5	[0.4; 0.6]	**0.4**
Window (single glaze)			
• *Frame Conductance U [W /m² K]*	7	[5.6; 8.4]	**7**
• *Glaze thickness * [mm]*	4	[4; 6]	**4**
Infiltration rate [ACH]			
• *Basement (classrooms)*	0.21	[0.15; 0.25]	**0.21**
• *Ground floor (classrooms)*	0.21	[0.15; 0.25]	**0.21**
• *First floor (classrooms)*	0.21	[0.15; 0.25]	**0.21**
• *Basement (corridors)*	0.21	[0.15; 0.50]	**0.26**
• *Ground floor (corridors)*	0.21	[0.15; 0.50]	**0.46**
• *First floor (corridors)*	0.21	[0.15; 0.50]	**0.46**
Shading coefficient			
• *Basement*	0.8	[0.45; 1]	**0.81**
• *1st floor classroom (T18)*	0.5	[0.25; 0.75]	**0.43**
Air node thermal capacitance (mult. factor)* • *Basement classrooms*	17.55	[1;20]	**12**
• *Basement corridors*			**8.5**
• *Ground floor corridors*			**13**
• *First floor corridors*			**6.5**

** The windows were evaluated as a discrete variable*
*** The Air node thermal capacitance is calculated as the product of indoor air capacitance and a multiplicative factor.*

Table 4 – Statistical indices of Reference Room1 (R.1) and 2 (R.2) in Period 1 (from 5th to 19th August)

Model type	**RMSD [°C]**		**CV(RMSD) [%]**		**R^2**	
	R. 1	**R. 2**	**R. 1**	**R. 2**	**R. 1**	**R. 2**
Partial-building calibration	0.42	0.66	1.52	2.27	0.99	1.00
Whole-building initial model	0.61	0.84	2.15	2.84	0.99	0.99
Whole-building 1st Calibration	0.60	0.83	2.12	2.80	0.98	0.98
1st Validation	0.67	0.83	2.72	3.29	0.98	0.98

Table 5 – Statistical indices of all the 9 monitored rooms in Period 1 (from 5th to 19th August): Initial whole-building model and calibrated whole-building model

Whole-building initial model							
Thermal zone		**RMSD [°C]**		**CV(RMSD) [%]**		**R^2**	
		Init. Model	**1st Cal.**	Init. Model	**1st Cal.**	Init. Model	**1st Cal.**
Basement	**B1**	0.47	**0.27**	1.81	**1.05**	0.96	**0.97**
Ground floor	**R1**	0.61	**0.60**	2.15	**2.12**	0.99	**0.98**
	B2	0.41	**0.41**	1.49	**1.46**	0.98	**0.98**
	B3	0.57	**0.61**	1.99	**2.14**	0.99	**0.98**
	B4	0.77	**0.77**	2.76	**2.76**	0.97	**0.97**
1st floor	**R2**	0.84	**0.83**	2.84	**2.80**	0.99	**0.98**
	B5	0.42	**0.38**	1.46	**1.33**	0.99	**0.99**
	B6	0.56	**0.50**	1.88	**1.66**	0.97	**0.97**
	B7	0.50	**0.29**	1.68	**0.97**	0.98	**0.98**
Average of the 9 zones		0.57	**0.52**	2.01	**1.81**	0.98	**0.97**

Table 6 – Statistical indices of all 9 monitored rooms: 1st validated model (from 20 August to 1st September)

Thermal zone		**RMSD [°C]**	**CV(RMSD) [%]**	**R^2**
Basement	**B1**	0.68	2.90	0.89
Ground floor	**R1**	0.67	2.72	0.98
	B2	0.29	1.21	0.99
	B3	0.91	3.65	0.98
	B4	0.44	1.80	0.97
1st floor	**R2**	0.83	3.29	0.98
	B5	0.45	1.81	1.00
	B6	1.02	4.03	0.97
	B7	0.59	2.35	0.98
Average of the 9 zones		**0.65**	**2.64**	**0.97**

Looking at the average value of the statistical indices calculated in the 9 monitored zones, the calibration of the multiplying coefficients *a*, *b*, *c*, *d* and ΔT_1

and ΔT_2 is effective in determining the improvement of the simulation, leading to a decrease in the average statistical indices: $RMSD_{avrg}$ = -16 %, $CV(RMSD)_{avrg}$ = -17 %, R^2_{avrg} = +3 % (Table 9). During the 2nd validation period (4th January-7th January), $RMSD_{avrg}$ and $CV(RMSD)_{avrg}$ are slightly worse than those of the calibrated model, while R^2_{avrg} improves. Generally, looking at the whole-building performance, including in Period 2, the $CV(RMSD)_{avrg}$ and those of the single rooms are inside the tolerance of ±30% indicated by ASHRAE Guideline 14 (2002), in all the models (initial, calibrated and validated).

4. Conclusions

In this work a calibration methodology based on a "multi-stage multi-level approach" has been presented. The calibration phase is split into two main levels: (i) the calibration of a small part of the building (i.e. partial-building calibration) and (ii) the subsequent calibration of the whole-building model (i.e. whole-building calibration). The main advantages of this method are that is it makes it possible (i) to extend inputs calibrated in the multi-stage calibration of a partial-building model in different periods to the entire building in order to build the whole-building initial model in the same periods and (ii) to use the measurements inside a small portion of a building during short periods (i.e.: short-term measurements in 9 rooms) to calibrate the whole building, avoiding any additional monitoring costs. This method was tested and validated in a real school building. The calibrated inputs of the partial-model of the school in Period 1 (non-occupied building, passive mode) and Period 2 (non-occupied building, heating system on) were extended to the model of the whole school building in order to build the whole-building initial model in the same periods and calibrate the residual unknown inputs. The application of this approach in this case study highlights the fact that the partial-building models calibrated in Period 1 (non-occupied building, passive mode) and Period 2 (non-occupied building, heating system on) are reliable approximations of the whole-building model in the same periods. In detail, the whole-building initial model in Period 1 was not significantly improved by the whole-building calibration. On the one hand, this could mean that the new inputs chosen for the multi-level calibration were not relevant for improving the whole-building model; on the other hand, this could prove the effectiveness of the partial-building model calibration and the representativeness of the rooms chosen as a reference for the entire building. The results obtained in the whole-building initial model in Period 2 are somewhat worse, in terms of the statistical indices ($RMSD_{avrg}$, $CV(RMSD)_{avrg}$ and R^2_{avrg}), than those of the partial-building calibrated model in Period 2, and the whole-building calibration proved to be more effective than in Period 1 in enhancing the model. This reveals that the inputs chosen to calibrate in this period had an effect on enhancing the model.

Table 7 – Input calibrated during the Period 2 (from 24th December to 4th January): multiplying coefficients of the radiators' supply temperature during Period 2

Parameters	Initial value	Range value	Calibrated value
a [-]	-1.108436	[-1.33; -0.89]	**-0.908436**
b [-]	60	[48; 72]	**53.5**
c [-]	54	[43.2; 64.8]	**45**
d [-]	22	[17.6; 27.192]	**27**
ΔT_1 [°C]	5	[3; 7]	**7**
ΔT_2 [°C]	10	[8; 10]	**8**

Table 8 – Statistical indices of Reference Room1 (R1) and 2 (R2) in Period 2 (from 24th December to 4th January)

Model type	RMSD [°C]		CV(RMSD) [%]		R^2	
	R1	R2	R1	R2	R1	R2
Partial-building calibration	0.37	0.92	2.39	6.13	0.92	0.93
Whole-building initial model	0.76	1.13	4.92	7.60	0.87	0.67
Whole-building 1st Calibration	0.43	0.81	2.76	5.48	0.87	0.68
1st Validation	0.41	0.82	2.68	5.52	0.88	0.70

A further development of this work will be to use the calibrated models in Period 1 and Period 2 in order to calibrate users' behavior inside the building in Period 3 (occupied building, passive mode) and Period 4 (occupied building, active heating) respectively. The inputs calibrated in the partial-building model (i.e. shading level and air change rates in the two reference rooms) will be extended to all similar thermal zones (classrooms on the ground and first levels) in order to construct the whole-building multi-zone initial model in the two periods. Following this, unknown inputs (i.e. shading level and air change rates of corridors and rooms located in the basement building) will be calibrated. Moreover, the calibration process can be extended to a further level by calibrating the whole-building model on the energy consumption for heating.

Table 9 – Statistical indices of all 9 monitored rooms in Period 2 (from 24th December to 4th January): Initial model vs calibrated model

Whole-building initial model							
Thermal zone		**RMSD [°C]**		**CV(RMSD) [%]**		**R²**	
		Init. Model	**1st Cal.**	Init. Model	**1st Cal.**	Init. Model	**1st Cal.**
Basement	**B1**	1.26	**1.29**	7.89	**8.09**	0.66	**0.53**
Ground floor	**R1**	0.76	**0.43**	4.92	**2.76**	0.87	**0.88**
	B2	1.05	**0.83**	7.31	**5.77**	0.76	**0.69**
	B3	1.07	**0.75**	6.94	**4.85**	0.84	**0.84**
	B4	1.06	**0.92**	6.92	**5.98**	0.64	**0.60**
1st floor	**R2**						
	B5	1.13	**0.81**	7.60	**5.48**	0.67	**0.68**
	B6	1.30	**1.16**	8.73	**7.78**	0.56	**0.49**
	B7	1.34	**1.05**	9.36	**7.34**	0.68	**0.65**
Average of the 9 zones		1.17	**0.97**	7.77	**6.47**	0.61	**0.58**

Table 10 – Statistical indices of all the 9 monitored rooms: 2nd validated model (from 4th January to 7th January)

Thermal zone		**RMSD [°C]**	**CV(RMSD) [%]**	**R²**
Basement	**B1**	0.45	2.96	0.92
Ground floor	**R1**			
	B2	0.65	4.40	0.90
	B3	1.21	8.80	0.89
	B4	1.02	6.92	0.92
1st floor	**R2**	0.59	3.93	0.87
	B5			
	B6	0.72	4.96	0.88
	B7	1.16	8.50	0.66
Average of the 9 zones		**1.02**	**7.11**	**0.84**

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