Method for Building Model Calibration to Assess Overheating Risk in a Passive House in Summer

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Abstract

Overheating is a major problem that may occur, especially in high-performing buildings. The insulation thickness that is currently installed in passive houses (around 30 cm) may indeed lead to severe overheating problems if this is some mitigated by adequate solar gains control and/or efficient ventilation schemes and strategies. This risk is expressed in percentage and calculated when the indoor temperature is above 25°C. For instance, the acceptable limit for a passive house is set at 5% over a year as defined by the Passive House Platform standard in Belgium (Vandenberghé & VanLoon, 2013).

To assess overheating, dynamic simulation is a valuable approach that can be used to calculate the overheating risk and to assess the efficiency of overheating control measures.

This paper presents an approach where a detailed simulation model of a passive house was developed (using TRNSYS Type 56), calibrated on the basis of measurements carried out in a typical house in Belgium and then used to compare different overheating mitigation strategies.

The accuracy of the simulated model was assessed by calculating statistical indices. When the calibration results have shown a good match between measured and simulated data, the model was used in dynamic simulations to determine the best solution to reduce the risk of overheating in house under study.

Introduction

Overheating risk is a major performance criterion to be evaluated, especially in high-performing buildings where the increase of the insulation level and the importance of the fenestration may lead to severe problems if not adequately mitigated. This is particularly true in passive houses where the heat demand is deliberately reduced through an efficient collection of solar gains and a good valorisation of internal gains (appliances and other electrical devices). To assess the overheating risk at design stage, the use of dynamic simulation is a well proven approach that can be used but which faces the specific problem of the relative high sensitivity of the simulation results to the assumptions made for the inputs to the model. Consequently, when this is feasible, and this naturally limited to existing and monitored buildings, the

calibration of the simulation tool appears as a mandatory step in order to increase the reliability of the simulation results. The field of model calibration has been intensively investigated in the recent years (Reddy, 2006), especially in the context of the performance gap which is very often observed when applying a non-calibrated model to an existing building. Generally, the calibration process aims at tuning some parameters of the model to make it match the energy consumption as widely found in the literature (Li, Tian, Lu, & Fu, 2018 ; Fabrizio & Monetti, 2015 ; Eguía Oller, Alonso Rodríguez, Saavedra González, Arce Fariña, & Granada Álvarez, 2018). However, if the model is to be used to study the thermal behaviour of the building, in particular the analysis of the risk of overheating, the energy consumption data are not relevant, therefore indoor temperature data should be used. Few studies to date cover this type of model calibration but the work of Roberti, Oberegger, & Gasparella (2015).

The purpose of this paper is to present a calibration methodology involving a preliminary sensitivity analysis followed by a “one after the other” modification of the dominant parameters an assessment by statistical indices computation. This method was carried out in order to calibrate a dynamic building model to analyse the risk of overheating in a passive house located in Belgium, see Figure 1. After calibration, the objective of the simulation was to determine the optimal actions to reduce or avoid this risk by changing parameters such as the type of solar protection control or the window opening ratio with an impact on the air renewal rate.

The paper will present the methodology used to achieve these goals and the results of the application of the methodology on a typical passive residential house located in Belgium and for which some monitoring results were available.

The first step was to calibrate this model using collected data on site with internal temperature sensors located in several rooms in the house as shown in Figure 2. Indeed, the in situ temperatures of the house served in this case as reference for the calibration while, generally the energy consumption data is used. The calibrated model was also used in order to carry out dynamic simulation of three types of action to avoid or reduce the overheating risk in summer. Parameters of the building model were adjusted

by a trial and error method in order to match the thermal response of the model with the temperature sensors measurements in the house. To assess the simulation model calibration, statistical indices were computed.

The temperature curves obtained for the simulated model are compared with those of the sensor data. The first assessment of the correspondence between both sets of data is first qualitative by simply observing the curves. However, one graphical method is not sufficient to make a statistical comparison. For this reason, a quantitative method was used based on a statistical index calculation. These indices were based on the AHSRAE guidelines (American Society of Heating Refrigerating and Air-Conditioning Engineers Inc., 2002) and compared to the recommended values. In parallel, Bertagnolo's work (Bertagnolio, 2012) was also used to determine these statistical indicators.

Methodology

This work was conducted in the framework of the EBC Annex 58 of IEA (International Energy Agency – Energy in Buildings and Communities Programme): “Reliable Building Energy Performance Characterization Based on Full Scale Dynamic Measurements” (Janssens, 2016). Annex 58 aimed at enhancing the energy performance characterization of buildings with a focus on the residential sector based on in situ measurements of buildings in use. It is frequently observed that real performance of buildings doesn't match the theoretical performance calculated during the design phase of building. The main contribution of the work in Annex 58 was to show how data collected during measurement campaigns were used in simulation models (Rehab et al., 2016). These models, can be sorted in three types (Rehab et al., 2016):

- Physical models: equivalent to the so-called «white box» model, they are essentially based on parameters whose values can be calculated on the basis of physical information such as thermal conductivity for example. For some parameters a calibration procedure is necessary to obtain a good estimate. These physical models are generally used in dynamic simulation software such as TRNSYS.
- Statistical models : also called «black box » they express relations between input and output variables without any hypothesis on underlying physical phenomena. A statistical algorithm is used to identify these parameters.
- Intermediate models: also called «grey box», they combine characteristics of both previous model families.

In a first step, the simulation model is tuned. One parameter is changed at a time, following an order determined by a preliminary sensitivity analysis conducted previously. Once the model is calibrated and correctly represents an overheating period (ie a period where the house is not heated), the model is used to

compare the efficiency of different strategies to mitigate the overheating risk and to elaborate design and control guidelines to be applied to other projects.

Application to a passive house in Belgium

The approach uses the data collected in a typical passive house located near Liège in Belgium. In this study, a "white box" physical model was used in TRNSYS.. Different measurement campaigns were conducted in this house in order to help in the development of performance verification techniques. The first one is a reconstruction of the energy balance of the house thanks to the collected data (Masy et al., 2016). A method with butane combustion was also tested in order to estimate simultaneously the heat loss coefficient and the air exchange rate of the house (André et al., 2016). Finally, a calibrated simulation model in TRNSYS (Solar Energy Laboratory Univ. of Wisconsin-Madison, TRANSSOLAR Energietechnik GmbH, Bâtiment, & TESS – Thermal Energy Systems Specialist, 2017) was used to evaluate the thermal performance of the house during summer period.

Modelling of the reference building: from reality to simulation model

A 3D model of the passive house (Figure 1) was developed in TRNSYS 3D plugin for Sketchup based upon a set of collected information from the owner of the house.

Building envelope and HVAC systems information was essentially extracted from the design calculations of the house, plans and interview of the owners help to determine their habits and behaviour (occupancy, ventilation control, solar blind control, etc...). This collection of information was done on a very informal basis. Therefrom the corresponding model characteristics were adjusted.

Figure 1: 3D model, 2D model (house views), reference building, north frontage.

Figure 2: Thermal zoning of the passive house used in TRNSYS simulations; localization of the temperature sensors is shown with blue points

Thanks to 3D modelling, the detailed internal and external radiation mode in TRNSYS could be selected. The choice of a detailed radiation mode was justified in this case because of the large glazing area, especially on the south frontage where the window ratio is about 39%. In order to best represent the reality, a correct distribution of direct solar radiation is indeed important (Solar Energy Laboratory Univ. of Wisconsin-Madison, TRANSSOLAR Energietechnik GmbH, CSTB – Centre

Scientifique et Technique du Bâtiment, & TESS – Thermal Energy Systems Specialist, 2017). To increase the accuracy of the model, some envelope characteristics are also detailed in Sketchup; for example, the windows recess of 10 centimetres or the presence of shading elements along the house (Abrahams, Scheuren, & André, 2018).

Weather data

The simulation model was developed in order to reproduce the thermal behaviour of the house during a short measurement campaign during the 2014 summer (from 11th July to 5th September 2014). These measurements included internal temperature in different rooms of the house. Figure 2 shows the location of the sensors (blue points). There was also a temperature sensor in the attic but the overheating evaluation did not seem relevant for this room. To calibrate the simulation model, weather data (external air temperature, relative humidity, direct and diffuse solar radiations) were required. The house is located about 20 km from the city of Liege. The Spatial Centre of Liege (SCL) provided the external air and dew point temperatures, the global, direct and diffuse solar radiation for 2014 for Liege, which is not too far from the location of the building and is acceptable.

Sub-hourly variables were transformed into hourly data and injected in TRNSYS. Presence of gaps and hybridization of data from different sources constituted a primary source of error for the simulations. This error has been reflected in the results (Eguía Oller et al., 2018).

Calibration method, statistical indices calculation and model validation

A calibration of the building model was performed in TRNSYS using a trial and error method. For this purpose, it was necessary to determine which parameters had the most influence on the simulation results. The sensitivity analysis performed following the IEA_EBC Annex 53 work (Pignon & André, 2012) in which six families of influencing factors on energy consumption in buildings are considered. These six families are divided in two groups; factors related to the human behaviour and factors not related to human behaviour. Each family includes several factors. To carry out calibration on air temperature in model it was decided to use only four of these families. Table 1 shows which influencing factors were used in simulations.

Table 1. Parameters selected to calibrate the building simulation model.

Not Human Behaviour	Human Behaviour
	Occupation factors
	-Number of unoccupied days per week
	-Internal gains
Building envelope	Indoor environmental quality
-Infiltration rate	-Ventilation rate
	-Over-ventilation rate
	-Shading rate
	Building operation
	-Temperature decrease during the day
	-Temperature decrease during the night

Only one factor was changed at each simulation run. Each calibration run was realized with a quarter-hour time step for a total of 1368 hours. This corresponds to the period from July 11 to September 5, 2014. At each time step (15 minutes) the simulated temperatures were compared with the real temperatures. In ASHRAE guidelines (American Society of Heating Refrigerating and Air-Conditioning Engineers Inc., 2002) two statistical indices are recommended to determine matching between simulated and metered data. They are hourly Mean Bias Error (MBE) and coefficient of variation of the root mean squared error (CV(RMSE)). These indicators are commonly used to evaluate the compliance of simulated and measured data of energy use. In the current study the work was done with internal air temperatures and, in order to compare temperatures, it was decided to work with six additional statistical indices: the mean square error (MSE), the root mean square error (RMSE), the mean absolute error (MAE), the mean absolute percentage error (MAPE) and the coefficients of correlation (R) and of determination (R^2). Nevertheless the MBE and CV(RMSE) were also computed and compared with the acceptable range for these indices, found in ASHRAE guidelines (American Society of Heating Refrigerating and Air-Conditioning Engineers Inc., 2002) and literature, (Roberti et al., 2015), (Fabrizio & Monetti, 2015). The range of validation for each indicator was based upon the work of Bertagnolio (Bertagnolio, 2012)

In this case, the difficulty of calibration lies in the fact that several rooms were monitored in the house and the model had to be simultaneously calibrated for all the rooms. However, changing a parameter could have a positive effect on the matching between measured and simulated temperatures in one zone and at the same time cause a discrepancy between data in another zone. When the calibration was considered satisfactory, the building calibrated model was used in dynamic simulation to analyse scenarios for controlling overheating in the house.

Results

Calibration of the simulation model

The simulated internal air temperature in the living room, obtained for the non-calibrated model, is shown in Figure 3. The curves are different and the simulated temperatures are higher than the measured temperatures. This model is characterised by no internal gain nor solar blind protection. The infiltration air rate is close to the passive house standard ($n_{50} = 0.6$ vol/h) and there is no over-ventilation. It also takes into account the unoccupied periods during the campaign. The results for the statistical indices for this model are shown in Table 2. The MBE for the non-calibrated model of the house is 10.3% and the CV(RMSE) is 14%. After calibration by trial and error procedure on the influencing parameters in Table 1 the results for a calibrated model are shown in Figure 4 and statistical indicators values are given in Table 3. The MBE and CV(RMSE) for this model are respectively -1% and 3%. The value of the living room indicators can be analysed as follows:

MSE is reduced by 12.15°C in the calibrated model; MAE is 0.53°C compared to 2.97°C in non-calibrated model; MAPE is reduced by 9.4% in calibrated model and RMSE is 0.65 for calibrated model. These results were obtained by changing the infiltration rate (0.03 vol/h compared to 0.6 in the initial model), the solar factor of shading by 1 and avoid windows opening by occupants. The very low value of the infiltration rate may be explained by the good management of the ventilation by the occupant and the overpressure induced by the double flow mechanical ventilation system. Another crucial point was the proper consideration of holiday periods, ventilation rate managed by the occupants (modified rate during the day, reduced by half in case of absence) and the opening of windows by occupants simulated with a well-defined schedule.

Figure 3. Comparison between the living room's monitored temperatures (light grey line) and simulated temperatures (dark grey line) for the non-calibrated building simulation model

Figure 4. Temperature curves –calibrated building simulation model

Table 2. Dispersion index values for the non-calibrated simulation model.

Non calibrated	MSE	MAE	MAPE	RMSE	R	R^2
Living room	12.57	2.97	11.5%	3.54	0.75	0.56
Room 1	22.75	4.26	17.8%	4.77	0.58	0.33
Room 2	33.86	5.27	22.3%	5.82	0.43	0.18
Room 3	19.88	3.88	16.4%	4.46	0.52	0.27
Office	30.81	4.98	21.0%	5.55	0.41	0.17
Bathroom 1	15.49	3.32	14.4%	3.94	0.47	0.22
Bathroom 1	17.31	3.48	15.2%	4.16	0.37	0.14

Table 3. Dispersion index values for the calibrated simulation model.

Calibrated	MSE	MAE	MAPE	RMSE	R	R ²
Living room (LR)	0.42	0.53	2.1%	0.65	0.79	0.62
Room 1 (R1)	0.97	0.70	3.0%	0.99	0.78	0.60
Room 2 (R2)	0.84	0.68	2.9%	0.91	0.73	0.54
Room 3 (R3)	1.55	0.98	4.1%	1.25	0.82	0.67
Office	1.03	0.82	3.5%	1.02	0.72	0.51
Bathroom 1	2.02	1.01	4.4%	1.42	0.77	0.59
Bathroom 1	2.25	1.12	4.8%	1.50	0.76	0.57

Overheating risk evaluation

The overheating risk is expressed in percentage to be compared with the annual percentage of overheating allowed by the Passive House Platform (PHP) in Belgium: a maximum value of 5% of time when the internal temperature in building exceeds 25°C is allowed.

In the house monitored in Liege the data showed that a risk of overheating existed in different rooms of the building, especially in the living room where the estimated annual overheating is 8% of time (Table 4). The calibrated model of the house has been used to find solutions to reduce this percentage. Three ways to avoid the overheating risk were tested by simulations:

- To change the temperature setpoint of solar blind protection activation (initially set at 26°C).
- To change the control of the solar blinds: initially the solar blinds were controlled by the internal temperature. The simulation tested a control based upon the horizontal solar radiation. The solar blinds are opened when the solar radiation on facade is lower than 120 W/m² and they are closed when it gets upper than 140 W/m². Two shading factors (SF) were also tested in this option. The shading factor values are 0.6 and 1 where 1 corresponds to a total closure of the solar blinds.
- To “manually” open the windows (MWO, manual window opening) at night when external air temperature is lower than internal air temperature (minimal temperature difference: 2°C). Two renewal air rates were tested, 2 vol/h and 4 vol/h, which are default values only selected to test the sensitivity of the model. In the reality, the realized flow rates will obviously depend on the weather conditions.

The results of each simulation are shown in Table 4. The overheating risk is expressed by an annual estimated percentage when the internal temperature in rooms exceeds 25°C. The first line of Table 4 represents the annual overheating computed in each room based upon the collected temperatures data by sensors during the short summer campaign in 2014. The overheating risk seems to appear in the living room and room 1 with values above the 5% recommended in Belgium. The different options simulated in TRNSYS seem to improve the situation in each room except for the solar radiation control of solar blinds with a shading factor of 0.6 that is the least efficient measure especially in the living room.

The most effective ways to reduce overheating in the living room and room 1 is the option with a control of solar blinds based upon solar radiation on the facade with a shading factor fixed at 1. The other options give also good results in terms of overheating reduction in each room of the house.

Table 4. Estimated annual overheating percentage (%) in the passive house for different scenario – results for a calibrated simulation model in TRNSYS; ¹shading factor for solar blinds; ²air flow rate through windows when a manual opening is applied.

	LR	Office	R1	R2	R3	Bath 1	Bath 2
Reference Overheating (%)	8	4	6	4	3	4	3
Setpoint solar blind (24°C)	3.7	1.4	3.7	2.0	0.4	1.8	0.4
Solar radiation regulation SF ¹ = 0.6	7.5	2.5	5.2	3.9	0.7	2.5	1.0
Solar radiation regulation SF ¹ = 1.0	1.6	0	0.8	0	0	0	0
MWO Air rate ² : 2 vol/hr	5.4	1.0	0.6	0.3	0.3	0.3	0.2
MWO Air rate : 4 vol/hr	4.7	0.8	0.3	0.1	0.1	0	0

Discussion

Calibration of the simulation model

It was possible to calibrate a simple simulation model using short sets of temperature data. However, the difficulties are to get on one hand reliable and complete weather data and on the other hand to obtain information about the house (architectural, structural, operational, etc.) in order to build a simulation model as accurate as possible. Sorting and organization of weather data represented the most time-consuming part besides the calibration test and validation. Another remark is the difficulty to get an accurate model in dynamic and multi-zone conditions. Indeed, the calibration of a given influencing parameter may result in a good fitting in a room but at the same time causes discrepancy of values in another zone. The problem is that in thermal dynamic simulations the variation of a parameter causes different responses in the thermal zones of the model due to occupancy factor for example or other phenomenon like sun exposure, inertia, etc. Another explanation of this difference is the sensors resolution of 0.5°C. This characteristic of the sensors is a primary source of uncertainty in the results of calibration. It was also difficult to estimate the good set of statistical indicators because currently there are no standards nor recommended value to determine acceptance criteria for models calibrated to internal air temperatures (Roberti et al., 2015).

Overheating risk evaluation

Among the various scenario considered the most efficient is the control of solar blinds based upon the solar radiation intensity with a shading factor of 1. However, this solution isn't cost efficient because it means changing the entire solar protection system and investing in a new type of sensors more expensive than the thermal sensor currently installed in the house. Moreover, with a shading factor of 1, the total closure of the solar blinds during the day could be uncomfortable for the occupants who may have to switch on the lights. For these reasons the scenario of night freecooling when the external air temperature is lower than the internal room temperature is recommended. The disadvantage is that this solution will depend on human interaction and sometimes the temperature seems to drop below 20°C (Figure5) which could be uncomfortable for the occupants. But this remains a very good way of fighting against overheating and moreover without any cost if the required flow rate can be realized by natural ventilation. Thanks to freecooling, the annual estimated percentage of overheating falls below 5% in the living room. There is a residual overheating percentage occurring during the holidays period where the occupants are not present (Figure5). It is nevertheless considered that if nobody is present to feel the overheating then there is not overheating problem at all.

Figure 5. Temperatures in the living room: in dark line the simulated temperatures obtained with TRNSYS with a night freecooling; in grey line the reference temperatures data (sensors), dot line represents the limit of 25°C. Circles show the two holiday periods.

Conclusion

This paper presented a systematic approach to evaluate the optimal solutions that could be used in a building to reduce or avoid the overheating risk. The procedure shows that it is possible to calibrate a simple model of building from a short period of data acquisition of in situ temperatures. In a second step, the model is used to assess the performance of a number of overheating risk mitigation strategies. The model could also be used in an

audit process to evaluate the comfort during summer under different climates.

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