

ExCalibBEM: Tool Development to Calibrate Building Energy Models

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Abstract

Calibrated Building Energy Models (CBEM) can provide numerous benefits to on-going building operations and identify retrofit measures and their feasibility. However, calibrating a BEM is not a trivial task. To date, it has essentially been based on the energy modeller's experience and the utilization of a trial and error approach to refinement. To effectively facilitate this complex process and the significant amount of data associated with it, a dedicated tool, called ExCalibBEM, is presently under development.

This paper presents the methodology adopted for the development of this calibrated BEM tool, which will be available free of charge. This tool is intended to assist practitioners and researchers in streamlining the calibration process by visualizing the differences between BEM results and measurements, suggesting input modifications and managing the calculation of parametric and optimization runs based on an objective function defined by the user. The tool is designed to deal with hourly and sub-hourly measurement data and simulated results generated by EnergyPlus or DOE2.2 engines. The GenOpt® optimization package, developed by the LBNL DOE laboratory, is integrated in ExcalibBEM and used to launch parametric and optimization runs.

Introduction

The energy saving potential in existing buildings is quite significant. In North America, more than 40% of the total energy consumption is related to the existing building stock, which translates to a substantial amount of opportunities for savings on the table for industry to capture. Calibrated Building Energy Models (CBEM) can provide numerous benefits to on-going building operations and identify retrofit measures and their feasibility. For example, CBEMs can be used to assess the influence of projected or implemented retrofit measures, and they can assist in the diagnosis of operational problems through fault detection. Eventually, the use of CBEMs has the potential to predict short-term demand profiles, which can lead to optimizing real-time building operations.

However, calibrating a detailed building simulation model is not a trivial task. A structured step-by-step method to calibrate a model is difficult to define and replicate. No consensus has been obtained on the subject. As the papers referenced in the next section demonstrate, several publications about calibration procedures describe specific processes applied to case studies. These processes require a lot of effort in terms of data preparation and manipulation and need to deal with many software applications for analyzing data and performing parametric and/or optimization runs.

To effectively facilitate part of a calibration process and the manipulation of a significant amount of data associated with it, a dedicated tool, called ExCalibBEM, is presently under development. This tool is intended to assist energy modellers and researchers in streamlining the calibration process by visualizing the differences between BEM results and measurement data, suggesting input modifications and managing parametric and optimizations runs based on an objective function defined by the user. The tool has been primarily developed and used to calibrate EnergyPlus models with total electric demand at 15-minute intervals, taking advantage of the availability of sub-hourly measured data provided by automated electricity meter reading. The paper presents a brief discussion on the calibration process. The calibration approach, the actual ExCalibBEM interface and future developments are described afterwards.

Calibration Process

The calibration process generally involves an iterative process. Initially, the simulation results are compared to real data. Different analyses are then conducted to select and modify the most influent set of parameters. Simulations are rerun with these modifications and the results are compared to measured data to see the impact. If the results are not satisfactory, other modifications are made. These iterations stop when either the results are within the proposed criteria or the user realizes the limitations of the process. Guidelines and standards published by organizations, such as ASHRAE Guideline 14 [ASHRAE, 2002] and IPMVP [Efficiency Valuation Organization, 2007] propose accuracy targets for qualifying a calibrated model based on statistical indicators such as the normal mean bias error (NMBE) and the coefficient of variation of the root mean square error (CVRMSE).

Past literature reveals several activities undertaken in the calibration of building energy models. Reddy (2006) presented a general literature review of different calibration techniques and procedures. The number of parameters involved in a building simulation program and the lack of measured information lead to a non-unique set of solutions since the problem is undetermined. The analyst relies on personal judgment to select best guessed values and calibrate the remaining parameters. More recently Rafty (2011) proposed an evidenced-based methodology that defines a source hierarchy for selecting parameters in order to calibrate models. The works published by the authors on calibrating building models [Sansregret & Millette (2010), Lavigne (2009), Lavigne et al. (2013), Daoud et al. (2011)], coupled with literature that is rich in case studies, has led to these observations:

- The calibration process requires a set of precise inputs on the building's performance (schedules, HVAC configuration, control settings, envelope characteristics, etc.), a reliable set of building consumption data in a preferably low timestep interval for a specific period of time, a detailed real-time weather data covering this period, a calculation engine able to match the level of desired precision and, of course, a good modelling expertise.
- The physics behind the building's energy consumption must be effectively predicted by the calculation engine in order to establish alignment on an hourly basis. Specific elements of the building should be addressed in detail by the calculation engine, like HVAC component interactions, controls operational schedules, load profile schedules, and so on. However, there are always model simplifications, assumptions and approximations that the user must take into account when analyzing the differences between simulated and measured data, as emphasized by Maile et al. (2012) in their publication.

- In order to obtain a convenient calibrated model, the operation of the building should be relatively stable during the analysis period covered by the measurements. An erratic consumption, such as oscillating demand or non-periodic behaviour could be hard to trap by the model. An analysis of the measurements before trying to model the behaviour should be attempted in detail. This generally leads to diagnose the building's energy consumption and may point out important operation problems that could be resolved.
- The visualization of the profiles is a crucial exercise in the analysis and comparison of simulated results and measurements. Specific visualization techniques are very useful, such as carpet plots and daily bin whisker plots reported initially by Bou-Saada & Haberl (1995). Fournier & Lavigne (2010) also proposed an innovative approach for analyzing and comparing daily load profiles with a clustering technique.
- There is a lack of integrated tools to perform model calibration. Calibrating a model involves dealing with a huge set of simulation results and measurements to visualize and analyze. Also, different processes should be employed to launch parametric/optimization runs. If all these tasks were performed in an integrated and structured way, the calibration exercise would be speeded-up and users would thus be able to develop more adapted approaches. Just to retrieve all the input needed for calibration work: i.e. a complete building model with all the detailed input, a reliable measured data set and real-time weather information in the proper format, is very time consuming and requires significant effort.

Proposed Calibration Approach

ExCalibBEM is intended to assist energy modellers and researchers in streamlining the calibration process by visualizing the differences between simulation results and measurements, suggesting input modifications and managing the calculation of parametric and optimization runs based on an objective function defined by the user. The idea behind the tool is to guide the user through this proposed simplified calibration approach:

a) Analyze measure data sets

The analysis of measured data is essential. The model should be calibrated on reliable and non-erratic behaviour. The measured data should follow the occupancy pattern of the building and react to weather solicitation. Adapted data visualization techniques should be used.

b) Launch simulation and compare it to measured data

A lot of information can be obtained after the first detailed simulation run over the measurement period. For example, the operational schedule input in the model, such as the start/stop of systems, could be verified with the measurements and eventually adjusted. Generally, this information is provided by building operators or the building automated system (BAS). There are often mismatches between measurement trends and the assumed operation. For example, the measurements could reveal some HVAC activity during weekends when the HVAC systems are supposed to be off. The comparison with measurements using visualization techniques can point out some discrepancies to explore. At this step, some problems could be detected (e.g.: a meter is missing, schedules shift because the weather file does not include the leap day, schedules are set to standard time as opposed to daylight saving time during the summer, etc.). It is also relevant to qualify the difference between the model and the measurements by computing the statistical indicators (NMBE, CVRMSE) to get a sense of the target closeness.

c) Specify a calibration period

Even if a long-term measurement period is available, selecting short calibration periods with different loads is beneficial. It reduces the simulation running time when conducting parametric/optimization runs and it allows to select periods with a predictable pattern. Also, it focuses the analysis just on specific periods, which is important when there is submersion of data. The authors habitually perform calibration for 3 specific weeks in the winter, summer and shoulder seasons respectively.

d) Identify key parameters and perform sensitivity analysis

The identification of the parameters to vary depends on several factors. Different approaches and techniques should be examined. For example, a specific analysis comparing the weather dependency of the simulation and the measurement results could put the emphasis on a specific set of parameters. There are a lot of possibilities to explore in this area. Nevertheless, running parametric studies on specified calibration periods will always be essential to define key parameters. Also, this task could detect model definition problems. (e.g.: no impact with an increase of the minimum outside air from 10% to 20%). The sensitivity analysis helps to group together parameters that have the same influence in a same situation. For example, a certain set of parameters may only have an impact during unoccupied winter periods. This could help to reduce the number of parameters and to set their limits properly before launching an optimization run.

e) Run optimization

When the key parameters to vary and their limits have been defined, an optimization process can be launched in order to obtain an optimized fit between the model and the measurements. The definition of the objective function, or the variable to be minimized, depends on the project objective. As a first approach, the CVRMSE between model results and measurement data at each timestep could be used. However, more detailed objective functions could be utilized if, for example, the model deals with multiple energy sources or sub-utility measurements. Pressing the optimizing button occurs at the end of the process and several back and forth adjustments should be made before getting there.

Tool Description

At the present time, ExCalibBEM interface addresses specific steps *d)* and *e)* of the proposed calibration approach, which are managing parametric and optimization runs. These steps are the core of the approach. Other features will be integrated to complete the proposed workflow, based on parallel developments described in the following section. ExCalibBEM is primarily designed to deal with hourly and sub-hourly measurements and simulated results generated by the EnergyPlus engine. The DOE2.2 engine is also supported.

The GenOpt® [GenOpt, 2011] optimization package developed by the LBNL DOE laboratory is integrated in ExCalibBEM in order launch and manage parametric and optimization runs. This package is intended for the minimization of a cost function evaluated by a detailed building simulation program, which reads inputs and writes outputs in a text format file, such as EnergyPlus. GenOpt® includes several algorithms such as generalized pattern search approaches and particle swarm optimization algorithms.

Presently, ExCalibBEM can be described as a simple and complete interface to GenOpt® with some interesting features to facilitate the generation of the input file template, the setup of the objective function for calibration purpose and the visualization of parametric/optimization runs and measured data.

Interface description

The ExCalibBEM interface is presented in Figure 1. This simple interface allows the user to input all the information needed to perform simulations (unique runs, parametric runs or optimization runs) and compare it with measured data.

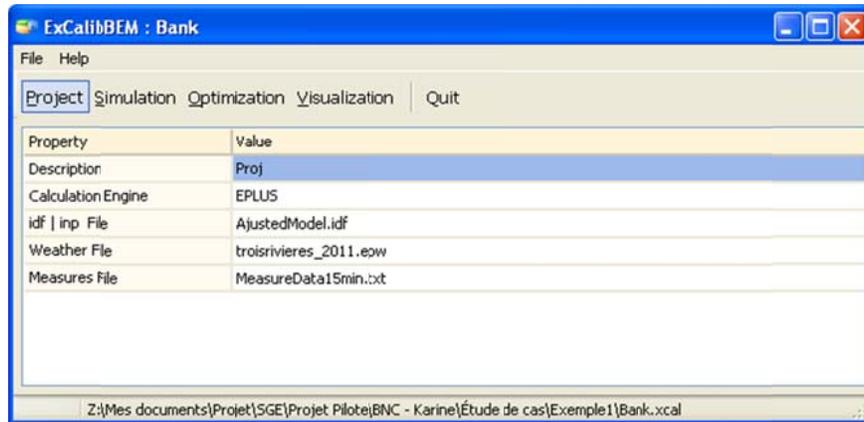


Figure 1: View of “Project” tab of the ExCalibBEM interface

The “Project” tab contains general input information, such as the paths of the simulation input file, weather data file and the measured data file. The “Simulation” tab allows to run the simulation file and to visualize all the related files (examples of EnergyPlus file extensions: idf, err, csv, eso, log). The “Optimization” tab contains all the information needed by GenOpt® to set up a run, such as the algorithm specifications, the definition of input parameters to vary and the objective function. This tab also allows to automatically generate all the files required by GenOpt® and to launch the optimization/parametric runs. Finally, the “Visualization” tab plots the simulation results and measured data file.

Input template file generator

The input template file represents a copy of the input file with specific parameter values replaced by an indicator. This file is used by GenOpt® to create the input file after each optimization/parametric run. One interesting feature of ExCalibBEM is the automatic generation of this template file. Normally, the user has to create it manually and this could easily lead to manipulation errors. ExCalibBEM proposes a practical way to define these indicators by linking them directly to the appropriate object names of the input file. Figure 2 shows an example of an indicator creation in the “Optimization\Parameters” tab. The indicator “PlugLoad-Office” has been attributed to the property “Watts per Zone Floor Area” of the specific “Electric Equipment” object names EQ-ZC-1-2, EQ-ZC-1-2 and EQ-ZC-1-8. Those property values will vary from 5 W/m² to 15 W/m². With this information, ExCalibBEM can automatically produce the simulation input template file required by GenOpt®.

The generated input template file can be visualized in the “Optimization\GenOpt Files\IDF” tab of the interface. As mentioned earlier, this tab allows to visualize all the files required by GenOpt® and produced by ExCalibBEM. Figure 3 shows the input template file of the previous example in an htm format. The indicator “PlugLoad-Office” replaces the value of “Watts per Zone Floor Area” for object EQ-ZC-1-2. All generated indicators are in red and can be easily retrieved by using the up/down button. The values in blue are just links to the definition of the object.

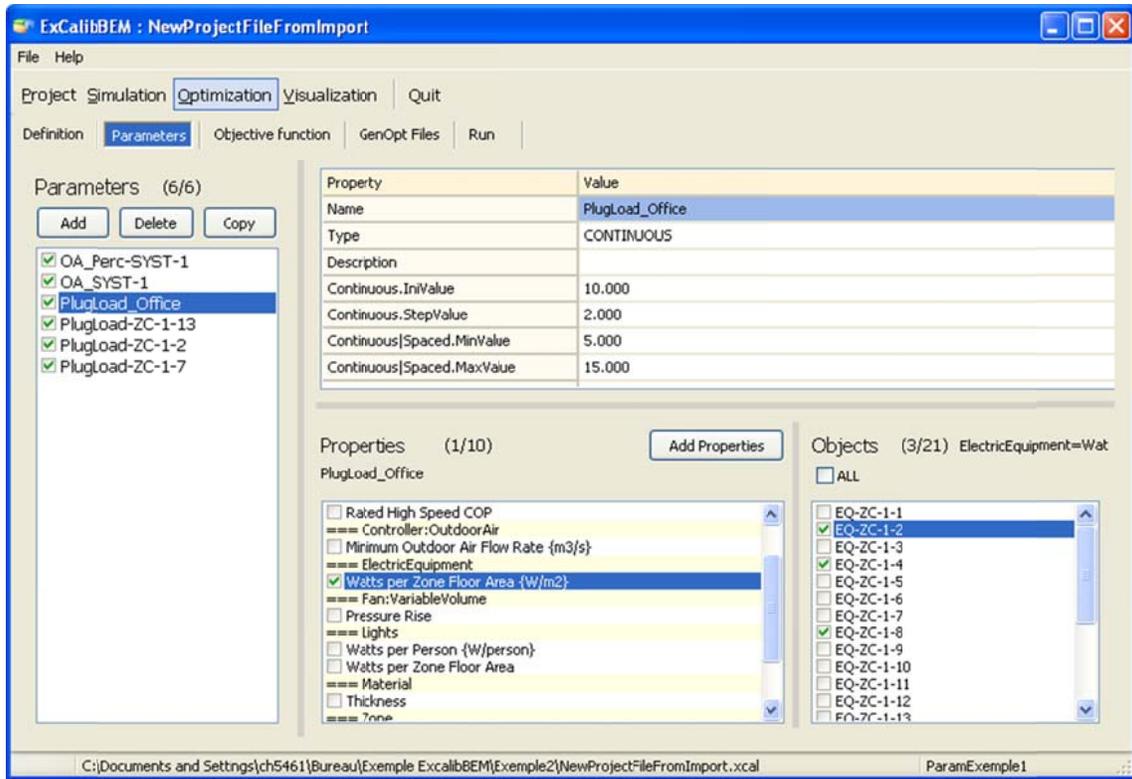


Figure 2: View of the parameter definitions of the ExCalibBEM interface

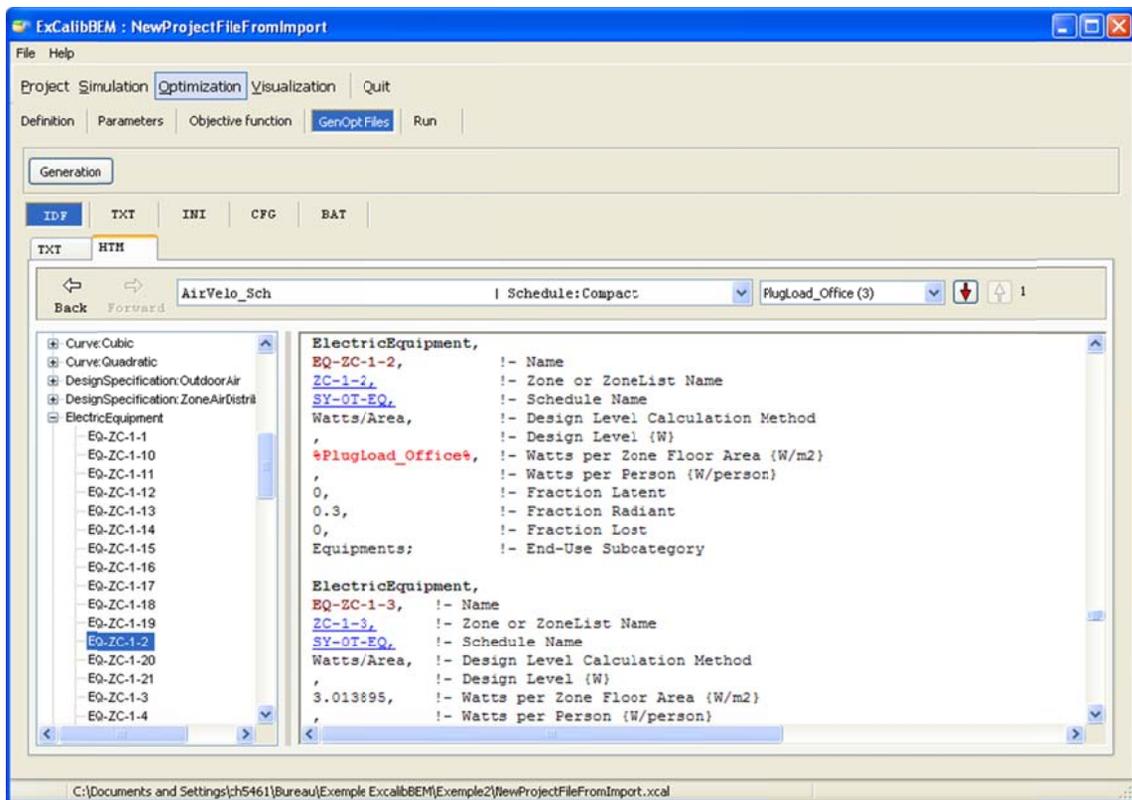


Figure 3: View of the "Optimization\GenOpt Files|IDF" tab of ExCalibBEM interface

Objective function setup

The objective function represents a value to be minimized in an optimization process. For calibration purposes, it can be described as a number that qualifies the difference between the simulation results and the measurements for specific periods. The value of the objective function should be printed in an output file after a simulation run in order to be processed by GenOpt® engine. Some post-processing capabilities are included in GenOpt® to allow the user to evaluate the objective function based on specific simulation output variables in the output file, however the functionality is limited.

ExCalibBEM allows to launch a specific program written in a script language (Python®) from its interface. This program generates a file after the simulation run which includes the value of the objective function in a specific output file. The installation package includes different libraries of objective functions. One of them evaluates the coefficient of variation of the root mean square error (CVRMSE) of specified variables from the measured data file and simulation results. The measurement data timestep should be greater than the report frequency of simulated output variables and could be between 1-minute and 1-month intervals. The use of the Python® script language provides all the flexibility needed by the users to modify the objective function code and to adapt it to their specific project. For example, this could be used to include a constraint on zone temperature set point not met or to compare minimum and maximum daily consumptions, hourly zone airflows or monthly bills.

The objective function program can also take into account the effect of the warm-up period at the beginning of the simulation run. It has been observed that results at the beginning of a simulation run for a specific period (for example, the 2nd week of February) can differ from the same simulation but run over a year. This difference is due to the warm-up of the simulation at the beginning of the run period. This impact has been analyzed when comparing the results of the concatenation of 12 monthly runs over a year with a year-round simulation in order to speed up the calculation time by using parallel computation [Garg et al. (2011)]. The authors showed a maximum deviation of 1340% on the hourly heating load at the beginning of a run period for a specific case. One proposed solution is to increase the number of days, for example to 7, before the run period of interest. To consider this effect, the objective function program allows to omit a specified number of days at the beginning of a run period in the simulation output file when processing the objective function.

Visualization tool

An important challenge when dealing with multiple output results files from parametric/optimization runs and measured data is to process them to facilitate their visualization and comparison. A specific tab called “Visualization” allows to select and plot specific output variables for each simulation output file and the measured data file as shown below in Figure 4. In this example, the results of two parametric runs, with high and low plug load values set at 2, are plotted against the total electric measurement of the building. The visualization tool synchronizes each profile on the same graphs even with different timesteps and different periods.

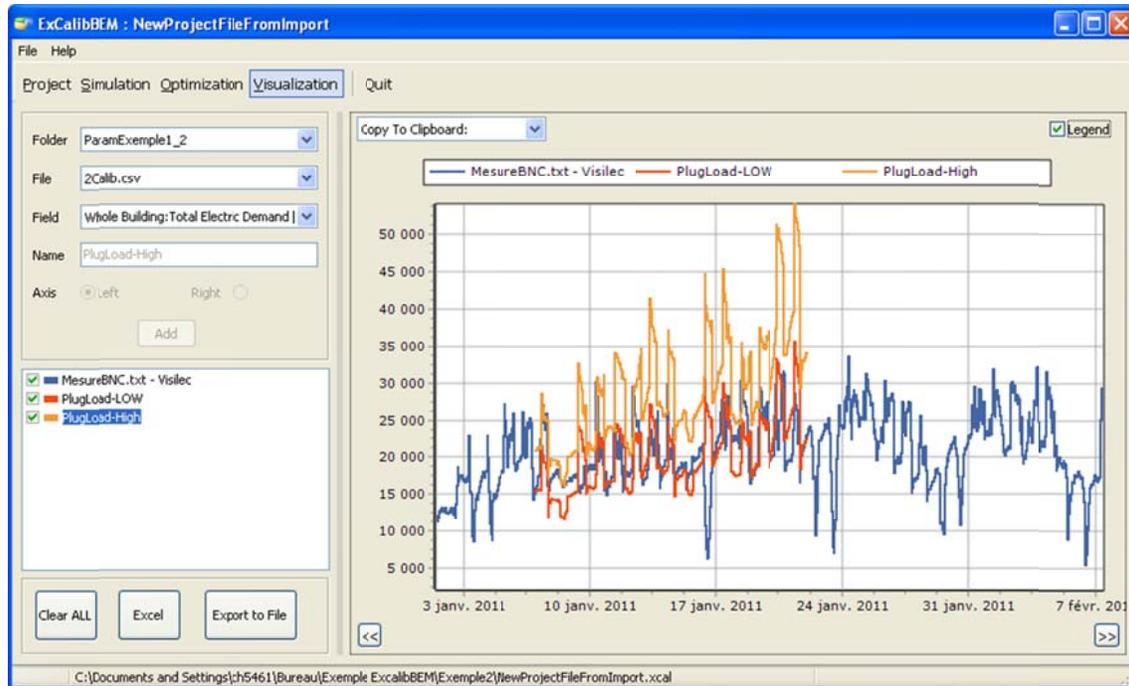


Figure 4: View of the “Visualization” tab of the ExCalibBEM interface

The graph includes some basic capabilities such as zoom and drag to easily compare the profiles. The “Export to file” button creates a text file with all the selected time series in order to be edited by other viewers.

Presently, the input measured data file is a text file with a predefined date/time format in the first column and the measured data fields in the following columns. This simple structure is suitable for a small quantity of measured datasets (for example, if only the consumption of the whole building is available). However, as explained in the next section, future developments suggest the need for the tool to be able to map measured data fields with the associated simulated object nodes.

Current and Future Development

Parallel on-going developments are conducted in order to facilitate the calibration process. These developments, which cover different areas, will be integrated or linked to ExCalibBEM in future releases. Some of these developments are still at their initial stages.

Advanced data visualization

Visualization data is a key element in multiple aspects of a calibration process. A proof of concept of different views and representations using Excel® spreadsheets and their pivot table functionalities is presently being developed. The idea is to include specific views into or linked to ExCalibBEM that address the following tasks.

- **Calibration period selection:** As mentioned at the “c)” step of the proposed calibration approach, selecting a calibration period is an interesting task to ensure reliable measured data periods and reduce the simulation time and the amount of output data generated. A weekly profile viewer, which the user can easily filter according to different elements such as the season, the month or the mean weekly temperature has been developed. This view is intended to facilitate the selection of

specific weeks with different climate solicitations, such as winter and summer week for example.

- **Validation operation schedule:** Comparing the operation schedule inputs in the model with measurements is possible using specific visualizing views. A proof of concept of the daily profile comparison between measurements and simulated data with easy filtering capabilities on specific days of the week and/or month has been implemented.
- **Statistical indicators:** The quantification of the difference between simulated and measured data is expressed by statistical indicators such as the NMBE or the CVRME. A specific view that graphically shows the impact of model iteration is relevant. The statistical indicators shown on bar graphs directly inform the user if the desired criteria have been met.

Coupling with cloud

In recent years, there is a strong interest in accelerating the simulation process by running simulations on remote servers such as private HPC clusters or public cloud computing resources. Work has been undertaken in order to set up adapted processes linked to these remote services to launch parametric/optimization runs from the ExCalibBEM interface. In order to maintain efficiency with hundreds of cores, the scalability of the distributed computations has been heavily fine tuned. A proof of concept implemented on private clusters has already been ported to Amazon EC2®. The easy access to these remote services facilitates the launch of batch of simulations. This functionality is useful in that it releases resources on user workstations and greatly shortens calibration time. By speeding up the calibration runs, more time for the exploration of optimization techniques becomes available.

Parameter selection and optimization algorithms

More research and analysis must be conducted in these two areas. Some approaches should be implemented in order to propose some key parameters to be selected by the user based on different analyses such as the dependency on weather (e.g.: the Spearman Correlation) or the building's energy signature. Also, suggestions should be provided to the user about which optimization algorithms should be used with their associated parameter values for different types of problems.

Integration into a Simulation Software Interface

One objective behind the development of the tool is to promote the use of building simulation by facilitating the calibration process. The idea is to eventually include some developed processes into free simulation software applications, such as SIMEB [SIMEB, 2013] or SIMERGY [SYMERGY, 2013]. Simplified interfaces with more constrained choices should be developed and adapted to be integrated into simulation software applications.

Coupling with BAS

An on-going pilot project is conducted to couple the information provided by building automated systems (BAS) with CBEM results. An optimization process that compares multiple outputs such as zone airflows and zone temperatures is in preparation. Calibration on HVAC systems operations will be the first step. This approach will require a more sophisticated structure that will map together BAS data points with the associated simulation object nodes. The authors plan to develop a proof concept.

Tool Development Objective

Hydro-Quebec, through the development of this tool, wants to increase its expertise in the field of building energy simulation. There is a high need for enabling CBEMs to evaluate different aspects of the electricity consumption of buildings, especially in the prediction of demand response strategies in the commercial and institutional sectors. Hydro-Quebec, by distributing this tool to their customers at no cost, will be promoting the use of simulation in order to improve building operations and reduce their operating costs. Also, distributing the tool to the scientific community for free will enhance networking and contribute to win-win collaborations.

Conclusions

This paper presented the methodology behind the development of ExCalibBEM. This tool is intended to help calibrate building energy models on high data frequency measurements. Presently, the tool provides an interface to speed up the setup of parametric and optimization runs for calibration purposes and helps the user to manage all the data generated by these tasks. Other developments are planned to guide the users through a more complete workflow.

The calibration of building energy models will always require a sound knowledge of building physics and simulation expertise. Currently, considerable effort is required to set up all the needed information properly and to manage all the data related to it. By facilitating some of these tasks through the use of a dedicated tool such as ExCalibBEM, energy modellers and researchers will be able to concentrate on developing and exploring new sets of techniques that will result in better calibrated models.

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