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Use of calibrated building performance simulation models in energy auditing

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Abstract: *This paper first presents a review of fourteen commercial building energy audits conducted in Ottawa, Canada. Of them, we identified that only one of these audits used an uncalibrated building performance simulation model. Many of them relied on heating and cooling degree day models to develop recommendations about the top energy conservation measures (ECMs) for building retrofits. Subsequently, a calibrated building performance simulation-based approach by using Autodesk Insight 360 platform was applied in one of the fourteen buildings to rank the list of same ECMs. We compared them to those that were identified in the energy audit report and discussed the underlying reasons behind the discrepancies between them. The results indicate that the use of calibrated building performance simulation models in energy auditing practice results in substantially different energy savings estimates and different building retrofit scenarios.*

Keywords: *building performance simulation, energy audit, calibration*

INTRODUCTION

Commercial and institutional buildings in Canada account for about 11% of the energy used in Canada (NRCAN, 2015[a]). About half of this is dedicated to space heating, cooling, and lighting (NRCAN, 2015[b]). Applying energy conservation measures such as upgrading envelope and HVAC equipment has the potential to reduce commercial buildings' environmental and economic impact and to provide comfortable, healthy, and productive indoor environments.

As an on-going research endeavour, analytic tools are developed to support decision-making for investments in retrofits. Over the last 20 years, energy audit methods were aimed to determine where, when, why, and how energy is being used (NRCAN, 2002). The definition of "building energy audit" ranges from a short survey of the building and its related facilities (also called a walk-through energy audit) to a detailed analysis using precise computer simulation and modelling tools.

Energy saving calculation is a vital part of an energy audit procedure. Several references including (ASHRAE, 2002) consider the standardized measurement and demand-saving calculations as a fundamental criterion to select the right energy-saving approach. This energy saving calculation deals with technical challenges such as how to address measurement and instrumentation verification, and handling uncertainties in predictions and tailoring the building energy models for specific applications.

Compared to a small office or residential buildings, the process to identify top energy conservation measures (ECMs) for the large commercial buildings is a challenging task due to unpredictable and uncontrolled heat flows. These flows are driven by a variety of factors such as HVAC complexities and the interaction of different operational elements, building operation schedules, occupancy patterns, lighting, auxiliary electric loads, building envelope and systems features. These conditions are difficult to inspect and handle with a regular walk-through energy auditing procedure. Application of building performance simulation and development of an energy model representing the energy behaviour of the whole building is of great utility in these cases. Developing a calibrated energy model for end-uses is trending in the literature.

Despite the academic maturity of the building energy calculation and modelling approaches, there is still a lack of widespread application of energy modelling and calibration in current commercial energy audit practices. This unpopularity mainly caused by barriers such as the trial and error nature of the process, availability of reliable data for model calibration, the absence of easy to use calibration tools and high dependence on engineering judgment of the user. Also, a limited retrofit budget drives decision-makers (building owners, facility/portfolio managers) towards neglecting large-scale investments recognized by energy modelling techniques and considering small investment solutions. The benefits are unclear to decision-makers, and they do not necessarily believe some advantages of the detailed building performance simulation (BPS) based energy audit instead of a primary walk-through / monthly bill analysis. This study aims to highlight the current state in commercial energy auditing practices and demonstrate the potential of

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a calibrated BPS-based energy audit procedure through a case-study.

Literature Review

An energy audit is a powerful tool to find energy saving opportunities and recommending a list of retrofit solutions to make buildings more energy efficient. ASHRAE specifies three levels of audits (ASHRAE, 2004). Level I or preliminary audit (also called a walk-through audit) considers some potential energy-saving opportunities identified through the assessment of utility bills and a brief inspection of the building. Audits of level II and III are comprised of an energy survey and an engineering analysis to determine the low-cost to significant capital investments to improve the building's energy efficiency. Although level II and III audits are more expensive, they are considered as better options when energy efficiency goals are defined, or a significant facility upgrade or renovation is intended. Furthermore, audit level III is comprised of a building energy simulation step to analyze energy consumption. Building energy performance can be simulated by creating a realistic model using some available engineering software packages to represent the building's energy behaviour.

A review of the basics of building energy estimation as a core task of every building energy audit procedure was presented by Fumo (2014). Also, a comprehensive method for the measurement of energy and demand savings was introduced by ASHRAE Guideline 14 (2002). This guideline proposed a detailed framework to consider three different approaches to measure energy savings in every energy audit practice: *(a) whole building approach, (b) retrofit isolation approach and (c) whole building calibrated simulation approach.* The whole building calibrated simulation approach includes a computer simulation tool to build a model of energy demand of the facility. The model which is created based on the pre-retrofit situation will be calibrated against measured energy use data. The guideline emphasizes some essential requirements and considerations for managing uncertainties in all operating measurements and sampling, saving calculation and modelling phases. Furthermore, the guideline has explained that a calibrated simulation model can be used when either pre-retrofit or post-retrofit whole building metered electrical data are not accessible. Finally, whole building calibrated simulation can provide savings from individual retrofits when only whole-building energy use data are accessible. Upon conducting two case-studies, Shapiro et al. (2009) concluded that a walk-through audit in a large commercial office building could only identify around the 7% of the energy-savings potential while by using a comprehensive energy audit method, up to 46% of the energy-saving potential can be identified. Shapiro et al. (2009) emphasized the risk of overestimation of energy saving opportunities as a common problem in simple walk-through audit practices without BPS. He has recommended to take an extra step and build a calibrated building energy model against utility bills to use as a tool to identify more ECMs and evaluate the improvements.

Calibrated building energy models are supposed to establish a satisfactory relationship between the outcome and measured data. Coakley et al. (2014) presented a review of methods to match building energy simulation to measured data. Fumo (2014) mentioned that calibrated BPS model-based approach could enable the model to anticipate the building energy consumption accurately. Reddy et al. (2007), as part of the ASHRAE Research Project 1051, developed a systematic calibration methodology, including parameter estimation and uncertainty determination. Their method consists of five components: (1) identify a BPS program with the ability of simulating different types of building systems and elements and setting up a realistic simulation input file; (2) heuristic determination of a set of influential parameters which correspond to the simulation program inputs and providing their best estimate and their span of variation; (3) executing a coarse grid search of influential parameters to narrow down the domain of parameters; (4) carrying out a guided search to identify the outstanding sets of influential parameters; (5) make predictions about the predesignated changes to the building and its related systems, and predict the level of uncertainty in the whole calibration process. Reddy et al. (2007) in a companion paper, presented the application of the proposed methodology in an existing office building and two synthetic office buildings. In several studies related to the implementation of calibrated whole building energy models, the authors developed several methodologies to enhance the calibration process: an evidence-based approach Raftery et al. (2011), a scalable and probabilistic methodology for large-scale investments of energy-related retrofits Heo et al. (2012), and the optimization of an envelope retrofit strategy based on changes in indoor environmental parameters and annual energy consumption measures Gücyeter et al. (2012).

A typical energy audit practice proposes a list of feasible retrofits based on the worthiness of the suggestions. Several criteria for the ranking of the retrofit proposals might be considered by the energy auditor. An energy consultant may consider the economic attractiveness of the investments required to improve the energy efficiency by examining a specific ECM or just use the reduction of energy use intensity (EUI) in a typical application to propose and rank retrofit solutions. Accordingly, more

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realistic ECMs lead to better retrofit decisions and more energy savings for the stakeholders. Zhenjun et al. (2012) reviewed the methodologies to perform retrofits. They defined critical phases of a sustainable building retrofit program which includes energy audits, building performance assessment and diagnosis, and energy saving estimation practices. They also proposed a systematic approach for sustainable building retrofits including the quantification of energy benefits assisted with an energy simulation method. Aslihan et al. (2016) proposed an approach for making optimal decisions in building energy efficiency retrofit projects. Their focus was mainly based on building energy modelling, sensitivity analysis of the selected input parameters, and optimization of the associated cost functions.

Motivation and objectives

The objective of this paper is to introduce the potential of a BPS based energy auditing procedure in identifying energy saving opportunities compared to a non-BPS based or a traditional energy auditing approach. Furthermore, a survey of commercial energy audits was carried out upon fourteen energy audit documents to understand the current state of the energy auditing practice better. Later, one of these fourteen buildings was selected for a case study. The case study was carried out by using annual hourly metered data for heating, cooling, lighting and plug loads of a large office building in Ottawa, Canada. By using the data, a calibrated model was developed by using the BPS tool Autodesk Insight 360. Autodesk Insight 360 uses EnergyPlus as its simulation engine for the sizing runs and DOE2 for the annual load calculations. Strengths and weaknesses of the BPS-based energy audits were identified. Also, a new list of the recognized ECMs was compared to the previous non-BPS based energy audit findings.

Review of commercial-grade energy audits section presents the review of the fourteen energy audit documents between 2008 and 2015 in Ottawa, ON. In the case study section, the case study model, energy use data records, and the model calibration process are presented. In results and discussion section, the ECMs selected by using the calibrated model is presented, and discrepancies between the non-BPS based energy audit and the BPS-based procedure were identified and discussed.

REVIEW OF COMMERCIAL-GRADE ENERGY AUDITS

A review of fourteen recent commercial building energy audit reports was conducted to acquire a snapshot of the current state of commercial energy auditing practice in Canada. The audit reports' results are shown and compared in Figure 1. Various ECMs recognized from the energy audits are based on an ASHRAE Level II type approach which is recommended by energy audit guidelines from Canadian Federal building initiative (NRCAN, 2002). ECMs' estimated energy saving potential ranged from 10% to 32%. Utility bill analysis using cooling and heating degree days and simple payback calculations for the overall annual energy cost savings have been performed in all reports.

As shown in Figure 1, a BPS based energy auditing procedure has been implemented in only one of the fourteen audits (building no. 5). Although the BPS procedure was applied by adjusting the building energy model based on the utility consumption data without following the ASHRAE Guideline 14 (2002), the estimated energy savings potential of the ECMs were much greater than the other buildings. Although the scope of these energy auditing projects has been defined under the same standard (NRCAN, 2002), the resulting ECMs from the BPS-based energy auditing method exhibit some distinct features. The energy audit of building no. 5 studied some sophisticated ECMs (such as HVAC system related ECMs) unlike the ECMs recognized in the rest of energy audits. Consequently, the BPS based approach was able to discover energy-saving opportunities like installation of a heat recovery loop at the make-up air unit, reducing the minimum outside airflow rate to a specific prescribed value, implementation of a unique variable air volume terminal unit control logic, CO_2-based demand controlled ventilation for AHUs and installation of occupancy sensors. Furthermore, a list of feasible ECMs is analyzed through rudimentary back-of-the-envelope calculations. While the other non-BPS based audits have focused on some walk-through surveys, and they resulted in easier to identify ECMs – e.g., replacing existing lights with high efficiency lighting.

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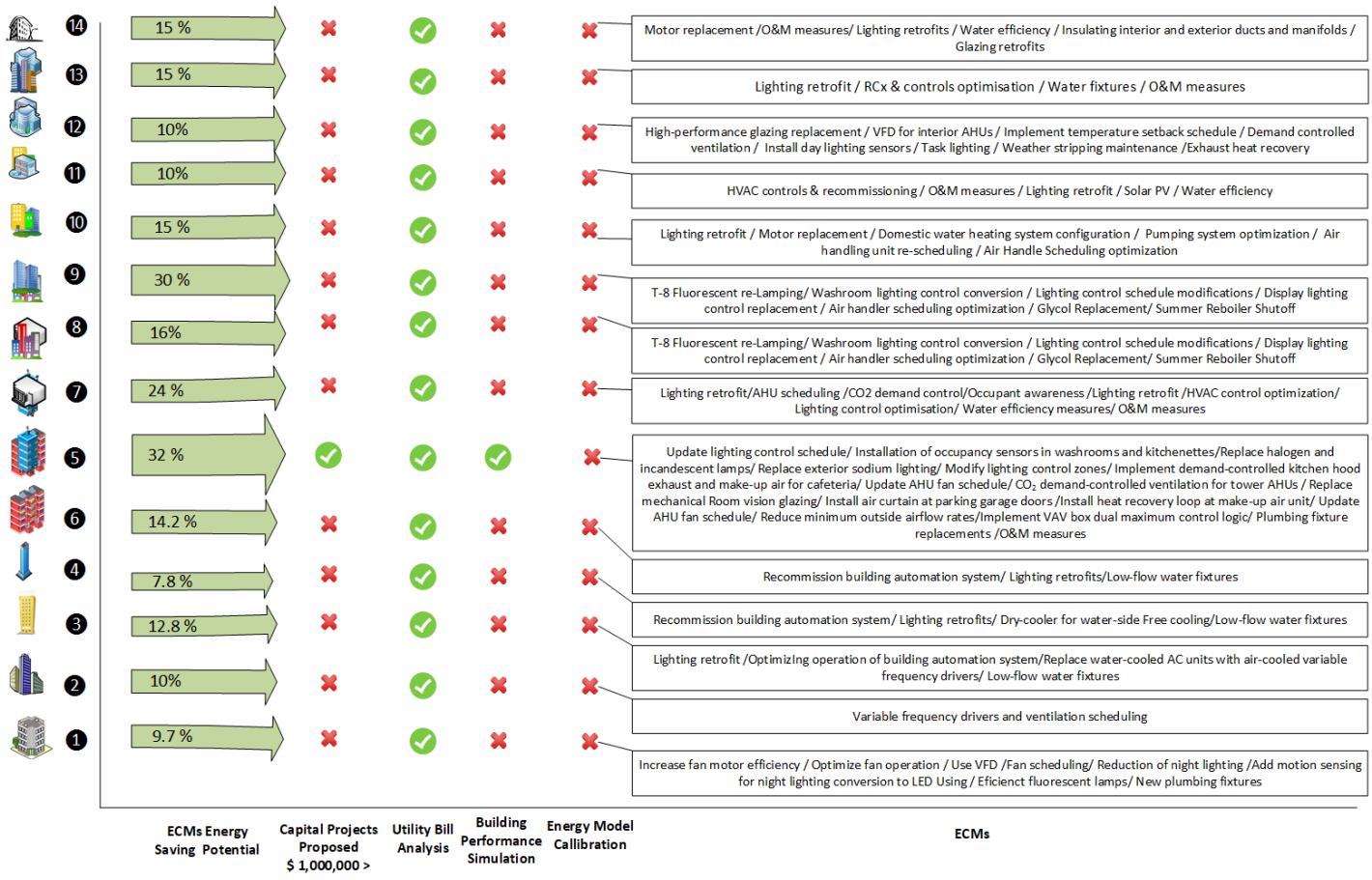

Figure 1: A review of commercial-grade energy audits

CASE STUDY

Overview of the building and data

One of the buildings listed in Figure 1 is selected for the case study. Our decision to select this building was based on the availability of a building energy management system archiving data from sensors, meters, setpoints, and schedules in this building. The availability of archived operational data helped us in building the calibrated BPS model. The selected building was a 22-storey office building (Building 12 in Figure 1). Recall that the energy audit for this building indicated only a 10% energy saving potential. Table 1 presents an overview of the building. The information is extracted from the energy audit document, engineering drawings, and sensor and meter data from the building energy management system database.

Overview of the model and calibration process

Figure 2 shows a geometrical representation of the model created using Autodesk Revit. Monthly utility data were used to calibrate the model by tuning the following model parameters: occupancy schedule, area per person, sensible heat gain per person, latent heat gain per person, lighting and power load density, outdoor air per area and per person, air infiltration rate, and HVAC system efficiency.

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Table 1: Building information for energy modelling

Type of Facility	Office
Office Spaces + Cafeteria	32,538 m^2
Year Built	1969
Mechanical & Electrical Rooms	3811 m^2
Storage	2,080 m^2
Total Gross Floor	38,430 m^2
Floors	21 floors above grade + a basement + a mechanical penthouse
Ventilation system hours of operation	6:15 a.m. - 11:59 p.m.
Glazing Area	25% of the Building External Area
Building Operation schedule	6:00 a.m. - 6:00 p.m. weekdays
Electrical energy intensity	134 kWh/m^2
Steam Energy Intensity	57 ekWh/m^2
Electrical Energy Intensity	62 ekWh/m^2
Building Energy Performance Index (BEPI)	254 ekWh/m^2
Occupancy	1800 people
Building Automation System (BAS) Type	Direct digital control

Figure 2: Geometrical representation of the model

Green Building Studio (GBS), the Autodesk's core building energy simulation and analysis engine for Revit and Insight 360 a cloud computing platform for integration of other cloud services like energy modelling, heating and cooling, load analysis, solar and lighting analysis, were used to find develop the BPS models. Insight 360, uses EnergyPlus as a simulation engine for sizing calculations and DOE2 for annual load calculations.

In this case study, electricity represents lighting and plug loads, steam consumption shows the building space heating and hot water requirements, and chilled water consumption indicates cooling. Note that building is served by a central heating and cooling plant. Thus, the heating and cooling loads, instead of electricity and natural gas, were metered regarding the chilled water and steam purchased by this building from the district heating and cooling plant. Monthly chilled water, electricity and steam consumption rates for 12 months have been calculated within the normalized mean bias error (NMBE) ranges recommended by international performance measurement and verification protocol (IPMVP) (EVO, 2002). The estimated consumption rates compared to the simulation values and are shown in Figures 3, 4 and 5. The results obtained with the NMBE of 7.3, -2.3 and -9.6 for the chilled water, electricity and steam consumption respectively. These values were all within the acceptable range for the monthly calibration criteria (EVO, 2002).

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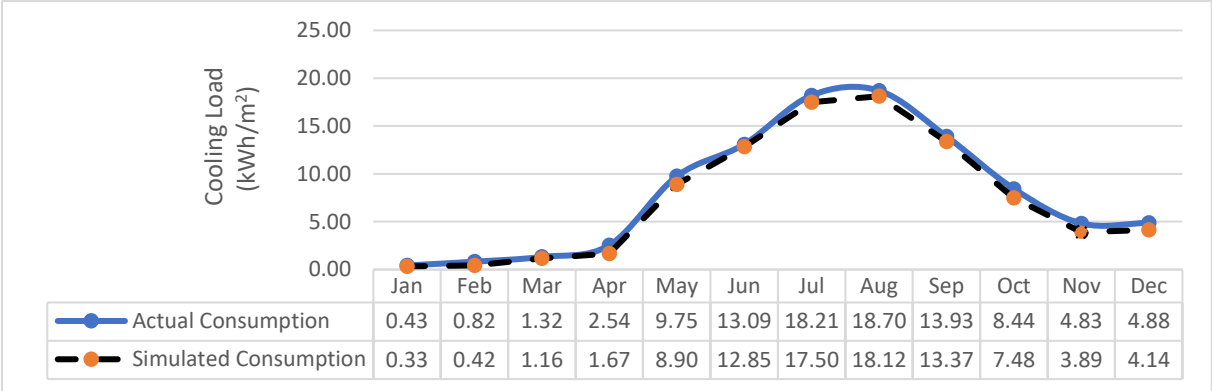
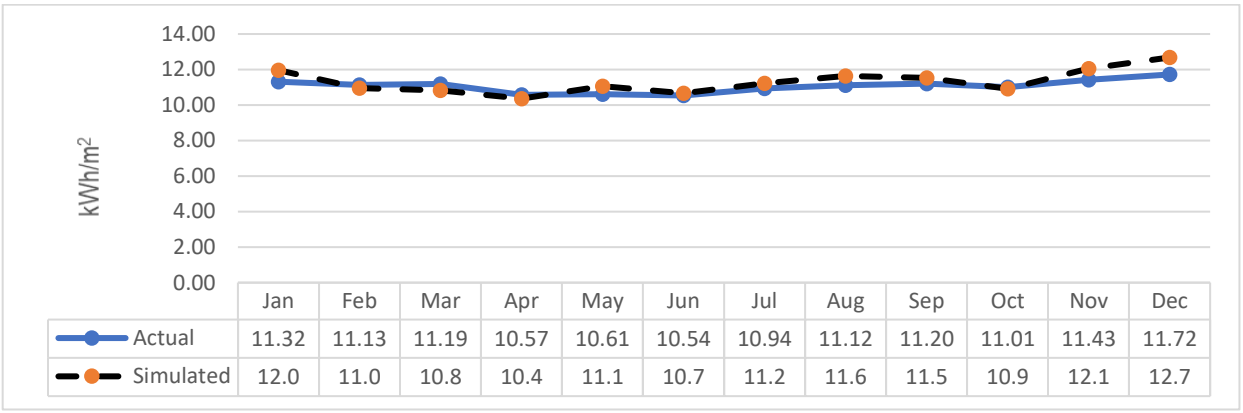


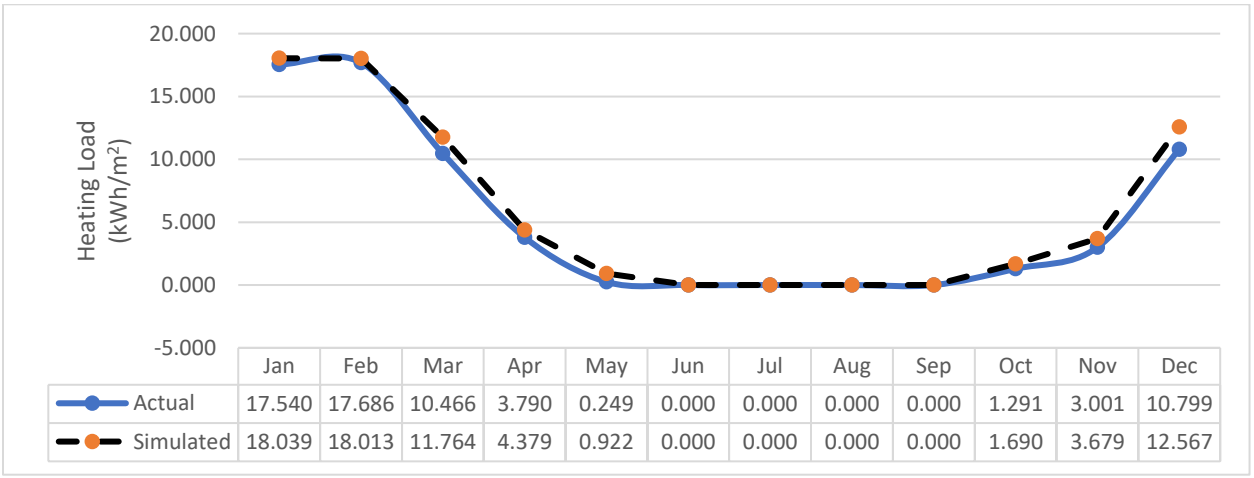
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Actual Consumption	0.43	0.82	1.32	2.54	9.75	13.09	18.21	18.70	13.93	8.44	4.83	4.88
Simulated Consumption	0.33	0.42	1.16	1.67	8.90	12.85	17.50	18.12	13.37	7.48	3.89	4.14

Figure 3: Actual and simulated monthly energy consumption for chilled water (NMBE% +7.3)



	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Actual	11.32	11.13	11.19	10.57	10.61	10.54	10.94	11.12	11.20	11.01	11.43	11.72
Simulated	12.0	11.0	10.8	10.4	11.1	10.7	11.2	11.6	11.5	10.9	12.1	12.7

Figure 4: Actual and simulated monthly electricity usage (NMBE% -2.3)



	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Actual	17.540	17.686	10.466	3.790	0.249	0.000	0.000	0.000	0.000	1.291	3.001	10.799
Simulated	18.039	18.013	11.764	4.379	0.922	0.000	0.000	0.000	0.000	1.690	3.679	12.567

Figure 5: Actual and simulated monthly steam consumption (NMBE% -9.6)

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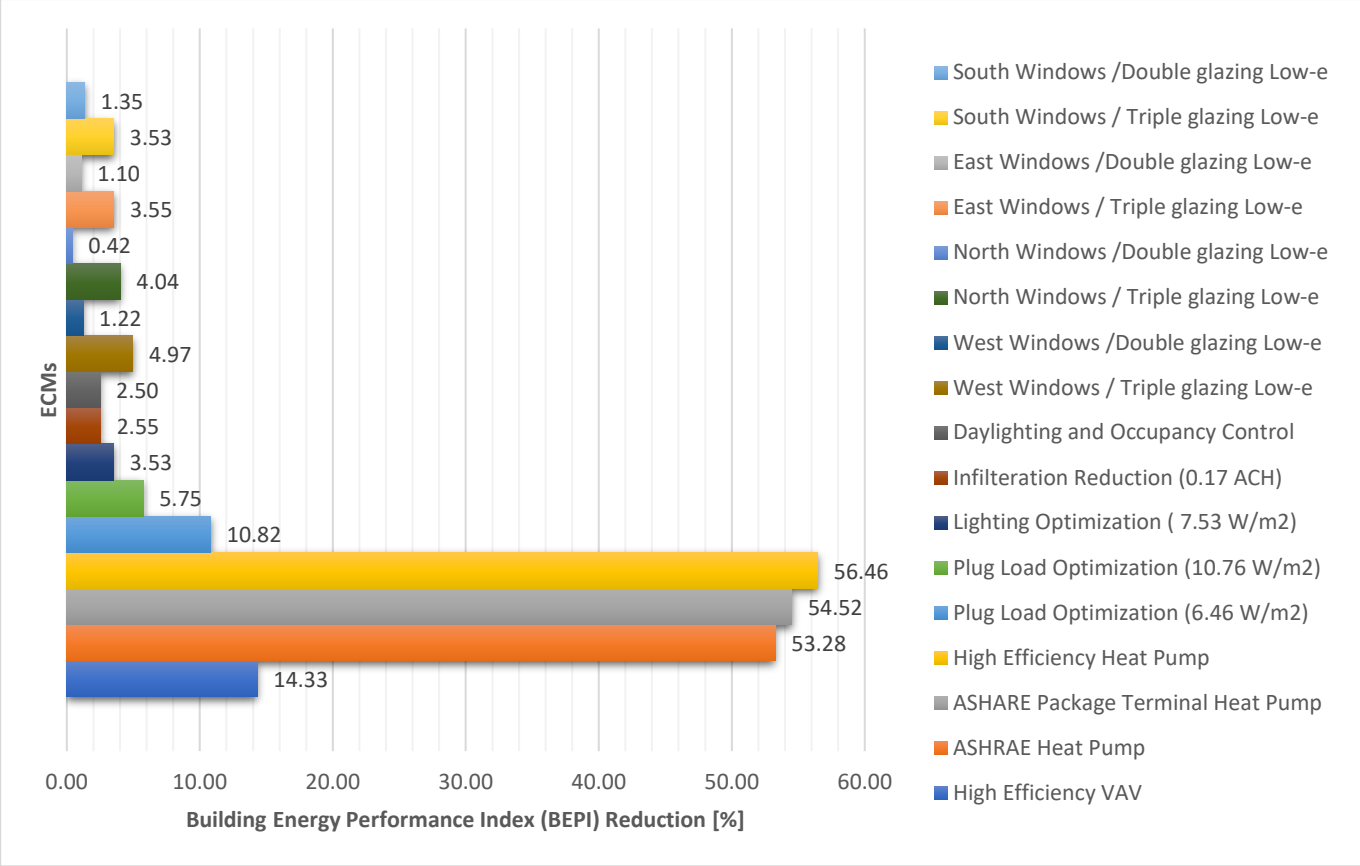

Figure 6: BPS based ECMs

RESULTS AND DISCUSSION

Insight 360 generated ECMs, and their corresponding impacts on building energy performance index (BEPI) are indicated in Figure 6. These 17 ECMs are classified in six main categories: (a) windows and glazing related ECMs, (b) plug load optimization, (c) daylighting and occupancy sensing, (d) infiltration, (e) HVAC and (f) miscellaneous ECMs.

The ECMs identified by this BPS-based energy audit were compared to the results obtained from previous non-BPS based energy audit procedure in Table 2. Although there are some similarities between the nature of the identified ECMs, the BPS based energy audit with energy model calibration has provided several exclusive ECMs, which are discussed here.

Windows and glazing related ECMs

The ECMs no. 10 to 17 in BPS based energy audit specifically address the energy efficient window glazing types and area while ECM no. 1 in non-BPS approach just points to high-performance glazing replacement. The overall energy saving percentage of BPS based approach for ECMs no. 10-17 has a value between 5% and 16% considering either Double or Triple Low-e glazing type while the non-BPS approach with 10% overall energy saving (for all ECMs).

Plug load optimization

As presented in Table 2, BPS based energy audit approach has provided ECMs no. 5 and 6 which are representing the energy saving potential of the plug load optimization. Energy saving opportunity of 11% and 6% was estimated if the plug loads controlled and maintained at the 6 W/m^2 and 11 W/m^2 levels, respectively.

Daylighting and occupancy sensing

BPS based energy auditing provided ECM no. 9 with 2.5% energy saving potential. Non-BPS energy auditing approach provided ECM no. 9 for daylighting sensor

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installation with no specific data related to its energy-saving potential.

Infiltration

ECM no. 8 under BPS based energy auditing approach has provided a limit for controlling building's infiltration to 0.17 ACH to acquire 2.54% energy saving in the building. Non-BPS based approach has introduced a similar concept with ECM no. 2 with the title of weather stripping maintenance and without a prescribed limit for controlling the infiltration.

HVAC

As indicated in Table 2, ECMs no. 1 to 4 in BPS-based energy auditing approach indicate considerable potential for energy savings through HVAC improvements. Although some of the ECMs require a considerable investment to accomplish, the magnitude of the energy-savings potential is a promising factor to consider. Implementation of high-efficiency VAV AHU system as recommended in ECM no. 1 with 14.33% energy saving potential is in line with the only HVAC related ECM of demand controlled ventilation which has been introduced in ECM no.3, in non-BPS energy auditing approach.

Miscellaneous

On the other hand, non-BPS based energy auditing approach has discovered some miscellaneous ECMs, which are related to water conservation (ECMs no. 6,7,8,9) and electrical energy saving ECM of no. 4, Variable frequency drive (VFD) for AHUs. It is essential to consider these different measures as they were developed through observing the real situation.

Discussion about the advantages of BPS based method

The energy retrofit industry is always searching for analytical methods that support decision-making for the implementation of ECMs. The reliability, validity and the resolution of ECMs are critical factors in ranking the retrofit options. With the use of calibrated BPS models in energy audits, energy savings from ECMs can be estimated accurately. Beyond analyzing individual ECMs one at a time, use of BPS in energy auditing practice renders the potential to better understand the coexistence of a group of ECMs. For example, an ECM to reduce the lighting energy use intensity is expected to affect the internal heat gains, which in return will affect the heating and cooling loads. Thus, a lighting-related ECM can affect the energy savings expected from an HVAC-related ECM (e.g., high-efficiency boiler or chiller). Note that it is hard, if not impossible, to incorporate these interactions among different ECMs within simple regression models or mere visual walk-through inspections. Moreover, improved accuracy in estimating the energy savings potential from a group ECMs is expected help decision-makers to justify investments towards medium-to-high cost retrofit options.

Modelling limitations

BPS-based energy auditing method provided a comprehensive set of ECMs to consider for energy retrofits. However, it is worth noting that there are several unresolved issues left for future work.

The current calibration procedure followed International Performance Measurement and Verification Protocol's (IMPVP) (EVO, 2002) monthly utility data-based calibration recommendation which inherently allows a greater error than ASHRAE Guideline 14 (ASHRAE, 2004).

The surface radiation and emissivity properties of internal and external surfaces like wall painting and carpet have not considered for the BPS practice, and this can incorporate some uncertainties regarding the energy performance of the building through the simulation period. Also, there are some individual internal heat gain sources like data centres and elevator operation which are not inserted into the model.

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Table 2: Comparing BPS-based with energy model calibration and non-BPS based ECMs

BPS-based Energy Auditing with Energy Model Calibration			Non - BPS based Energy Auditing	
No	**ECM**	**Energy Saving Potential (%)**	**No**	**ECM**
1	High-efficiency VAV	14.33	**1**	High-performance glazing replacement
2	ASHRAE heat pump	53.27	**2**	Weather stripping maintenance
3	ASHRAE package terminal heat pump	54.51	**3**	Demand controlled ventilation
4	High-efficiency heat pump	56.46	**4**	VFD for Interior AHUs
5	Plug load optimization (6.46 W/m^2)	10.82	**5**	Implement temperature setback schedule
6	Plug load optimization (10.76 W/m^2)	5.75	**6**	Replace urinals with low flow
7	Lighting optimization (7.53 W/m^2)	3.52	**7**	Replace lavatory aerators
8	Infiltration reduction (0.17 ach)	2.54	**8**	Ultra - low flow water closets
9	Daylighting and occupancy control	2.5	**9**	Reset mixing valve on all lavatories
10	West windows / triple glazing low-e	4.96	**10**	Replace 32 Watt, T8 fluorescent lamps with 25 Watt
11	West windows / double glazing low-e	1.22	**11**	Install daylighting sensors
12	North windows / triple glazing low-e	4.03	**12**	Task lighting
13	North windows / double glazing low-e	0.42	**The overall percentage of energy reduction potential by implementing the ECMs = 10%**	
14	East windows / triple glazing low-e	3.54		
15	East windows / double glazing low-e	1.09		
16	South windows / triple glazing low-e	3.53		
17	South windows / double glazing low-e	1.35		
The overall percentage of energy reduction potential by implementing a proper combination of ECMs >50%				

CONCLUSION

A review of fourteen recent commercial building energy audit documents demonstrated the lack of calibrated BPS model use in the auditing practice. Although there are some differences between various levels of energy auditing which comprise computer simulation step to provide more detailed results (ASHRAE, 2004), the idea of building performance simulation based energy auditing is defined to make a typical energy auditing practice more comprehensive in recognizing energy saving opportunities.

BPS based energy auditing with the ability to develop a calibrated energy model using the utility consumption history was studied with a case study to demonstrate its advantages over the non-BPS based energy auditing approach. BPS based energy auditing led to a different set of ECMs than those reported in the actual audit report. Implementation of the 17 ECMs identified from this procedure can offer more than 50% energy saving. On the other hand, non-BPS based energy auditing was shown to only provide 10% energy savings by the implementation of 12 ECMs.

Although the current research has benefited from built-in features in Revit and Insight 360 to provide comprehensive and diverse ECMs in building energy, the energy model calibration procedure still needs expert judgement and availability of high resolution and fidelity metered data. Ongoing research towards the development of easy to implement and more accurate calibration platforms using the data from building information systems is recommended to recognize a useful list of energy saving opportunities for energy retrofits.

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