Detailed Monitoring and Energy Model Development of an Existing Multi-Unit Residential Building in Toronto, Canada

Marianne F. Touchie[1], Kim D. Pressnail[2]

ABSTRACT

Energy modeling is a useful tool for evaluating the efficacy of possible building energy retrofit measures. Traditionally, energy models are developed using data collected from building floor plans and site visits and then calibrated using utility bills. In the work presented here, an energy model for an existing multi-unit residential building (MURB) was developed using this initial approach. Next, a refined approach was taken. Using data gathered from a suite-based monitoring program, input data uncertainties in the energy model were addressed. Data from one year of monitoring were assembled to characterize the actual building performance and to calibrate this refined energy model. The output of this refined model was compared to the output from the initial modeling approach in order to identify which parameters could be used to improve the model accuracy. It was found that the interior temperature measurements and the sub-metered suite electricity use were the most helpful in refining the energy model. However, other data collected including window operation and differential air pressures were useful for determining how the building was operating. The use of a local weather file generated from a roof-top weather station was also helpful and has been discussed.

BACKGROUND

Many North American jurisdictions are striving to improve the energy standards for new buildings. However, to significantly reduce energy-use and the related environmental burden of our building stock, existing buildings must be energy retrofitted. Planning an energy retrofit usually begins with an assessment of the building condition and the collection of energy-use data. In recent years, the municipal government and other bodies in Toronto, Canada, have begun this assessment phase for an important City asset: the thousands of multi-unit residential buildings (MURBs) that provide an estimated 55% of dwellings in the City (Touchie et al. 2013).

A typical assessment process involves generating an estimate of the impact associated with particular retrofit measures. To generate such estimates, a building energy-use model is developed for the subject building and then calibrated with utility bill data. Once calibrated, the model can then be used to assess potential energy and greenhouse gas emission savings associated with various retrofit measures. However, the calibration of models that accurately predict energy-use in buildings is somewhat of an art (Reddy 2006). It is well recognized that just because a model has been calibrated using gross building energy data, it does not necessarily follow that accurate predictions of retrofit energy savings will result. While there is uncertainty in any computer simulation, an indication that the calibrated model may not be an accurate predictor of retrofit energy savings occurs when the predicted energy end-use components, or the predicted interior conditions, do not match observations of the existing building. However, confidence in the accuracy of the modeling output increases when the calibrated model output

[1] Marianne F. Touchie, Toronto Atmospheric Fund and University of Toronto, Toronto, ON
[2] Kim D. Pressnail, University of Toronto, Toronto, ON

not only matches the utility data, but it also accurately predicts the observed energy end-use components and the interior conditions.

Unfortunately, energy-use patterns and interior conditions in MURBs are not as well documented as commercial buildings. Given the sparse data for MURBs and the complexity and interrelated nature of residential energy consumption (Swan and Ugursal 2009), an energy modeler seeking to improve the calibration of an energy model must make many assumptions. Such assumptions, particularly with regard to occupant behavior and interior conditions, may lead to inaccurate retrofit energy savings predictions.

STUDY APPROACH

An energy model based on information from building floor plans and audit reports was developed. Whole-building utility bill data were calendarized and weather normalized to the standard weather data available in the energy modeling software. Then, the model was calibrated using these processed utility data. Herein, this model is known as the "Initial Approach." To reduce the level of uncertainty associated with the assumptions used in the Initial Approach model, a detailed monitoring program of an existing MURB was undertaken. Energy consumption, interior conditions, and local weather data from one year of monitoring were assembled to characterize the actual building performance and to calibrate an energy model based on the monitored data. This model is referred to as the "Refined Approach." After development and calibration of the two energy models, the modeled suite temperatures and energy end-uses were compared with the monitored data. This approach was taken to demonstrate the potential for improvement in the accuracy of the energy model predictions compared to calibration with gross utility data. The monitored parameters which were most useful for improving the model accuracy are discussed. This work is presented in the context of Toronto MURBs, but the approach and the findings are applicable to other cold-climate urban regions.

SUBJECT BUILDING

Over 40% of MURBs in the City of Toronto were constructed during the 1960s and 1970s (Touchie et al. 2013). MURBs of this vintage exhibit similar features such as exposed floor slab edges, air-leaky exterior envelopes, pressurized-corridor make-up air supply, hydronic baseboard heating without suite-based controls and no central air conditioning. In an attempt to maximize the applicability of the findings of this work, a subject MURB in Toronto with similar characteristics was selected. The selected building, constructed in 1968, is 20-stories and includes the characteristics described above. Also, as is typical in these building types, occupants do not pay directly for their utility use. It is one of two student family housing buildings at the University of Toronto and is similar to many Toronto MURBs of this vintage.

ENERGY MODEL DEVELOPMENT

The Quick Energy Simulation Tool (eQUEST[3]), developed by the U.S. Department of Energy (DOE), was used to model the subject MURB in this study. In addition to modeling new construction, this whole-building energy simulation program was chosen because it is commonly used in industry for retrofit measure assessments.

[3] eQUEST is in the public domain.

Modeling began by inputting building information that was known with some certainty. Most building details were determined from floor plans, an audit report, interviews with the building manager, and site visits. These data included: occupant density, fenestration ratio per elevation, building envelope details, boiler and tank capacities and quantities, and fan and pump power. For unknown parameters such as fan air flow rates and envelope air leakage, estimates were made using values found in the literature (CMHC 1998; Hanam et al. 2011). These parameters were held constant for both the Initial and Refined Approach models. Other unknown parameters such as lighting and plug loads, DHW consumption, zone temperatures and loop capacities were varied in order to calibrate the model.

Initial Approach

By comparing preliminary models based only on building inputs with those that have been calibrated using monthly utility data, many researchers (Hanam et al. 2011; Danielski 2012) have shown the value of energy model calibration. Therefore, once the base model was developed, it was calibrated using energy consumption data from utility bills.

Energy consumption

Without access to a complete weather file that matches the period covered by the available utility bill data, the modeler must first normalize the billing data to the local area standard weather year used by the energy modeling program. In this case, the Toronto weather file in eQUEST is based on the Canadian Weather for Energy Calculations (CWEC) standard weather year data gathered at the City's main airport.

Historical utility billing data from 2009 to 2013 were used for the weather normalization process. For example, the monthly natural gas consumption was plotted against the monthly heating degree days in the historical utility billing year and a regression analysis was used to determine the equation for the line-of-best-fit. This equation was then used with the monthly heating degree days of the CWEC standard weather year to determine estimated heating energy use during a standard weather year. This process is further described in Touchie et al. (2013). Note that monthly electricity use derived from utility bills was not adequately correlated to heating or cooling degree days so was not weather-normalized. Herein, this weather-normalized data will be called "processed utility bill data." The resulting energy-use intensity of the subject building following this normalization was 374ekWh/m^2. This building energy-use intensity was greater than the median energy-use intensity of a sample of Toronto MURBs, (Touchie et al. 2013), but it was still within the range of the sample. Since they are performing at the upper end of the energy-intensity spectrum, such buildings provide the greatest opportunity for performance improvement. Thus, the operation of such high energy intensity buildings need to be better understood.

Calibration using utility bills

Many energy model calibration techniques have been developed (Reddy 2006; Reddy et al. 2007; Hubler et al. 2010). For this work, a calibration procedure similar to that outlined by Hubler et al. was followed. Calibration of the Initial Approach model began with adjusting the DHW consumption to match the average natural gas consumption for the three months in which there was no space heating (June, July and August). The consumption resulting from the model calibration was compared to the literature to ensure the modeled value was reasonable (Energy Management and Research Associates 1994; CMHC 2001).

The remaining natural gas and electricity consumption calibration was carried out iteratively as waste heat from electricity loads affects the heating and cooling requirements of the building. To begin, lighting and plug loads were scaled up from the default values in each zone to match the electricity consumption in the shoulder seasons. Next, the set point temperatures and heating loop capacities were adjusted slightly to ensure that the zones were modeled at the default set point temperatures and that the modeled natural gas consumption closely matched the weather-normalized actual consumption. Finally, the cooling capacity was adjusted to match the summer electricity consumption. The resulting modeled natural gas and electricity consumption profiles are shown in Figure 1 along with the actual consumption data weather-normalized to the CWEC standard weather year.

The American Society of Heating, Refrigeration and Air Conditioning Engineers' (ASHRAE) Guideline 14, Measurement of Energy and Demand Savings (ASHRAE 2002), recommends and describes the use of a statistical technique to compare the modeled and measured data. The coefficient of variation of the root mean square error (CVRMSE) measures how well the modeled values fit the measured data. Improved model calibration is indicated by a lower CVRMSE. Guideline 14 states that the maximum allowable value of CVRMSE is 15% when using monthly data. In comparing the processed utility data with the output from the Initial model, the CVRMSE for natural gas was 12% and for electricity was 4.9%. Therefore, the model was considered appropriately calibrated.

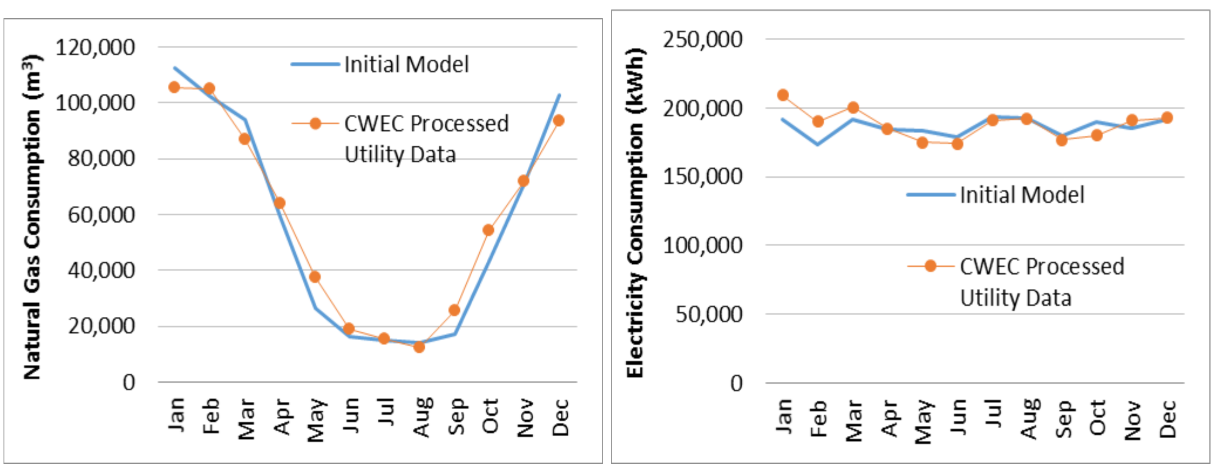

FIGURE 1: Comparison between Modeled and Processed Utility Data for Natural Gas and Electricity Consumption Profiles

Refined Approach Methodology

A building monitoring program was designed and implemented between April 26th, 2012 and April 25th, 2013. This monitoring program was developed to improve upon the results from the Initial Approach. Specifically, the goal was to better represent actual building performance thereby reducing model uncertainty.

The monitoring program involved observation of three key areas: local weather, energy consumption and suite interior conditions. Table 1 provides a summary of the monitoring program encompassing these three areas. In the remainder of this section, the weaknesses of the Initial Approach are identified for each area and then the Refined Approach is introduced.

	Parameter	**Equipment**	**Model**
Weather Conditions	Temperature, Relative Humidity, Solar Radiation, Wind Speed and Direction, Rainfall	Weather Station	Wireless Vantage Pro2 6152 (Davis Instruments 2013)
Energy Consumption	Whole-building Natural Gas	Energy Meter	PowerHawk 6312 with 200A-80-mA Solid Core Current Transformers (Triacta 2013)
	Whole-building Electricity		
	Suite-based Electricity		
Suite Interior Conditions	Temperature	Data logger (SMT A2) and sensors (Structure Monitoring Technology 2013)	Cantherm MF58104F3950 Beta 4390K
	Relative Humidity		Honeywell HCH-1000-001
	Window Displacement		Model 404 BI Technologies
	Differential Pressure		SDP1000-L025

TABLE 1: Summary of Monitoring Program

Weather Data

The normalization process used in the Initial Approach introduces error, through both the calendarization and the estimation of the energy performance in the standard weather year. Furthermore, standard weather year data are typically based on 30-year historical averages. As the climate changes, these weather data may no longer be representative of the current and future heating and cooling degree-day profiles. This could result in retrofit savings estimates that are in error. To mitigate the effect of these issues, a weather station was placed on the roof of the subject building to capture the characteristics of the urban microclimate to which the building was exposed. The data, collected in 15-minute intervals, were then used to generate a custom weather file for use in the eQUEST simulation. In this way, actual weather conditions could be paired with actual energy consumption rather than relying on weather-normalized values.

Energy Consumption

Sub-hourly interval data can be used to characterize daily and hourly energy consumption patterns. So, electricity and natural gas data were collected from the subject building in 15-minute intervals. Additionally, suite-level electricity consumption was sub-metered in order to estimate the split between suite-based and common area electricity use which was not available from the bulk-billed utility data. Due to the power panel configuration and occupant permission requirements, the sub-metered data were only captured for five suites.

Suite Conditions Comparison

In addition to the model predicting actual energy-use, it should also generate interior conditions similar to the actual building. Energy models often use standard air temperatures, such as the default air temperatures used in the Initial Approach model, instead of air temperatures based on empirical data (Kavgic et al. 2012). However, interior air temperatures are not just the product of thermostat settings but they are also influenced by occupant behaviour (Jian et al. 2011).

To determine the suite conditions for the Refined Approach model, a number of parameters were monitored. Interior air temperature and relative humidity were recorded along with the temperature of the radiator fins to determine how the heating system responded to the interior and exterior conditions. Displacement sensors were used to observe when occupants opened windows and balcony doors. Finally, the effects of the ventilation and exhaust systems and stack effect were monitored using differential pressure sensors across the exterior envelope, between the suite and the corridor, and at the bathroom and kitchen exhaust fans.

A total of seven suites were monitored for a one-year period. The in-suite monitoring system included of a series of wireless data loggers/transmitters with built-in temperature and relative humidity sensors. Three suites were "fully-monitored" with temperature, relative humidity, displacement and differential pressure sensors. Four additional suites were "partially-monitored" with temperature and relative humidity sensors only. The approximate location of the data loggers and sensors in the fully-monitored suites is provided in Figure 2.

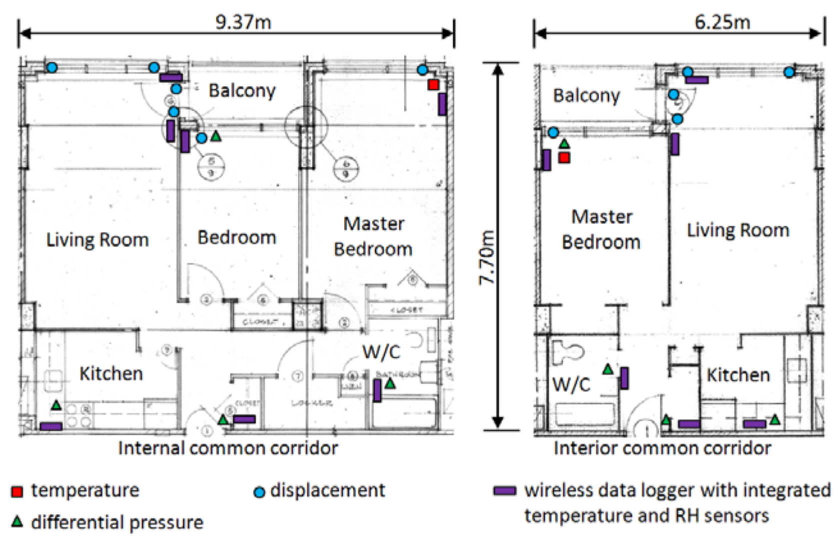

FIGURE 2: Location of data loggers and sensors

REFINED APPROACH DATA ANALYSIS AND DISCUSSION

Here, the differences between the Initial and Refined Approach models are compared in terms of the weather, energy consumption and suite condition data.

Weather Data Comparison

Table 2 shows the total heating and cooling degree-days from the standard weather file, the subject building weather station data and the weather data collected from the City's main airport during the monitoring period. Clearly the monitoring period data are warmer than the standard weather year data. Furthermore, the subject building weather station data shows the effect of the urban heat-island. Thus, the inner-city location of the subject building was warmer than the Toronto airport during the monitoring period. This means that the energy model based on the

Initial Approach would have a higher variable natural gas load and lower variable electricity load compared to the model based on the Refined Approach.

	Toronto International Airport (CWEC)	Toronto International Airport (May 2012-Apr 2013)	Subject Building (May 2012-Apr 2013)
Heating Degree-Days	4089	3571	3333
Cooling Degree-Days	13	56	68

TABLE 2: Comparison of Heating and Cooling Degree-Days (°C·day)

Energy consumption data

With the greater resolution data provided by the monitoring program, daily and sub-hourly consumption patterns were examined. Monthly and sub-hourly natural gas consumption data are presented in Figure 3. The monthly profile was expected, but the 15-minute interval data suggests that the controls of the system might not be optimized given the wide range of consumption that occurs during these short intervals. While there are no peak charges for natural gas, frequent cycling can lead to more maintenance, premature failure of the boilers, reduced seasonal efficiency, and difficulty maintaining set point temperatures (Damianos et al. 2007).

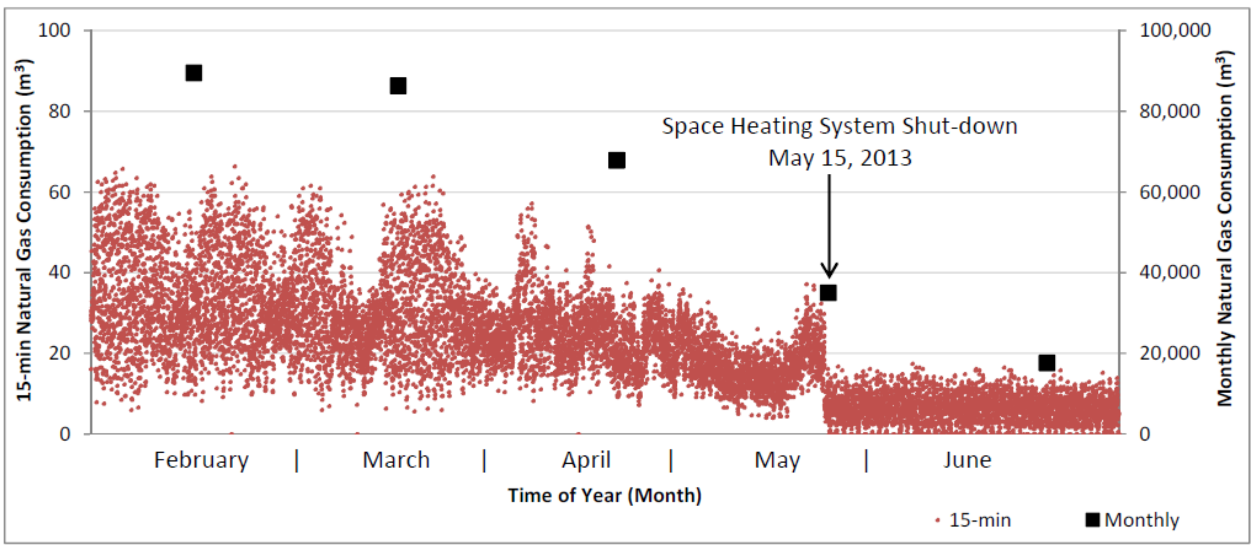

FIGURE 3: Natural Gas Consumption

Electricity

Figure 4 shows how the daily and monthly whole-building electricity data vary with the exterior temperature. The increase in cold-weather consumption can be due to a number of factors including: shorter days that require more lighting; increased occupancy; the possible use of supplemental heating devices. The increase in summer electricity use is likely due to the use of suite air-conditioners (A/C).

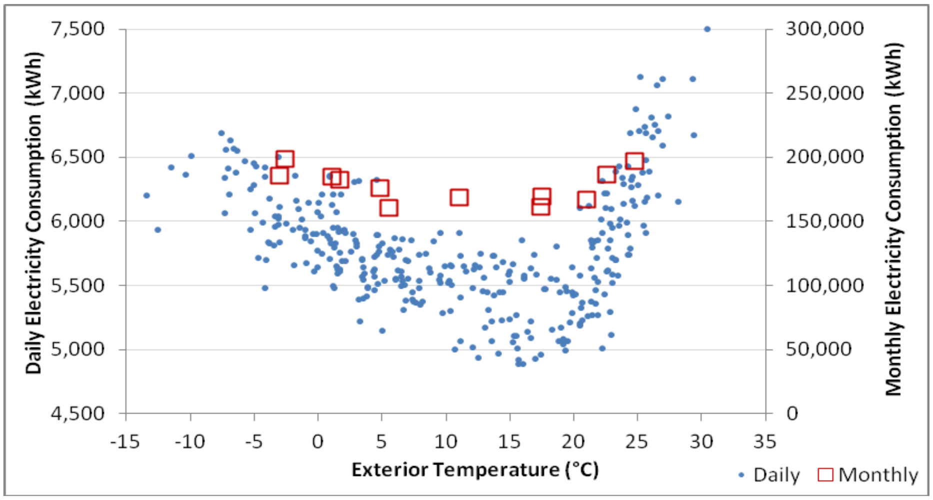

FIGURE 4: Electricity Consumption

Within the small sample size of sub-metered suites, there were both one- and two-bedrooms suites as well as suites with and without A/C. There were large variations in suite-level plug and lighting loads, even during the winter when the A/C would not be contributing to the electric load. Based on the average wintertime daily consumption normalized by floor area, the highest consuming suite used more than twice the lowest consuming suite which is consistent with the results from a CMHC study (Hart 2005). In the summer, when warmer temperatures prompted the use of window A/C units, this difference grew to over four times. Note that utilities in this building are not sub-metered and therefore the bulk-billed utility costs are included in the rent paid by occupants.

Using the number of suites with A/C and the suite orientation, the monitored suite data were extrapolated in order to estimate the breakdown of electricity use in the building. On an annual basis, the suite loads represented an estimated 42% of the total building electrical load. However, it is important to view these findings in the context of the limited sample size.

After comparing the electricity consumption of the subject building to other studies, it became clear that MURB electricity use can vary dramatically, both in magnitude and in the split between suite-based and common area loads. While the sub-metering of a selection of apartment loads was helpful in estimating the breakdown between suite-based and common area loads, further sub-metering of major equipment loads could would have been helpful in refining the model further.

Suite Conditions

Various issues occurred which affected the quantity of the suite condition data acquired. Of the total possible number of data points available for collection during the monitoring period, the proportion recorded ranged from 14% to 61% depending on the suite. The results of the suite condition analysis must be viewed in the context of this sparse data.

Temperature and relative humidity

Temperature and relative humidity can be used to assess how “comfortable” the suites are during different seasons. The comfort zone described in ASHRAE Standard 55 2010 Thermal

Environmental Conditions for Human Occupancy (ASHRAE 2010) forms the basis of assessing the comfort conditions in the monitored suites for one winter month and one summer month. Determination of the zone of comfort for each suite is described in Touchie (2014). Figure 5 shows the dry bulb temperature and relative humidity data for January and July, for the two suites with the largest quantity of data, with respect to limits of the comfort zone described in ASHRAE Standard 55 2010. While the temperatures of only two rooms are shown here, the temperatures observed in other rooms in the suite and other suites are consistent with these findings as the occupants have no control over the hydronic heating system in their suites. They can only choose to open or close the window or install supplementary heating or cooling systems as needed. In addition to this objective data, it would have been helpful if the tenants could have been surveyed. Unfortunately, the researchers were not able to conduct occupant surveys to verify the actual occupant perceptions of comfort in their suites.

The south-facing suite has higher living room temperatures in both January and July, likely due to solar gains. Using the comfort zone as a guide, it is clear that the south-facing suite 14B is uncomfortably warm during a large portion of July (82% of the data points collected). The south-facing suite also overheats in January (25% of the data points collected are warmer than the comfort zone). Note the different ASHRAE comfort boundaries. This is due to the way in which operative temperature was estimated since the mean radiant temperature was not monitored. Complete details of the estimation process and resulting comfort boundaries can be found in Appendix K of Touchie, 2014. The average summer and winter interior suite temperatures were used to make appropriate adjustments to the suite zone temperatures in the energy model.

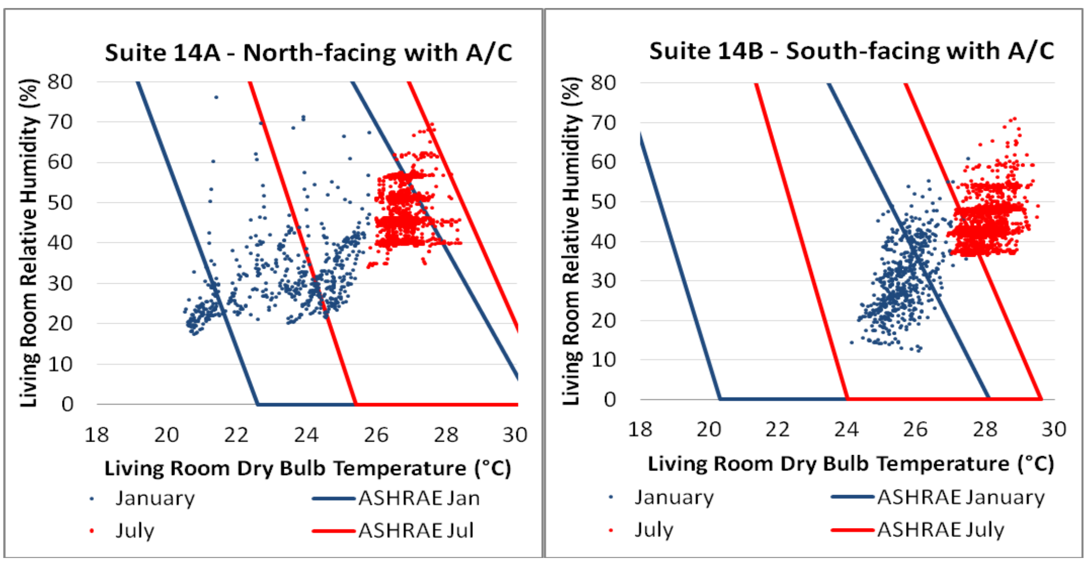

FIGURE 5: Suite temperature and relative humidity

Other parameters

While temperature was the only suite condition that could be directly incorporated in the energy model, analysis of the additional data collected revealed some interesting findings.

Window opening can be an indication of occupants' dissatisfaction with their interior environment (Jian et al. 2011). Through window displacement and temperature data, it was determined that residents of the subject building open their windows frequently, even during cold weather periods. This behaviour contributes to increased space heating loads through uncontrolled air leakage driven by stack effect. These findings are similar to a study (Kavgic et al. 2012) of winter indoor temperatures and window operation in apartment buildings.

Based on the temperature and differential pressure data collected as well as the equation for stack pressure (Hutcheon and Handegord 1995), the pressures driving exfiltration and infiltration at the top and bottom of the building were estimated to be +26Pa and -50Pa, respectively, with reference to the interior of the building, on one January day. Stack pressures of this magnitude are similar to those measured in a study of pressure differences in MURBs conducted by the CMHC (CMHC 2005).

The ventilation system in the subject building is primarily designed to prevent the cross-contamination of smoke and odours between suites by positively pressurizing the corridors. However, the effectiveness of this strategy depends on the ability of the supply fan to overcome stack effect. A correlation of the differential pressures between the corridor and the suites and the exterior temperature showed that, with colder temperatures, corridors became negatively pressurized. This pressure regime was opposite of the design intent of the system. However, despite the seemingly ineffectual corridor ventilation system, the monitored suites still appear to be well ventilated. Based on the monitored negative pressure of the suites with respect to the exterior and the observed window operation, fresh air is likely supplied primarily through uncontrolled infiltration.

While this additional monitoring data provides some insight into building performance, the parameters that can be used directly in model calibration are limited. The two most important pieces of information gleaned from the monitored data collected are the interior temperatures and the estimated electricity use breakdown between suites and common areas derived from the electricity sub-metering. Rather than relying on the model defaults in eQUEST, these collected data can be directly inputted into the energy model. It was expected that, with these data, the model accuracy would be improved.

MODEL CALIBRATION USING THE REFINED APPROACH

The Refined Approach model included three major changes from the Initial Approach model. Instead of a standard weather file, a weather file reflecting the actual weather conditions (with an 18% difference in heating degree days) that the building was exposed to during the data collection period was used. As well, the zone temperatures and the ratio of common area and suite-based electricity use were based on the data collected.

The zone temperature set points were increased from the defaults so that the average zone temperatures were equal to the average monitored temperatures in each season. Average temperatures of the monitored suites were assumed constant for the entire building. In reality, since the monitored suites were close to the neutral pressure plane, the suites above would likely be warmer while the suites below the neutral pressure plane would likely be cooler than the suite average. Using the estimates of the split between suite-based and common area electricity consumption, the loads assigned to the “residential” zones were decreased while the common area loads including corridors, office space and the day care were increased.

The CVRMSE values for both the Initial and Refined Approach models, compared to processed utility data and monitored energy consumption, respectively, are shown in Table 3 (lines 1 and 3). Also shown, is a comparison between the Initial Approach model and the monitored energy consumption data collected from the subject building (line 2). It is clear that the Initial Approach model is a reasonable representation of the processed utility data (normalized to the standard weather year). However, it is not sufficiently representative of the actual building performance as indicated by the exceeded limits specified in ASHRAE Guideline 14.

	Natural Gas	**Electricity**
1. Initial compared to processed utility data	12.0%	4.9%
2. Initial compared to monitored energy consumption	22.3%	7.8%
3. Refined compared to monitored energy consumption	10.9%	4.2%
Shaded cells indicate where the ASHRAE Guideline 14 has been exceeded		

TABLE 3: The coefficient of variation for various modeling methods

DISCUSSION

The objective of this work was to determine the incremental benefit of building monitoring prior to energy model development. Thus, this discussion focuses on the three areas that positively influenced the accuracy of the energy model: suite temperatures, sub-metered electricity consumption and use of a weather file with actual data versus standard weather data.

The modeled energy end-uses from both the Initial and Refined Approaches are shown and can be compared in Figure 6. The difference in heating and cooling loads can be attributed to the differences in the number of heating and cooling degree-days in the two weather files. As noted earlier, that heating system efficiency, infiltration and all other envelope details were the same for all models. The difference in DHW load can be attributed to a need to adjust the DHW consumption per person for recalibration of the Refined Approach model during the summer months. As the electricity consumption data derived from the utility bills were not weather normalized, some of the electricity consumption was not allocated to space conditioning in the Initial Approach model. The Refined Approach model indicates that the electricity required for cooling was actually greater than indicated by the Initial Approach model.

Envelope component losses, infiltration and ventilation losses were also determined from the eQuest simulation reports. The higher proportions of infiltration, window and wall losses from the Initial Approach occur for two reasons: the greater number of HDDs in the standard weather year data and the increased suite-based electrical loads compared with common area loads. The suspected cause of the difference in ventilation loss proportions is due to zone temperatures differences.

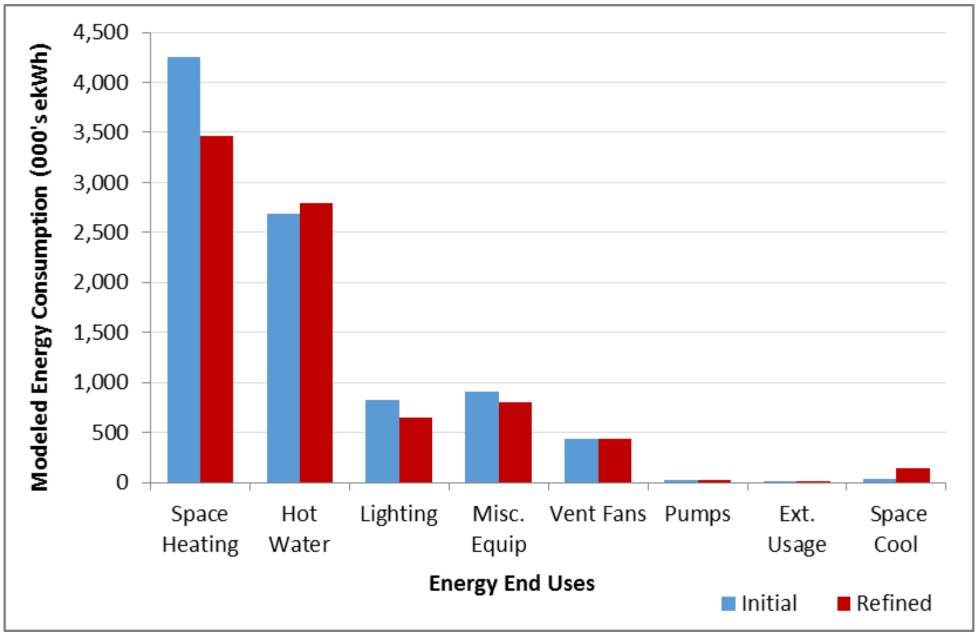

FIGURE 6: Modeled energy end uses

Suite-based electricity use

Without extensive sub-metering of major equipment and consumption in specific zones, determining electricity end-uses for the purposes of energy modeling is challenging. With the availability of the suite-based electricity consumption data gathered during the monitoring period, the split between suite-based and common area electricity use was found to be different than the eQUEST program defaults in the Initial Approach model. A similar result was found by Hanam et al. (2011, p7) where suite-based electrical loads in uncalibrated models were over-estimated prior to calibration with metered suite-based electricity consumption data.

Zone Temperatures

The set point temperature of a building can significantly affect energy consumption (Leung and Ge 2013), so it is important to capture this data for energy modeling purposes. The temperatures using the eQUEST defaults in the Initial Approach model were up to 5°C lower than the suite temperatures used in the Refined Approach model. For comparison, the Initial Approach model was run with the actual weather file from the monitoring period and was found to use 26% less natural gas. By comparing the natural gas consumption between this new model and the two existing models, it was determined that about 17% of the natural gas reduction was due to a decrease in the heating degree-days found in the weather file. This is consistent with the difference in the heating degree-days between the monitoring period and the standard weather year. The remaining 9% was due to a combination of the lower set point temperatures and the higher waste heat from the suite-based electrical loads.

CONCLUSIONS AND RECOMMENDATIONS

Using whole-building energy consumption data and a customized local weather file from the one-year monitoring period reduced the errors associated with calendarization and weather normalization of the utility bill data. The monitored suite temperatures were found to be higher than the default temperatures which affected the variable natural gas consumption. Sub-metering of suites was useful in developing an estimate of the average electricity intensity for all suites in the building. However, sub-metering of major mechanical equipment would also have been helpful in further defining the common area plug, lighting and equipment loads.

A comparison of the modeled and measured energy consumption data showed that the Refined Approach model fit the monitored data slightly better (CVRMSE: 10.9%) than the Initial Approach model fit the processed utility data (CVRMSE: 12.0%). More importantly, a comparison between the Initial Approach model and the monitored data showed a poorer fit (CVRMSE: 22.3%), indicating the limitations of the Initial Approach.

While this approach has only been used with one building, it illustrates the potential for improving energy models by gathering more detailed data on actual building operation prior to the modeling effort. Improving the performance of existing buildings is one of the keys to reducing the impact of buildings on the environment. In order to promote implementation of energy retrofits on a broad scale, estimates of retrofit energy savings must be accurate. Determining an accurate baseline energy model is the first step to developing a realistic estimate of retrofit measure performance and additional data such as monitored temperatures and electrical sub-metering can make these estimates more representative of actual performance.

ACKNOWLEDGEMENTS

The authors gratefully acknowledge the assistance provided by the University of Toronto’s Director of Student Family Housing, Gloria Cuneo, and the Subject Building Operations Manager, Fraser Anderson, as well as the funding provided by the Natural Sciences and Engineering Research Council (NSERC) and the Neil B. Hutcheon Bequest.

REFERENCES

American Society of Heating, Refrigerating and Air-Conditioning Engineers. 2002. ASHRAE Guideline 14-2002 Measurement of Energy and Demand Savings.

American Society of Heating, Refrigerating and Air-Conditioning Engineers, ASHRAE Standard 55-2010 Thermal Environmental Conditions for Human Occupancy.

Canada Mortgage and Housing Corporation. 1998. Field Testing to Characterize Suite Ventilation in Recently Constructed Mid- and High-Rise Residential Buildings.

Canada Mortgage and Housing Corporation. 2001 Analysis of the Annual Energy and Water Consumption of Apartment Buildings in the CMHC HiSTAR Database. Technical Series 01-142.

Canada Mortgage and Housing Corporation. 2005. Assessment of Suite Compartmentalization and Depressurization in New High-Rise Residential Buildings. Technical Series 05-112.

Damianos, X.S., Day, A.R., Ratcliffe, M.S. 2007. The development of a dynamic model to simulate boiler controls. Building Services Engineering Research and Technology, Vol. 28, No. 2, pp. 105-116.

Danielski, I. 2012. Large variations in specific final energy use in Swedish apartment buildings: Causes and solutions. Energy and Buildings, Vol. 49, pp. 276-285.

Davis Instruments. 2013. Wireless Vantage Pro2™ & Vantage Pro2™ Plus Stations, Accessed July 5, 2013, Available at: http://www.davisnet.com/product_documents/weather/spec_sheets/6152_62_53_63_SS.pdf

Energy Management and Research Associates. 1994. Energy use and domestic hot water consumption. Energy Authority Report 94-19.

Hart, D., Energy and water consumption load profiles in multi-unit residential buildings. 2005. Technical Series 05-119, Research Highlights Canadian Mortgage and Housing Corporation.

Hanam, B., Finch, G., Hepting, C. 2011. Metered calibrated energy simulation of high rise residential buildings: lessons learned, presented at the 13th Canadian conference on buildings science and technology, Winnipeg, MB.

Hubler, D., Tupper, K., Greensfelder, E. 2010. Pulling the levers on existing buildings: A simple method for calibrating hourly energy models. ASHRAE Transactions, Vol. 116, pp. 261-268.

Hutcheon, N.B., Handegord, G.O.P. 1995. Building Science for a Cold Climate, Institute for Research in Construction.

Jian, Y., Guo, Y., Liu, J., Bai, Z., Li, Q. 2011. Case study of window opening behaviour using field measurement results. Build Simulation, Vol. 4, pp. 107-116.

Kavgic, M., Summerfield, A., Mumovic, D., Stevanovic, Z.M., Turanjanin, V., Stevanovic, Z.Z. 2012. Characteristics of indoor temperatures over winter for Belgrade urban dwellings: Indications of thermal comfort and space heating energy demand. Energy and Buildings, Vol. 47, pp. 506-514.

Leung, C., Ge, H. 2013. Sleep thermal comfort and the energy saving potential due to reduced indoor operative temperature during sleep. Building and Environment, Vol. 59, pp. 91-98.

Reddy, T.A. 2006. Literature review on calibration of building energy simulation programs: uses, problems, procedures, uncertainty and tools. ASHRAE Transactions, Vol. 112, pp. 226-240.

Reddy, T.A., Maor, I., Panjapornpon, C. 2007. Calibrated detailed building energy simulation programs with measured data – Part I: General methodology (RP-1051). HVAC&R Research,Vol.13.2 pp. 221-241.

Structure Monitoring Technology. 2013. A2 Wireless Data Loggers, Accessed July 5, 2013, Available at: http://smtresearch.ca/products/a2-wireless-data-loggers

Swan, L.G., Ugursal, V.I. 2009. Modeling of end-use energy consumption in the residential sector: A review of modeling techniques. Renewable and Sustainable Energy Reviews, Vol. 13, pp. 1819-1835.

Touchie, M.F., Binkley, C., Pressnail, K.D. 2013. Correlating energy consumption with multi-unit residential building characteristics in the city of Toronto. Energy and Buildings, Vol.66, pp. 648-656.

Touchie, M.F. 2014. Improving the energy performance of multi-unit residential buildings using air-source heat pumps and enclosed balconies. Ph.D. thesis, Department of Civil Engineering, University of Toronto, Toronto, ON.

Triacta Power Technologies Inc. 2013. PowerHawk Smart Meters 6X20 High Density Meters, Accessed July 5, 2013, Available at: http://www.triacta.com/tm/datasheets/Triacta-6X20-High-Density-Meter.pdf