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BUILDING SIMULATION CALIBRATION USING SENSITIVITY ANALYSIS

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ABSTRACT

This paper presents first steps of a methodology for calibration of building simulation models through definition of the parameters that most affect the main electric end-uses of a building. The first step consists on a good definition of constant loads (plug loads, lighting and occupation) and its schedules. The next steps are directed to calibrate the envelope variables. Sensitivity analysis is applied over the estimated cooling and heating loads in order to specify more accurate values for those inputs that present great impact on the total thermal load. The methodology is proposed to minimize the long time spent in the calibration procedure during a building simulation task. A case study is presented where the annual electricity consumption predicted by EnergyPlus simulation was only 1% lower than actual value. The calibration was obtained after four iterations over the base case model. The building under analysis is a public office one with 26,274 m² of area and annual electric consumption of 4,462 MWh (172 kWh/m².year).

INTRODUCTION

In the last three decades, simulation tools have been used to analyse the thermal behaviour, energy consumption and systems operation of buildings. The Building Energy Software Tools Directory lists over 290 programmes for buildings energy efficiency evaluation (DOE, 2005).

The complexity of physics phenomena guiding the thermal behaviour of buildings requires multidisciplinary knowledge from users. The large amount of input data makes the simulation programmes restrict to universities and research centres, which can employ specialists in different subject areas. The development of more friendly interfaces, customized to user needs, would allow the dissemination of simulation tools into design offices. Developers and researchers have been spending great efforts in order to optimise the modelling and calibration activities (Wittchen et al, 1995; Kosonen and Shemeikka, 1997; Déqué et al., 2000; Ellis and Mathews, 2001). Most of these works has focus on simplified interfaces or even simplified tools, requiring a small number of input parameters to accelerate the modelling step.

The time consumed on modelling task is one of the reasons that implies on the discrete use of building simulation tools by design offices. This issue can be softened by a more accurate calibration of the model and uncertainty analysis over input parameters.

Some researchers have explored calibration methodologies and reported their experiences in the simulation of existent buildings. Pedrini et al. (2002) describe a method, which combines analysis of building design plans and documentation, walk-through visits, and electric and thermal loads measurements. Applying the methodology in the simulation of a 26,000 m² office building using VisualDOE program, the authors got a simulated energy consumption 0.2% higher than measured valued. The differences in monthly consumption achieved a maximum of 9.2%. The authors draw attention to the need of a good set of default values adjusted for typical buildings and sensitivity analysis tools embedded in simulation software. These features could help the user in definition of important input parameters, assuming default values for non-significant variables.

Tamburrini et al. (2003) presented a case study where the calibration occurred in three steps of data description. According to authors, there are two considerable barriers to be transposed in building simulation: (1) there are important uncertainty about the right values for variables that represent a real building; and (2) if these right values were inserted in the simulation tool. The main question is that changing a few inputs will provide large variation in the outputs. But in the initial stages of modelling the user does not know what variables have higher impact in the outputs. Some techniques for sensitivity analysis have been integrated in building simulation tools. But only expert users are able to deal with this kind of analysis, with focus on suspected inputs.

This paper presents a methodology for calibration that combines energy audit and sensitivity analysis. The analyst should define the model in coherent order of input definition. From the several input values that a building model for energy simulation requires, a dozen can be defined as priority, seeking for the better representation of energy end-use.

CALIBRATION OF BUILDING MODELS

Calibrating the energy end-use

Building simulation tools have been used for testing retrofit alternatives worldwide. But results provided by software would not be worth if the base case was not correctly calibrated, i.e., the virtual model of the building under analysis must represent faithfully the thermal and energy behaviour of that building. To achieve this objective, one has to compare measured performance data with those values predicted by the software. In this task, the user finds out a lot of input parameters that can be adjusted to obtain the reference results. Even when the total energy consumption is calibrated, the major question remains on: is the electric end-use well represented by the model?

As the simulation tool is used for retrofit analyses, it is very important that the software accurately predicts the energy used by the building. The annual and the monthly energy consumption can be quite well estimated but the end-use composition (lights, air-conditioning, plug loads, etc) can be far away from reality. In this case, any retrofit analysis will provide uncorrected results.

Waltz (1992) highlights that a good accuracy in simulation results can be achieved through a complete understanding about the software used and the building under analysis. In addition, the energy analyst must ever suspect about the results provided by the computational tool, evaluating tests as necessary. Such behaviour is not practical for design offices. For example, architects may not be able to check the right input values for HVAC systems, as the mechanical engineers sometimes are not much concerned with the thermal properties of the building envelope.

A survey carried out by Wilde and Voorden (2004) covering design of 3 office buildings in the Netherlands has showed that most of energy efficiency concepts and components are selected during the conceptual design stage. Simulation tools are applied eventually to certify the results predicted previously based on rules of thumb. The lack of clearly results from software push designers to make their decisions based on early experience and intuition.

In the most cases of building energy simulation the analyst is unable to execute measurements by end-use, what makes the calibration process difficult and doubtful. But every building has electrical loads that demands a constant power value or has a regular pattern of use. When the electric company measures loads profiles, the analyst can predict the installed power and schedules very close to reality. This source of data is generally available in large buildings with demand charge on the billing structure. Some sensitivity analysis can be run in this step to check the influence of a misunderstanding in the operation routine, for example, in the monthly energy consumption. Others electrical loads, more dependent on weather variables, can be calibrated in a next step. In this group of input parameters it can be included the characterization of:

- the envelope: thermal properties of walls, windows, roof and floor, and air infiltration rates;
- the building geometry: some simplification are made in the first model, which can results in significant influences in the thermal and energy behaviour of the building; and
- the air-conditioning system: capacity, efficiency, performance curves, set point temperatures, ventilation rates and operation.

Sensitivity analysis integrated in this step may provide essential information about what parameters would receive special attention by the analyst.

Sensitivity analysis in building simulation

Sensitivity analysis techniques have been used to estimate the error embedded in the simulation results as a consequence of input uncertainties (Lomas et al., 1991; Lomas and Eppel, 1992; Wit, 1997; Wit and Augenbroe, 2002; Macdonald, 2002). Such techniques, besides the particularity of each method, consist basically on varying the inputs and verify the consequent variation over the outputs. Hence the specialist can recognize those inputs that cause significant variations in the outputs or what parameters are more significant in a specific simulation tool. Through this analysis some input parameters could be classified as unimportant for a specific building model and the user could adopt default values for them.

Carrol and Hitchcock (1993) developed a method to automate the calibration process using sensitivity analysis and optimisation technique to minimise the difference between the predicted and the measured monthly energy consumption of buildings. The user defines the so-called high-level inputs for a building model and the method indicates, automatically, the low level variables that have to be adjusted in order to calibrate the model. This methodology was put to test, guiding the user right way in the calibration procedure. But the authors detected that the use of this kind of methodology is only applicable by experienced users, as the optimisation routine defines the input data without taking into account the reality of the building. Numerous simulations are carried out and input values are changed until the monthly energy consumption is calibrated.

Fürbringer and Roulet (1999) presented the concept of the Sensitivity Analysis Module (SAM), which was incorporated into COMIS software in order to quantify the accuracy of a simulation. That methodology provides reasonable guidance to analyst in the calibration of the parameters with higher impacts in the outputs and feasibility for calibration.

Purdy and Beausoleil-Morrison (2001) highlight that the insertion of unnecessary details in a building model can contribute to increase the uncertainty in simulation results. Thus, building physics knowledge and simulation experience are crucial when software make available several degrees of freedom. The simplification of input data could be a time-consuming task in the modelling step. To solve this problem, user-friendly interfaces should indicate what parameters are really important for a specific model. Using ESP-r software for simulating a residential building in Canada, the authors conclude that there are significant differences in the heating thermal load predicted for single-zone models and multi-zone ones, so the internal walls should receive more attention.

Macdonald et al. (1999) have incorporated two methods for uncertainty analysis in the ESP-r program: differential sensitivity and Monte Carlo analysis. The methods use a predefined database with occupancy and thermo physical property uncertainties. But the authors recognize that the sensitivity analysis results can be complicated for an inexperienced user. Macdonald (2002) had characterized the uncertainty profile of 3 parameters: thermo physical property of materials, internal gains and infiltration rates. According to author, these are the basic parameters for a building simulation procedure in a cold climate.

Sensitivity analysis has been used to identify the level of uncertainty in building simulation results. Some applications take advantage of this kind of analysis to help the analyst in the selection of best energy conservation measures (ECM's). Others researchers and developers have incorporated sensitivity analysis techniques in building simulation tools to help the user in the calibration step. In these cases, the common task relies on the simulation of a hundred cases applying a systematic disturb on predefined inputs. This is a time consuming task that, sometimes, slow down the use of simulation software as a design tool.

CALIBRATION METHODOLOGY

The methodology for calibration of building simulation models presented in this paper is divided in 6 stages:

1. Calibration of power and schedules of constant loads, such as lights and plug loads;
2. Simulation of design days for thermal loads analysis;
3. Sensitivity analysis over input parameter related to significant heat gains/loss;
4. Adjustment of input values of high level of influence and uncertainty;
5. Whole year simulation;
6. Final adjustments.

The first step consists on the calibration of monthly electric energy consumed by constant loads, e.g. lights and equipments (plug loads). These electrical loads can be relatively well described with a quick energy audit through the building or from design plans and documentation. Initial simulations are done to check the information surveyed at the building. In this stage, a generic geometry can be inserted in the software, allowing the simulation to run.

After the calibration of constant loads, the envelope dependent loads (air conditioning) are verified through sensitivity analysis. The analyst must define the basic geometry of the building under analysis (volume and shape). This level of architectural description includes:

- exterior dimensions (width, depth and height);
- number of floors;
- conditioned areas (with a very simple internal zoning scheme, such as 5-zones: one internal and 4 perimeter zones);
- window-to-wall ratio and glass type;
- wall, roof and floor constructions.

In this task, the software being used could offer some default values for the building type and use to help the analyst in the development of the building model, which will be the "base case".

With the base case, a previous simulation is run for two design days (winter and summer) and main heat flow components are calculated from output reports and classified according to its source (second stage of calibration):

a) Windows (transmitted and absorbed solar heat gain, and conduction due to difference of temperature between exterior and interior surfaces);

b) Walls (conduction heat gain or loss due to difference of temperature between exterior and interior surfaces);

c) Roof (conduction also);

d) Floor (conduction also);

e) Plug loads;

f) Lights;

g) People;

h) Infiltration (heat gain or loss due to exterior air infiltration into the building).

Heat flows are computed as absolute values, so the total heat flow through window, for example, will account with heat gain during solar hours plus the absolute value for heat loss during nighttime.

In this step, the total cooling or heating load extracted or added to the entire building is analysed running design days simulation (a winter and a summer design day). Total heat flow for each source is integrated through the simulated day. Those heat sources with higher values will indicate what parameters should receive special attention in the third stage of calibration procedure.

The variables related to each heat source are listed in table 2. The sensitivity analysis is developed changing the input values for each variable under analysis. The influence of each parameter is calculated from equation 1 below, that represents the "influence coefficient" (Lam and Hui, 1995).

$$IC = \frac{\Delta OP \div OP_{BC}}{\Delta IP \div IP_{BC}} \quad (1)$$

Where ΔOP and ΔIP are changes in output and input, respectively; and OP_{BC} and IP_{BC} are the output and the input base case values. This sensitivity coefficient is dimensionless and represents the percentage of changing in the output due to a percentage of perturbation in the input.

Parameters are sorted from the highest influence coefficient to the lowest, and the firsts should be the focus of further adjustment, when necessary, in the fourth stage of the calibration. Probably, not all variables need to be adjusted, but the analyst may verify those with suspect inputs values. The sensitivity analysis is useful to guide the user in this evaluation, and the model can be progressively sharpened.

The fifth step of the calibration is the whole year simulation. Monthly and annual energy consumptions predicted by the simulation tool are compared to recorded data. If monthly values disagreements are higher than 20% or annual consumption is 5% different from recorded data, the user needs to go back to the third stage of the calibration.

Table 2 Heat flow components and the input variables that should be changed in the sensitivity analysis.

HEAT SOURCE	INPUT VARIABLES
Windows	- Dimensions (WWR and Floor-to-floor height) - U-value - Shading coefficient - External solar protection
Walls	- Dimensions (total area and azimuth) - U-value - Thermal capacity - Short-wave absorptance
Roof	- Dimensions (total area and azimuth for sloped roofs) - U-value - Thermal capacity - Short-wave absorptance
Floor	- Dimensions (total area) - Basement underground - U-value - Thermal capacity
Equipments	- Power - Schedule
Lights	- Power - Schedule
People	- Quantity - Metabolic rate - Schedule
Infiltration	- Infiltration rate with schedules

APPLICATION

The methodology described above was applied in the modelling process of a public office building for energy simulation in the software EnergyPlus. The main characteristics of this building are presented in figure 1.

First stage of calibration

At the first stage of calibration, a simple geometry was inserted as input file, with total electric load installed for lighting and plug loads. Schedules of operation for these loads were inserted also.

Electric loads were surveyed at sample zones in the building. Initially, lighting power density was estimated as 30.0 W/m² and the plug loads density was 7.0 W/m². These loads were supposed to be operating at 100% from 7:00 to 18:00 during weekdays and at 20% in the remaining time (weekends and nighttime).

Building era: 1978
Location: Florianópolis, Santa Catarina, Brazil
Latitude: 27.40°S, **Longitude:** 48.33°W]
Area: total = 26,274m², conditioned = 19,030m²
Architecture: Square shape floor plan with 90 x 90 m, with a 30 x 30 atrium at the centre.
WWR: 82% with movable solar protection.
Floors: 5 (3 + 2 underground)
Light Power Density: 30.7 W/m² (conditioned area)
Equipment Power Density: 5.8 W/m² (cond. area)
Occupation: 800 people (23.8m²/person)
Schedules: from 7:30 to 17:30 (weekdays)
HVAC: central plant with 2 centrifugal chillers with 420 tons each; and 66 fan-coils.

Figure 1 Building description

This simplified level of information is considered sufficient to start the calibration of constant loads profile. Figure 2 presents the monthly electricity consumption by end-use at the first stage of calibration. Data recorded by the electric company between November/2003 and October/2004 were used for comparison.

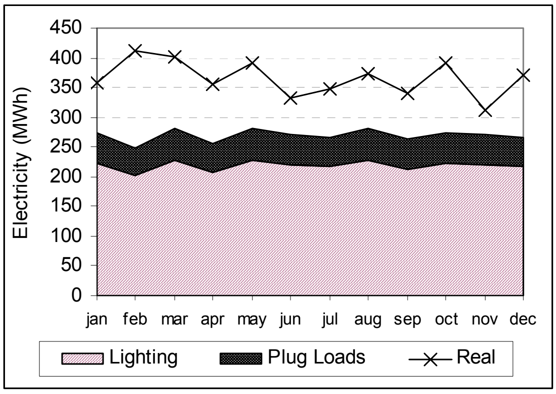

Figure 2 - Electricity consumption estimated for lighting and plug loads end-use vs. real monthly consumption.

The sum of lighting (2,618 MWh) and plug loads (611 MWh) electric energy consumption reaches 79% of the annual recorded value (4,385 MWh). The remaining portion of 21% (920 MWh) of the total consumption could be credited to air-conditioning system. At this point, the analyst should perform some verification by hand in order to assure that this simulation result presents good agreement with the reality.

It is known that the building under analysis has an 840 tons central plant. Assuming a COP of 1.1 kW/TR and a pattern of use of 10 hours per day (7:00 to 17:00), only for weekdays, the annual electric energy consumption for plant would be 2,439 MWh. This value is more than two times the energy consumption predicted above (920 MWh), what indicates that the constant loads representation may be overestimated.

If the hourly load profile of the building is available, the constant loads representation can be verified graphically, as presented below.

Figure 3 shows the hourly profile of electric loads predicted by simulation (First Model curve) and the demand curve monitored (Real curve) in the building by the electric company. A representative day of September was chosen to plot this graph, as in this day the air-conditioning was not in operation. It can be observed in the graph a large difference between the curves in the after work times (from 19:00 to 23:00). This difference suggests that the schedule for these loads should be reorganized in this period. The schedule values were changed from 20% to: 65%, 50%, 45%, 40%, and 30%, from hour 19:00 to 23:00. The curve resulted for this second model is presented in figure 3 also (Second Model curve).

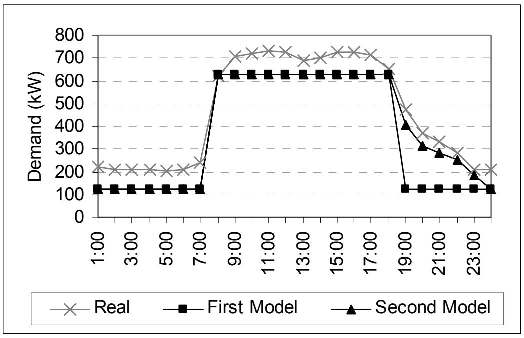

Figure 3 Comparison between electric demand of constant loads and electric demand measured in the building.

Second stage of calibration

After the electric energy consumption of constant loads was calibrated, thermal loads analysis is done simulating the model for the design days. In this specific case study, as the building does not use a heating system, even in the winter, the analysis covers only the cooling design day.

Table 3 shows the participation of each heat gain (or loss) source of the building in the total heat flux verified to the design day. The left column shows the heat sources sorted from the higher level of participation. The right column shows the same heat sources, except those ones already calibrated. At this point, lighting and plug loads are considered well represented in the model. Thus, the analyst should focus on windows characterization, as this heat source represents 54% of the total heat flux through the building verified in the design day. The next stage of calibration (sensitivity analysis) will be developed over this component.

Table 3 Participation of heat sources over the total heat flux verified in the building for the design day.

ALL HEAT SOURCES			EXCLUDING LIGHTING AND PLUG LOADS	
Lighting	35%		Windows	54%
Windows	32%		Floor	24%
Floor	14%		Roof	14%
Roof	8%		People	6%
Plug loads	7%		Infiltration	2%
People	3%		Walls	1%
Infiltration	1%		Plug loads	-
Walls	0%		Lighting	-

Third stage of calibration

The previous stage of the calibration indicated a significant influence of windows in the thermal performance of the building. Sensitivity analysis for the inputs related to this component (table 2) should be performed.

Design day simulation was done for 5 test cases, varying: window dimensions, U-value, shading coefficient and external solar protection. The input and output changes, as well as the influence coefficient for each input are presented in table 4. A purchased air system was inserted in conditioned areas in order to quantify the total cooling energy variation from each case to the base case.

Table 4 Influence coefficients for 5 parameters related to windows.

Case (Input)	Base Case IP	% IP value	% OP value	%OP / %IP
WWR	90%	-22.2%	-3.2%	0.145
U-value (thickness)	3 mm	100.0%	2.2%	0.022
Shading Coefficient	1.013	-3.2%	-2.2%	0.697
Solar protection	0.50	-50.0%	-5.4%	0.107
Floor to floor height	5.00m	20.0%	3.5%	0.173

The sensitivity analysis over the 5 parameters indicated high influence of shading coefficient over the total cooling load. A variation of 3.2% applied in this parameter resulted in a 2.2% of variation in the output (total cooling load). For each 1% of variation in this input there is almost 0.7% of variation in the cooling load.

The order of influence observed through sensitivity analysis was: (1) shading coefficient; (2) floor to floor height; (3) WWR; (4) external solar protection; (5) glass thickness (U-value).

Fourth stage of calibration

From the list of influence coefficients presented in table 4, some considerations and adjustments were made in the model. Three parameters with higher influence coefficient receive more attention:

1. Shading coefficient: the window glass is surely a single clear 3 mm, so the shading coefficient was not changed from the case base description.
2. Floor to floor height: value adopted in the base case was an estimative. Right values were obtained from design plans, resulting on a difference of 3.2m in the total height of the building and a significant increase on windows area.
3. WWR: was recalculated from a detailed analysis into design plans. A value of 82% was verified, instead of 90% that was adopted in the base case simulation.

A new model was created with the right floor to floor height value and WWR of 82%, and the calibration procedure was conducted to the next stage.

Fifth stage of calibration

A whole year simulation was conducted for the new model (base case adjusted in the fourth stage), and the total electric energy consumption could be analysed.

EnergyPlus (version 1.2.1.022) templates and macros were used for modelling HVAC systems and plants. As a template for centrifugal chillers is not available yet, the building was simulated with 4 pipe fan-coils and a purchased chilled water plant. The monthly energy consumption of the plant was computed as the total purchased cooling load multiplied by a COP of 3.2 W_{cap}/W_{el} (1.1 kW/ton). This value was measured in another survey conducted in the building (Pedrini, 1997).

Future work in the development of the methodology of calibration will cover systems and plants, so that the input parameters related to these electric end-uses could be analysed. At this time, only constant loads and envelope variables are being tested under the methodology proposed.

Figure 4 shows a comparison between the simulated and real monthly electric energy consumption. The highest difference was observed in February, when the predicted value was 21% higher than recorded consumption. The annual consumption estimated by simulation was 12% lower than the real value. In the next stage of calibration, final adjustment will be made to the model.

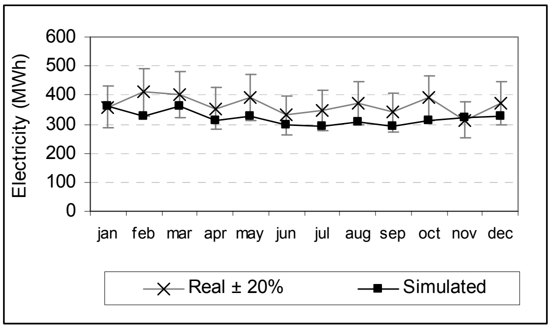

Figure 4 Comparison between real and simulated monthly electric energy consumption of the building, after the 5th stage of calibration.

Sixth stage of calibration

The hourly profile of energy use predicted for a representative day of the March month was analysed and a significant difference to the real power profile on nighttime was still observed (figure 5).

Investigation over the high value of electric power recorded at night have shown that part of the first floor is occupied 24 h/day, with air conditioning continuously switched on. Changing the schedule for this zone results in a model with hourly power profile very close to reality (Adjusted curve in figure 5), and annual electric energy consumption only 1% lower than actual value. The higher monthly difference was observed at January (20%), as can be seen in the figure 6.

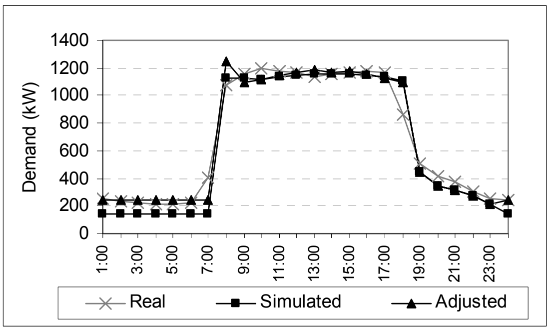

Figure 5 Comparison between real and simulated hourly power profile.

At this point, the model is calibrated. The electricity end-use for the building model is divided between: lighting (59%), air conditioning (30%) and plug loads (11%).

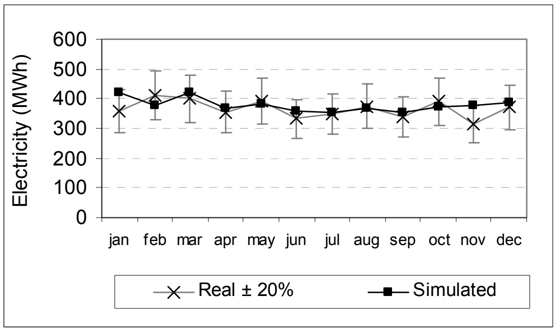

Figure 6 Comparison between real and simulated monthly electric energy consumption of the building, the 6th stage of calibration - final model.

CONCLUSIONS

A methodology for adaptative calibration of a building model was presented. An office building was simulated in the EnergyPlus and the model was calibrated in six stages. This methodology was tested over an existent building, but it will be especially valuable for new building modelling.

Initially, constant loads were calibrated based on energy audit and analysis of the building hourly power profile. A base case with some default values was simulated for a design day and the analysis over the main heat flux into the building indicate input parameters that should receive more attention in the modelling phase. In this specific case, windows were identified as the most import component of heat gain and loss. Sensitivity analysis over variables related to window characterization helped to adjust the energy estimative provided by simulation. Some adjustments were made in the parameters with higher influence coefficient and a whole year simulation was conducted. The monthly energy consumption was very close to recorded data, but a final adjustment was made in the model and the higher monthly difference got 20%. The annual energy electric consumption estimated by simulation was only 1% lower than recorded value after four iterations applied over the base case model.

Rather than performing several hundreds simulations to carry out a sensitivity analysis over the base case, this methodology required only five cases, filtered by previous thermal analysis of the model. The time spent on modelling and calibration phase was notably minimized, but could not be measured in this work because the methodology was changed and adapted during the case study simulation. Others tests will be made to check the effectiveness of the method and extend it to allow the analysis over system and plant variables.

As future work, adequate default values should be investigated to help the user in the definition of base case characteristics. A database could be used for different sizes and types of buildings (commercial, residential, public, etc.). Sensitivity analysis could be also implemented to check the influence of the uncertainty embedded in specific default values.

Sensitivity analysis developed in this work considered linearity effect of the input parameters. Some variables have not linear behaviour. In addition, some inputs are influents on others. This kind of inter-correlation should be checked also.

The method was tested in EnergyPlus program, but it can be applied to other energy simulation program. For practical application in EnergyPlus, a graphical interface is needed to achieve the objective of the method: minimize the hard work on modelling and calibration phase.

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