UNIVERSITE DE LIEGE

FACULTE DES SCIENCES APPLIQUEES

DEPARTEMENT D'AEROSPATIALE ET MECANIQUE

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Simulation assisted audit & Evidence based calibration methodology

DRAFT

Stéphane BERTAGNOLIO (*)

Vincent LEMORT

Thermodynamics Laboratory

University of Liège

Sart Tilman Campus, B49

B-4000 Liège

Belgium

Philippe ANDRE

BEMS

University of Liège

Arlon Campus

B-6700Arlon

Belgium

(*) corresponding author: stephane.bertagnolio@ulg.ac.be

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SIMULATION ASSISTED AUDIT METHODOLOGY

1. INTRODUCTION

As mentioned in the first chapter, building energy simulation tools can be of a great help when conducting an energy audit. Krarti (2000) integrates the development and the use of a building energy simulation model in the audit procedure, mainly for selecting and evaluating energy conservation measures at detailed audit stage.

It is now proposed to extend the use of BES models to other steps of the audit process, such as, benchmarking and inspection stages.

1.1. Simulation for Benchmarking

While normalization is required to allow comparison between data recorded on the studied installation and reference values deduced from case studies or statistics; the use of simulation models allow to assess directly the studied installation, without any normalization needed. Indeed, applying a simulation-based benchmarking tool allows an individual normalization and allows avoiding size and climate normalization.

So, rather than looking for very global weather indexes, it seems rational to use a simulation model and run it over a few thousands of hours corresponding to one typical year. The current capabilities of computers and simulation tools make this approach very efficient and allow considering the climate as it is, without any simplification.

1.2. Simulation for Inspection

As explained here above, global monthly consumptions are insufficient to allow an accurate understanding of the building's behaviour. Even if some very rough results can be expected from the analysis of monthly fuel consumption, global electricity consumption records analysis do not allow to distinguish the energy consumption related to AC from the consumption related to other electricity consumers.

Even if the analysis of the energy bills does not allow identifying with accuracy the different energy consumers present in the facility, the consumption records can be used to calibrate building and system simulation models. To assess the existing system and to simulate correctly the building's thermal behaviour, the simulation model has to be calibrated on the studied installation. Of course, basic data as building envelope characteristics or the type of HVAC system are easily identified but infiltration rate or actual ventilation flow rate have to be adjusted.

The iterations needed to perform the calibration of the model can also be fully integrated in the audit process and help in identifying required measurements and critical issues. Unfortunately, no systematic calibration procedure adapted to audit already exists. The adjustment of the developed simulation model will be discussed later.

1.3. Simulation for ECMs evaluation

After having been calibrated to recorded data, the baseline model can be used to analyse the actual performance of the building and to identify the main energy consumers (lights, appliances, fans, pumps …). At the end of the audit process, selected energy conservation opportunities can be implemented, assessed and compared to each other.

2. BUILDING ENERGY SIMULATION (BES) MODELS CALIBRATION

2.1. *NEED FOR CALIBRATED BUILDING ENERGY SIMULATION MODELS*

Since the 1960s, building energy simulation was more and more investigated to help in improving energy performance of buildings and HVAC&R systems. Initially, building energy simulation (BES) models were mainly used for design purposes (Lebrun and Liebecq, 1988). More recently, the area of application of BES models was extended in further (post-construction) stages of the building life cycle, such as building operation optimization, technical and economical evaluation of Energy Conservation Measures (ECMs), commissioning and functional performance testing (Visier and Jandon, 2004), fault detection and diagnosis (Jagpal, 2006), building energy management (Lebrun and Wang, 1993) and energy audit (Auditac, 2007; Harmonac, 2008, Krarti, 2000). At the same time, graphical user interfaces were developed to facilitate use of such complex tools (Spitler, 2006).

Using BES models to help in understanding the thermal behavior of an existing situation requires the BES model to be able to closely represent the actual behavior of the building under study. The fitting of a BES model to an existing situation involves using as-built information, survey observations and short and/or long term monitoring data to iteratively adjust the parameters of the BES model. This adjustment process is called "calibration".

- This definition of the calibration process leads to numerous questions:
- What are the initial objectives of the calibration? What is the calibrated BES model intended for?
- Which level of details is required for the model? Which type of BES model should be used? Which level of accuracy do we need to reach?
- Which type of data should we gather from the building and which difficulties do we have to face? What are the time-step and the accuracy of the measurements?
- How should we proceed to adjust the parameters of the model? On which parameters should we focus?
- How can we define "accuracy" of the calibration? How much are we confident in the quality of the calibration and what are the abilities of the calibrated model? Does it match with the pre-defined objective (control optimization, ECMs evaluation...)?

Ahmad and Culp (2006) have developed a test time-limited blind protocol to evaluate the range of discrepancies encountered when using uncalibrated simulations. Two time limits were arbitrary defined to simulate the building in the realm of usability by industry. Level 1 modeling was mainly based on available design data while Level 2 modeling included as-built and operating information obtain from the maintenance personal. Simulated and recorded energy use data for four buildings were then compared. Discrepancies of +/- 30% were observed when comparing recorded and simulated total energy uses of the buildings. For individual components such as chilled water or hot water consumptions, discrepancies exceeded +/- 90%. The authors also pointed the importance of operation and occupancy when trying to calibrate a BES model. If the simulations did not adequately represent the real operation of the considered building, improving the level of detail in the representation of the envelope, schedules and mechanical equipment may not improve the prediction capabilities of the simulation.

2.2. *USE OF CALIBRATED BUILDING ENERGY SIMULATION MODELS*

Calibrated building energy simulation models can be used for various applications, from optimization of HVAC system operation to continuous commissioning and evaluation of energy and money savings related to energy retrofit.

Liu and Claridge (1998) present an example of use of a simplified calibrated model for optimization purposes. The authors show how calibrated models can be used to identify HVAC system problems and to develop optimized HVAC control strategies. The energy savings measured after implementation of the optimized control strategies are consistent with the computed savings. Costa et al. (2009) are developing a “key factors” methodology intended to help energy managers in optimizing the operation strategy in relation to both energy efficiency and indoor comfort. This optimization methodology is based on the use of a very detailed calibrated BES model. Usually, these applications require very detailed and specific simulation models able to realistically take into account all the major influences involved in the operation of HVAC&R systems. Of course, the calibration of such detailed models requires more detailed and specific information (complete as-built data, numerous measurements…) compared to simplified models.

Another common application calibrated BES models is the evaluation and the comparison of ECMs (Kaplan et al., 1990, Chen et al., 2006, Pan et al., 2007, Cho and Haberl, 2008a and 2009). Three major standards are currently used for guiding in measuring, computing and evaluating savings achieved by energy efficiency retrofits: the ASHRAE Guideline 14-2002 (ASHRAE, 2002); the IPMVP - International Performance Measurement and Verification Protocol (EVO, 2007) and the FEMP - Federal Energy Management Program (USDOE, 2008) Monitoring and Verification Guide. These standards mention calibrated BES models as a possible mean to evaluate energy conservation measures but provide only general rules and guidelines to perform the calibration and no detailed calibration method.

ASHRAE (2002) provides also useful remarks about when calibration should be used or not for ECMs evaluation. So, calibration should be applied when:

- Pre or post-retrofit whole-building metered data are not available (making evaluation of ECMs impossible) or are available but savings from individual retrofits are desired;
- Savings cannot be estimated using measurements only;
- It is impossible to isolate the effects of the retrofit and interactions should be taken into account;

On the contrary, calibration approach should not be used when:

- ECMs could be analyzed without building simulation;
- The building cannot be simulated (presence of large atriums, underground buildings, complex shading configurations…);
- The HVAC system cannot be simulated (certain control options cannot be represented…);
- The retrofit cannot be simulated;
- Project resources and financial issues are insufficient to support development and use of calibrated simulation.

Kaplan et al. (1990) have shown that, even if the calibration seemed to be successful, the finely calibrated model was not necessarily able to ensure an accurate analysis of ECMs because of lack of data on the pre-retrofit situation and use of an “imaginary” baseline building. The authors conclude that, when having to evaluate ECMs after their implementation, it is necessary to monitor the building before the implementation of the ECMs or with the ECMs turned off to evaluate accurately the related energy savings.

Despite of this observation, in the frame of an audit of an existing building, it seems rational to use a calibrated model to perform objective evaluation and comparison of ECMs before any retrofit work. Even if the results of this evaluation are not fully validated after implementation and verification of the ECMs, the "main trends" should, at least, have been highlighted.

As pointed by Reddy (2006), in addition to identification, selection and evaluation of ECMs and related savings, calibrated BES models are also commonly used for these more specific purposes:

- To help in improving specific components models used in a more global simulation program;
- To help building's owners in understanding patterns in thermal energy and electricity use of their building;
- To disaggregate the electricity consumption of a building by identifying the fraction of the whole electricity use dedicated to plug loads, lighting, fans, pumps, humidification…

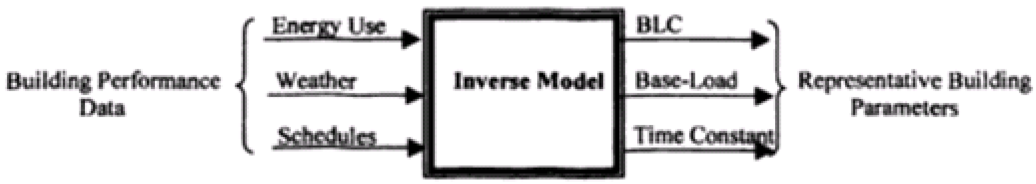
Particularly, for the auditing targeted work described before, several factors should be taken into account by an energy auditor when selecting a BES model, including reproducibility, sensitivity, accuracy and ease of use (Krarti, 2000, Adam et al., 2006). These considerations lead to the development of specific simulation tools adapted to energy audit purposes and constructed according to the information and questions commonly encountered during an audit procedure.

2.3. TYPES OF BUILDING ENERGY SIMULATION MODELS

As mentioned before, an important issue when starting an energy audit is the selection of the BES model to use (Krarti, 2000). Depending of the type (residential, school, health...), the size and the complexity of the building to audit, the model will have to account for various conditions and attention must be paid to the level of details required to perform the analysis. As pointed by Waltz (2000), when trying to calibrate a model to 10% accuracy recorded data to evaluate ECMs with Typical Mean Year (TMY) or Typical Reference Year (TRY) weather data, you should not try to reach a 1% accuracy calibration: "You don't need a 1% answer to a 10% question."

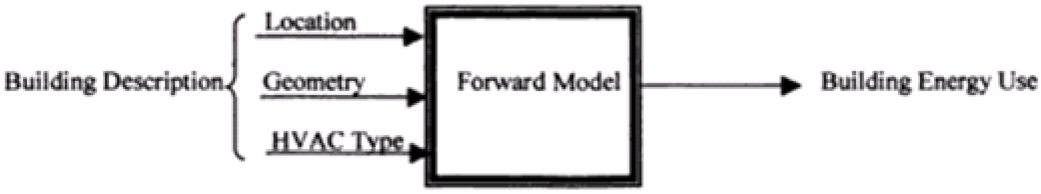
Different criteria can be considered in order to classify BES models. Basically, inverse and forward modeling techniques should be differentiated:

- Inverse models are generated basing only on measured data and generally rely on regression analysis (Fels, 1986, Kissock, 2002, Reddy et al., 1999) to deduce representative building parameters (building heat transfer coefficient, building time constant...). Reddy et al. (1999) propose an inverse model parameter identification scheme to estimate building and ventilation parameters from non-intrusive monitoring of heating and cooling energy use. It appears that the identification process is accurate when daily data over an entire year are used to perform calibration of this model. In the frame of the ASHRAE RP-1050 research project and in relation with the ASHRAE Guideline 14-2002, Kissock et al (2002) developed an inverse linear calculation toolkit for the purpose of measuring energy savings. The toolkit includes the algorithms necessary to find the best-fit for three, four and five-parameters change-point models and to evaluate the uncertainty of model predictions and saving. The main limitation of this modeling method



(To be adapted from Krarti, 2000)

- Forward modeling involves using physical models able to predict the future of a system described by some parameters (geometry, location, nominal performances...). The calibration of such models implies an iterative tuning process of the parameters of the model to match recorded data. The most famous forward building energy simulation models are DOE-2 (LBL, 1980), Trnsys (Klein, 2007), EnergyPlus (US-DOE, 2009).



(To be adapted from Krarti, 2000)

Even if inverse models are generally more simple than forward ones, their flexibility is limited by the representative building parameters used to formulate the model and the accuracy of the recorded data used to calibrate the model. For example, it is not possible to evaluate the impact of replacing an existing chiller by a more efficient one if no parameter of the inverse model deals chiller performances. On the contrary, forward models are more flexible and rely on physical models which can be adapted to various situations. Moreover, these models can be continuously updated to take additional influences into account (e.g. developing/implementing a more detailed chiller model to take into account of the improvement of part load performances due to the replacement of the chiller).

Secondly, once generally distinguishes static and dynamic BES models, respectively, not able or able to take into account of the thermal inertia of the building structure when computing energy balances. Thirdly, single zone and multi zone models can also be compared. The first ones can only simulate the building as a unique zone and cannot consider heat, air and humidity transfers between the different zones of the buildings. Multi zone models can simulate simultaneously a small or large number of zones and allow representing the heat, air and humidity transfers between zones and the simultaneous heating and cooling demands occurring in the building.

Considering only forward models and basing on these two last criteria, Lydberg (1987) have compared BES tools from an auditor's point of view and provide the following comments:

- Static single-zone models, involving a very limited number of parameters and simplified calculations as degree-days calculations, are generally not sufficient for audit of air-conditioned buildings;
- Static multi-zone models are generally appropriate for the evaluation of ECM's related to the building envelope but not adapted to the evaluation of ECM's related to intermittent heating/cooling. These models work with a time step from one day up to one month and give only average values;
- Dynamic single-zone models work with a time step of one hour or less and consider the building interior as uniform. These models can predict peak values and can be used to evaluate ECM's related to air conditioning system. However, multi-zone systems cannot be represented;
- Dynamic multi-zone models are the most detailed models and allow very accurate calculation of indoor conditions and heating/cooling demands. Generally, these models are used for

design purposes, require a detailed description of the building and the coupled system and more efforts to be calibrated to the studied installation (due to the larger number of parameters);

HVAC system models, based on simple static to very detailed dynamic models of HVAC components are generally coupled to building simulation models or used for specific purposes (as HVAC system design or commissioning).

Reddy and Maor (2006) have also compared the most common "simulation approaches" and distinguish five types of building energy simulation tools:

- Spreadsheet programs ;
- Simplified system simulation method ;
- Fixed schematic hourly simulation programs;
- Modular variable time step simulation programs;
- Specialized simulation programs.

Spreadsheet programs (1) and steady state simplified methods (2) have shown their limits in predicting the energy use of modern buildings. Specialized programs (5) are mostly dedicated to the simulation of particular phenomena (such as contaminants movement, air stratification…). Quasi-steady state fixed schematic hourly simulation (3) programs are generally based on the LSPE (loads - secondary system - primary system - economics) sequential approach. Flexible modular simulation programs (4) are based on more realistic models and take all the interactions (building/system/control) into account.

For audit purposes (energy use breakdown and ECMs evaluation), the simple LSPE approach seems sufficient. Studying interactions between control and HVAC components performances and capacities (by means of a modular approach) could be useful to help the auditor in identifying energy wasting. However, this requires a more accurate and detailed description of the building, its system and the control laws.

Simplification of BES models can also occur at other levels than the calculation approach. Generally, simplified models differ from the detailed ones only in the definition of the building (zone typing, types of walls…) and the HVAC system (HVAC components consolidation…) but perform also dynamic building simulations and steady-state system simulations and can provide useful and accurate results. Moreover, it has been highlighted that variances in simulation results among different users are generally larger than those resulting from the use of different (detailed or not) calculation methods (Lydberg, 1987; Liu et al., 2004).

The level of detail required for the calculation of heating and cooling demands can be very different (Adam et al., 2006). For heating calculations, the major issues are a correct description of the building envelope and a reasonably accurate evaluation of the air renewal (including infiltration and ventilation). For cooling calculations, the fenestration area and orientation, the level and distribution of the internal gains, the ventilation rates and the geographical location and the usability of the thermal mass (if present and accessible) appear as critical issues.

On the building side, Cho and Haberl (2008b) have demonstrated that the use of a simplified box-shaped geometry causes only a very small deviation on the energy consumption results. As-built and simplified geometry models should be compared in different situations but we can fairly assume that, for common buildings, the use of a box-shaped geometry does not introduce important errors.

Liu et al. (2004) propose five rules that should be followed for AHU consolidation:

- The consolidated AHUs should be the same type (dual-duct, single-duct, VAV, CAV…)

- The consolidated AHUs should serve similar zones (interior zones and/or external zones but no mixing…)
- The AHUs should have similar minimum outside air intake ratios and the same outside air control
- The zones served by the AHUs must have similar occupancies, similar peak loads and similar load profiles
- The consolidated AHU air flow is equal to the sum of each individual AHU's airflow

By following these rules, AHU consolidation can be applied without important loss of accuracy.

These simplifications are often welcome for practitioners since, most of the time, the large amount of input data restricts the simulation programs to researchers. As pointed by Westphal et al. (2005), the development of more friendly interfaces, customized to user needs, would allow the dissemination of simulation tools into design offices.

2.4. *GATHERING DATA*

Burch et al. (1990) categorizes the monitoring methods in two classes:

- Macrostatic methods based on time-integration of the building energy balance, such as classical utility bill analysis or long-term or short-term energy measurements. These techniques are the most commonly used;
- Macrodynamic methods combine identification methods (such as the PSTAR method, developed by Subbarao, 1988a) and use of the building's dynamic energy balance. These techniques are generally employed in residential buildings.

Most commonly available data are utility billing data. Monthly gas consumptions and whole-building monthly electricity and peak demands are generally available for at least one complete year. However, the data available when starting an energy audit may vary a lot from case to case.

In some buildings, one can find separate energy or power meters measuring local or end-use (e.g. lighting, HVAC, chiller...) electricity consumptions and demands. The use of these meters is not mandatory in the European tertiary building sector but is more common in some countries, such as Korea (Yoon et al., 1999; Yoon et al., 2003).

Cooling and heating energy or demand meters can also be encountered. Once again, these meters are not common in Europe (except for very large buildings) but can be often encountered in US.

Building Energy Management Systems (BEMS) are also very useful when performing an inspection. BEMS programs can often be used to perform measurements without requiring any additional sensor. Of course, the quality of the measurements has to be checked and evaluated before analyzing the results. Open source BEMS programs are also of a great help to identify the control laws as the basis for operating the HVAC system.

It appears that the problem of weather data gathering is still a problem for analysts having to calibrate a BES model. ASHRAE (2002) considers that collecting hourly weather data corresponding to the same time period as the energy data used for calibration is a minimal requirement to perform calibration. Sometimes, modern buildings are equipped with their own weather station. Even if this is very useful, weather data are rarely complete and some values are often missing (e.g. solar radiation) and should be completed from other sources of data. Moreover, in most cases, actual weather data is not available and should be obtained from another source.

To simplify modelling and prevent this lack of data, Liu et al. (2004) treat solar radiation as a linear function of the outdoor drybulb temperature. Even if this approach can be envisaged to be used with simplified calculation methods, such as the ASHRAE modified bin method (Knebel, 1983) used by Liu et al. (2004), this hypothesis can lead to large errors when studying largely glazed commercial buildings, strongly influenced by solar gains. The related error is even larger when applying this hypothesis to hourly BES models.

Typical weather data, such as TRY or TMY data, is sometimes used to perform calibration. This requires normalizing energy consumptions (by means of signatures) to allow comparison. However, the use of average data to perform calibration can induce important errors and ASHRAE Guidelines 14-2002 strongly discourages this approach.

Hopefully, in our countries, recent actual hourly weather data are generally available for at least a few weather stations. When having to perform calibration, hourly weather data from the nearest location should be used when actual local weather data is not available. This allows performing a better calibration than the one performed by mean of, sometimes poorly representative, TRY or TMY weather data.

Of course, the data available when starting the audit process can be completed by means of short-term or spot measurements. These measurements are generally realized by means of (portable or not) data loggers and can help in quantifying some specific energy uses (e.g. lighting power density, fan power...), check some operation parameters (e.g. supply air temperature and flow rate) or patterns (e.g. ventilation schedule). The decision to perform these measurements is generally taken as function of the needs of the auditor and depends mainly of his own experience.

Other specific measurements and tests, developed for residential applications (e.g. blower door, dynamic tests), can be used to determine and quantify critical parameters such as infiltration rate and thermal inertia. However, these measurements are more intrusive and, most of time, not feasible in existing non-residential buildings.

The PSTAR (Primary and Secondary Term Analysis and Renormalization) method (Subbarao, 1988a) is a short term monitoring method which has been developed at the end of the 80's for residential applications. It includes measurement protocols and provides a simplified (static or dynamic) model to calibrate.

This method aims in estimating the parameters of a realistically complex building model basing on the data obtained during an inspection (or audit) and short term (typically a few days) monitoring data. Each zone of the studied building is described by an air energy balance expressed as a sum of heat flows. One particularity of the method is the great freedom allowed to the user in defining the terms of this energy balance to take into account. Each heat flow may be a primary unknown (firstly estimated by a simple audit calculation and secondly renormalized by means of monitoring data), a secondary one (obtained by calculation only) or a measured one (obtained by direct measurement only). Once the model described, a test plan has to be constructed to allow identifying the parameters of the model.

Typical measurements used when applying the PSTAR method are:

- Outdoor, indoor and supply air temperature measurements;
- Incident solar radiation measurement;
- Lighting and plug loads power measurements;
- Ventilation rate measurement;
- Infiltration rate measurement (blower door test);

- Supply and return air flows diffusion measurement (tracer gas);

In addition with these measurements, some specific tests have to be realized to force each "primary" term to become dominant in the energy balance during a short period (e.g. make the steady-state conduction term dominant by suppressing the night setback for one or more nights). These tests have been commonly applied in the residential sector but are generally not feasible in nonresidential buildings due to their very intrusive character.

After "renormalization" (or calibration), the model can be used for long-term extrapolation, energy savings evaluation, fault detection, HVAC operation optimization…

Since its development, the PSTAR method has been applied several times to residential buildings (Subbarao et al., 1988b; Carrillo et al., 2009) but very rarely to office buildings. Only a few examples exist, as the one described by Burch et al. (1990) which have applied the PSTAR method to a 12000 m² office building.

The time-period, the time-step and the accuracy of the gathered measurement data are also very important issues. Usually, monthly data for a whole year can be collected at the beginning of the audit process and are used to perform calibration. Kaplan et al. (1990) use three "snapshot" periods instead of an entire year of data. A hot, a cold and a temperate month are extracted from monitored data in order to calibrate a DOE2 model.

It is easy to admit that as short is the measurement time step, as useful are the measurements. Indeed, compared to long time step data (e.g. monthly records) short time step data (e.g. daily or hourly measurements) allow correlating energy use with weather and operating schedules (distinction between week and weekend days, more accurate correlation between outdoor temperature and gas consumption…) and identifying operating patterns (e.g. electricity base load). Averaged recorded data (e.g. billing data) is less useful and smooth weather and operation influences. It is impossible to deduce any schedule or operating profiles from such data. Lunneberg (1999) affirms that, in mild climates, large non-residential buildings are often internal load-dominated rather than weather-dominated. This observation indicates a large dependence of the building energy use to operating and occupancy schedules and confirms the need to properly estimate occupancy and operating schedules (Pedrini et al., 2002).

Measurements accuracy has also to be considered before any analysis. Indeed, errors of approximately 5% are common when working with data recorded manually because of approximate recording periods. When using short term measurements equipments, the accuracy of the data logger has to be taken into account when analyzing the results.

2.5. BES MODEL CALIBRATION

The calibration of a forward building energy simulation program, involving numerous input parameters, to common building energy data is a highly under-determined problem that would results in a non-unique solution (Carroll and Hitchcock, 1993). As noticed by Kaplan et al. (1990), it will never be possible to identify the exact solution to the calibration problem and limiting ourselves to a unique plausible solution would make the prediction accuracy of the calibrated model very questionable. Moreover, calibration requires a dynamic matching over one year between computed and measured values and not a static one at one condition (Reddy and Maor, 2006).

- The most common calibration methods can be classified as proposed by Reddy (2006):
- Manual iterative calibration based on the user's experience and consisting in an adjustment of inputs and parameters on a trial-and-error basis until the program output matches the known data;

- Calibration based on specific graphical representations and comparative displays of the results to orient the calibration process;
- Calibration based on special tests and analytical procedures involving specific intrusive tests and measurements, such as the PSTAR method (Subbarao, 1988a) described above;
- Analytical and mathematical calibration methods involving use of optimization algorithms.

Of course, all these methods are not exclusive and could be coupled (e.g. use of graphical and statistical analysis methods to support iterative manual calibration, semi-automatic procedures coupling mathematical and heuristic manual methods).

2.5.1. Manual calibration methods

Manual methods are the most commonly used. Numerous authors and practitioners use this kind of method to adjust the parameters of detailed BES models. Unfortunately, these methods are highly dependent of the user's experience and rarely applied in a systematic way.

Kaplan et al. (1990) presented a methodology to evaluate the ECMs already implemented in a monitored building. This was done by calibrating a DOE2.1 model to recorded data and deriving a "baseline" (or pre-retrofit) model without ECMs. This work is one of the first successful calibrations of a detailed simulation model.

The manual iterative calibration performed by the authors involves 9 steps to tune the model within the specified tolerances. Unfortunately, the authors provide only general guidelines and rules to perform the calibration. The changes and adjustments between two iterations are purely subjective and based on user's experience.

Another typical example of manual iterative calibration is the one presented by Pan et al. (2007).The paper presents the calibration of an e-Quest (DOE2 based simulation tool) model of a commercial building located in Shanghai. Building geometry and zoning were simplified to save calculation time. The calibrated model is then used for energy-use breakdown and ECMs evaluation. The model was calibrated in four steps:

- Replacement of TMY weather data by actual 2004 weather data for Shanghai;
- Refining HVAC system operating schedules according to measurements and site survey;
- Refining internal loads according to on-site measurements;
- Adjusting infiltration rate according to on-site observations.

Even if some explanations of the remaining errors are proposed, this typical calibration of a commercial code to monthly billing data does not satisfies all the tolerances prescribed by common calibration standards (ASHRAE Guideline 14-2002, IPMVP and FEMP). Moreover, the calibration performed here is fully heuristic and is not based on any systematic or logical calibration procedure. Unfortunately, no consideration on sensitivity of the model is given by the authors.

Pedrini et al. (2002) present a general calibration methodology based on three major steps:

- simulation from building documentation;
- walk-through audit;
- and end-use energy measurements.

The proposed methodology is successfully applied to calibrate a DOE2.1 model to several case studies buildings but stays very general and is not as systematic as it could be. The authors affirm reaching a final error of about 0.2 % on annual energy consumption which can be highly questionable. Indeed, this is equivalent to try “answering a 10% question with a 1% answer” (Waltz, 2000). The importance of coupling the calibration work to a sensitivity analysis is also noticed but not developed.

Westphal et al. (2005) present a calibration method similar to the one proposed by Pedrini et al. (2002). This method is applied to the EnergyPlus software and combines energy audit techniques and sensitivity analysis. This calibration method starts with the calibration of lights and plug loads, followed by a short sensitivity analysis (using design days simulations) allowing identifying the most influential parameters to adjust in priority. The main advantage of this sequential approach is the integration of a simple sensitivity analysis into the calibration process. However, the approach does not follow the classical way to perform energy audit and studies building base loads before its envelope and HVAC system. Moreover, numerous hypotheses (on the building and the equipments) are needed at the beginning of the calibration process and make the methodology not easily reproducible.

In his paper, Lunneberg (1999) describes how short-term monitoring of key internal loads (measurement of key electrical end-uses and hourly load profiles) was successfully applied to DOE-2 simulation of an existing commercial office building located in California. Even if the author does not integrate this technique into a systematic calibration process, some very interesting findings and conclusions are highlighted:

- Monthly, weekly and daily schedules are important and should be monitored.
- Using schedules provided by the building operating staff or standardized schedules can lead to large over/under-estimation of energy use;
- Care must be taken when considering a behavior, a schedule, an area or any tenant as “typical” and representative of the building under study.

Yoon et al. (2003) provide a systematic manual iterative calibration methodology of the DOE 2.1E code based on a so-called “base load analysis approach” combining analysis of monthly billing and sub-metered data commonly available in Korean buildings (watt meters are commonly installed in Korean buildings to monitor the various electricity end use). The purpose of this study is to use a calibrated model in the frame of an energy audit procedure to evaluate ECM’s.

This approach includes seven steps:

- Base case modeling (basing on available documentation);
- Base load consumption analysis using data analysis techniques such as the ones provided by Lyberg et al. (1987);
- Swing-season calibration
- Site interview and measurements
- Heating and cooling seasons calibration
- Validation of calibrated base model using graphical and statistical techniques
- Application of the calibrated model to evaluate ECM’s

Classical statistical indexes (MBE; CV(RMSE)) and gas and electricity signatures are used to validate the calibration. Due to the large cooling demands commonly encountered in Korea, the electricity signature allowed to identify the base load consumption quite easily. Moreover, the fifteen watt meters already present in the buildings were used to disaggregate the electricity consumption and quantify the electricity end uses. As an example, during the typical week day considered for “base load analysis”, it was found that the fraction of the global electricity consumption due to lighting, HVAC, plug load and elevators were, respectively, 31%, 16%, 41% and 12%.

This first systematic manual method highlights interesting issues, such as the usefulness of electricity end-use measurements and manual data analysis to identify some parameters of the model. Unfortunately, this procedure cannot be directly transposed for European applications due to the impossibility to identify base load and HVAC electricity consumptions from whole-building electricity data.

Liu et al. (2004) presented another example of systematic two-level calibration method for simplified building and AHU energy consumption models. The simplified model used consists in a two-zone (interior – exterior) building model coupled to a consolidated AHU model. This simulation model (called “AirModel”, Liu, 1997) has been developed by the Energy Systems Laboratory (ESL) at Texas A&M Univesity in the 1990’s and is based on the ASHRAE Simplified Energy Analysis Procedure (SEAP, Knebel, 1983).

The two-level calibration method focuses on the weather dependence of the model (1st level) and on the time schedule dependency (2nd level) and uses measured hourly values of heating and cooling energy consumptions. The first step of the calibration process relies on the use of the AHU heating and cooling energy signatures described by the same authors in another report (Liu et al., 2003).

Raftery et al. (2009) are developing a calibrated EnergyPlus model to allow the building manager to optimizing the operation of the HVAC system using a “key factors” methodology (Costa et al., 2009). The proposed calibration methodology is intended to be applied to the EnergyPlus program and is based on three core principles:

- Use of a detailed BES model that represents the real building as closely as possible;
- Application of a reproducible and scientific method;
- Obtain and use measurements from energy monitoring systems (EMS) and building automation systems (BAS)

This classical manual iterative calibration methodology includes measurements issues and tries to keep the calibration process as systematic and “evidence-based” as possible. In this frame, the BES model being calibrated should be used to investigate possible further measurements. Data gathering is fully integrated to the iterative calibration process.

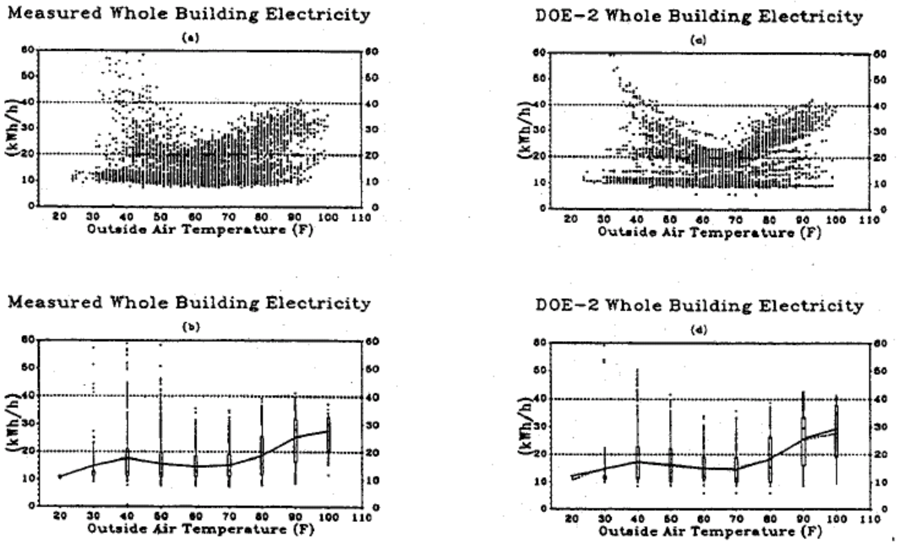
The initial as-built model is supposed to be similar to a very detailed BES model created at the design stage. A very detailed zone typing and HVAC system description based on extensive design data (Building Information Model, As-built drawings, Operation & Maintenance manuals...) is used.

Due to this very detailed description of the building, the manual iterative calibration process requires the installation and use of an important number of energy monitoring systems and the gathering of an important quantity of measurements. Till now, no sensitivity issues have been included in the calibration process and only the very first steps of the calibration (development of the initial model and basic STEM) have been applied to a real building located in Ireland.

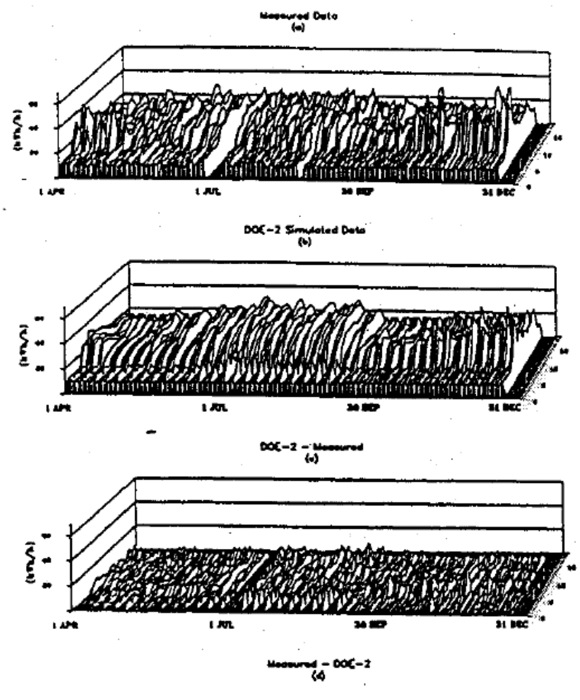
2.5.2. Graphical and statistical methods

Bou-Saada and Haberl (1995) propose a calibration method including bin analysis on different time-scales and statistical indices such as MBE and CV(RMSE) to analysis the goodness-of-fit of the model. This procedure was used to calibrate a DOE2 model of a building located in Washington D.C. to hourly whole-building electricity (WBE) data.

In addition to classical time-series plots and scatter plots, the authors use binned box-whisker-mean plots displaying maximum, minimum, mean, median and percentile points for each data bin for a given period. This new graphical method allows the author to view and analyze the weather and schedule dependent hourly energy use. 3D surface plots and statistical indices are also used to have a global view of the differences between measured and computed hourly values to help in identifying seasonal or daily patterns in the comparisons.



Scatter and box-whisker mean plots (Bou-Saada and Haberl, 1995)



3D surface plots (Bou-Saada and Haberl, 1995)

McCray et al. (1995) propose another graphical method to calibrate a DOE2.1 model to an entire year of hourly or 15 minute metered whole-building energy use. The Visual Data Analysis (VDA) method allows quickly comparing the results and reviewing the parameters of the model during a calibration process. The accuracy criteria is based on classical statistical indices (MBE and CV(RMSE)).

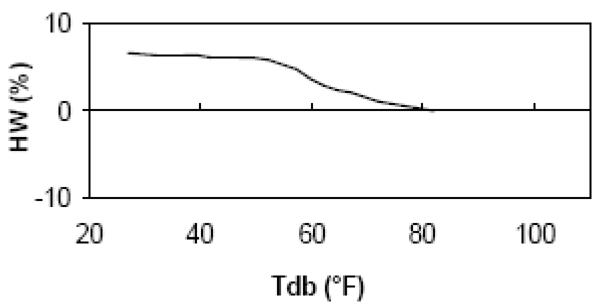
The graphical methods proposed by Bou-Saada and Haberl (1995) and McCray et al. (1995) suit well with the calibration of simulation models to hourly measured data. With only whole-building monthly data, these advanced graphical methods are of less help and a very systematic and logical calibration method has to be applied to limit the number of simulation runs and make the calibration process efficient.

Wei et al. (1998) found that calculating, normalizing and plotting the difference between measured and predicted heating and cooling consumptions was useful to help in calibrating building energy simulation models. This "signature method", based on daily heating and cooling energy consumptions, has been extended to other climates and types of HVAC system by Liu et al. (2003). The signatures provided in these reports have been generated by means of the "AirModel" tool (Liu, 1997).

For a given system type (CAV, VAV…) and climate, the "calibration signature" (graph of the difference between measured and computed data as a function of outdoor temperature) has a characteristic shape that depends on the reason for the difference.

$$\text{Calibration signature} = \frac{-\text{Residual}}{\text{Maximum measured energy}} \times 100\ \%$$

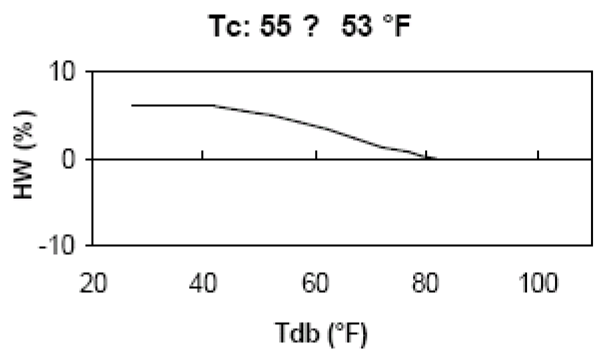
$$\text{Residual} = \text{Simulated consumption} - \text{Measured consumption}$$



Example of heating calibration signature (Liu et al., 2003)

So, "characteristic signatures" can be generated and published for different systems and climates. Then, the comparison of the "calibration signature" to this "characteristic signature" can help in performing the calibration of the model.

$$\text{Characteristic signature} = \frac{\text{Change in energy consumption}}{\text{Maximum energy consumption}} \times 100\ \%$$



Example of cold deck temperature characteristic signature (Liu et al., 2003)

The method is easy to follow and generalize but is actually based on data currently not available (hourly or daily hot water and chilled water consumptions). It could be envisaged to extend this method to typical European buildings, systems and climates and to commonly available data: WBE (Whole-Building Electricity) and NG (Natural gas or fuel consumption). Another advantage of this method is that it allows to couple sensitivity issues and calibration.

2.5.3. Automated calibration methods

Carroll and Hitchcock (1993) summarized the work done by the team of LBNL onto the development of automatic calibration methods for the RESEM (Retrofit Energy Saving Estimation Model) tool (Carroll et al., 1989) based on the ASHRAE modified bin method (Knebel, 1983). A semi-automatic numerical calibration algorithm has been developed and implemented. The calibration is performed by minimizing an objective function constructed as a weighted sum of the difference between computed and recorded data. Model's parameters are categorized in "high-level" and "low-level" characteristics. In a first time, the user is allowed to select the "high-level" characteristic suspected to be the source of the discrepancies, then, the calibration algorithm tunes the "low-level" parameters related to this characteristic. The proposed method is applied to calibrate the RESEM tool to yearly data but could be adapted to be used with smaller time scales (as monthly or weekly data). The existence and uniqueness of solutions issues are already discussed in this paper. Since minimization algorithm are more efficient with a limited amount of parameters, the authors suggest also to begin a calibration with a heuristic selection of most influential parameters (basing on sensitivity analysis and experience of the user) to limit the calibration time and the number of simulation runs.

More recently, Lee and Claridge (2003) have presented another automatic calibration of a simplified building energy simulation model based on the ASHRAE Simplified Energy Analysis Procedure (Knebel, 1983) to measured data. This automatic calibration is performed by means of a commercial optimization program used to minimize the error between measured and computed hot water and chilled water consumptions. For the studied case, the model was calibrated to simulation data to which a small amount of white noise has been added. Five parameters have been considered: cooling coil leaving air temperature, room temperature, heat transfer coefficient of the building envelope, supply-air volume and outdoor-air flow fraction. The optimization algorithm used by the authors is able to provide objective free of local-minima.

The calibration method used here seems to be efficient and very promising. However, it must be noticed that this type of calibration is, most of the time, applied to simplified calculation method (such as the ASHRAE modified bin method) rather than detailed simulation models. Such numerical algorithms involve the use of a large number of parameters and simulation runs and cannot be easily adapted to dynamic hourly simulation tools.

The calibration method developed in the frame of the ASHRAE RP-1051 research project by Reddy and Maor (2006) is based on the same approach as the one proposed by Carroll and Hitchcock (1993) but uses a detailed hourly simulation code (DOE2.1), perform calibration to monthly billing data and include sensitivity analysis issues to identify a plausible set of solutions instead of an hypothetical unique solution.

A, even very good (satisfying all the accuracy criteria as the ones recommended by ASHRAE), calibration to the utility bill will not guarantee accurate fit at the end and may yield very bad and unsatisfactory prediction accuracy when using the calibrated model for energy and economic evaluation of ECM's. For that reason, it is commonly accepted that using a small number of most plausible solutions is more robust than using only one feasible calibration solution to make predictions.

In the frame of the ASHRAE RP1051, Reddy and Maor (2006) have recognized that fact in their approach and have developed a calibration procedure based on the DOE2 model and using only monthly billing data. This calibration procedure involves heuristic steps (definition of a set of influential parameters basing on walk-through audit and inspection), advanced mathematical methods (Monte-Carlo method, use of optimization algorithms…) and numerous trials and simulation runs. This heavy, sophisticated and partially “black-box” calibration method allows identifying a subset of most plausible solutions to this under-determined problem.

Lavigne (2009) has developed a semi-automatic calibration procedure implemented in DOE2.1 software. This calibration process involves common engineering rules and optimization algorithms and requires monthly electricity consumption, electricity peak demand and real local weather data. This methodology has been successfully applied to two existing buildings, using electricity as a unique energy source, resulting in maximal errors of less than 14%.

Two steps are involved in this calibration process:

- Pre-calibration, requiring no simulation run but simply analyzing the available recorded billing data to extract useful information (building heating and cooling global heat transfer coefficients, base load consumption...) and identifying critical parameters (ventilation rate, envelope performance...). A five-variable energetic model is used (ASHRAE Fundamentals, 2001) for this first analysis.
- Calibration, involving a Marquardt-Levenberg optimization method in order to minimize a objective function defined as a sum of differences between measured and computed data.

Combining intuitive and mathematical methods to calibrate detailed BES models, as done by Reddy and Maor (2006) and Lavigne (2009), is certainly an attractive solution to the calibration problem and an interesting compromise between black-box methods and full manual iterative processes. However, it seems difficult to integrate such methods with measurements issues and to make the calibration process as reproducible and flexible as a manual method. Indeed, some hypotheses on the available data have to be done when developing such a methodology and some parameters (as schedules) cannot be easily adjusted during the automated calibration.

2.5.4. Accuracy of calibrated BES models

A calibration process consists in adjusting the parameters of a model through several iterations until it agrees with recorded data within some predefined criteria. The definition of these criteria is a complex issue and, to date, it is impossible to determine how close a tolerance need to be to fulfill the calibration objective (Kaplan et al., 1990).

Usually, the authors (Yoon et al., 2003; Pan et al.,2007; ASHRAE, 2002) recommend using Mean Bias Error, Root Mean Square Error and Coefficient of Variation of the Root Mean Square Error to evaluate calibration accuracy. This multiple variable analysis allows preventing any calibration error due to errors compensation. Indeed, the common Mean Bias Error (MBE) approach is an important measure of calibration but has the disadvantage that large compensating errors can lead to a zero MBE (Yoon et al. ,2003).

MBE: Mean Bias Error

$$\text{MBE} = \frac{\sum_{i=1}^{n}(Q_{pred,i} - Q_{data,i})}{n\bar{Q}_{data}}$$

Using CV(RMSE) in addition to MBE to describe the variability of the results allows preventing this compensation problem.

RMSE: Root Mean Squared Error

$$\text{RMSE} = \frac{\sqrt{\Sigma(Q_{pred,i} - Q_{data,i})^2}}{n}$$

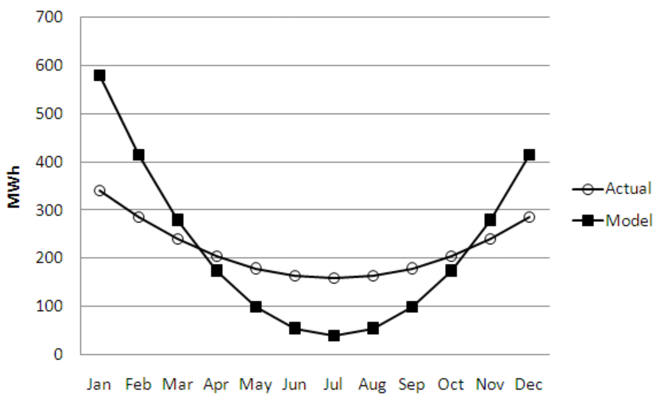
CV(RMSE): Coefficient of Variation of Root Mean Square Error

$$\text{CV(RMSE)} = \frac{\text{RMSE}}{Q_{data}} = \frac{\frac{\sqrt{\Sigma(Q_{pred,i} - Q_{data,i})^2}}{n}}{Q_{data}}$$

Where

$Q_{pred,i}$: predicted value during period i
$Q_{data,i}$: measured value during period i
Q_{data} : measured avg during the period

Figure x illustrates a typical situation where the MBE (about 1%) would indicate a accurate and successful calibration. However, the CV(RMSE) is largely bigger (about 15%) and proves that the calibration is not completed. Of course, plotting the curves would have also permitted to indentify directly the discrepancy.



Waltz (2000) considers that a maximal difference of 5% between annual recorded and computed energy consumption is a realistic objective for BES model calibration. The three standards dealing with calibration (ASHRAE, 2002; EVO, 2007; US-DOE; 2008) provides also numerical criteria (table x) to calibrate BES models to building energy use data. The values proposed by ASHRAE Guideline 14-2002 and FEMP are the same but very different from the ones proposed by IPMVP.

Calibration tolerances

Index	Waltz (2000) (%)	ASHRAE 14 (%)	IPMVP (%)	FEMP (%)
MBEyear	+/- 5			
MBEmonth		+/- 5	+/- 20	+/- 5
CV(RMSE)month		+/- 15	+/- 5	+/- 15

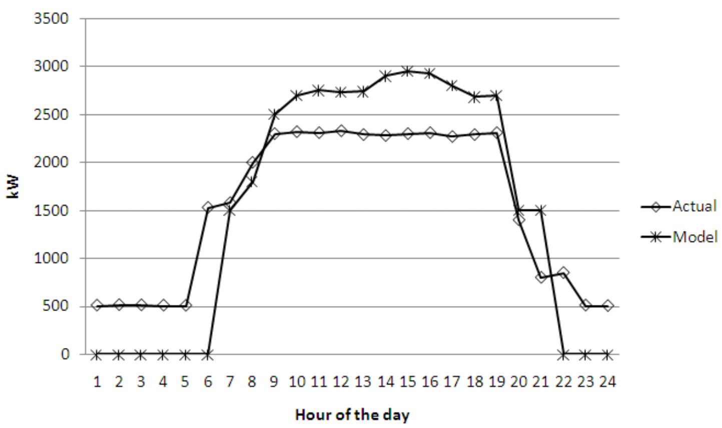
Instead of a unique set of tolerances, Kaplan et al. (1990) have proposed different tuning tolerances (table x) depending of the energy uses (lighting, cooling, heating, fans…) and tuning periods (monthly, daily, hot period, cold period…).

End-Use	Tuning Period Weather Type	Monthly End-Use Tolerances	Daytype Profile Tolerances
INT. LIGHT	ALL	±5%	±15%
EXT. LIGHT	ALL	±5%	±15%
DHW	ALL	±5%	±15%
RECEPTACLES	ALL	±5%	±15%
HEATING	COLD	±15%	±25%
HEATING	TEMPERATE	±25%	±35%
COOLING	HOT	±15%	±25%
COOLING	TEMPERATE	±25%	±35%
FANS	HOT, COLD	±15%	±25%
FANS	TEMPERATE	±25%	±35%
BLDG. TOTAL	ALL	±10%	±15%

End-use specific tolerances (Kaplan et al., 1990)

Statistic indices should not be the unique way to evaluate the accuracy of the calibration and could lead to a "blind" calibration missing numerous influences (weather, occupancy, operation…). Waltz (2000) recommends comparing monthly profiles (to visualize any seasonal effect in the building energy consumption) and even daily and hourly energy use profiles in the case of a medium or a large building (where building and system operation can have an important influence on building energy use, as mentioned before). Some of the graphical methods and tools described earlier (Bou-Saada and Haberl, 1995; McCray et al., 1995; Liu et al., 2003) can also be used as calibration quality estimators.

Figure x shows a typical example of comparison between computed and measured electricity demand for a summer day. Once again, because the two curves correspond to similar energy uses, the difference between the simulation and actual situation cannot be observed by means of aggregated data (such as daily values).



Electricity demand comparison (adapted from Waltz, 2000)

ASHRAE Guideline 14-2002 provides also mathematical method to evaluate the savings uncertainty in the case where utility bills are the source of the energy use data and weather data are used as the only independent variable. Basing on the CV(RMSE) and on the Student's t-distribution, it is proposed to compute the saving uncertainty (U), applying to the totals savings determined for a meter, by means of the following formula:

$$U = t \times \frac{1.26 \times CV(RMSE)}{F} \times \sqrt{\frac{n+2}{n \times m}}$$

Where,

U = relative uncertainty in a reported energy saving

t = Student's t distribution (available in Statistics textbooks)

CV(RMSE): Coefficient of Variation of the Root Mean Square Error

F = computed fraction (%) of the baseline energy use that is saved for a given period (m)

m = number of periods

n = number of data points or periods in the baseline period

For example, a monthly energy saving of 20% on the whole-building electricity consumption computed by means of a baseline calibrated BES model resulting in a CV(RMSE) of 12% leads to an uncertainty of 32.1% (90% confidence level) on the estimated saving. So, the savings should be included between 13.6 and 26.4 % (90% confidence level).

3. CALIBRATION-BASED AUDIT METHODOLOGY

The main assumption of this work is that the calibration (and the calibrated model) should not be seen as an end in itself but as a mean to perform efficient and advanced energy audits.

For this auditing targeted work, a simplified forward dynamic multi-zone simulation model will be developed and implemented in an equation solver. First, this BES model will be used for benchmarking purposes. Then, it will be integrated in a calibration method adapted to audit purposes. This systematic manual iterative method will include sensitivity issues in order to help the auditor identifying critical points needing further investigation. Graphical and statistical methods will be used in order to quantify and evaluate the accuracy of the calibration. Finally, the calibrated baseline model will then used to evaluate ECMs and savings uncertainty. A graphical representation of the whole calibration methodology is given in Figure x.

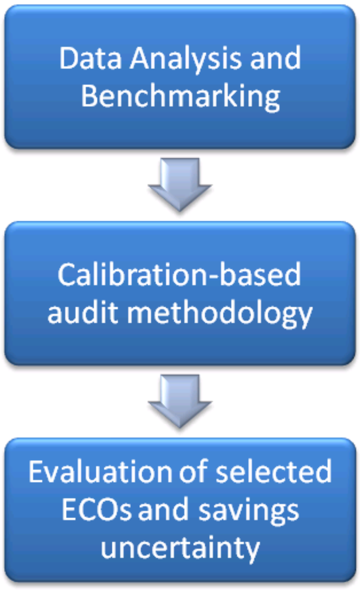


FIGURE 1: AUDIT METHODOLOGY

3.1. *PRELIMINARY ANALYSIS AND BENCHMARKING*

This first step of the audit methodology consists in (Figure 2):

- Gathering the as-built and utility data;
- Apply a first treatment and analysis method to this data;
- Use the BES model to perform benchmarking.

Classical analysis methods, such as thermal and electrical signatures (Lydberg, 1987) will be used to determine a maximum of information from the utility data. Heating signature will be used to determine the global heat transfer coefficient of the building which can be cross-checked by a "design analysis" (Bertagnolio et al., 2008a) As-built data will also be collected and summarized to determine the main consumption items of the building.

The benchmarking consists in a comparative evaluation of the building performance. In the frame of the present audit methodology, it is proposed to use the developed BES model for benchmarking purposes. This can be done by describing the main characteristic of the building and its use and by supposing this building equipped with a typical HVAC system presenting standard performance (Bertagnolio and Lebrun, 2008b). The HVAC system performances are defined in accordance with recent EPBD standards (CEN standards series) and international reference standards (such as ASHRAE Standard 90.1-2007).

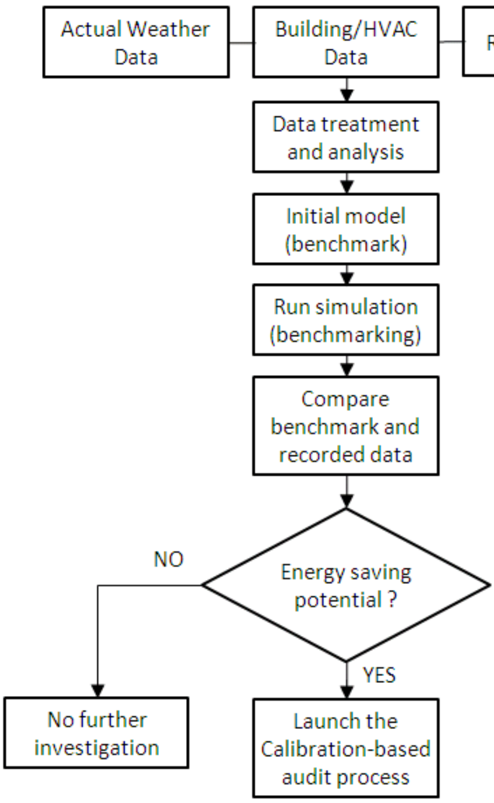


FIGURE 2: GRAPHICAL REPRESENTATION OF THE PRELIMINARY ANALYSIS AND OF THE BENCHMARKING

3.2. CALIBRATION-BASED AUDIT PROCESS

The following calibration based audit process (Figure 3) is launched if the benchmarking indicates that potential energy savings should be studied in the building. The calibration starts directly at the beginning of the inspection, before realizing any additional measurement. The integrated iterative calibration methodology integrates all the measurement and calibration issues in order to result in a calibrated baseline model satisfying predefined tolerances and criteria.

Then, the calibrated baseline model can be used to evaluate the selected ECMs. Of course, the selection of ECMs is purely heuristic and results of the analysis and observations of the auditor. Typical weather data sets (TRY or TMY) should be used to evaluate the ECMs after their implementation in the baseline model. The uncertainty on computed savings is then evaluated by means of the CV(RMSE)-based method proposed by ASHRAE (2002).

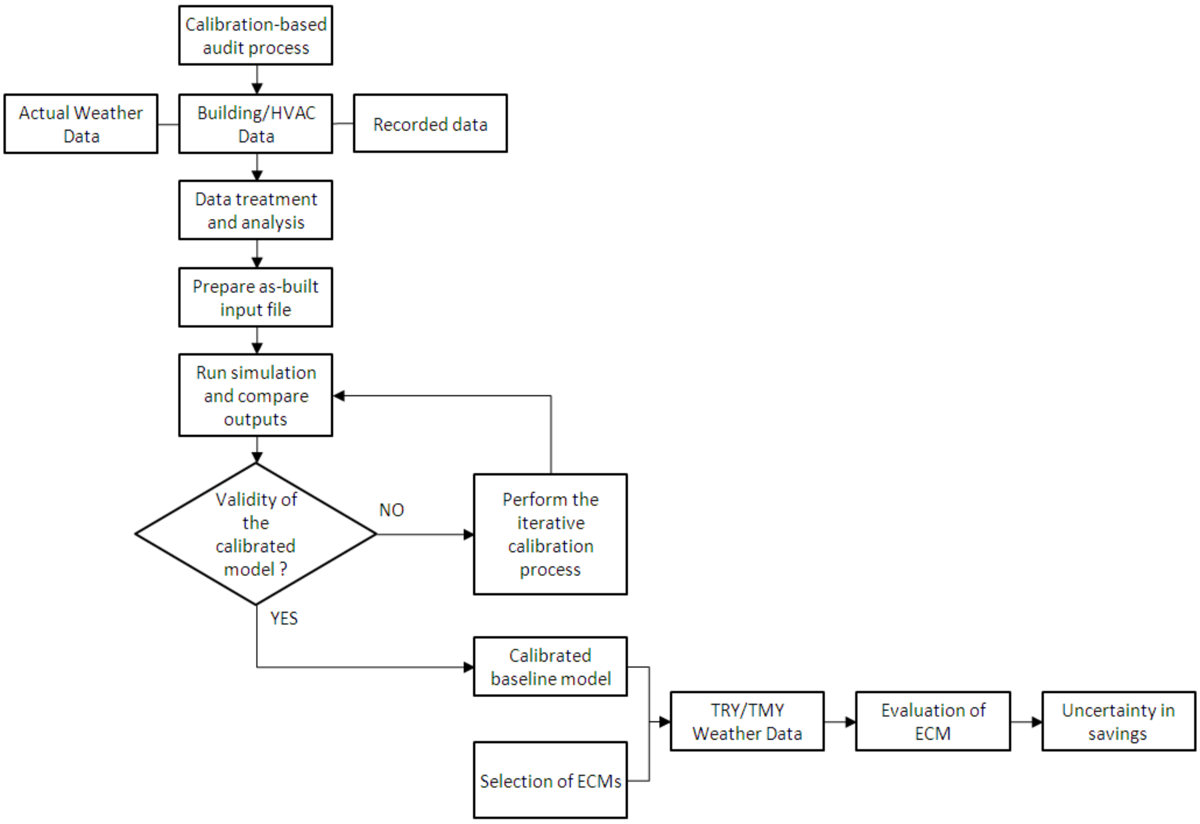


FIGURE 3: GRAPHICAL REPRESENTATION OF THE CALIBRATION BASED AUDIT PROCESS

3.3. EVIDENCE BASED CALIBRATION METHOD

The iterative calibration method is fully integrated into the audit methodology. The first step of the inspection consists in preparing and "as-built" input file to run a first simulation of the actual building and its system. This simulation run is the first step of the calibration process.

After that, simulation results should already be compared to the recorded data used to perform calibration (usually utility billing data). The next step will consist in identifying the source of discrepancy between the simulation and the real situation. If the source of the problem does not appear as evidence, the user should consider a first influencing parameter. The main parameters (or parameters categories) will be classified as function of their impact on simulation outputs for different building-HVAC configurations. This classification work is based on the results of a preliminary sensitivity analysis.

A range of variation for the selected parameter will be defined and two simulation runs ("min/max simulation") will be performed. If the parameter has not a significant influence on the simulation outputs, the next influencing parameter should be considered. If it is not the case (significant influence of the parameter), spot or short-term measurements should be envisaged to quantify this item. If the measurement of such item is not feasible, a classical (manual or automated) iterative calibration process should be applied. If the measurement can be done, the gathered value will be used to update the simulation model and a new simulation run will be done. Then, the process starts till the calibration tolerances/criteria are satisfied (Figure 4).

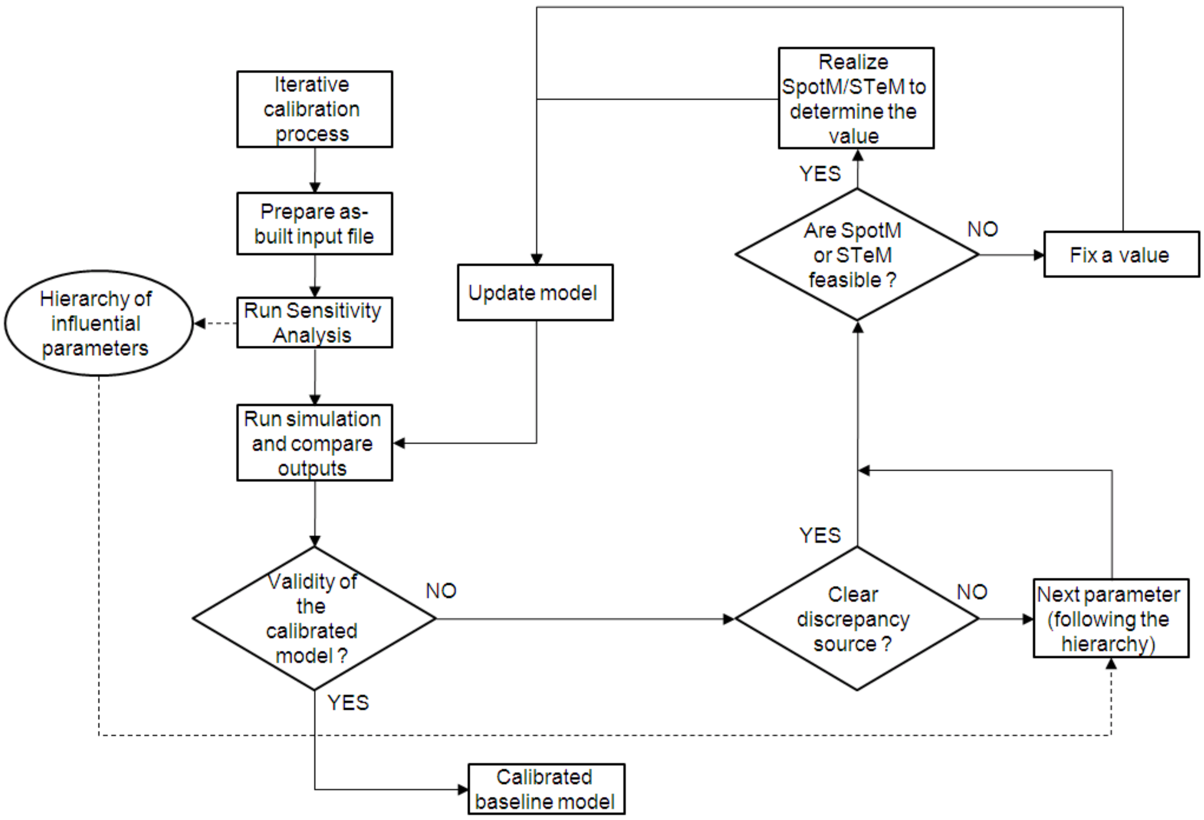


FIGURE 4: EVIDENCE BASED CALIBRATION METHOD

4. SUMMARY

Calibration cannot be avoided when pretending applying a BES model to an existing building. In the frame of an energy audit and in addition to pre or post-retrofit evaluation of ECMs, calibrated BES models could be used along the auditing process to help the auditor identifying points needing further investigations (Raftery et al., 2009). For this auditing targeted work, simulation models and calibration methods adapted to the needs and constrains of energy audit will be developed.

As pointed by Liu et al. (2004), numerous authors have calibrated detailed simulation models (DOE-2, EnergyPlus, Trnsys…), developed calibration procedures and attempted to compile calibration guidelines and manuals. Various calibration methods already exist, including manual iterative methods (Kaplant et al., 1990; Yoon et al., 2003; Liu et al., 2004), graphical methods (Bou-Saada and Haberl, 1995; McCray et al., 1995; Liu et al., 2003), methods based on specific tests (Subbarao, 1988a; Burch et al., 1990) and automatic methods (Carroll and Hitchcock, 1993; Lee and Claridge, 2003; Reddy and Maor, 2006).

Fully automatic methods are very powerful but are generally heavy to handle and limited because of their reduced flexibility (pre-defined required data and impossibility to integrate specific monitoring data in the calibration process). Existing semi-automatic including heuristic steps are a good compromise but still have limited flexibility. Moreover, these methods are fully black-box methods and can lead to unrealistic calibrated models if not well controlled and understood by the user. Therefore, these methods don't suit very well with energy audit (where available data and measurements can vary a lot from cases to cases) and other more adapted methods should be considered.

Methods relying with specific monitoring tests, such as the PSTAR method (Subbarao, 1988a), have been developed for residential applications and are not well adapted to non-residential office buildings where the required intrusive tests cannot be easily realized.

Methods combining manual iterations and graphical/statistical tools seem to be well adapted to energy audit purposes. These methods are very flexible and could be adapted to most cases. Moreover, these methods allow the auditor identifying, visualizing and apprehending the behavior of the building under study during the calibration process. However, attention should be paid to keep the calibration method systematic and reproducible and to integrate sensitivity issues.

To reach these objectives, there is a real need for simple, robust and easy-to-use BES models and calibration method. A compromise has to be found between model accuracy, reliability, flexibility and simplicity. It should be noticed that, generally, simplified models differ from detailed ones mainly in the definition of the building and the HVAC system but are also able to perform accurate simulations.

Sensitivity, accuracy and uncertainty issues have also been pointed as important issues by the authors. Because the calibration stays a highly undetermined problem, sensitivity analysis should be coupled to the calibration process in order to identify the most influencing parameters and result in a plausible set of solutions instead of a hypothetical unique solution. Accuracy and uncertainty issues can be studied by means of classical statistical methods.

An evidence-based calibration method integrating field measurement and sensitivity issues is proposed in order to be applied during the audit process to assist the auditor in his task.

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