COMPUTER MODEL OF A UNIVERSITY BUILDING USING THE ENERGYPLUS PROGRAM

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ABSTRACT

This paper presents the development of a computer model of an academic building using the EnergyPlus program and its calibration with monitored data. The new Concordia Sciences Building (CSB), located in Montreal, has a total floor area of 32,000 m^2. The size and the complexity of the heating, ventilation and air conditioning (HVAC) and heat recovery systems make the modeling process a challenge and an excellent opportunity to evaluate the capabilities and features of EnergyPlus in this particular context.

KEYWORDS

Building, modeling, calibration, EnergyPlus, cold climate.

INTRODUCTION

Several simulation tools are available to evaluate the energy performance of buildings. EnergyPlus, a state-of-the-art building energy analysis program, which features the best capabilities of DOE and BLAST programs, was first released in 2001. Since its first distribution, several versions were released with new features and increased accuracy of simulation results. This study is performed with version 1.3.0, which was released on April 28th, 2006.

Several researchers have compared and evaluated particular features of the program in specific context. In spite of this, a limited amount of information has been published so far about the calibration of building models developed by using the EnergyPlus program or about the comparison with measured or simulated data from large buildings in cold climate. Bellemare et al. (2002) modeled an institutional building with 54 interior zones and related Variable Air Volume (VAV) systems. They predicted the supply air temperature and airflow rate for selected rooms and compared the predictions with monitored data, and they obtained similar trends of variation. The comparison between predictions made by EnergyPlus and DOE-2 program also indicated similar trends when the EnergyPlus input was modified to respect the conditions of the DOE-2 program such as the use of constant room temperature to determine the zone heating/cooling load. Under this set of conditions, the average room temperature difference over a week is 0.24°C and the average airflow rate difference is 9%. Ellis and Torcellini (2005) have simulated a tall building having an overall floor area of 240,000 m^2. Their analysis was mainly focused on the stack effect and the use of floor multipliers, while HVAC systems were entered through the purchased air option that is offered by the EnergyPlus program.

This paper presents the development of a computer model of an academic building using the EnergyPlus program and its calibration with monitored data. The building under study was submitted for Commercial Building Incentive Program (CBIP) application, which uses the DOE-2 program as the engine for EE4 program to estimate the annual energy cost and consumption of the proposed building versus the performance of a reference building.

BUILDING CHARACTERISTICS

The CSB is located on the Loyola campus in Montreal and has a total floor area of 32,000 m^2. The building is divided in three main sectors: sector A, B and C (Figure 1).

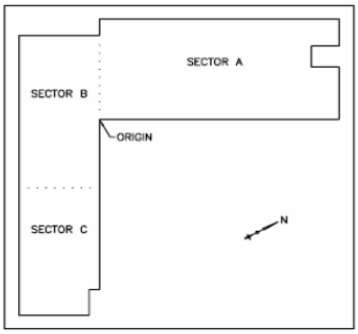

Figure 1 Building layout

Sector A is the heart of the building and mainly consists of laboratories and offices. Sector C is located on the south-west side of the building, and sector B is the Bryan wing, an existing building that is integrated to the CSB. The majority of the envelope infrastructure has been conserved and the interior has been redesigned to accommodate the new university needs.

Building exterior envelope

According to the design specifications, the building has walls with the overall thermal resistance varying between 2.6 and 3.1 m^2·°C/W and roofs between 2.8 and 4.2 m^2·°C/W. Most walls are insulated brick completed with an air space, a vapour barrier and one or two layers of gypsum board. The roofs are built-up of a bitumen membrane, a concrete layer, two types of insulation, a plywood panel, a vapour barrier and another concrete layer. Two types of glazing are present: double low-E clear with film 6 mm/6 mm air gap and double low-E clear 6 mm/13 mm air gap. The glazing accounts for about 32% of the total area of exterior walls (PMA 2003). The fenestration assemblies are either curtain walls with aluminium framing completed with thermal break or fixed aluminium with thermal break frames. The ceiling height varies between 2.4 and 2.6 meters.

HVAC systems

Mechanical systems are designed to maintain the indoor thermal parameters within the comfortable range. Since the main activities of the building are teaching and research in fields such as biology, chemistry and biochemistry, the size and system requirements are quite large. To reduce the zone loads, motion detectors were installed in all rooms of the CSB. The motion detectors shut off lights after an adjustable delay of no activity. When lights shut off, a signal is also sent to the building automated system to reduce the amount of air sent to the room. For laboratories, the supply airflow rate is changed from 10 air changes per hour (ACH) during occupied hours to 6 ACH while unoccupied. This is further reduced to 3 ACH at night time. The ventilation is brought back to 10 ACH whenever occupants are present (Lemire and Charneux 2005). Other room types are restricted to a minimum of 3 ACH, if located on the perimeter, and 1.5 ACH if it is an interior zone (PMA 2003).

The VAV system of sector A is served by four identical air handling units (AHU-1 to AHU-4), each having a design airflow rate of 37.75 m^3/s. The overall cooling and heating capacity for this sector is 3310 kW and 4580 kW, respectively. The VAV system of sectors B&C is served by two identical air handling units (AHU-7 & AHU-8). The design airflow rate for the whole system is 75.5 m^3/s, the cooling capacity is 1655 kW and the heating capacity is 2340 kW. The animal laboratories, which are located in the second basement west wing of sector A are supplied by a separate 100% outside air system (AHU-5 & AHU-6). The zone requirements of the animal laboratories are satisfied by two identical 11.8 m^3/s systems having a total cooling capacity of 550 kW and a total heating capacity of 1150 kW.

The total supply airflow rate of each system is composed of the amount of air required for cooling/heating purposes plus the additional amount of air that must be supplied to laboratories, to compensate for the air exhausted by the laboratory hoods. Thus, a large amount of energy is required to heat and cool the outdoor air introduced into the building. To reduce the energy burden, a run around heat recovery glycol loop is installed between the exhaust air stream and the oudoor air stream. Variable frequency drives are also installed on fans to improve efficiency at part load operation. For all units, filters and coils are selected for a face velocity of 2.03 m/s (Lemire and Charneux 2005). This reduces the total system pressure loss and allows the use of smaller electric motors. Variable frequency drives are also installed on fans to improve efficiency at part load operation.

Primary systems

A thermal central plant serves all sectors of the building, where different systems have been installed, (Figure 2).

Plate heat exchangers recuperate the heat rejected from chillers (CH-1 & CH-2) and from exhaust gases from two existing boilers to pre-heat the heating water. During the summer season, the heating water system, which is used for re-heat purposes only, operates on 35ºC supply and 29.4ºC return water temperatures. The water temperature is increased to 51.7ºC supply and 29.4ºC return during the winter season. The heating water is also pre-heated via a plate heat exchanger using the condenser water that is circulated between the cooling towers and central plant chillers (CH-1 & CH-2). If heat recuperated via the heat recovery system is insufficient to achieve the required water temperature, a tube and shell heat exchanger is used to further heat up the water using steam produced by a 96% efficient natural gas boiler having a capacity of 815 kW.

Steam is supplied from the boiler to the humidifiers installed in the air handling units. The heating water also serve the plate heat exchangers that warm up a 50% glycol solution from 26.7ºC to 48.9ºC to be supplied to the glycol heating coils installed within each of the air handling units.

The chillers have the cooling capacity of 3165 kW (900 tons) each, and a coefficient of performance (COP) of 5.76. Chilled water cooling coils operating between 5.6/13.3ºC water temperatures provide the cooling required within the building. Two additional chillers (CH-3 & CH-4) are included within the building to serve the fan coil units, during the winter and part of the shoulder seasons.

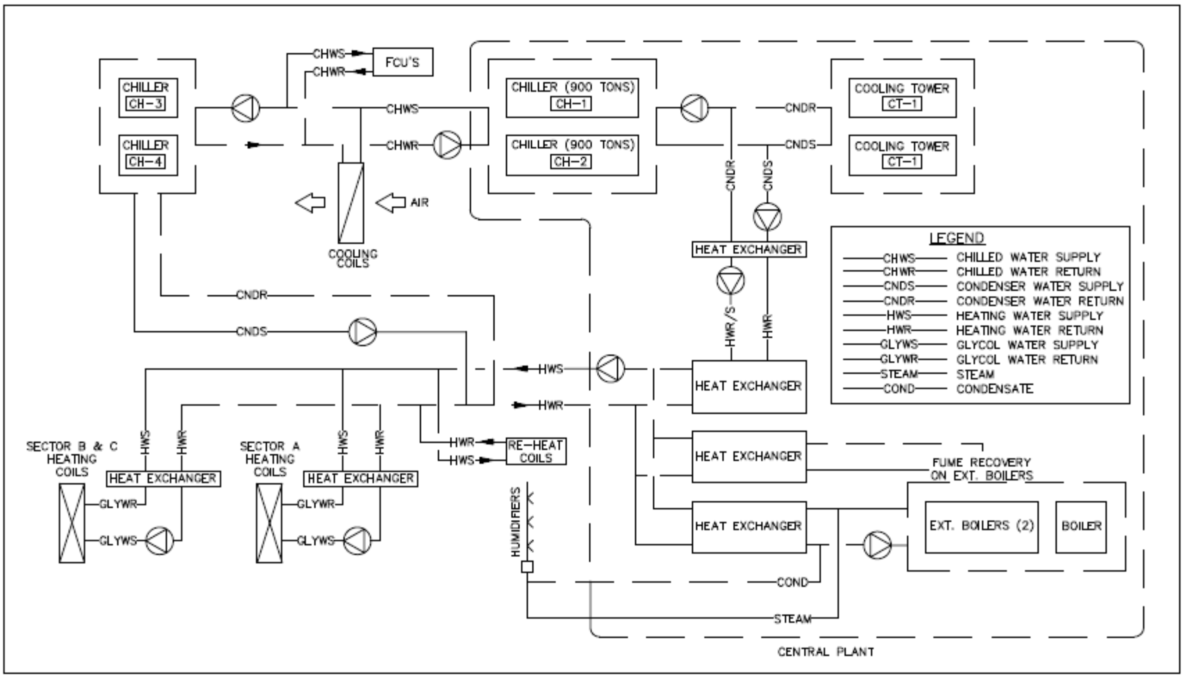

Figure 2 Simplified schematic of HVAC systems and central plant

Fan coils units are located mainly in electrical rooms, telecom rooms and cold rooms, and run all year around. The condensers of chillers CH-3 & CH-4 are also connected to the heating water loop to pre-warm the heating water.

The combination of energy efficient measures and operating strategies has led to a 50% reduction in energy consumption compared to the Model of National Energy Code of Canada for Buildings (MNECCB), and thus, the Sciences building qualified for the CBIP application (Lemire and Charneux 2005).

DEVELOPMENT OF THE COMPUTER MODEL

The initial phase in the development of the computer model consists of collecting the architectural, mechanical and electrical data required for the preparation of the input file. The input file reflects the geometry of the building and its characteristics having an impact on thermal loads as well as the description of HVAC systems. The accurate modeling of the components/subsystems of the building and mechanical systems have a significant impact on the building energy use. The files provided by the mechanical consultant were helpful to create the initial input file in this study. The DOE-2 file, that contains the building description, is translated into an “*.idf” input file compatible with the EnergyPlus program. This conversion is realized through the use of a utility program named DOE2Translator provided as a pre-process program by EnergyPlus. The translation program provides incomplete design object information, and therefore additional work and several modifications are required to obtain a working input file for the EnergyPlus program.

Architectural systems

The complexity of the building has led to many modeling issues related to the determination of space loads. Given the size of the building and its vocation, a large number of thermal zones and building surfaces (walls, roofs, partitions, floors), with a significant impact on heat transfer phenomenon, are used to develop the input file (Table 1).

Table 1 Number of zones and surfaces by sector

SECTOR	NUMBER OF ZONES	PLENUMS	NUMBER OF SURFACES
A	58	14	1154
B&C	39	12	619
ANIMAL LABS	6	N/A	79
TOTAL	103	26	1853

The origin of each zone must be defined in reference to the origin of the building/floor, using x, y, z-coordinates. The origin is located at the ground floor level of the lower left corner of sector A (Figure 1). In order to obtain more accurate results, it is recommended to include every surface within a zone. In the case of one interior partition that separates two zones, the vertices of this partition must be defined in both zones. This condition helps in obtaining the same surface area on both sides of the partition. This way, the conservation of energy principle applied to the partition is respected.

Since most of the building has plenum spaces, several plenum zones are created to estimate the variable air temperature inside each plenum, which has an important impact on the cooling and heating loads of the corresponding zones as well as on the mixing air temperature in the air-handling units. Temperature within a zone is controlled and kept close to its set point temperature, while plenum temperature is uncontrolled and fluctuates depending on heat gains and losses between the plenum and surroundings.

The use of plenums has increased the complexity of the input file, but it has also simplified the definition of ceiling/floor as an internal surface. The floor layout being considerably different from one floor to another, it is a challenge to define ceilings and floors with identical superficies, in order to meet the program condition for respecting the conservation of energy principle. The problem is resolved by defining a plenum between two surfaces (a ceiling and a floor). The floor of each plenum is divided in pieces to match the ceilings of the zone located below. Similarly, the ceiling of each plenum is divided in pieces to match the floor of the zones located above. In zones where there is no plenum, such as mechanical rooms, the ceiling towards adjacent spaces is left unfilled. By leaving the information blank, no heat transfer between zones is taken into consideration, however, the heat storage capacity of the object is still taken into account. The floor slab having a high thermal mass and the temperature difference between the two zones being relatively small, the amount of heat transfer between two zones located on two adjacent floors is minimal and can be neglected. This approach simplifies the model by limiting the total number of surfaces to be included in the input file.

In terms of internal loads, the EnergyPlus program requires the information to be entered as the total installed power (W) for each zone. Thus, the required data for the EnergyPlus program are calculated using the zone area as defined through the x, y and z-coordinates and information provided in the converted file.

Infiltration is evaluated only for above ground perimeter zones. Air tightness in large building is extremely hard to evaluate. As a guideline for model input, Kaplan and Canner (1992) recommend using 0.2 (l/s)/m^2 of gross exterior wall area, while calculations based on the MNECCB (1997) are based on 0.25 (l/s)/m^2 as natural infiltration rate. Infiltration is assumed to occur only when the HVAC systems is OFF. When the system is ON, no infiltration occurs due to building pressurization. For this building, the systems are always ON and thus no infiltration should occur. Therefore, the air infiltration rate is set to zero in the input file.

HVAC systems

A number of runs were required to achieve practical results. To ease the entry process for HVAC systems in EnergyPlus, compact HVAC systems were originally used. Compact HVAC objects provide a shorthand way of describing standard HVAC system configurations. Those models include built-in default data and user input data entry for basic system options. EnergyPlus automatically sets up loops, branches and node names for the specified objects. Each object can be expanded in the following runs to detail each component. This approach abbreviates and simplifies the initial modeling. The expanded inputs can be grouped in three different categories: 1) zone sizing inputs, which set the design requirements of the zone; 2) water-side equipment inputs, which set the re-heat design requirements and branches; and 3) air-side zone equipment inputs, which describe the air side connections, the equipment installed (VAV with re-heat) and the room set point.

For simplification, all air handling units providing air to a specific sector are combined into one large unit having an equivalent capacity of all the air handling units for that sector.

Primary systems

The complex structure of the central plant cannot be directly simulated by EnergyPlus. Therefore, the approximation used in the model is described here. The building is provided with steam boilers and steam-to-water heat exchangers to provide heating water to the VAV re-heat coils and the heating coils of the air handling units (see Installed Heating Water Loop in Figure 3). Two independent loops are modeled: a glycol (heating) loop for heating coils of the air handling unit (see Modeled Heating Water Loop in Figure 3) and a heating water loop (low and high temperature varying throughout the seasons) which is connected to the heat recovery loop and provides heating water to the VAV re-heat coils (Figure 4). Heating coils located in the air handling units use a 50% ethylene glycol mixture. Steam-to-water or water-to-water heat exchangers are not yet available in the EnergyPlus version that was used in this study. Therefore, the heating loops are both set up as heating water loops and boiler efficiencies are adjusted to take into account the combined effect of the boiler and heat exchanger efficiencies (Figure 3).

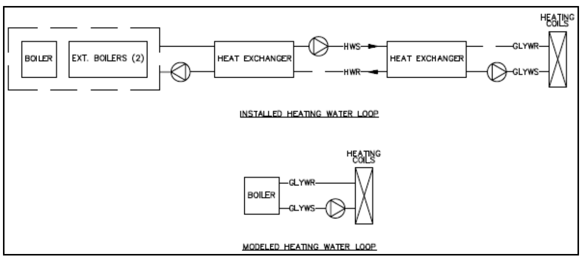

Figure 3 Schematic of the heating water loop

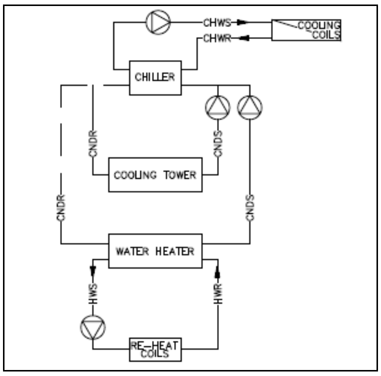

Figure 4 Schematic of the simulated cooling and reheat loops

To simulate the heat recovery, the heating water boiler is replaced by a water heater. The water heater recuperates the heat rejected by the condenser and provides the additional heat required to maintain the supply heating water set point temperature for the re-heat coils. The condenser is connected to the water heater and to the cooling tower (Figure 4). In the actual building, two sets of chillers are installed: one set of two chillers (CH-3 & CH-4) operate during the winter and part of the shoulder season, providing cooling to electrical/utilities rooms during the winter months, and the second set of chillers (CH-1 & CH-2) is in the central plant and provide additional cooling to the building during the summer and shoulder seasons, if required. Since the two sets of chillers never operate simultaneously, only one large chiller, having the capacity of chillers CH-1 & CH-2, is included in the model. The supply and return temperatures for chilled and condenser water loops are modified throughout the seasons to reflect the actual on-site operating conditions.

Additional heat recovery measures are present in the building but are left out for simplification purposes. For instance, the heat recovery on the exhaust air stream that uses glycol coils is not included in the model because of the absence of glycol heating loop. Also, the steam humidifiers are replaced by electrical humidifiers in the input file since it is the only available option in the EnergyPlus version used in this study.

SIMULATION RESULTS

The building was submitted for CBIP, and therefore, the DOE-2 file generated for the application provides a platform to compare different features and simulation results of the DOE-2 and EnergyPlus program. Also, information about as-built and as-operated thermal performance of the CSB is obtained from the Monitoring and Data Acquisition System (MDAS) through the collaboration of the Physical Plant of Concordia University. Data from 49 sensors are collected every 30 minutes. The collected information is compared with the EnergyPlus predictions, such as supply airflow rate, and supply and return air temperatures.

Inter-program comparison

The development of input files for EnergyPlus and EE4 programs is rather different. The EnergyPlus input file is built using the IDF editor, no interface being available at the start of this project. EE4 on the other hand has a complete interface that assists in the data entry process. The EnergyPlus input file has 103 zones and 1853 surfaces, while the EE4 input file has 75 zones.

To evaluate the overall performance of the EnergyPlus program, annual indices, such as specific annual electricity use (kWh/m^2), are compared with information from the CBIP application and specification cut-sheets. The cooling coil loads are compared to the design coil capacity. The load needed to accommodate the hood ventilation requirement is evaluated using airflow rate ratio. For sector A, the total cooling coil load is estimated at 1720 kW, while a capacity of 3310 kW is available. For sectors B and C, the estimated cooling coil load is 1090 kW, while the installed capacity is 1640 kW. The estimated and design airflow rates are different, and consequently the cooling coil loads estimated by the EnergyPlus program are lower than the design loads.

In the existing central plant, the design of the heating and cooling equipment is complex and it can not directly be simulated by the EnergyPlus program. For instance, there are many heat recovery systems present in the building that are not included in the model. Thus, no attempt is made to estimate the cooling and heating electricity consumption due to differences between the building and EnergyPlus model operating conditions. The annual electricity consumption is only evaluated for secondary systems, fans, and building components such as lighting and appliances. The electrical consumption estimated by EnergyPlus, in terms of kWh/m^2 (Table 2), is compared with data predicted by the DOE-2 program.

Table 2 Annual electricity consumption per floor area estimated by EnergyPlus

ITEM	CONSUMPTION, kWh/m^2
LIGHTING	47.5
APPLIANCES	38.0
FANS	36.6

For the lighting electricity consumption, a value of 56.4 kWh/m^2 was estimated by the DOE-2 program for the same schedules of operation and internal loads, while the EnergyPlus estimation is 47.5 kWh/m^2. For appliances, the electricity consumption estimated by EnergyPlus is 38.0 kWh/m^2 compared to 38.8 kWh/m^2 from DOE-2. For fans, the estimated values are also in agreement: 36.6 kWh/m^2 for the EnergyPlus program versus 31.0 kWh/m^2 from DOE-2.

The cooling/heating loads of zone no.16, a fully interior zone, are compared to investigate the impact of different calculation methods in the absence of exterior surfaces. The variation of daily loads, as predicted by both programs, is similar (Figure 5).

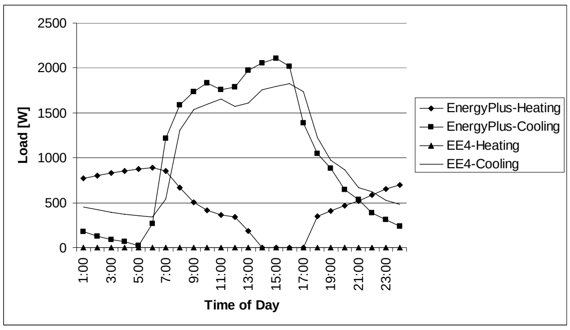

Figure 5 Daily cooling and heating loads of the core zone no.16

For cooling, the EnergyPlus prediction is about 14% higher than the peak load from EE4. Since the room conditions are identical, the difference in peak loads is supposed to come from the difference in mathematical models used for cooling load calculations. The DOE-2 program uses the weighting factors method, while EnergyPlus program uses the heat balance method to estimate the variation of indoor air temperature within or outside the limits imposed by the thermostat and the corresponding zone loads. The exterior environment plays no role in this difference, since zone no.16 is a core zone with no exterior surfaces.

To further investigate this issue, the schedule of internal gains of zone no.16 is modified to introduce an instanteneous lighting load of 10 kW at 9:00 on the summer design day. It is assumed that 85% of load goes to the space and 15% to the plenum. Figure 6 shows the response of the zone cooling load as predicted by both programs.

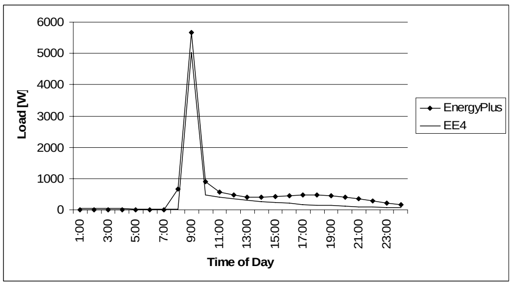

Figure 6 Instantaneous load responses for zone no.16

Since the peak load predicted by EnergyPlus is about 11% higher than in EE4, and the subsequent hourly loads are also higher, it is concluded that the difference in mathematical models, including default values, is the cause of such difference in peak cooling loads. Overall, the results estimated by both programs are in agreement and comparaison with measured data should lead to a better evaluation of the computer model developed using EnergyPlus.

Calibration with measured data

Model calibration is essential to ensure that the architectural, mechanical and electrical systems are properly modeled and integrated together for the purpose of estimating the building energy performance. Calibration of the computer model of a large building can be labour intensive even for an experienced modeler. It requires a throughout understanding of the architectural layout and mechanical systems as well as of the assumptions, default values, mathematical models and limitations of the energy analysis program. Kaplan and Canner (1992) have made recommendations for the maximum allowable difference between predicted and monitored data. For instance, the prediction of energy use for interior loads such as lighting, receptacles or domestic hot water is satisfactory when the difference is within 5% on a monthly basis and 15% on a daily basis. However, the acceptable difference may increase up to 15-25% (monthly) and 25-35% (daily) for the simulation of HVAC systems. The annual simulated energy use should be within 10% of collected information, while a difference less than 25% is acceptable on a seasonal basis.

In this paper, the calibration of the case study is carried out separately over two periods with different operating conditions: period A, from March 20th to May 3rd 2006, which corresponds to the shoulder portions of the spring season, when the cooling coils are not in operation, and period B, from May 4th to June 20th 2006, when the mechanical cooling system is in operation. The simulation of two distinct operation periods has the advantage of avoiding some compensating errors that can occur when the calibration process is performed over one year, with periods of different operating conditions.

The goal of the calibration presented in this paper is the development of a computer model of a large institutional building that predicts well the following directly measured variables: the supply airflow rate, and the supply and return air temperatures.

During the calibration, the input file is modified to achieve an acceptable degree of convergence between measured and estimated data. First of all, the setpoints have been modified based on the analysis of collected data. Also, the compensating airflow rate for laboratories exhaust is added to the estimated results made by EnergyPlus, since the supply airflow rate calculated by the program corresponds only to space cooling loads. Figure 7 shows the variation of supply airflow rate for sector A for two weeks (March 26th to April 8th) during period A, which is from March 20th to May 3rd 2006.

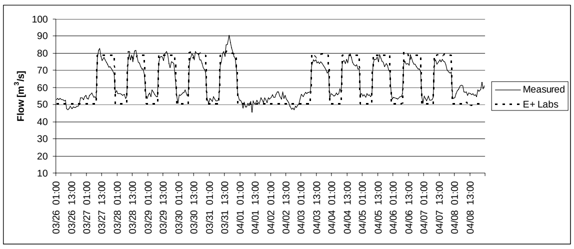

Figure 7 Supply airflow rate from March 26 to April 8 (2 weeks in period A); sector A

Figure 8 shows the variation of supply airflow rate for sector A for two weeks (May 28th to June 10th) during period B, which is from May 4th to June 20th 2006.

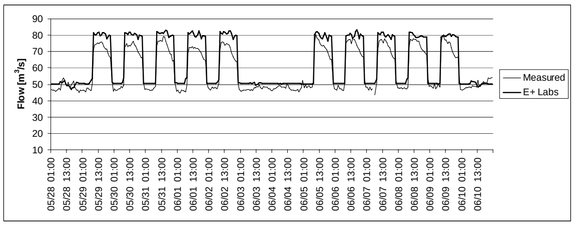

Figure 8 Supply airflow rate from May 8 to June 10 (2 weeks in period B); sector A

In terms of supply airflow rates, the measured and predicted values show similar trend for both calibration periods. For the spring season, the differences between the predicted and measured variables under comparison (airflow rates and air temperatures) are below the recommended value of 25% for HVAC systems (Tables 3 and 4) (Carner and Kaplan 1997). This demonstrate that the EnergyPlus predictions are in agreement with the data collected by the MBAS at the CSB.

Table 3 Calibration results for the spring season; sector A

ITEM	MEASURED	E+	R.D., %
AIRFLOW, m³/s	60.42	60.05	-2.69
$T_{S/A}$, °C	16.34	16.53	-1.13
$T_{R/A}$, °C	21.74	20.93	3.73

Table 4 Calibration results for the spring season; sectors B&C

ITEM	MEASURED	E+	R.D., %
AIRFLOW, m³/s	20.27	21.39	-5.51
$T_{S/A}$, °C	15.94	16.23	-1.79
$T_{R/A}$, °C	22.05	22.98	-4.23

COMPUTER PROGRAM ENERGY SIGNATURE

To complete the analysis of the use of the EnergyPlus program to simulate large buidling with complex electro-mecanical systems, the energy signature of the computer program, when the annual simulation for sectors B&C is performed, is presented (Figure 9). Data are collected every 8 seconds while the simulation is running. The energy signature is defined by the variation of electric current, in Amps, measured on the supply electric line of the desktop computer (the monitored is not measured).

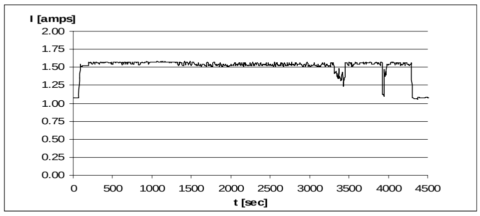

Figure 9 Energy signature of the EnergyPlus program; annual simulation for sectors B&C

For comparison purposes, the energy signature of the DOE-2 program for sectors B&C over the same period is presented (Figure 10).

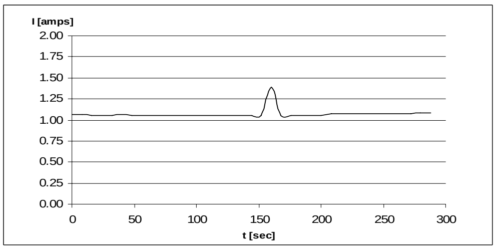

Figure 10 Energy signature of the DOE-2 program; annual simulation for sectors B&C

Since the simulation times are quite different (~75 min for EnergyPlus versus ~1 min for DOE-2), the dimensionaless energy signature is given in Figure 11.

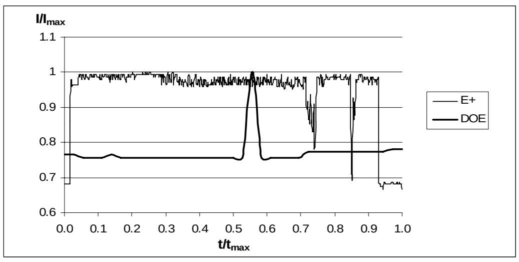

Figure 11 Dimensionless energy signature of EnergyPlus and DOE-2 program; annual simulation for sectors B&C

Results show that the EnergyPlus program uses a high amperage throughout the simulation, while the DOE-2 program, which has a much shorter cumputing time, has an almost instanteneous peak.

CONCLUSION

Modeling the Concordia Sciences Building using the EnergyPlus program was a challenge in many ways. The large number of zones and surfaces has made the definition of the architectural systems a long and labour intensive process. Recent developments of graphical user interfaces (GUI) for the EnergyPlus program should accelerate and simplify the overall data entry process for architectural features.

In terms of HVAC systems, the use of compact HVAC objects has quite simplified the process. By getting the loops, branches and nodes to be automatically defined by the program, it was possible to properly interconnect all of the components of the HVAC systems without compromising the complexity of the secondary systems.

For primary systems, many components used for the heating of large buildings for cold climates, such as glycol heating coils and water-to-water heat exchanger, are not yet available within EnergyPlus. Thus, due to these limitations, the central plant was simulated as two separate entities, one for sectors B&C and one for sector A.

The inter-program comparison and the calibration exercise indicates that the computer model developed with the EnergyPlus program gives good estimations of variables used in this study.

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