CALIBRATION OF AN ENERGY MODEL OF A NEW RESEARCH CENTER BUILDING

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ABSTRACT

This paper presents an assisted model calibration, as a combination of data mining from Energy Management Systems and evidence-based calibration. The case study model of an existing institutional building was developed using the eQuest energy analysis program. The paper presents a few examples of information extracted from EMS and their impact on the model calibration of the air-side loop of HVAC system.

INTRODUCTION

Model calibration is the process of developing a building energy model through successive changes of inputs and parameters with the goal to predict as closely as possible, not only the measured whole building annual/monthly energy consumption and cost, but also some key indicators of energy performance at the systems/components level. The calibration process is successful when the difference between measurements and predictions of selected indicators are below a given threshold. The use of a good calibrated model gives confidence in the estimates of energy savings due to renovations/retrofits in an existing building.

In the past, the trial and error calibration approach was widely used. That technique is time consuming and not always reliable. The results of the building energy model depend on the energy simulator's experience with the selected program, the time allocated for the calibration that he/she can bill the client, and the knowledge of design and operation characteristics of the building and HVAC system.

The comparison of the predicted energy use with monthly utility bills is a common practice. Kaplan et al. (1990), Bronson (1992), Clarke et al. (1993), recommended the use of hourly data, if available, for calibration. Haberl et al. (1998a, 1998b) and Bronson et al. (1992) used 3-D graphs to compare the differences between measured hourly data and predicted results. Reddy (1999) proposed the modification of input variables as the results of an optimization method that minimizes the difference between predicted and measured indices of performance. Reddy (2007a, 2007b) proposed a calibration method in which a preliminary model is developed based on available data and walk-through audits and heuristics. Influential parameters are identified, using heuristic knowledge and experience, along with their preferred values and the range of variation. Finally, Monte Carlo (MC) simulations are performed and a set of calibrated models for the building are obtained, rather than a single calibrated model. Monfet et al. (2008) presented the calibration of an EnergyPlus model of a university building by comparing the supply airflow rate, and the supply and return air temperatures, over two periods of different operating conditions. Liu et al. (2011), proposed the use of calibration signature and characteristic signature, which allow for better understanding of the reasons of differences between predictions and measurements, and then could suggest the inputs to be changed. Raferty et al. (2009, 2011) developed an evidence-based calibration methodology in which a change to input data is allowed only if there is evidence, and any change is automatically registered by a version control software. Lavigne (2009) presented an assisted calibration approach. Coakley et al. (2011) proposed a statistical calibration methodology that starts with the development of an evidence-based model, followed by Monte-Carlo simulations using randomly sampled model inputs, and uncertainty analysis. Several calibrated models are obtained that satisfy the condition of maximum difference between hourly predictions and measurements. Millette et al. (2011) discussed the development of assisted calibration that uses monthly utility bills, engineering rules and optimization algorithms. Shrestha and Maxwell (2011) presented the calibration of a EnergyPlus-based model of a test facility, extensively instrumented, by comparison between the measurements and simulation results at zone, system, and plant level. Bertagnolio et al. (2012) presented an evidence-based calibration of a simplified dynamic hourly model that uses technical specifications, measurements, and sensitivity and uncertainty analysis to predict the whole building energy use. Monfet and Zmeureanu (2013) used the identification of performance values/curves of chillers for the model calibration.

In conclusion, the trial and error approach and the optimization approach could lead to models having an acceptable difference between predictions and measurements. These approaches could be useful when no sufficient reliable data is available. Although an experienced energy modeler can predict the annual or monthly overall building energy use within a few percentages of utility bills, he/she might not achieve the calibration of systems or components. The authors preferred to explore the evidence-based calibration approach, and propose in this paper a calibration sequence for building energy models of existing institutional buildings using data available from the Energy Management Systems (EMS). The changes made to the input parameters are based on reliable data. Once the evidence-based calibrated model is obtained, the energy modeler could explore further the calibration with the sensitivity and uncertainty analyses.

METHODOLOGY

In general, the EMS installed in commercial and institutional buildings are not designed and implemented for research purposes to provide thousands of measurement points. Budget constraints and fast access to recorded data limit the number of installed sensors to the minimum required for the control and operation of HVAC systems. However, data already recorded by EMS could provide useful information for the calibration of building energy models. Such measurements are available to us from the EMS installed in a new university building through the collaboration of the university's physical plant.

The goal of our study is to develop a calibration sequence for a building energy model of existing commercial or institutional buildings using data available from EMS. In our opinion, the model calibration should not be limited to random or mathematically derived changes of inputs and parameters. We propose the use of the assisted calibration as a combination of data mining from EMS and evidence-based calibration. We used the eQuest energy analysis program (eQuest, 2010) because of its large users' base. Natural Resources Canada used eQuest for the development of new CAN-QUEST energy simulation software for the compliance analysis with the Model National Energy Code of Canada for Buildings (MNECB 1997) and the new National Energy Code for Buildings (NECB 2011) .

Instead of limiting the comparison to the annual or monthly whole building energy use, the calibration phases should correspond to the main blocks of building detailed energy calculations: Loads, Secondary Systems, and Primary Systems. The proposed bottom-up approach has the following sequence:

a) Selection of measurement points available in the EMS and transfer of data to the user's database;

b) Verification of data quality and treatment (removal, correction or replacement of missing data, outliers, abnormal operation);

c) Data mining to extract the values of operating variables that would become inputs in the energy analysis program; only a few examples are presented here:

- average, maximum and minimum air temperatures in each thermal zone in terms of time to assess the thermostat set point under regular operation, and night or week-end set-up or set-back;
- maximum supply air flow rate in each room and minimum flow ratio, in case of VAV system;
- derived measured space cooling load in each room from measurements of supply air flow rate, and room-to-supply temperature difference;
- derived equivalent schedule of operation (lights, equipment, people) in each room;
- derived schedule of operation of air-handling unit (AHU);
- maximum supply air flow rate and minimum flow ratio at AHU;
- cold-deck temperature reset in terms of outdoor air temperature ($T_{outdoor}$);
- ratio between the outdoor air flow rate and supply airflow rate versus $T_{outdoor}$;
- switch-over temperature of economizer; and
- supply air flow rate signature versus $T_{outdoor}$;
- cooling coil load versus $T_{outdoor}$.

d) Development of the initial building model using design specifications, drawings, information from the commissioning and operation teams, and information from data mining. An equivalent step-change thermal load is defined for each zone, based on derived measured space cooling load and derived schedules of operation;

e) Calibration for the supplied airflow rate and indoor air temperature, as the most important criteria, at the zone level when the measurements are available; it is important that the variation with time of predictions follow closely the measured profile;

f) Calibration of the air-handling unit (AHU) for the supply air flow rate and temperature;

g) Calibration at AHU for hydronic or DX cooling coil, and hydronic or electric heating coil load;

h) Calibration at AHU for the electric input to fans and energy use;

g) Calibration at the chilled/hot water loop level, including chillers/boilers for the water flow rate and electric input and energy use; and

h) Whole building model calibration.

This paper discusses only the model calibration of air-side loop of HVAC system, at the zone level and AHU level (items a to f), applied to a case study building. It shows results, limitations and need for additional developments. The calibration for energy use is beyond the purpose of this paper.

CASE STUDY

The building of Research Centre for Structural and Functional Genomics (Genomics building) of Concordia University, in Montreal, was built in 2011 with a total floor area of 2000 m^2, over three floors about ground and a basement. The building has 48 offices, conference rooms and laboratories.

Figure 1 Research Centre for Structural and Functional Genomics of Concordia University

The main HVAC system is composed of two Variable Air Volume (VAV) handling units installed in parallel, with the total supplied air flow rate of 42.5 m^3/s, and terminal reheat boxes. Heat is recovered from the evacuated air and then is used to preheat the air before it enters the air handling unit. The chilled water is supplied, depending on the building cooling load, either from the central plant that serves the campus, or from a 500 tons chiller installed in Genome Building, or from 2x100 tons chillers installed in a neighbor building.

Measurements

The following variables, recorded every 15 minutes by the EMS, from June 1st to August 30th 2012, were used: (i) the supply airflow rate for each room; (ii) the indoor air temperature from each room; (iii) the supply and return airflow rates at AHU; (iv) the supply and return air temperatures and relative humidity at AHU; and (v) the outdoor air temperature (T_{OA}) and relative humidity measured with a weather station on the campus.

Data was converted to hourly and daily average values. First, three consecutive days with the highest outdoor temperature during each month were selected for analysis and calibration: June 8th to 10th; July 18th to 20th; August 14th to 16th. Second, the calibration was extended to the three months of summer. Figure 1 shows, as an example, the daily average supply airflow rate signature of one thermal zone (1.6NE) of the ground level, facing northeast. During the occupancy (the upper set of points) and the unoccupied periods (the lower set of points), the supply airflow rate is not influenced by the outdoor air temperature.

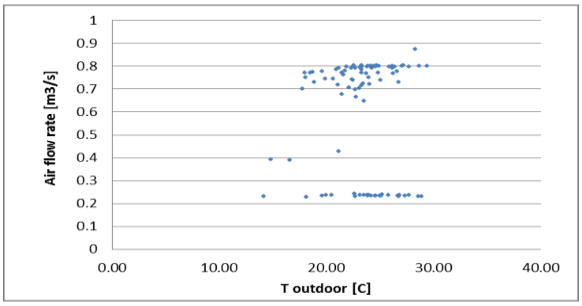

Figure 2 Daily average measured supply airflow signature of thermal zone 1.6NE

Development of the eQuest input file

To facilitate the development and to find quickly errors in the input file, the first file was developed using the simplified wizard, and based on technical specifications, drawings, measurements from the EMS, and specifications from the ASHRAE standards 90.1 and 62.1 and MNECB.

Fifteen thermal zones were defined by grouping rooms of similar orientations and patterns of occupancy, and using information from architectural drawings to define the walls, floors, roofs and interior partitions.

The eQuest program offers the option to export the hourly values of more than 150 variables. We used this option and exported the hourly values of some variables for the comparison with measurements. After correcting errors in the input file, we realized that the simplified wizard cannot handle the complexity of an HVAC system, and we converted the file to the detailed wizard for the rest of study. Any changes done in the detailed mode would be lost if the user decides to return to the simplified mode.

The changes made to the input parameters are based on the analysis of available measurements: supply airflow rate, supply air temperature, room air temperature and derived cooling load. This is not an uncertainty analysis. Some examples of evidence-based changes are presented below:

a) The initial information indicated that the thermostat set point was constant at 23.2°C in all rooms throughout the entire period. However, the measurements revealed that the indoor air temperature varied from one room to another, and the thermostat set point was increased during weekends. Table 1 shows for four zones the measured average zone air temperature. The change to the thermostat setting had a significant impact on the calculation of supply airflow rate, by reducing or eliminating the predicted airflow rates in weekends (Figures 3 and 4 for zone 1.6NE, and Figures 5 and 6 for 1.4SW).

Table 1
Measured daily average zone air temperature

ZONE	**MEASURED AIR TEMPERATURE [°C]**	
	Occupied	Unoccupied
1.4 SW	24.7	30.8
1.6 NE	23.9	26.1
3.1NE	23.4	25.4
3.5 SE	22.9	25.2

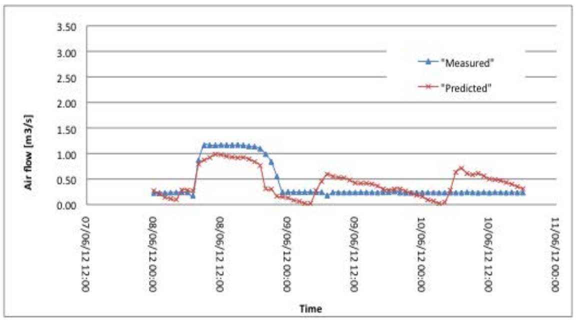

Figure 3 Measured vs. predicted hourly supply airflow rate in zone 1.6NE over three days in June 2012, with constant set point temperature of 23.9°C

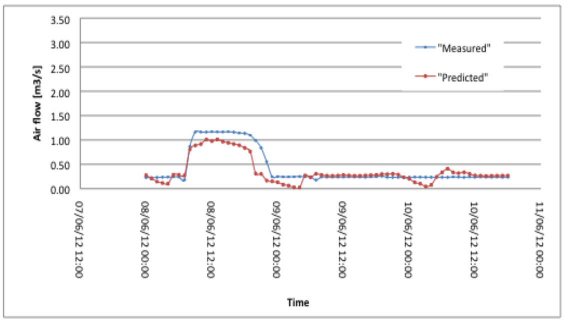

Figure 4 Measured vs. predicted hourly supply airflow rate in zone 1.6NE over three days in June 2012, with thermostat setup during unoccupied hours (26.1°C)

b) In a building with offices and laboratories for research, there are random hourly and daily schedules of utilization, which is almost impossible to implement as a regular pattern of usage. Hence, we defined for each room an equivalent rectangular-shape daily schedule. The maximum and minimum values of internal loads from lights were initially defined based on installed luminaires data, available in the architectural plans, and corrected based on measured loads during the day and at night, respectively.

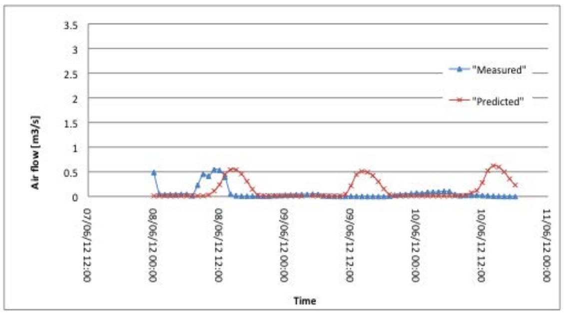

Figure 5 Measured vs. predicted hourly supply airflow rate in zone 1.4SW over three days in June 2012, with constant set point temperature of 24.7°C

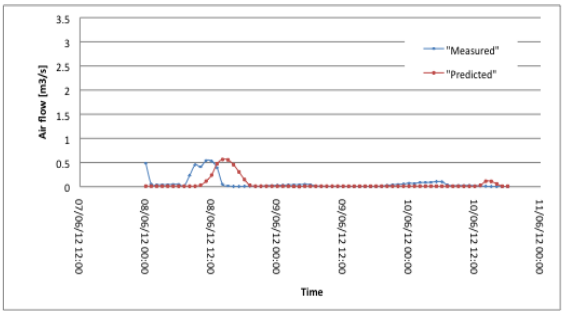

Figure 6 Measured vs. predicted hourly supply airflow rate in zone 1.4SW over three days in June 2012, with thermostat setup during unoccupied hours (30.8°C)

c) The calibration improved when we used different schedules (e.g., lights, thermostat setting) for each thermal zone.

d) The design specifications indicated that during the day the supply airflow rate should correspond to 10 air changes per hour (ACH) during occupied hours, while for unoccupied hours during the day it is limited to 6 ACH, and for unoccupied hours during the night, the maximum allowed airflow rate is 3 ACH. We preferred to input the maximum supply airflow rate as measured on each thermal zone (as the average of all rooms in the zone) instead of the design ACH. Table 2 shows for three zones the maximum and minimum measured supply airflow rate, compared with the design values.

e) Analysis of measurements revealed that the system does not operate as initially specified at 30% minimum supply airflow, when cooling loads are small. Therefore, for each zone and air-handling unit, we extracted the minimum airflow for the summer period, and input the minimum flow ratio, as requested by eQuest (Table 2).

Table 2
Measured vs design daily average airflow rate

ZONE	MEASURED AIRFLOW RATE [m^3/s]		DESIGN AIRFLOW RATE [m^3/s]	
	Occ.	Unocc.	10 ACH	3 ACH
1.4SW	0.82	0.01	1.02	0.31
1.6NE	1.26	0.22	1.02	0.31
3.5SE	2.76	1.65	4.52	1.35

f) Since at the beginning of September 2012, the actual weather data file was not available (any energy modeller could face this situation), we used initially the CWEC weather file for Montreal, available with the program. Early January 2013, we obtained the Montreal 2012 weather file from Weather Analytics (2013), based on measurements at Montreal International Airport. The outdoor air temperature measured on the campus during the summer of 2012 was on the average higher by 3.6°C than the value from the CWEC weather file; the difference was reduced to 1.5°C when the Montreal 2012 file was used. Figure 7 shows the airflow rate for three days in July 2012 for zone 1.4SW, as predicted with CWEC file and Montreal 2012 weather file, respectively. For this particular zone, the average airflow rate is 0.51 m^3/s, when CWEC file is used; and 0.36 m^3/s when Montreal 2012 file is used. The mean measured airflow rate for these three days is 0.24 m^3/s. The use of Montreal 2012 weather file reduced the peak supply airflow rate 0.15 m^3/s compared with the result from CWEC file.

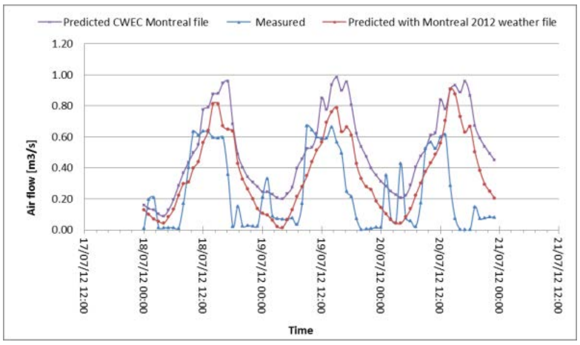

Figure 7 Measured vs. predicted airflow rate for zone 1.4SW with CWEC and Montreal 2012 weather files, for three days in July 2012.

g) The exterior shading from nearby buildings reduced the cooling load of zones of North and Northeast orientations. The side fins (Figure 1), which are placed on all the windows reduced also the solar heat gains for all orientations. Figure 8 shows the difference of airflow rates, without and with side fins from a preliminary simulation run.

h) Blinds are used throughout the building and are controlled manually and in a random fashion that cannot be monitored, therefore the blinds were assumed to be fixed in a certain position.

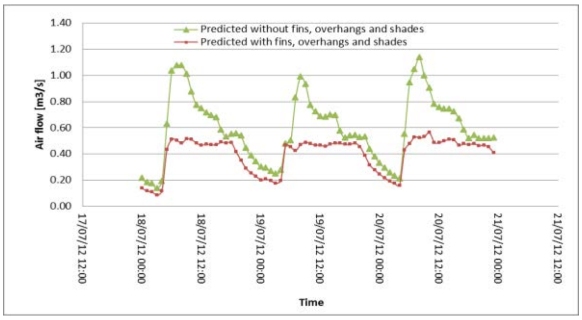

Figure 8 Measured vs. predicted airflow rates for zone 1.6NE, without and with fins and building shades, for three days in July 2012.

i) When making changes to the input parameters, we followed Rafferty's (2011) suggestion to have a hierarchy of sources of information, giving the highest confidence to continuous and short-term measurements, followed by direct observations, information from the building operation and commissioning team, technical specifications and drawings, and finally standards and by-laws.

Results of model calibration at zone level

The eQuest program predicted the hourly cooling load and indoor air temperature for each thermal zone. The hourly values of supply air flow rate of VAV systems, although are calculated internally by the program, are not exported through the hourly report. Hence, this variable was calculated separately. The supply air temperature for each room was assumed to be equal to the air temperature leaving after supply fans.

On the other hand, only the supply airflow rate for each room and indoor air temperature were measured. Hence, the cooling load was calculated from those measurements, using the same assumption that the supply air temperature is equal to the air temperature after supply fans. The zone-averaged measured hourly values were compared with the corresponding predicted zone hourly values. The results show good agreement between measured and predicted cooling load and supply airflow rate.

The measurement uncertainties are: i) ±2% for room and AHU supply and return airflow meters; ii) ± 1°C for duct temperature sensor; and iii) ± 0.3°C for room temperature sensor. The uncertainty of cooling load based on measured supply airflow rate and temperature difference was estimated at 24-30%.

The calibration was performed for all thermal zones, for the selected three days and for the whole cooling season. As examples, Figures 9 and 10 show the comparison for zone 3.1NE (for both cooling load and supply airflow rate), over three days in July, while Figures 11 and 12 show the comparison for zone 3.5SE. Figure 17 shows the calibration results for the summer period for zone 1.3NE.

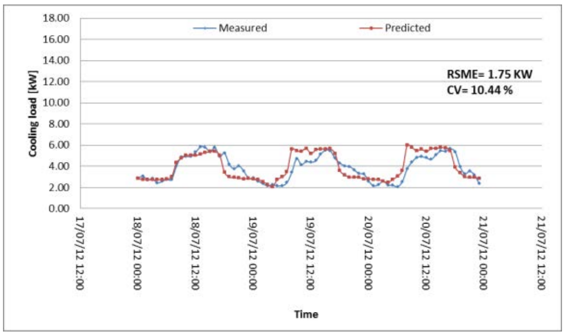

Figure 9 Measured vs. predicted hourly cooling load of thermal zone 3.1NE over three days in July, 2012

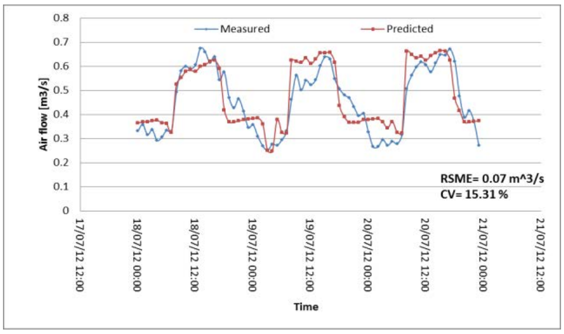

Figure 10 Measured vs. predicted hourly supply airflow rate in zone 3.1NE over three days in July, 2012

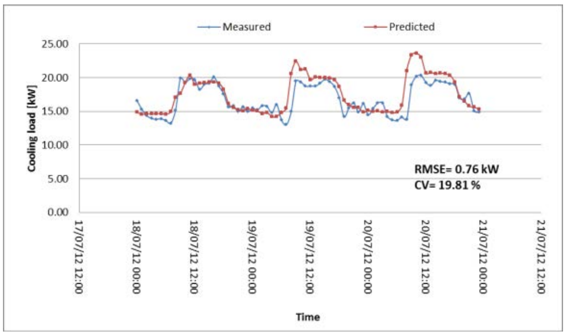

Figure 11 Measured vs. predicted hourly cooling load of zone 3.5SE over three days in July, 2012

Figures 13 and 14 show the daily average supply airflow signature of two zones vs. daily average outdoor air temperature, for the whole cooling season. The outdoor air temperature has a minor impact on the load and airflow rate in both zones. The hourly predicted results are in good agreement with measurements, as the CV does not exceed 20%.

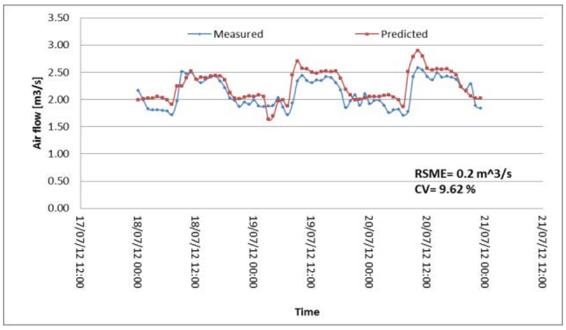

Figure 12 Measured vs. predicted hourly supply airflow rate in zone 3.5SE over three days in July, 2012

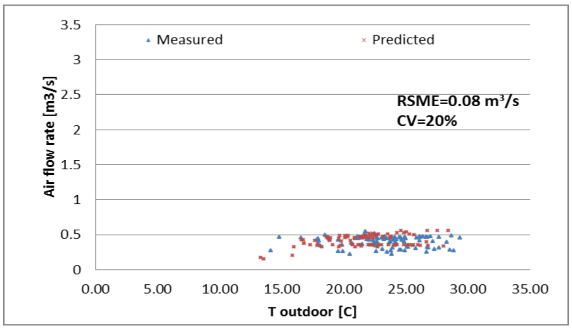

Figure 13 Supply airflow rate of zone 3.1NE vs. outdoor air temperature for the cooling season

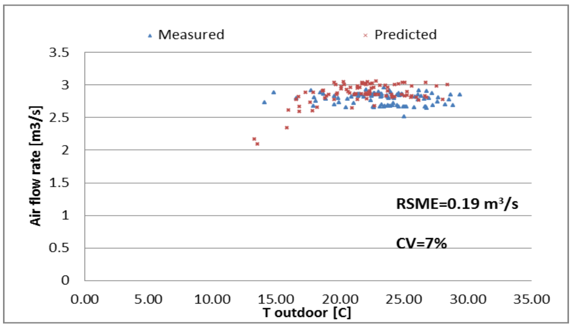

Figure 14 Supply airflow rate of zone 2.5SE vs. outdoor air temperature for the cooling season

Results of model calibration at AHU level

The measured daily average supply airflow rate at AHU was 13.14 m^3/s compared with the predicted value of 14.57 m^3/s (Table 3); while the summation of airflow rates measured on the floors 1 to 3 was 9.21 m^3/s (compared with 10.63 m^3/s). The average difference between predicted and measured supply airflow rate is 11.2%. The difference between the measured supply airflow rate in the air-handling unit and the summation of the airflows to all the zones is equal to the airflow rate supplied to the basement, and leaks in air ducts.

The predicted and measured daily average supply airflow signature vs. daily average outdoor air temperature compare well over the complete cooling season (Figure 15). The upper set of points corresponds to the occupied periods, while the lower set of points corresponds to the unoccupied periods.

Table 3
Supply airflow rate at air handling unit vs. summation of supply airflow rates of zones-measurements vs. predictions

	MEASURED AIRFLOW $[m^3/s]$		**PREDICTED AIRFLOW $[m^3/s]$**	
	Sum of zones	AHU	Sum of zones	AHU
Average	9.21	13.14	10.63	14.57
RSME AHU $[m^3/s]$				2.96
CV AHU [%]				23

The predicted and measured daily average supply airflow signature vs. daily average outdoor air temperature compare well over the complete cooling season (Figure 15). The upper set of points corresponds to the occupied periods, while the lower set of points corresponds to the unoccupied periods.

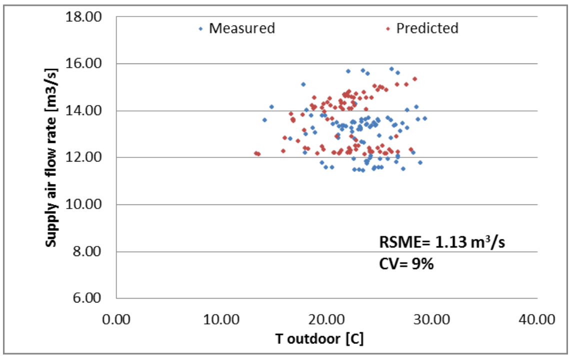

Figure 15 Measured vs. predicted daily average supply airflow rate from the AHU vs. outdoor air temperature

The comparison of measured and predicted supply air temperature is not straightforward. The supply air temperature (T_S) leaving the fan is measured. On the other hand, the program calculates the cold deck temperature (i.e., the air temperature leaving the cooling coil) using a reset in terms of outdoor air temperature (the default is a constant T_{CD}). The increase of temperature, when the air passes through the fan, is set by the program at 1.87°C for VAV systems. Hence, T_S is calculated internally by adding T_{CD} and 1.87°C. However, only the hourly values of T_{CD} are exported from eQuest. From measurements, we input the following reset conditions: T_{CD} = 14.5°C when T_{OA} = 29.4°C or higher; and T_{CD} = 15.3°C when T_{OA} = 14.1°C or lower.

Figure 16 shows the daily average supply air temperature signature of AHU vs. daily average outdoor air temperature over the complete cooling season.

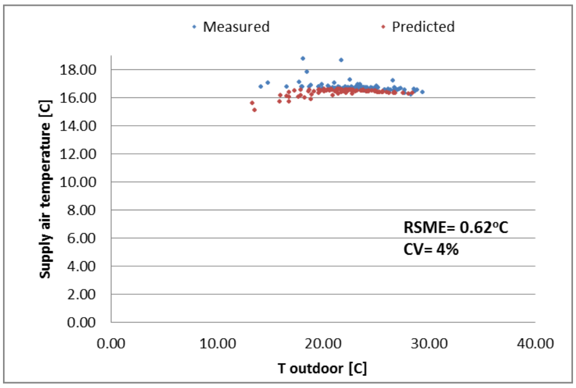

Figure 16 Daily average supply air temperature signature of AHU vs. daily average outdoor air temperature

CONCLUSION

The availability, analysis and use of measurements from EMS, installed in existing commercial and institutional buildings, could be of great help to the model calibration, and especially for the calibration of HVAC system model. The paper presented a few examples of information extracted from EMS and the impact on the model calibration. The sequence presented in the paper should give confidence in the calibrated model, although some differences still exist between measurements and predictions. There was no additional fine-tuning of variables by trial-and-error. Once the evidence-based calibration is completed, the user might have the choice (1) to stop the calibration process, and use calibrated model for the purpose it was developed, or (2) to continue the process with the sensitivity and uncertainty analyses.

The energy modeller should be aware of limitations in the simulation algorithms, uncertainties in measurements, faults in sensors, differences between the inputs and actual random loads.

Future work would focus on following topics:

- the calibration of swing and heating seasons;
- the calibration of water-side loop of HVAC system and energy use;
- the development of the data mining and automatic export of information, and the coupling between the data mining module and the input file;
- the development of a prototype tool for the coupling with eQuest program, and the free distribution to energy modellers for testing.

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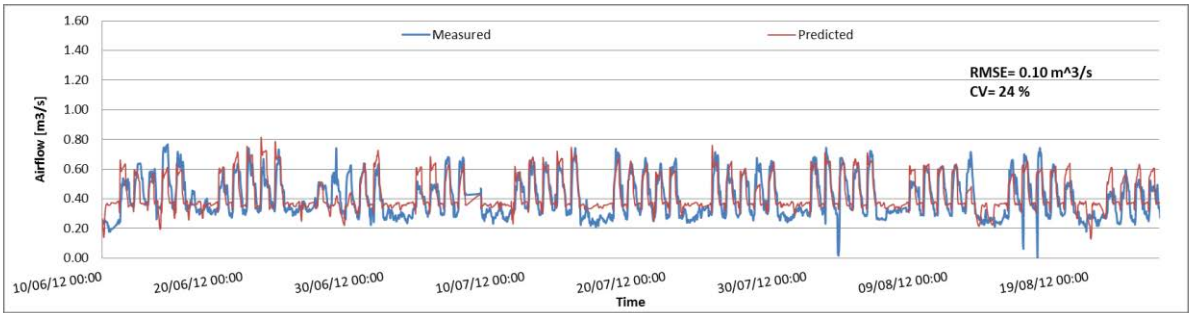

Figure 17 Measured vs predicted airflow rate for zone 3.1 NE for the summer period