IMPROVING THE PERFORMANCE OF A WHOLE-BUILDING ENERGY MODELING TOOL BY USING POST-OCCUPANCY MEASURED DATA

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ABSTRACT

Energy performance of a university building is modeled and compared to the actual measured performance of the building. Two energy models are developed in this work: *design* model and *as-built* model. The *design* model is based on the input parameters calculated by a consulting company for LEED submission. The *as-built* model is built using different input parameters for envelope performance and occupancy. The impact of these parameters on the simulation results are reported and discussed.

INTRODUCTION

More than 40% of world's total energy consumption comes from building sector (WBCSD, 2009). According to United Nations Environment Program (UNEP, 2009), almost 80% of the building energy is due to the operational energy of the building over its life span. Hence, energy efficient buildings can greatly contribute to the sustainable development of the world. Over the past decades, many building energy modeling tools have been developed to assist designing new buildings and retrofitting the existing ones (Crawley et al., 2008). The quality of a whole-building energy simulation and the reliability of its predictions depends on the quality of the underlying physical sub-models and the required input parameters. Energy simulation consultants depend on information provided to them by third parties, and also on the resources (namely time and fees) they are given to allow for additional analysis to provide higher quality input parameters. If input parameters are not carefully provided to the building modeling software, final outcomes of the so-called "uncalibrated" simulation can be far from reality. As an example, Ahmad and Culp (2006) have reported 30% errors for the annual energy consumption of a building and up to 90% error in individual components for an uncalibrated simulation. Several approaches have been proposed to systematically change the input parameters so that the final output energy of the software mimics the actual performance (Yoon et al., 2003; Reddy, 2006; Sun and Reddy, 2006; Heo et al., 2012). These approaches are of particular interest in building retrofit industry where realistic predictions are vital. Systematic calibration is usually applicable to simplified building energy models with limited input parameters due to limited on-site measurement data.

The input parameters to a whole-building energy simulation software can be categorized as: 1) Weather data 2) Envelope performance 3) Occupancy information 4) HVAC sub-models. A typical meteorological year (TMY) weather data is used in the design phase of a building to represent a range of weather information over many years. For predicting the real performance of a building, actual local weather data is required. The best approach for obtaining actual weather data is to utilize a local weather station. Also, there are several private companies that claim to provide real-time weather data. Bhandari et al. (2012) have shown that the uncertainties associated with this type of weather data can cause up to 7% error in the annual building energy and up to 40% in the monthly loads.

Envelope performance has a primary role in energy efficiency of buildings. This element is represented by several C-values and U-values which fit into a one-dimensional heat transfer model of the modeling software. This parameter is usually calculated based on the materials and thickness of different layers of the building envelope. Additional analysis can be done for higher quality U-values by auxiliary softwares such as THERM and WINDOW (No et al., 2008) or in-house two or three-dimensional finite element and finite difference codes (Van Dessel and Foubert, 2010). These more advanced approaches help to identify thermal bridges that can be further verified with infrared thermography (Grinzato et al., 1998). This is of particular importance for concrete and steel frame as opposed to wood frame buildings (Kony and Kossecka, 2002).

Occupancy behavior and satisfaction in buildings is one of the most challenging issues in achieving a sustainable building. More energy efficient technologies can result in higher energy consumptions due to the complex behavior of occupants (Gram-Hanssen et al., 2012). The occupancy behavior is usually assumed in the design phase of the building according to standards. Post Occupancy Evaluations (POE) can be performed by site audit and surveys to have a better estimation of occupancy behavior in the building. Statistical approaches can be used to better quantify occupants behavior based on measured performance data (Dodier et al., 2006; Virote and Neves-Silva, 2012). More advanced measurement techniques can be used for real-time occupancy monitoring (Li et al., 2012).

Total energy performance of a building is highly dependent upon the technology of the HVAC systems. Whole-building energy simulation softwares are usually based on simplified models for complex HVAC systems and control strategies (Binks, 2011; Calderone, 2011). These simplifications results in high level of uncertainties in individual components performance predictions. Wang et al. (2012) have shown that HVAC set-points and sequence of operations can drastically change the annual energy consumption. Also, the uncertainties in the prediction of a building heating and cooling load which is due to the weather data, occupancy and envelope performance get reflected through HVAC components energy consumption (Shrestha and Maxwell, 2011). These uncertainties are higher for buildings with unconventional heating and cooling systems and more advanced HVAC sub-models needs to be used. On the other hand, advanced models require more input parameters that are not usually available to building energy modelers. Therefore, simplified static simulations are sometimes more accurate compared to more advanced dynamic simulations (Murray et al., 2012). Even successful energy simulations occasionally have over-predictions and under-predictions for energy consumptions at the component level in a way that result in a total energy prediction close to reality (Binks, 2011; Calderone, 2011).

In this work, annual energy performance of the Centre for Interactive research on Sustainability (CIRS) building was simulated. It was anticipated by the consulting company that this building become net-energy positive. The mechanical systems are designed so that the building can transfer the excess thermal energy to a nearby building. However, monitoring the performance of the building after commissioning shows that this building cannot significantly transfer thermal energy. It is clear that such estimations are based on the output of the building energy modeling calculations. In this work, the modeling results are compared with actual measurements. The effect of using more accurate U-values for building envelope on the total energy use was investigated. More information on the occupants capacity of the building are available after commissioning the building and these new informations along with the uncertainties are implemented in the model and the results are discussed.

In the following sections, first an overview of the CIRS building is presented. Next, the whole-building energy model is described. The simulation results are then presented and discussed. The final section is about future directions in this work in progress.

CIRS BUILDING

The Centre for Interactive Research on Sustainability (CIRS) is a large, multi-purpose university building located at the Vancouver campus of University of British Columbia. This is a 4-storey building with approximately 5700 m^2 floor area. The building has a high performance envelope and is mainly made out of wood. This building is composed of five main areas as shown in 1:

- Office spaces for staff, graduate students and professors
- An auditorium with approximately 460 seats
- Common area between the two office wings with an atrium
- A café at ground floor
- A blasement that has storage rooms, showers, mechanical, electrical, security and data rooms.

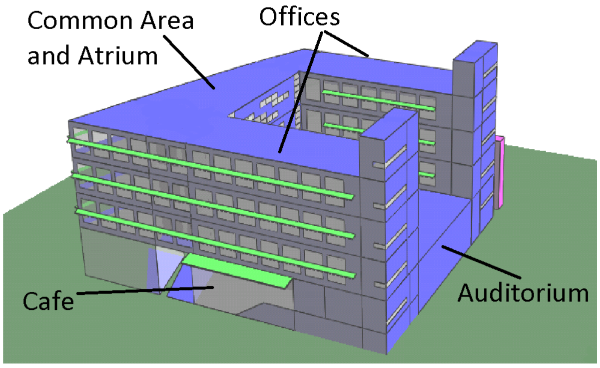

Figure 1: 3D model of the CIRS building

HVAC systems

This building does not get any heat from campus district energy steam/hot water system. The heat sources of the building are as follows:

- Waste heat recovery from an adjacent building
- 30 geothermal boreholes
- Waste heat recovery from exhaust air streams of CIRS

All recovered heat come to a main heat recovery header which is connected to six heat pumps:

- Three water-to-air heat pumps serving café, main electrical room, security room and data room.
- Three water-to-water heat pumps providing heat to the hot water loop.

The hot water loop is connected to air handling units heating coils, unit heaters, force flow heaters, radiant slabs and perimeter radiators. During the summer, heat pumps are in cooling mode and use geothermal loop to extract heat from the building through chilled water loop.

Unit heaters and force flow heaters are used in storage rooms, stairs, washrooms, showers and near entrances. Café and common areas on all floors are equipped with in-floor heating using slab integrated hot water loop. There are two air handling units in this building. One is dedicated to the auditorium and has both hot water heating coil and chilled water cooling coil. The other AHU serves the offices and only has hot water heating coil. Both AHUs have demand controlled ventilation with CO_2 sensors. The office spaces are designed for displacement ventilation with supply grills under the raised floor. There is also perimeter radiators in offices for supplemental heating.

ENERGY MODEL

IES - Virtual Environment (2012) was used for energy modeling of this building. The geometry was created from the as-built drawings using ModelIT module of the software. Apache module is used for dynamic simulation along with ApacheHVAC module for HVAC modeling. Real-time weather data is measured by a weather station located at the roof of an adjacent building. An energy modeling of this building was done by a consulting company for LEED submission using eQuest. The input parameters used in that model is transferred to Virtual Environment where more realistic representation of the mechanical systems are possible compared to eQuest. Two different energy models are constructed in Virtual Environment:

- *Design model* is based on the input parameters that are used in the eQuest model.
- *As-built model* is based on more realistic estimation of the envelope U-values and occupancy information.

Table 1 shows the envelope construction U-values for both models. The U-values in the design model come from the original eQuest model for LEED submission. THERM 6.3 and WINDOW 6 are used to calculate more accurate U-values for the as-built model by considering two-dimensional heat transfer effects. Figure 2 shows a sample cross-section of a window frame modeled in THERM 6.3. Curtain walls are modeled with frames in THERM and recalculated back in WINDOW.

Table 1: Envelope construction U-values (W/m^2K)

	Design Model	As-built Model	Change %
Walls below Ground	0.233	0.265	14
Walls above Ground	0.187	0.289	55
Slab on Ground	0.057	0.057	-
Roof	0.142	0.268	89
Green Roof	0.142	0.194	37
Ground Floor Glazing	1.977	1.533	22
Other Glazing	1.977	2.498	26

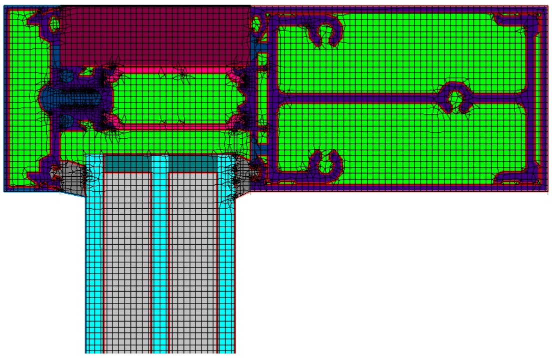

Figure 2: Sample cross-section of a window frame modeled in THERM.

Table 2 summarizes the occupancy information used in the two models. For the design model, occupancy data are assumed based on the Model National Energy Code of Canada for Buildings (MNECB, 2011). Post-occupancy capacity of the building is available. Hence, the number of people occupying the building is changed between zero and the maximum occupancy in the as-built model. This gives an estimate of the uncertainties in the energy use associated with the occupancy variations.

Table 2: Occupancy Information

	Design Model	As-built Model (max)
Office	20 m^2/person	7 m^2/person
Auditorium	460 people	460 people
Café	4 m^2/person	4 m^2/person
Atrium	50 m^2/person	11 m^2/person
Washroom	30 m^2/person	30 m^2/person

The occupancy schedule is the same for both models. The office hours are from 8am to 5pm. The auditorium is run for only six hours from 9am to 3pm representing four classes per day. Plug load and lighting is kept consistent between the two models based on the LEED submission report. Details of the plug load and lighting are shown in Table 3.

Table 3: Plug load and lighting power density (W/m^2)

	Plug Load	Lighting Power Density
Office	6.9	7.0
Auditorium	5.0	16.0
Café	20.0	8.1
Atrium	1.0	8.8
Storage	N/A	3.2
Mechanical Rooms	N/A	5.9
Washrooms	N/A	5.8
Corridors	N/A	6.6

The HVAC system is the same in both models. The waste heat recovery system and the geothermal loop are modeled by defining a heat transfer loop in Virtual Environment. This heat transfer loop is connected to three water-to-air heat pumps to serve Café, electrical room, security room and data room. Virtual Environment does not have the capability to define a water-to-water heat pump. Hence, a water-to-air heat pump is defined and directly connected to the hot water coils in the air-handling units and unit heaters. However, the perimeter radiators cannot be defined in this way. As a work-around, a hot water loop was defined with an electric boiler to provide hot water for the perimeter radiators. The heat load of the boiler is then converted to an equivalent electricity consumption using the coefficient of performance of water-to-air heat pumps. The shop drawings are used to provide as much information as possible to the energy model. The rest are kept as the default softwares values.

DISCUSSION AND RESULT ANALYSIS

CIRS building was commissioned late 2011. Reliable performance data are available from April 2012. In this section the measurement data from April 2012 to November 2012 is compared with model predictions. Figure 3 shows the difference between model prediction and measured lighting energy. This figure shows that the model is under-predicting the actual consumed lighting energy.

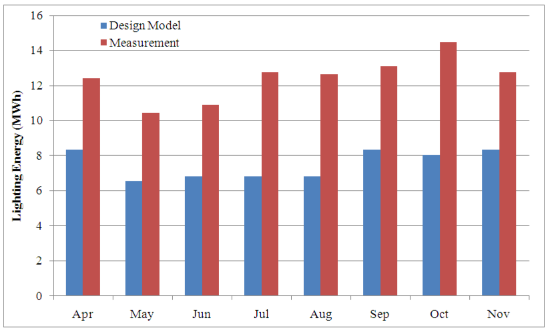

Figure 3: Simulated vs. measured lighting energy

The monthly variation in lighting energy use is less in the simulated model than in reality. This is due to the uncertainties from occupants behavior which is not reflected in the model. Figure 4 shows the monthly energy consumption of ventilation fans. This parameter is predicted relatively well except in June and November. Further investigation using daily consumption data is required to diagnose this.

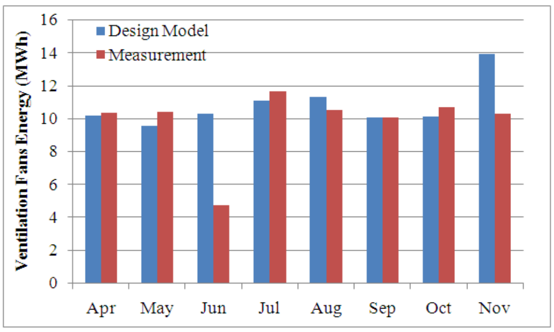

Figure 4: Simulation vs. measured total ventilation fans energy

Plug load, hydronic pumping energy consumption and heat pump energy use are shown in Figure 5. This figure shows that the model substantially under-predicts these two parameters specially during cold months. This is partly due to the heat recovery system that harvest waste heat from the adjacent building. This process requires a large amount of pumping energy. Moreover, the hydronic processes in the water-side of the HVAC system is simplified to a great extent. It is not possible to represent different components with the actual control sequences. On the other hand, the plug load is simply based on model national energy code that does not necessarily reflect a specific case in reality. Further studies are required to separate plug energy from hydronic pumping and heat pumps energy use to determine the relative validity of underlying assumptions and input parameters.

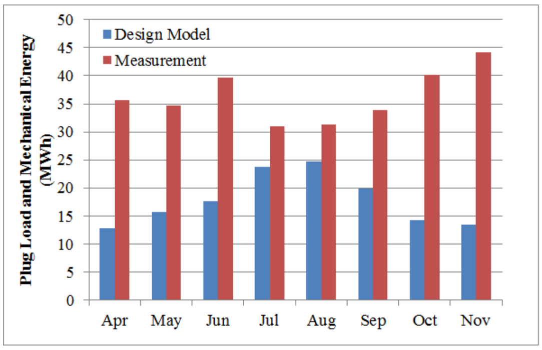

Figure 5: Monthly variation of plug load and mechanical energy. Mechanical energy consist of hydronic pumping consumption and heat pumps energy use.

The modeled total energy consumption of the building is compared with the actual measurements in Figure 6. This figure shows that the simulation based on the design input parameters is under-predicting the real performance of the building.

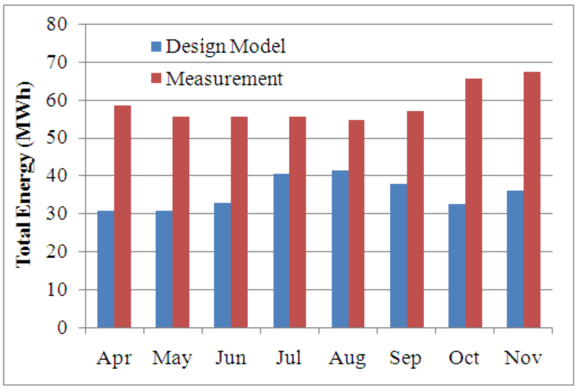

Figure 6: Total energy consumption of the building for the design input parameters.

Figure 7 shows the effect of changing the U-values on monthly variation of the total energy consumption of the building. In this case, the occupancy information in the as-built model and the design model are the same and only U-values are changed according to Table 1. This figure shows that in spite of the fact that the more accurate U-values are significantly changed, they do not improve the results to a great extent.

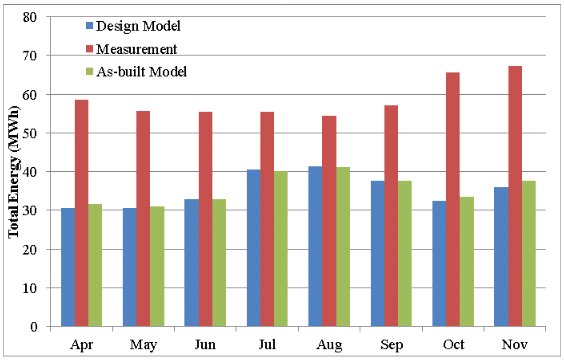

Figure 7: Effect of U-values on the total energy consumption of the building.

In figure 8, the energy consumption of the building is shown for maximum occupancy and no occupancy. According to this figure, a substantial uncertainty in the monthly energy performance of the building is due to occupancy. This emphasis the importance of occupancy monitoring for accurate prediction of building energy use.

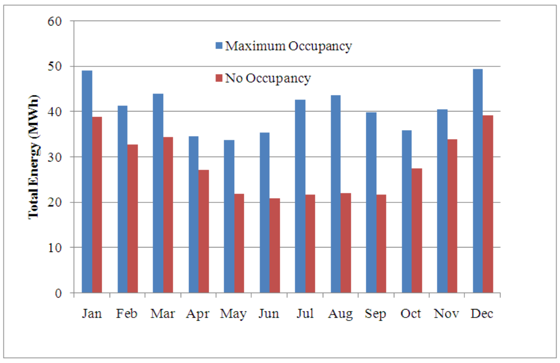

Figure 8: Effect of occupancy on total energy consumption of the building in the as-built model.

The total energy consumption of the building for both the design model and the as-built model are shown in figure 9 along with the measurement data. The as-built model represents the average of maximum occupancy and no occupancy cases with the uncertainties shown with error bars. The difference between the green line in figure 9 and figure 7 is occupancy; in figure 7 the occupancy is based on Table 1 and in figure 9 is the the average of maximum and zero occupancy. Both models under-predict the actual energy performance of the building. This is mainly due to the under-prediction of the lighting energy, plug load, heat pump energy and hydronic pumping energy as discussed above. Also, this figure shows that the assumptions for occupancy in the design phase of the building can greatly affect the final energy consumption of the the building.

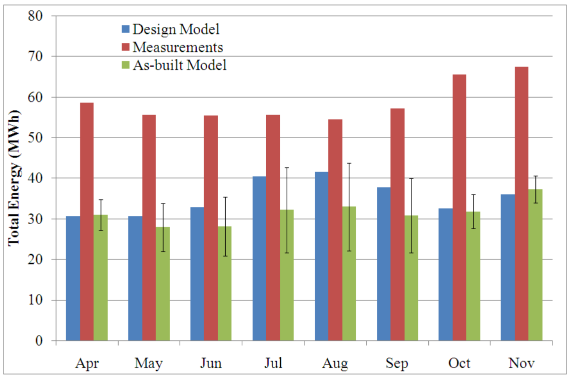

Figure 9: Comparison between the prediction of the design model, as-built model and actual measurment of total energy consumption of the building. Error bars in the as-built model are due to occupancy.

CONCLUSION

In this work, the actual energy performance of a building is compared with two energy models: the *design* model which is based on the input parameters calculated by a consulting company for LEED submission and the *as-built* model with more realistic information of occupancy and envelope performance. This building relies on ground-source heat pumps for heating and cooling and also waste heat recovery as additional heating source. Lessons learnt are as follows:

- Underlying assumptions for plug load and lighting in the design phase are not necessarily reflecting the actual case.
- A building with such unconventional heating and cooling system is a challenge to the whole-building energy simulation softwares.
- Using two-dimensional calculations significantly change the U-values; however, the final energy use of the building is not very sensitive to this parameter.
- Occupancy information can greatly affect the monthly performance of the building. This uncertainty is higher during hot months and lower during cold months.

This study shows that the results of building modeling calculations can deviate from reality to a great extent. Such tools can be very helpful for evaluations of different options during the design phase where relative performance is important. However, in case of the CIRS building these results were used to anticipate that this building would be net-energy positive. This work shows that, the uncertainties associated with modeling simplifications and occupancy behavior are substantially high that such claims should be taken in a more conservative way.

FUTURE WORK

This is a work in progress. The discrepancy between modeling and simulation needs to be diagnosed in more details. CIRS is equipped with more than 3000 sensors that records different performance parameters every minute. This provides a unique opportunity to validate the simulation results on a daily and hourly basis. A blower door test is scheduled to be done to determine the air-tightness of the building envelope and provide realistic values for infiltration rates.

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