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Calibration of building energy simulation models based on optimization: a case study

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Abstract

This study applies an optimization-based approach for calibrating building energy models using monitored data. The calibration was carried out on a test building coupling the EnergyPlus energy simulation tool with the GenOpt optimization tool. The objective function was set to minimize the difference between simulated and monitored energy consumption. For evaluating the model accuracy, the Mean Bias Error (MBE) and the Coefficient of Variation of the RMSE (Cv (RMSE)) were calculated and found consistent with ASHRAE guideline 14 limits for a model to be considered calibrated.

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Keywords: Calibration; Building simulation; Optimization-aided calibration; validation; Monitoring.

1. Introduction

So far disagreement between simulated and monitored building energy consumption has become a common research issue. To this regard today building simulation concerns not only building design but also building operation, diagnosis and commissioning [1]. In particular, an extensive interest into building monitoring and operation diagnostic led to more frequent applications of building models calibration for the energy assessment. In order to have accurate results and make simulation predictions match closely real consumptions, calibration has become an essential process to be carried out for building simulation.

Usually, when data from monitoring are not available, building models are developed based on rules-of-thumb and on designers' experience. Indeed for calibrating a building model, the definition and the process of tuning the building

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input data has high relevance. Among all input data, it is especially important to accurately define, by means of sensitivity and uncertainty analysis, those data having a major impact on the building energy consumption.

This study presents a methodology for calibrating building energy models based on monitored data. An optimization-based approach was chosen and carried out based on the coupling of the EnergyPlus simulation software with the GenOpt optimization program. A test building located in a Belgian university campus was selected as case study for testing the methodology. A short monitoring period of one month, during the winter season, was investigated for calibration on an hourly basis.

2. Methodology

The aim of this study is to present a simplified methodology to be used by professionals as well as by researchers, for the calibration of dynamic building energy models. The methodology described and applied within this paper was defined referring to a detailed literature review on the most recent approaches used for calibration [2] and in particular to Tahmasebi [3]. An optimization-based calibration methodology, builds on a four-step methodology, was studied and applied to a test building. In general, the process of optimization, as applied nowadays to building simulation, consists into finding the parameters optimal values for a better building energy performance. As applied to calibration, optimization regards the parameters tuning for a better matching with the building measured data.

In Step 1 the building energy assessment is carried out by means of a dynamic energy simulation tool. The model defined at this stage is uncalibrated and based on the design data and standard boundary conditions.

From Step 2 to Step 4, the process of calibration, divided into three sub-stages (Pre-processing, Optimization and Post-processing and Validation) is performed. Depending on the input data availability, 4 different calibration levels can be distinguished as defined by Reddy in [4], from a first one based on as-built data and a more detailed one based on audit information, inspection and monitoring. The calibration conducted within this study fulfills with calibration level 4. Step 2 “Pre-processing” represents the very first stage of calibration, regarding the collection of data to use for tuning At first, an analysis on the metered data and on the building model input data was carried out. Metered meteorological data (e.g. outdoor dry bulb air, relative humidity, etc) are used for creating a real weather file for the simulations and other data from monitoring (e.g. indoor ambient temperature, heating energy consumption) are also processed. When calibrating a building model, the presence of different sources of uncertainty [5] should be considered by means of sensitivity and uncertainty analyses. Within this study, due to the large computational time related to the use of a dynamic energy simulation tool, sensitivity and uncertainty analyses are not conducted but, based on a detailed literature review [2], a set of parameters, referred as the most influencing the building energy consumption, is defined. Each influencing parameter is constrained in a range between a lower and an upper bound, representing the relative uncertainty domain. The selected parameters are gathered into four categories (site, building envelope, operation, building system). For calibration, the optimization objective function is set on the building heating energy consumption. Four different files to be used in the optimization phase (where EnergyPlus is coupled with GenOpt) are prepared; the initialization file specifies the files location; the configuration file sets the configuration of the simulation program; the simulation input template file as a copy of the energy model where the values of each parameter, to be altered during optimization, are replaced by its variable name; the command file specifies all the parameters to be altered in the energy model, their variation constraints and the algorithm selected to perform the optimization.

During Step 3, the optimization-based calibration is performed: the building model parameters are altered, based on constraints, until the optimization problem is solved. The optimization is defined, within the initialization file, through a specific error-minimizing objective function aimed at reducing the difference between measured and simulated data. The optimization process stops when the minimum difference is found, that means that simulated heating energy consumption of the case study matches closely the monitored data. Different optimization runs are performed to find the “best estimates” for calibration, varying within each run, different parameters in the energy model (e.g. internal gains, building envelope features, etc).

Finally, Step 4 post-processes the optimization outputs for validating the calibrated building model based on its accuracy. The Mean Bias Error (MBE), the Root Mean Square Error (RMSE) and the Coefficient of Variation of the RMSE (Cv(RMSE)) are calculated and verified to be consistent with the ASHRAE guideline 14 limits [6], respectively ±10% and 30% on hourly basis.

3. Case study

3.1. Building characteristics

The case study is the two-storey test building "Jacques Geleen", located in the Ulg environmental campus, in Arlon, Southern Belgium. The building was chosen first for the availability of monitored data and second, considering the small and manageable dimensions (total gross floor area of 162 m^2), for the affordable time estimation either for the modelling and the simulation process. Being a test building, it is built around a climatic room, surrounded by a buffer area. At each side of the climatic room two main zones can be identified: a two storeys office area on the north-east side of the building, including a small service area on the ground floor, and a technical room on the south-east side. The climatic room ceiling faces the unconditioned attic. A schematic 3d-skecth of the ground floor is pictured in Fig.1. The building has an all wooden structure and envelope. Windows are equipped with exterior wooden blinds that were shut during monitoring.

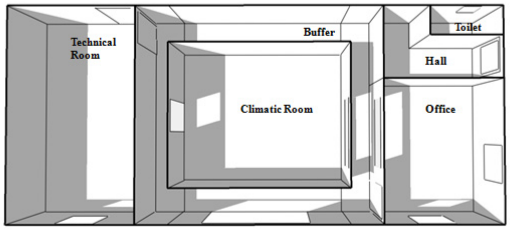

Fig. 1. Schematic 3d view of the ground floor.

3.2. Energy model

An energy model of the case study was created in EnergyPlus (version 7.0). The modeling was carried out in compliance with Step 1 of the methodology. Given the small dimensions, the modeling was quite detailed. A thermal zone was defined for each room (seven thermal zones in total); four conditioned zones (climatic room, office, buffer and upper-floor office) and three not conditioned (technical room, attic, toilet). The building envelope constructions, which U-value are reported in Table 1, were characterized in compliance with as-built technical documentation. Subsequently, during calibration, the thermal features of the building envelope material were altered. Except for the window in the upper-floor office, a wooden vertical venetian was modeled and applied to all exterior windows. Moreover, for higher accuracy in the simulations, the neighboring and buildings facing the case study were modeled as shading surfaces with their own reflectance properties.

Table 1. Thermal features of the main building envelope components of the case study.

Envelope component	Exterior wall	Roof	Ground slab	Window	Interior wall	Ceiling
U-value [Wm^2/K]	0.235	0.241	0.316	1.1	0.396	0.161

As the building is only used for experimental activities, occupancy was not considered. The definition of internal gains was limited to appliances (two computers in the office and a server in the attic) and other unlikely rated gains in the technical room. The two computers installed power was initially set to 230W based on a literature review. Based on on-spot-investigations, the server installed power was fixed to 120W. The natural ventilation and infiltration air flow rate was set to 0.43 ACH on the basis of blower door test investigations in some zones and to 0.5 ACH on the other zones. The office areas, the climatic room and the buffer were conditioned by means of electric resistances with a 20°C constant heating set point. Some resistances were equipped with PID controller and others with an on/off controller. A fan was set next to each electric resistance for diffusing the heating in the ambient air. The heating set point temperature was set as scheduled in function of the measured ambient air temperature. The monitoring period extends from the 8th of February to the 5th of March. Table 2 reports the heating energy consumption of the first "uncalibrated" energy model simulation. Even is at the whole building level simulation results are close to measured data, great discrepancies were noted between measured and simulated energy consumption in the single zones. Moreover, given the building small extent, a thermal zone calibration was chosen to be performed rather than a calibration at the whole building level.

Table 2. Measured and simulated (before calibration) heating energy consumption of the case study.

Energy consumption	Climatic Room	Buffer	Office	Office (1st floor)	Whole building
Measured [kWh/m^2]	1.0	18.9	5.9	11.4	37.2
Simulated [kWh/m^2]	4.6	16.7	4.7	10.6	36.6

3.3. Calibration

According to step 2 “Pre-processing”, metered meteorological data from the university campus weather station were processed for creating the real weather file. Other data from monitoring (e.g. indoor ambient temperature, heating energy consumption) were retrieved from ambient sensors located in the case study rooms. A set of the parameters considered as the most influent on the building energy consumption, was defined based on a detailed literature review [2]. For each parameter, a constraint, with a lower and an upper bound, was set. For the material properties parameters, the variation constraints (lower and upper bounds) were always set to 25%, while for the material thickness was limited to a 10%. An extract of the equipment internal gains parameters altered during optimization is reported in Table 3. For instance, the installed power in the attic room was set to 120W based on to on-spot measurements, while the computers power was set to 140W as initial value, with a lower bound of 80W and an upper bound of 230W, based on a literature review.

Table 3. Extract of the equipment related parameters altered during optimization.

Equipment: Power [W]	Starting value	Min	Max	Step	Variation range
Technical room	100	75	125	5	25%
Office	140	80	230	5	based on literature review
Attic	120	120	120.00	-	constant
Equipment: Radiative fraction [-]	**Starting value**	**Min**	**Max**	**Step**	**Variation range**
Technical room	0.5	0.375	0.625	5	25%
Office	0.5	0.375	0.625	5	25%
Attic	0.5	0.375	0.625	5	25%

As described in the methodology, during stage 3, the calibration was performed based on the optimization function. GenOpt was run, coupled with EnergyPlus, for optimizing the influencing parameters to make the simulated heating energy consumption match the measured one. A hybrid generalized pattern search with particle swarm optimization algorithm was used as generally recommended algorithm for problems where the cost function cannot be simply and explicitly stated, but can be approximated numerically by a thermal building simulation program. The optimization process stopped when the minimum absolute difference was found, that means that simulated heating energy consumption of the case study matched closely the monitored one. Two main sets of optimization runs were performed. First, a series of runs (from Calibration 1 to 6) was performed varying time dependent parameters (equipment, infiltration and ground temperature). Second, from Calibration 7 to 11, building envelope related parameters (thickness, density, conductivity and specific heat) were included in the optimization process. During stage 4 data from the calibration process were post-processed. For evaluating the model accuracy, the MBE and the Cv(RMSE) were calculated.

4. Results

Generally, one iteration should be sufficient to calibrate the building model. However as the process of calibration is a highly undetermined problem that leads to a non-unique solution [7], eleven calibration runs were performed. For each run, GenOpt recalled the EnergyPlus program and reached the objective function minimum after approximately 1500-1600 EnergyPlus simulations. Table 3 reports the list of the parameters involved in the GenOpt optimization process: the initial value (uncalibrated model), the defined constraints (lower and upper bound) and the final (calibrated) value for Calibration run 11 of each parameter.

Table 3. Thermal features of the case study building envelope main components for Calibration run 11.

	Initial value	Lower bound	Upper bound	Final value
Ground temperature				
Core	6.96	8.050	14.90	8.65
Perimeter	7.38	8.510	15.21	9.04
Internal gains				
Technical room: Power [W]	100	75	125	75
Technical Room: Radiative fraction [-]	0.5	0.25	0.75	0.35
Office: Power [W]	140	80	230	80
Office: Radiative fraction [-]	0.5	0.25	0.75	0.65
Attic: Radiative fraction [-]	0.5	0.25	0.75	0.75
Ventilation				
Office: infiltration [ACH]	0.43	0.1	1	0.3
Technical Room: infiltration [ACH]	0.5	0.1	1	0.9
Climatic Room: infiltration [ACH]	0.43	0.1	0.75	0.1
Buffer: infiltration [ACH]	0.43	0.1	0.75	0.75
Attic: infiltration [ACH]	0.5	0.1	1	0.2
Office 1st fllor: infiltration [ACH]	0.43	0.1	1	0.46
Entrance: infiltration [ACH]	0.43	0.1	1	1
Building envelope*				
OSB Panel 12mm				
Thickness [m]	0.012	0.009	0.015	0.011
Conductivity [W/ mK]	0.13	0.097	0.162	0.162
Density [kg/ m^3]	650	487	812	812
Specific Heat [J/kgK]	1880	1410	2350	2162
Rockwool 89mm				
Thickness [m]	0.089	0.07	0.11	0.08
Conductivity [W/ mK]	0.04	0.030	0.050	0.05
Density [kg/ m^3]	100	75	125	120
Specific Heat [J/kgK]	920	630	1050	874

* Only a selection of the materials parameters is reported.

MBE and CV(RMSE) were calculated and verified for each conditioned zone based on the heating building energy consumption. Table 4 reports the results of Step 4 of the calibration process (validation) related to the calibration run 5 (1st stage) and to the run 11 (second stage). MBE is always consistent with the ±10% threshold limit recommended by the ASHRAE guidelines 14 for hourly calibration, while Cv (RMSE) significantly improved during the second set of runs (run 11). In fact, in calibration run 5 MBE is consistent to the constraint limit due to compensation errors but except for the Climatic Room, the other zones are beyond the 30% limit. Initial calibration runs didn't achieve good results (MBE and Cv(RMSE) always out of threshold limits). The inclusion of non-time dependent variables, such as material proprieties, allowed considering the decaying of the building envelope and light "disagreements" between design and as-built construction, and achieving a better model performance.

Table 4. Validation results: values of MBE and Cv(RMSE) in calibration run 5 and 11.

	Heating energy consumption [kWh/m^2]			**MBE [%]**			**Cv(RMSE) [%]**		
	Measured data	run 5	run 11	Uncalibrated model	run 5	run 11	Uncalibrated model	run 5	run 11
Climatic Room	1.0	1.0	1.0	352	0.58	0.83	8696	14.34	20.40
Office	5.9	6.0	5.9	-20	2.14	-0.14	490	53.01	3.51
Office (1st floor)	11.4	11.7	11.4	-7	3.00	0.06	177	74.94	1.54
Buffer	18.9	18.5	18.9	-11	-2.22	-0.01	286	0.01	0.19

With regard to the variation of the parameters values during the calibration runs, in general the most stable parameters are those related to the building envelope, whose final values have light deviations from the respective initial values. On the contrary, the most unstable parameters are those related to the internal gains and ventilation rates. Fig.1 depicts the tuning results of some parameters. As it can be observed, for the installed power of the office computers and the infiltration rate of technical room, the tuning final value significantly varies during the calibration runs. In particular, while computer power achieved the same final value from run 8 to 11, the infiltration rate still assumed different values. On the other hand, the variation of the materials thermal properties is milder, that means they hold a smaller influence on the optimization process.

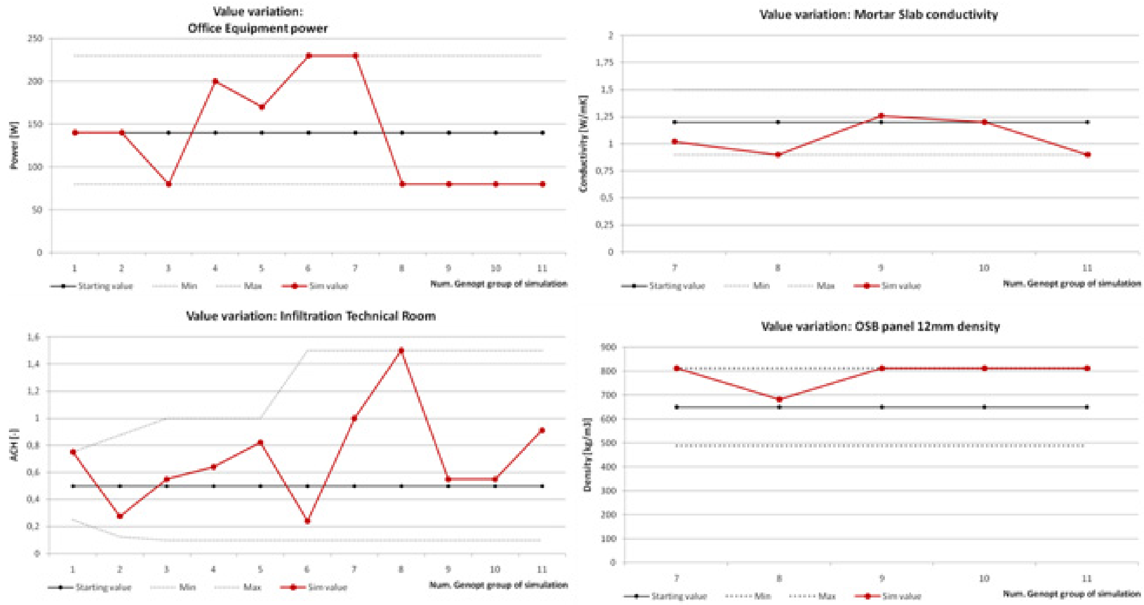

Fig. 1. Value variation of the office equipment parameters during the various calibration runs.

5. Conclusion

An optimization-based calibration was conducted on a test building for a short-term monitoring period. This automated approach was preferred to a manual approach for the possibility of including a higher number of parameters and changing simultaneously more than one parameters. The validation of the building model was based on the hourly threshold limits of the MBE and Cv(RMSE) statistical indices. Undoubtedly, further improvements can be made to refine the calibration process: statistical indices may be integrated in the optimization objective function and additional variables such as the indoor ambient temperature can be employed for calibration beyond the building energy consumption. The methodology should also be tested on more complex buildings and for a longer monitoring period.

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