CALIBRATION OF A DETAILED SIMULATION MODEL TO ENERGY MONITORING SYSTEM DATA: A METHODOLOGY AND CASE STUDY

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ABSTRACT

This paper outlines a novel methodology for calibrating building energy simulation (BES) models through the use of an evidence-based approach and detailed simulation modelling. The proposed calibration methodology is applied to a 30,000m^2 office building. The case study illustrates the results of calibrating the model to Energy Monitoring System (EMS) and other readily accessible data. The paper concludes with a discussion on the current state of calibrated BES modelling and building measurement frameworks.

INTRODUCTION

The development of calibrated building energy simulation (BES) models involves a process of using genuine as-built information, surveys and measured data to update the input parameters of the initial simulation model so that it closely represents the real operation of the building. This process confirms the analyst's knowledge of the building and often brings to light opportunities for energy savings that had heretofore gone unnoticed (Waltz 1999). These calibrated BES models can be used to investigate various energy conservation measures (ECMs) for feasibility and cost effectiveness. Calibrated BES models can also be used to improve energy performance by optimising building control strategies. (Costa et al. in press)

Three standards govern the bounds within which a simulation model can be considered calibrated – these are ASHRAE Guideline 14 2002 (ASHRAE 2002), the International Performance Measurement and Verification Protocol (IPMVP) (Efficiency Valuation Organisation 2007) and the Federal Energy Management Program (FEMP) Monitoring and Verification Guide (US DOE 2008b). These documents primarily apply to Measurement and Verification (M&V) projects and recommend calibrated simulation as one of several means by which to quantify savings due to proposed ECMs. However, none of these standards prescribes a methodology to actually perform the calibration. There are several methodologies that are described briefly in journal articles (Pan et al. 2007), (Pedrini et al. 2002) and others that purely discuss case studies (Norford et al. 1994), (Iqbal & Al-Homoud 2007). However, there is no accepted standard methodology.

In conjunction with this issue, a general lack of complete, coherent measured data and information frustrates any calibration effort. In cases where detailed drawings and manuals related to buildings are available they are often not current. Even when Energy Monitoring Systems (EMS) and Building Automation Systems (BAS) are installed, there are often significant gaps in the measurement framework from an energy consumption perspective (O'Donnell 2009). Many of the required measured data-streams are often missing, and values for these need to be either assumed or estimated by the analyst.

These two issues often combine to create situations where analysts must adjust myriad input parameters without sufficient evidence in order to tune the model to whatever measured data is available (Troncoso 1997). These adjustments often significantly decrease the credibility of the BES model and are "highly dependent on the personal judgment of the analyst performing the calibration" (Reddy 2006).

METHODOLOGY

This paper proposes a new methodology for the development of calibrated BES models, outlined in Figure 1, based on three core principles:

1. Detailed BES models that represent the real building as closely as possible with currently available tools;
2. Reproducibility as understood from the principles of scientific methods;
3. Detailed energy monitoring systems (EMS) and building automation systems (BAS) to supply the measurements needed to perform the calibration.

Initial model

This methodology assumes that a BES model was created at the design stage and is available as a starting point for the calibration process. However, if none is available, one can be created according to standard practice and design information.

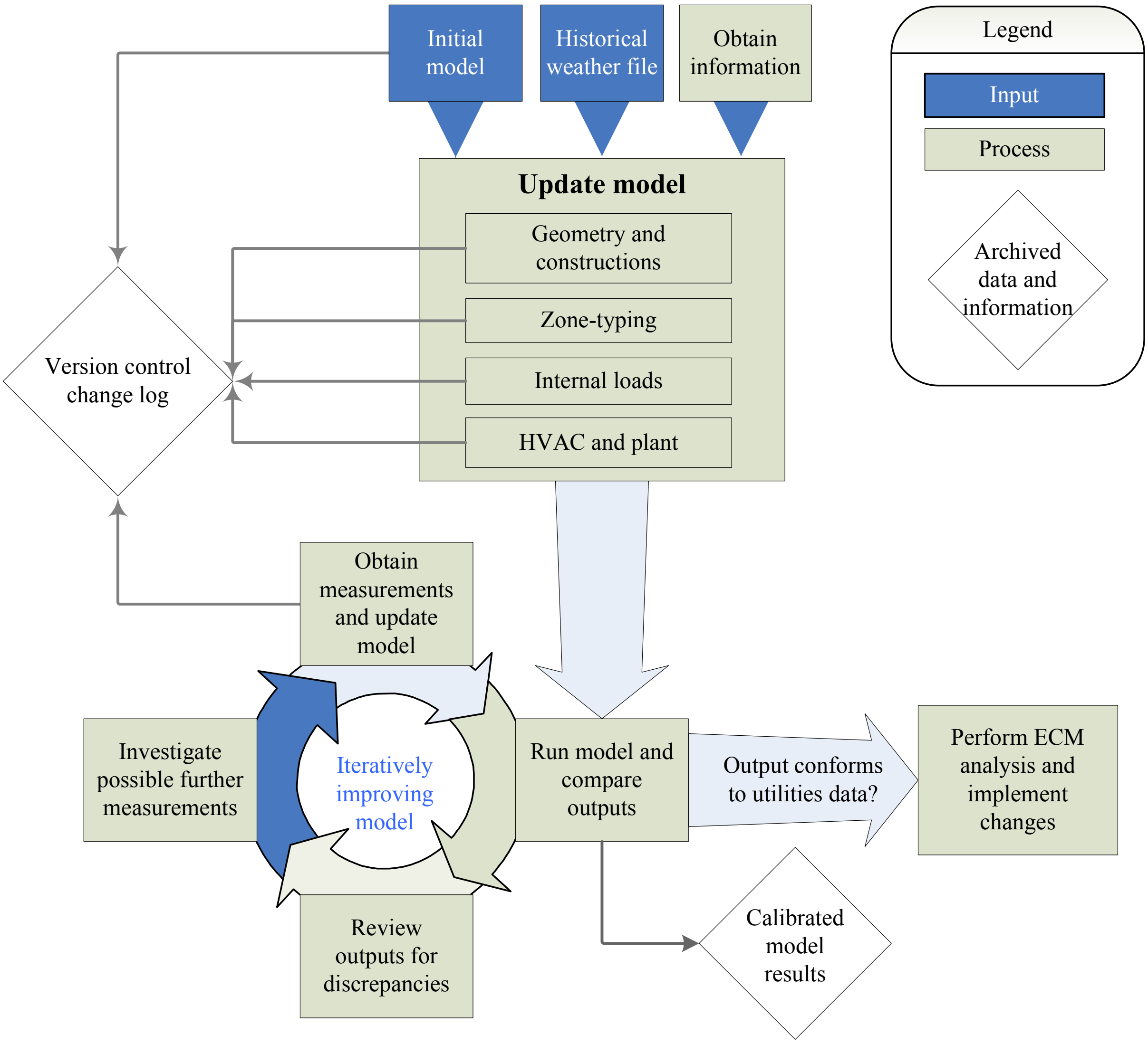

Figure 1 Calibration methodology

Obtain readily accessible data and information

At this stage of the process, the analyst(s) should obtain all readily available data about the building. A recommended, but by no means exhaustive, list of sources is given below:

1. A Building Information Model (BIM);
2. As-built drawings;
3. Operation and Maintenance (O&M) manuals;
4. Energy Monitoring Systems (EMS);
5. Building Automation Systems (BAS);
6. Surveys and interviews.

The availability of a BIM drastically reduces the time needed to create a simulation model as it inherently contains a large amount of the required information. In fact, the creation of BES models can become a semi-automated process through the use of translation middle-ware *if* building information is readily available and is organised in a systematic fashion. For example, IFC based BIMs can store all the geometry, construction, HVAC and electrical information needed to create a simulation model and are an invaluable resource to the analyst.

In the author's experience it is imperative that any information obtained from a document, such as 'as-built' drawings, should be verified by visible inspection and that physical surveys of the building are the most reliable and useful source of information. A detailed survey at the zone level is required to verify and identify such inputs as geometry, constructions and air supply methods. On a systems and plant level a visual survey and building operator interviews are needed to verify such inputs as O&M information and operating schedules. A survey during the night and other unoccupied periods can also be an important source of information and are a recommended practice.

Once all of this information has been obtained it should be categorised into input parameters and output results. For example, general plug loads are clearly a simulation input, where-as measured room air temperatures are simulation outputs. Because of the nature of these two types of data, input parameters are generally obtained from the EMS while simulation outputs are obtained from the BAS.

Update model inputs

In order for simulation to become more of a science than an art, it is necessary to bring the scientific method of *evidence based decision-making* to the calibration process. To improve the reproducibility and reliability of calibrated models all changes to the input parameters should be made according to a clearly defined hierarchy of priority. For example, sources based on direct observation should be the first priority, followed by data obtained from benchmark studies, then standards, and finally, information from the initial model. Changes should not be made unless the evidence comes from a source higher up in the heirarchy.

In order to improve the reproducibility of the calibration process it is necessary to keep a history of the decisions made along with the evidence on which these decisions were based. This can be done by utilising version control software. This software issues a new version of the model whenever a modification is made and automatically stores all previous versions, allowing users to review the calibration process at a later date. The description of the change is also stored with each successive version in a change log *along with the evidence on which the change was based*. This ensures that changes are not made on an ad-hoc basis and that the supporting evidence will be available to multiple analysts and future users.

Geometry and constructions

Using the information obtained in the previous section from a site survey and as-built drawings or a BIM, it should now be possible to update the model geometry and constructions to reflect changes to the building since the initial design model was created.

Zone-typing

The objective of zone-typing is to separate thermal zones in such a way as to minimise the inaccuracies incurred by using large zones that span multiple unique spaces. These large spaces may have opposing loads which counter-balance each other, or have numerous different uses, ventilation rates and methods of conditioning.

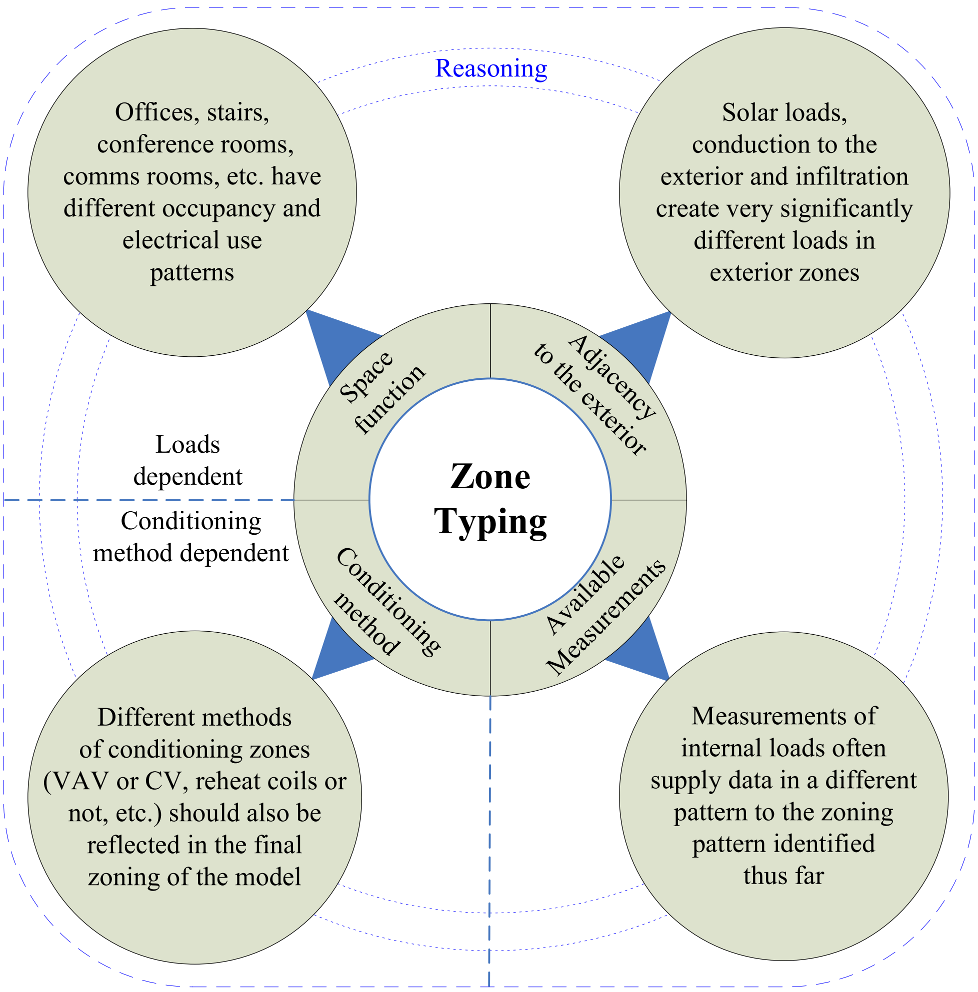

Figure 2 Zone-typing

In this methodology the process of deciding on the various types of thermal zones used in a BES model depends on characteristics that fit into two broad categories: space loads and conditioning methods. The various characteristics and the reasoning behind their inclusion are outlined in Figure 2. It should be noted that when walls are removed in order to agglomerate multiple spaces into one zone, care must be taken to ensure that their thermal mass is taken into account.

As opposed to the often-used core and 4 perimeter zones method, this process results in a more detailed BES model that more closely represents the reality of building operation. This allows analysts to investigate specific Energy Conservation Measures (ECMs) at finer resolutions.

HVAC and Plant

Finally, system and plant information should be updated based on information obtained from the BIM, O&Ms, site surveys and operator interviews. Special attention should be paid to ensure that operating set-points and schedules that have been previously verified are included in the model.

Run the model and compare model outputs to utility level measurements

In this step, the results of the simulation are compared to utilities level measurements using the cumulative variation of root mean squared error (CV RMSE) method on a monthly basis according to whichever of the three aforementioned standards are being used. Generally, the first simulation run will not agree well with the measured data, and further investigation will be necessary.

Review outputs using visualisation techniques

This section focuses on problem identification and solution in order to improve the accuracy of the model. Outputs from the simulation should be grouped or separated as needed in order to form a counterpart with each available physical measurement stream. For example, if there is a meter monitoring the load of a motor control cabinet supplying a group of fans, these should appear in a similar grouping in the outputs. All available physical measurements that correspond to outputs from the simulation should be compared and examined for discrepancies. As there is an overwhelmingly large amount of data generated by simulation programs and measurement systems it is essential to employ numerous different visualisation and mathematical techniques along with standard line plots, such as:

1. Carpet or surface plots (Baumann 2004);
2. Scatter plots and matrices of dependent scatter plots (Baumann 2004);
3. Outlier analysis (Seem 2007);
4. CV RMSE analysis on a yearly, monthly and daily basis.

Investigate possible further measurements using sensitivity analyses

The analyst should identify possible sources for discrepancies noted in the previous step. Assuming that the discrepancy is not due to a clear modelling error, changes to input parameters related to the proposed source should be preliminarily investigated in a manner similar to sensitivity analysis – i.e. values should be modified within reasonable limits to verify that a change will have a significant effect. This reduces the total number of measurements to be obtained as it will identify which changes are minor or trivial.

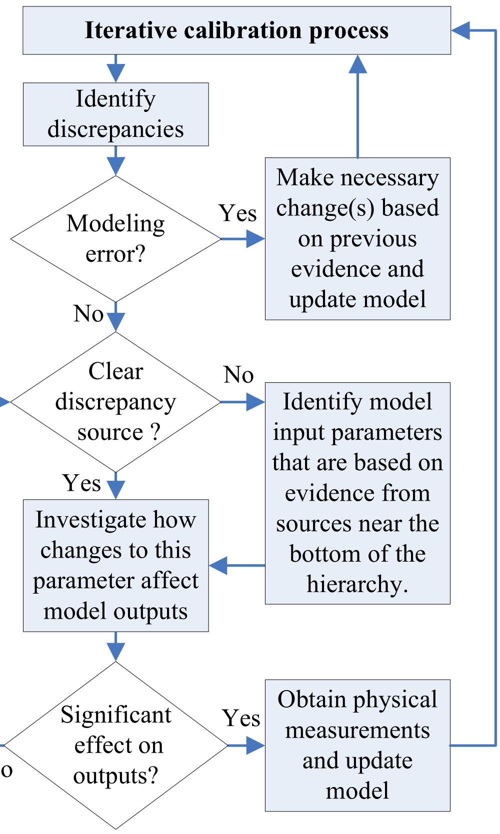

Figure 3 Investigation of further measurement

As the currently available standards only contain criteria for analysis on a monthly basis, it is hoped that in the future an accepted standard will be published that contains more detailed criteria for identifying discrepancies and deciding what is a significant effect. In the absense of such standards, in order to maintain reproducibility and the principle of evidence-based decision-making the criteria used *must be consistent throughout the calibration effort* and stored using the version control software along with a synopsis of the results of each investigation.

Obtain measurements and update model

The measurements identified in the previous step should be obtained and the model updated accordingly. The overall process of the previous four steps should be repeated in order to iteratively improve the BES model until the simulation reaches the desired level of accuracy. Above all, the documentation of changes to the model must be kept updated, and the evidence upon which decisions were made must be stored along with the each change to the model. Without working in this manner, the calibration process is not reproducible.

Perform Energy Conservation Measure analysis

The nature of the calibration process implies that the analyst will identify numerous areas for improvement. This is because the analyst can only include in the model what is explicitly known about the building. Discrepancies between simulated and measured data are often due to problems with the real building and often offer opportunities to improve energy performance. Once the model has been calibrated to a chosen standard using the methodology outlined in this paper it can be used to investigate the viability of ECMs according to a recognised protocol, such as the IPMVP (Efficiency Valuation Organisation 2007). Once the measures have been implemented, the actual savings should be compared to those predicted by the model.

CASE STUDY

In order to test and improve upon this methodology, a large office building in Ireland was simulated. This 4 storey building has a floor area of approx. 30,000m^2. The top three floors contain open office space and conference rooms, and the ground floor contains kitchen, canteen, and facilities areas. The building is conditioned by a variable air volume (VAV) system. This building was chosen as it was recently constructed (2003), is relatively well documented and also because it has an extensive EMS, BAS and an on-site weather station.

Initial model creation

As building energy simulation is still a relatively rare practice in Ireland, no initial model was available and hence one was created for this research project. EnergyPlus was used as the simulation engine based on a comprehensive literature review of program capabilities (Crawley et al. 2008). This program has been validated against experimental measurements and through comparative testing with the BESTEST suite (Henninger et al. 2004). The initial model was created according to design documentation such as the scope document and as-built drawings. Values from best practice models (US DOE 2008a) were used where required information was unavailable.

An Industry Foundation Class (IFC) based BIM of the geometry and constructions was created using as-built drawings and verified by site survey. An EnergyPlus input date file (IDF) was created from the BIM automatically using GST/IDF Generator; a newly developed data transformation tool from the Lawrence Berkeley National Laboratory (Maile et al. 2007). The HVAC systems, internal loads and miscellaneous other objects were added to the this IDF file using EnergyPlus Macro language and Visual Basic macros in an Excel spreadsheet.

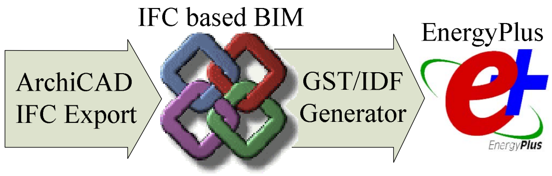

Figure 5 Geometry & constructions translation

In order to improve the reproducibility of the calibration process, a change log was kept using TortoiseSVN – an open-source automatic version control software. This tool was used to store each version of the model, a description of modifications made between versions and the evidence based on which each change was made.

Zone-typing

The difference between standard core-and-4-perimeter zoning practice and zone-typing can be seen in Figures 6 and 7 respectively.

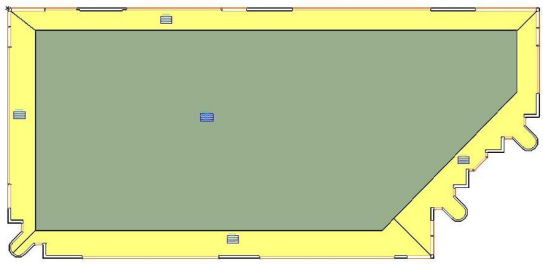

Figure 6 Traditional zoning

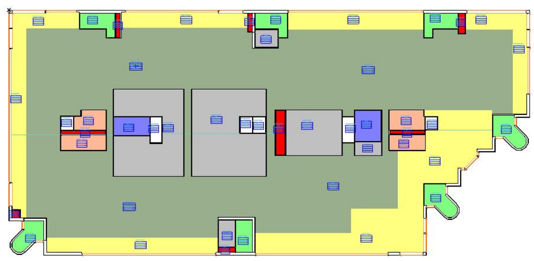

Figure 7 Detailed zoning after zone-typing

The advantages of using this detailed zoning strategy are numerous, and can best be illustrated with an example from this building. The central core consists of conference rooms that use constant volume air supplies with reheat. During unoccupied periods these zones have virtually zero internal loads because lighting is occupant controlled and the only equipment present is a projector on standby. In these conditions the supply air requires heat to maintain the room set-point temperature. This effect would not be captured by a less detailed zoning strategy as the space cooling and heating loads in a single large zone can easily negate each other.

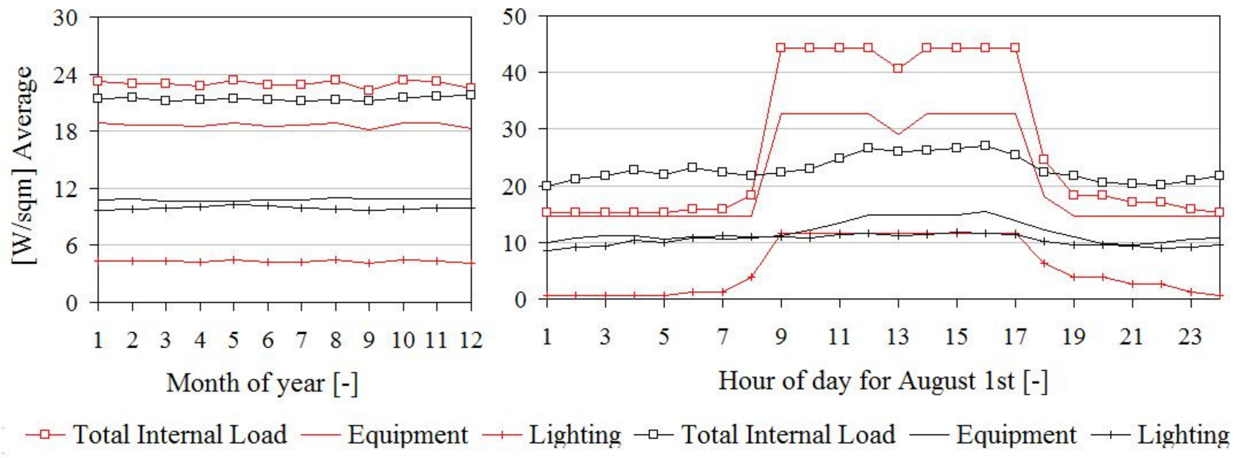

Figure 8 Updated model (black), using actual measured data, vs. initial model (red) energy use per floor area.

Internal Loads

Measured data from the EMS was used for updating lighting and equipment loads. Average values were used for measurement streams which were constant within a maximum error of ±5% over any given timestep. Day-typing was performed on the remaining data-streams in order to identify a pattern; unfortunately, due to the electrical layout and positioning of the metering devices, much of the data did not conform to a daily pattern within the ±5% error stated above. Thus, no simplified schedules could be created and the *actual measured values* for these data-streams were simulated by the model on an hourly basis. Occupancy data was updated based on room booking databases, occupant surveys and human resources interviews.

As can be seen from Figure 8, the differences between the total energy consumption of the initial and updated models are relatively minor when viewed on a monthly basis. In fact, the differences in total consumption would be much larger if extreme peak values, taken from design documentation, had not been used for initial model plug loads. Once total consumption is broken down into lighting and equipment loads, very significant differences can be seen between the initial and updated models. However, It truly becomes apparent just different the models are when the data are viewed on an hourly basis.

HVAC and Plant

The model inputs related to HVAC and plant were updated based on the as-built drawings, O&M s and BAS information. The characteristics of the conditioning method for each zone such as air flow rates and heating coil maximum capacity were assigned to the air supply based on verified as-built drawings and commissioning information.

Measurement issues and current progress

Although a detailed BAS was present for this building, the BAS focused entirely on measurements related to air handling unit operation. The EMS focused entirely on electrical load and did not include flow meters to measure district heating and cooling consumption. Until complete annual consumption data is available calibration efforts have been limited to updating the model to readily accessible data

However, even at this stage of the process several opportunities for improving energy efficiency and building operation have been identified

1. In June, lighting load from 9pm until 7am increased by approximately 12kW in one half of the building. This was identified from the EMS data and was due to a change in control strategy which went un-noticed for the remainder of the analysed data-period;
2. From the archived BAS data it was discovered that the Air Handling Unit (AHU) coil set-points were often incorrectly set. For example, the cooling coil set-point temperature was sometimes lower than the heating coil set-point, causing both to operate simultaeneously;
3. It was also noted from the BAS data that the air economisers were operating incorrectly as the temperature set-point for the mixing box was higher than for the cooling coil.

These three points illustrate the value in having a technical expert review measured data related to energy consumption on a regular basis. As well as these changes to operating strategies, numerous possibilities for retrofit were noted during the calibration process. In the author’s experience with office buildings which support 24 hour manufacturing, partial night–time occupancy results in a common design flaw. Designers do not take into account the fact that only small areas of the building need to be conditioned outside of normal office hours. Hence, the building layout and installed HVAC systems do not allow for conditioning of a small portion of the total floor area. Thus, all HVAC equipment must operate continuously resulting in significant energy waste. In this case-study, the office AHUs operate as normal during the night despite the fact that the building is less than 10% occupied during this period. A proposed ECM that will be investigated with the calibrated model is a retrofit of the office layout and HVAC systems so that it is possible to use night-time set-backs for temperature set-points and ventilation rates.

DISCUSSION

The construction sector is currently the only industry in which it is common practice to supply a product without fully testing it (Bazjanac 2005)– In general, buildings are handed over after commissioning without any feedback from measured operational performance. (Bordass et al. 2001). Imagine if this was the case, for example, in the automotive industry - Automobiles would be designed, simulated and built as usual, but there would be no feedback to the designers whether or not the vehicle performed as expected. Building analysts, operators and owners simply do not have the necessary information to make informed decisions (O'Donnell 2009). If real improvements in actual performance are to occur, this situation is clearly untenable. Any means of designing high quality buildings depends on the feedback of measured operational performance of real buildings to the designers and simulators. This is not possible without organised energy monitoring systems and calibrated BES simulation.

Unfortunately, EMSs are costly and many owners consider the required investment prohibitive. Often, measurement devices are the first items to become 'value-engineered' out of a project that goes over-budget. However, costs are dropping, and will do so more rapidly in the future. Currently, up to 70% of the cost of an EMS is related to wiring (Jang et al. 2008), but with the advent of wireless sensor technologies, such as those being developed by the BuildWise (BuildWise 2007) project, this cost will dissipate. Also, the cost of three phase electrical metering devices, a major component of any EMS, is also decreasing as new technologies and designs are being produced (Sarkar & Sengupta 2008).

An interesting problem was encountered during this research – although the building has a large number of sensors related to energy monitoring, there are significant gaps in this framework. For example, as district heating is not monitored, the performance of the plethora of Variable Air Volume (VAV) hot water reheat coils cannot be evaluated. Also, even though there are measurements that together monitor the total building electrical load, many of these sensors are located in a less than optimal positions. For example, many of the panels supply a combination of very different load types – lighting, general plug loads, VAV fans, etc.. This impedes a users ability to immediately identify the cause of an unexpected change in measured consumption.

There is a clear need for a complete, coherent and effective measurement framework so that it is possible to measure real operational performance of buildings. Such a framework should consist of a BIM, a detailed EMS and a comprehensive BAS. This framework would drastically reduce the time required to calibrate a BES model as measured data would be readily accesible, and would improve the accuracy of the final model as these measurements would be available in an organised manner. In fact, if all information was available in a consistent, organised fashion, it will be possible to automate not just the creation of an initial model, but also a large part of the calibration itself. However, this is a long way off considering the level of information available regarding current building stock.

CONCLUSIONS

This paper proposes a new methodology for the development of calibrated BES models based on a systematic, evidence-based approach. This will improve the reproducibility of calibrated BES modelling and hence improve the credibility of the final model. The results to date from using this calibration methodology as part of a case-study based on readily accessible data are also presented.

With currently available tools and the previously discussed issues regarding building information, it is difficult to calibrate a BES model in a cost-effective manner. The levels of measurement need to improve and automated processes must be developed before this is truly feasible. Also, the guidelines and protocols used for determining when a simulation is calibrated need to improve and move away from aggregate monthly consumption data analysis methods towards *HVAC component* based hourly techniques. This methodology does not address these problems; it focuses on increasing reproducibility as a step towards improving the results and credibility of calibrated BES models. Future users will be able to review the decisions made throughout the calibration process, both improving their understanding of assumptions made and reducing the likelihood of analysts tuning input parameters without supporting evidence. Also, it is possible to more closely model real building operation through the use of detailed simulation models as described in this methodology.

FUTURE WORK

Future work on this methodology will focus on completing the calibration of the simulation outputs to match the BAS data. A fully calibrated model will be completed using the proposed methodology once the required measurement devices are installed. In light of the measurement inadequacies discovered in this building and numerous others, a minimum measurement framework will be developed for implementation in buildings as part of further research. This framework will support the calibration process, measurement of operational energy performance, and high resolution benchmarking between buildings.

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