Method of sensitivity analysis applied to a NECB-2017 reference institutional building

Pedro Rafael Guaraldi da Silva[1], Radu Zmeureanu[1]

[1]Centre for Zero Energy Building Studies, Department of Building, Civil, and Environmental Engineering, Gina Cody School of Engineering and Computer Science, Concordia University, Montreal, Canada

Abstract: *This paper proposes a method of sensitivity analysis that is useful as a tool for energy code updates by assessing the potential increase of Key Performance Indicators (KPIs) due to changes in design input variables. Further updates of NECB-2017 prescriptive requirements should consider prioritizing modifications of design input values based on their impact on these KPIs. The sensitivity analysis of the energy efficiency of the case study building indicates that the minimum energy performance requirements of HVAC equipment, such as chillers, boilers, fans and pumps have the highest impact amongst the studied variables. Applying these changes to NECB requirements would significantly modify the KPI values at the whole-building, system and equipment levels.*

Keywords: *building energy performance, building energy modelling, code development, sensitivity analysis, NECB*

INTRODUCTION

Building energy-related codes are used by building designers and operators to ensure that the building is designed and operated according to the best engineering practices. Since they act as a compilation of the best engineering practices available, these documents are under constant revision and update.

Methodologies that correlate the energy use or the energy cost with certain design alternatives or with the efficiency of individual equipment have been used to determine which changes would be the most effective. This process of code development can be improved and complemented with methodologies that are computationally efficient and that yield results that are easy to interpret. These results often come in the form of sensitivity coefficients, indicating the priority changes that future code updates will focus on.

Improving how building energy codes are developed is a relevant step in achieving a more sustainable and productive society due to the mechanics of energy supply and demand inherent to human activities. Energy consumption is closely related to the economic development of a country. Socio-demographic factors, such as population and age structure, influence economic growth which translates directly into how energy is used by the residential, commercial, industrial and transportation sectors (Dincer & Dost, 1996).

An increasing trend in energy consumption can be seen worldwide. In Canada, the average increase of the total final consumption of energy is around 13% every decade, while the total for all OECD countries average 7% (IEA, 2015). Projections for the world energy consumption indicate an increase of nearly 50% between 2018 and 2050 (EIA, 2019).

In Canada, the electric power selling price has risen by 250% from 1981 to 2019 (Statistics Canada, 2019a). The conventional crude oil price has risen by 200% and the natural gas price has risen by 40% in the same time frame (Statistics Canada, 2019b).

In OECD countries, total building energy consumption is expected to increase by an additional 13% from 2018 to 2050 (EIA, 2019). In Canada, residential, commercial and institutional buildings account for 28% of the total secondary energy use. If the current trends remain the same, their total energy consumption is expected to increase by an additional 17% from 2016 to 2050 (NRC, 2016).

As a direct response to the increase of energy use in buildings, codes were developed to address energy efficiency in the design, construction and operation stages. Examples of such building energy related codes are:

- In France, Réglementation Thermique (RT), with its first edition as a decree in 1974 (Ministère de l'Égalité des territoires et du Logement, 2011).
- In the U.S., ASHRAE Standard 90.1, with its first edition in 1975 (ASHRAE, 2013).
- In Canada, National Energy Code for Buildings (NECB), with its first edition in 1997 (NRC, 2017).
- In Québec, E-1.1, r. 1 - Regulation respecting energy conservation in new buildings, with its first edition in 1983 (Ministère de l'énergie et des ressources, 2019).
- In the U.K., CIBSE Guide F, with its first edition in 1998 (CIBSE, 2004).

In addition to building codes, several sustainability and energy performance labels have been developed. Examples of these labels are the LEED certification (USGBC, 2019), and the PassivHaus certification (Feist & Ebel, 1998).

The development of building energy codes has had a great impact on the energy consumption of buildings. Compliance with the ASHRAE 90.1-1989 Standard led to a 15% reduction of the building energy use when compared to the 1975 version, the 2004 version led to about 30% reduction, and the 2013 version led to about 50% reduction. It is expected that the future versions of the ASHRAE 90.1 Standard would lead to a 70% reduction of building energy use by 2025 (Rosenberg, Jonlin, & Nadel, 2017). As for the Canadian counterpart, NECB 2017 would improve building energy efficiency by up to 15% when compared with the NECB-2011 version, and it is expected that future versions of NECB would reach the goal of Net Zero Energy Ready buildings by 2030 (NRC, 2017).

Given the major role that such codes play, attention is drawn to the process used in code development and how the process can be improved. The main steps used in the process of performance-based building energy efficiency code development are outlined, as follows (Isaacs, 1999):

1. Development of prototypical building(s) seeking to accurately represent the building stock, normally taken at national or regional levels.
2. Assessment by computer modelling of their energy use in a range of climates for a number of Energy Conservation Measures (ECM).
3. Evaluation of Key Performance Indicators (KPIs), usually the whole-building annual or life-cycle cost and/or the energy use of each option.
4. Selection of the most suitable options for inclusion in the code.

The exhaustiveness of evaluating a number of ECMs under a combination of building prototypes (offices, schools, supermarkets, etc.) in different climates calls for modelling tools that are robust in their capacity to model complex systems, accurate in their prediction of the energy use and have decent computational times (Rallapalli, 2010). Many of these tools were developed over the past 50 years and are used extensively in building energy prediction. Examples of such tools are DOE-2, EnergyPlus, eQUEST, ESP-r and TRNSYS, each one with varying features and capabilities (Crawley, Hand, Kummert, & Griffith, 2005).

The outputs of modelling tools for this purpose are the selected KPIs or can be used to derive KPIs that will be useful in new versions of the code. Several KPIs with different interpretations and focuses can be found in the literature. The most prominent and frequently used are the whole-building annual energy use, known as Energy Use Intensity (EUI) (Girgis-McEwen & Ullah, 2018) and the life-cycle cost (Madison, Usibelli, & Harris, 1994).

One way of evaluating the ECMs is by analysing the impact that the change of design inputs has on the selected KPIs. This is usually done by means of sensitivity analysis, where local and/or global methods are used, respectively, to explore the design space of input variables around a base case solution or on the whole space of input variables, and combinations thereof (Saltelli et al., 2008; Tian, 2013). Although many papers found in the literature discussed sensitivity analysis in building energy simulation, only a few of these papers proposed methods that are applicable to energy code development. These studies are listed below.

1. Girgis-McEwen & Ullah (2018) applied local sensitivity analysis to evaluate the impact of energy efficiency measures on the whole-building annual energy use of NECB-2015 prototypical buildings in different climatic zones in Canada. Amongst the ECMs evaluated, there are changes in the fenestration area, envelope thermal transmittance, lighting system, and energy efficient equipment and strategies.
2. Irwin et al. (2016) applied the local sensitivity analysis over a series of ASHRAE 90.1 compliant baseline models for different building types and Canadian climate zones. The improvement of the EUI for each case is presented for three ECMs: the increase of chiller COP and boiler efficiency, and a reduction of the Solar Heat Gain Coefficient (SHGC) of windows.
3. Bowley et al. (2018) applied multiple-linear regression, through global sensitivity analysis, to evaluate the impact of retrofits on the residential building stock in the city of Victoria, BC, Canada. The retrofits are grouped into building shell and heating system. The impact anaylsis focuses on the annual energy consumption, operating cost and carbon emissions, and the initial investment for the selected retrofits.
4. Song et al. (2014) applied a meta-modelling approach based on Treed Gaussian Process (TGP), through global sensitivity analysis, to evaluate the impact of ECMs (i.e., changes of the thermal characteristics of building envelope, internal heat gains and HVAC system) on a case study building model. The impact is evaluated over the annual heating and cooling energy use, and the annual carbon emissions.

This paper presents a method for evaluating the sensitivity of selected KPIs. The method uses as the reference model the prescriptive and performance requirements of NECB-2017. The results aid in determining if some code prescriptions should be modified, based on their impact on the KPIs. Understanding and quantifying the sensitivity of KPIs due to changes of design inputs could help policy makers and the parties involved in the development of such codes (Mechri, Capozzoli, & Corrado, 2010). The method is applied to a case study institutional building in Montréal, QC. A set of energy KPIs spanning across the whole-building, system and equipment levels is selected in addition to the building Energy Use Intensity (EUI).

METHOD

The following steps taken in the present study are listed.

1. Creation of a case study (reference) building energy model, developed to be compliant to NECB-2017.
2. Selection of the design input variables, and assignment of numerical value ranges for each variable.
3. Selection of the KPIs.
4. Creation of a Batch Master table and the required slave tables containing the information regarding the input

variables to be passed on to the eQUEST program (Madison, 2012), and the batch mode simulations.

5. Extraction and organization of the results.
6. Calculation of the derived KPIs.
7. Calculation of the sensitivity coefficients.
8. Analysis and recommendations for code updates.

Building Energy Model Development

The building envelope, loads and systems are modelled to fully embody the energy efficiency requirements of NECB-2017. The airtightness of the envelope was set as a constant value per unit area of external envelope, respecting the maximum air leakage present in the code. The fully compliant case study reference building model serves as a benchmark to evaluate the impact of NECB energy efficiency requirements on selected KPIs.

The chosen building is the Centre for Structural and Functional Genomics building, a research facility of Concordia University. This research facility comprises mainly office and laboratory spaces served by ancillary conference rooms, storage rooms and corridor spaces.

The case study building was modelled using the eQUEST program. In addition to its wide range of applications, eQUEST has a user-friendly graphical interface that assists in creating and changing DOE-2 input files in a straightforward manner. It is also quick in producing results, presenting reduced runtimes for projects with a high number of spaces (Rallapalli, 2010).

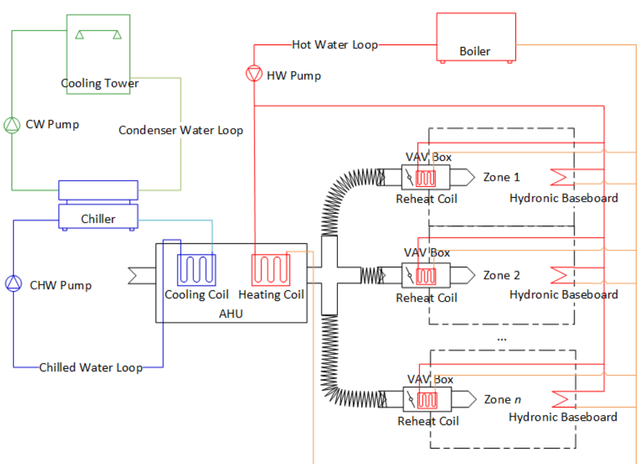

Figure 1: Water-side HVAC System representation.

A representation of the water-side system modelled in eQUEST is presented in Figure 1. The chilled water loop comprises a water-cooled water chiller, a chilled water (CHW) pump and a central cooling coil. The condenser water loop consists of a cooling tower and condenser water (CW) pump. The hot water loop consists of a natural gas-fired boiler, a hot water (HW) pump, a central heating coil and a set of baseboard heaters and reheat coils installed in each zone.

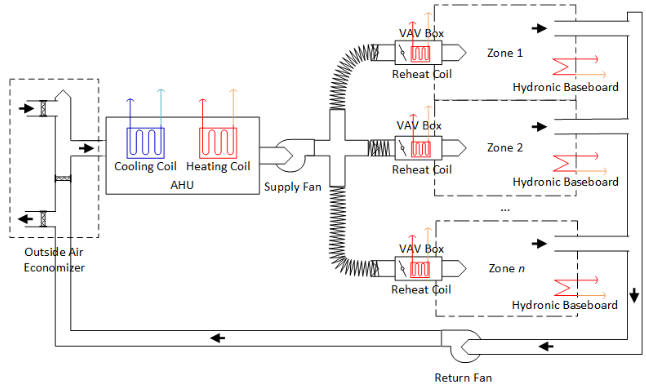

Figure 2: Air-side HVAC System representation.

A representation of the air-side system modelled in eQUEST is presented in Figure 2. The system is a multi-zone Variable Air Volume (VAV) system with VAV boxes with reheat. An outdoor air economizer is also present. No Energy Recovery Ventilators (ERV) or Heat Recovery Ventilators (HRV) were considered, since the supply air flow rate is below the required threshold prescribed by NECB-2017.

Selection of Design Input Variables

Table 1: Input data for sensitivity analysis.

Variable	Base Case	Case 1	Case 2	Case 3	Case 4
Envelope - Thermal Transmittance of Assemblies					
Walls (W/m²-K)	0.247	0.200	0.225	0.275	0.300
Roof (W/m²-K)	0.156	0.050	0.100	0.200	0.250
Windows (W/m²-K)	1.9	1.5	1.7	2.1	2.3
Water-side HVAC System - Main Equipment Efficiency					
Chiller COP (kW_{th}/kW_{ele})	5.547	4.5	5.0	6.0	6.5
Boiler Eff. (kW_{th}/kW_{ele})	83%	75%	80%	85%	90%
Cooling Tower EIR (kW_{ele}/kW_{th})	0.013	0.009	0.011	0.015	0.017
Water distribution system - Pump Combined Efficiency					
HW Pump	66%	55%	60%	70%	75%
CW Pump	69%	55%	60%	70%	75%
CHW Pump	67%	55%	60%	70%	75%
Air-side HVAC System - Fan Total Efficiency					
Supply Fan	55%	45%	50%	60%	65%
Return Fan	30%	20%	25%	35%	40%
Zones - Temperature Setpoint					
Heating (°C)	22.0	20.0	21.0	23.0	24.0
Cooling (°C)	24.0	22.0	23.0	25.0	26.0

The design and operating variables used as inputs in the sensitivity analysis are listed in Table 1. The base case corresponds to prescriptive and performance requirements of the building envelope (Part 3 of NECB-2017), HVAC Systems (Part 5 of NECB-2017) and of the whole-building energy performance (Part 8 of NECB-2017).

Each of the 13 variables are varied one at a time for 5 different values, creating an input space of 65 building energy models. These 13 variables were selected as inputs to the sensitivity analysis because they are listed in NECB-2017. The NECB-2017 prescribes minimum performance requirements to these variables given to their relevance in the building operation and to their contribution to the building energy consumption.

Selection of Key Performance Indicators

The KPIs are calculated from the simulation results at three levels: whole-building, systems and equipment. Each level of KPIs brings a different perspective on the impact of changing the values of design variables. The list of KPIs, calculated on an annual basis is presented below.

Whole-building KPIs:

a. Energy Use Intensity per floor area (EUI) (GJ_{en}/m^2);
b. Peak Electric Demand per floor area (W_{en}/m^2);
c. Energy Cost per Energy Consumption[1] ($/$GJ_{en}$); and
d. Energy Cost per floor area ($/$m^2$).

System KPIs:

a. COP of Heating System[2] (kW_{th}/kW_{en});
b. COP of Cooling System[2] (kW_{th}/kW_{en});
c. COP of both Heating and Cooling Systems[2] (kW_{th}/kW_{en});
d. Peak Cooling Coils Load per floor area (kW_{th}/m^2);
e. Peak Heating Coils Load per floor area (kW_{th}/m^2);
f. Total Building Heating and Cooling Loads per Total HVAC Energy Consumption (kW_{th}/kW_{en});
g. Supply Airflow Rate per floor area (L/s-m^2);
h. Combined supply and return air fans power demand per supply air flow rate[3] (W_{en}/L-s).

Equipment KPIs:

a. Chiller COP (kW_{th}/kW_{en});
b. Boiler Efficiency (kW_{th}/kW_{en});
c. Cooling Tower Performance[4] (kW_{en}/kW_{th});
d. Heating Pumping Power Demand[5] (W_{en}/kW_{th});
e. Heat Rejection Pumping Power Demand[5] (W_{en}/kW_{th});
f. Cooling Pumping Power Demand[5] (W_{en}/kW_{th}).

The subscript *en* refers to the energy input to an equipment, system, plant, space, zone or building, while the subscript *th* refers to the thermal energy output. The following superscripts are used: (1) this KPI is calculated as the sum of the utility bills from all energy sources, divided by the sum of the energy input from these energy sources; (2) this is the COP of the whole system, including main equipment (e.g. chillers, boilers) and ancillary equipment (e.g. cooling towers, fans, pumps); (3) this is the energy needed by the supply and return air fans used for the air distribution system; (4) this KPI includes the energy input of all ancillary equipment of the cooling tower (e.g. fans, recirculating pumps), and (5) this is calculated as the peak energy required by the pumps divided by the peak thermal loads of the cooling, heating or heat rejection system.

These KPIs were selected as outputs to the sensitivity analysis from the literature review due to their relevance in representing the overall impact of ECMs on the performance of buildings in energy code development applications. Some of the above listed KPIs are also used as means of measuring if a proposed model has a superior performance to a reference model (e.g. items a and d of the whole-building KPIs), or as means of indicating compliance to code requirements (e.g., items g and h of the system KPIs, and item f of the equipment KPIs).

Batch Processing in eQUEST

Within eQUEST native functionalities, there is a batch processing feature that allows users to execute limitless consecutive simulations. This feature relies on a relatively easy to build database that contains instructions to be passed to the DOE-2.2 engine to modify specific parameters, generating new models from a base file (Lerond, 2017).

This database is comprised of a Batch Master table that indicates which combinations of input variables will be used to generate a new model from a baseline model (Madison, 2012). The Batch Master table contains references to slave tables that are saved as separate files to store the numerical values to be assigned to each input variable. All the tables are all stored in .csv format and can be created using any spreadsheet tool such as Microsoft Excel.

By using this feature, the effort otherwise required to analyse the impact of many permutations of design decisions on the building energy performance is considerably reduced. A comma separated value (.csv) output file is generated automatically at the end of each batch process. The simplified results available in this output file are useful to detect trends and allow for a rapid evaluation of the simulation runs.

In the present study, results of specific KPIs are needed for a more complete evaluation of the potential changes in the requirements of NECB-2017. A MATLAB code was developed to extract certain results directly from the .SIM files and saved in a separate folder of choice. The .SIM files are detailed files that eQUEST generates for each model run, containing information on building loads, system, plants and economic calculations.

Sensitivity Analysis

In sensitivity analysis, the sensitivity of an output variable is studied as a function of the change of one or a set of input variables, explored around a base (reference) point. The regression method is widely used in building energy analysis due to this method being easy to implement, fast to compute and easy to interpret the results (Tian, 2013).

This paper uses a matrix form implementation of the regression method, where the Sensitivity Coefficients (SCs) that shows the impact of an input variable X on a KPI Y is given (Ryan, Wild, Voulgarakis, & Lee, 2018):

$$SC = (X^T X)^{-1} X^T Y \quad (1)$$

Where X is a matrix composed of the inputs X_n for the sensitivity analysis and Y is the vector of the KPIs, each distinct one denoted by Y_n. Both X and Y were normalized over the values for the baseline case (Eq. (2) and Eq. (3)).

$$X=(X_n-X_{base})/X_{base} \quad (2)$$

$$Y=(Y_n-Y_{base})/Y_{base} \quad (3)$$

Through the normalization all variations are represented as SC in percent changes over the base case; this allows the comparison of input variables that have distinct units.

DISCUSSION AND RESULT ANALYSIS

The proposed method can be applied in all levels of analysis (whole-building, system and equipment). This allows for policymakers and building engineers to understand how each of these levels respond to a given change in the building design. As such, this tool can be adapted to the scope of the user for topical applications, such as in studies that focus on improving only the performance of the building envelope or the HVAC system, or for holistic applications, such as in studies that focus on reducing the energy consumption or the energy cost. A focus is given in this section of result analysis to the whole-building KPIs, since these are the most used indicators in building energy code development, as uncovered in the literature review. One of the reasons contributing to the popularity of whole-building KPIs as the metric to guide future updates is that policymakers are interested in reducing either the total energy consumption or the total energy cost of the building through any combination of code endorsed ECMs.

The sensitivity coefficients are presented in Table 2. The whole-building KPIs are presented in Figure 3 to Figure 5. The SC values portrayed in the following figures represent the change in the KPI for one unit of change in the input variable value. During the implementation of the regression method, a linear behaviour was found for all KPIs and input variables.

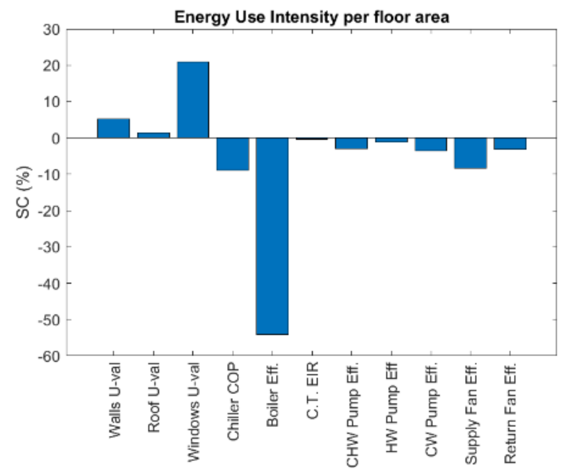

Figure 3: Sensitivity coefficient of the Energy Use Intensity per floor area versus input variables (positive coefficients relate to an increase in energy consumption).

Table 2: Sensitivity Coefficients for all KPIs

Level	KPI	Walls U-val	Roof U-val	Windows U-val	Chiller COP	Boiler Eff.	C.T. EIR	CHW Pump Eff.	HW Pump Eff	CW Pump Eff.	Supply Fan Eff.	Return Fan Eff.	Heat Temp. SP	Cool Temp. SP
Whole-building	a.	5.16	1.41	21.02	-9.01	-54.16	-0.39	-2.95	-1.21	-3.55	-8.41	-3.21	9.06	-2.2
	b.	1.23	0.44	1.19	-41.86	-	-2.35	-3.35	-0.9	-3.94	-18.97	-8.18	-0.11	-1.5
	c.	-1.83	-0.42	-8.32	-5.28	18.68	-0.27	-0.41	0.05	-0.48	-3.84	-1.69	-2.72	0.05
	d.	3.29	0.98	12.86	-14.16	-34.87	-0.52	-3.44	-1.29	-4.05	-12.56	-5.04	6.41	-2.13
System	a.	2.54	0.31	10.08	-	83.84	-	-	2.13	-	10.08	5.	1.35	1.05
	b.	0.61	0.23	1.43	47.93	-	1.38	16.64	-	19.31	13.96	6.64	0.48	-1.26
	c.	-0.56	-0.18	-4.01	11.36	68.46	0.32	3.91	1.73	4.58	5.11	3.71	-1.22	-1.35
	d.	1.96	1.39	0.43	-	-	-	-	-	-	-10.	-3.49	-0.22	-3.52
	e.	7.56	1.89	25.62	-	-	-	-	-	-	4.06	1.79	-0.22	-3.52
	f.	-0.4	-1.53	-9.41	11.36	68.46	0.32	3.91	1.73	4.58	11.19	4.29	-12.7	2.84
	g.	2.87	-0.34	4.95	-	-	-	-	-	-	-	-	-	-
	h.	-0.02	-	-	-	-	-	-	-	-	-70.62	-34.7	-	-
Equipment	a.	-0.01	0.19	-1.12	100.4	-	-	-	-	-	0.67	-0.83	1.57	-3.47
	b.	0.28	0.03	1.21	-	100.	-	-	-	-	-0.03	0.02	0.79	0.12
	c.	-0.04	-0.04	-0.09	2.25	-	-84.83	-	-	-	0.38	0.13	0.01	0.09
	d.	-0.06	-	-0.32	-	-	-	-	-106.1	-	0.16	-	0.01	0.09
	e.	-0.16	0.05	0.19	0.15	-	-	-	-	-120.19	-0.18	-0.01	-	-
	f.	0.24	-0.01	0.04	-	-	-	-113.03	-	-	0.14	0.11	-	-

In Figure 3, the SCs of the EUI are presented for the selected input variables. Amongst the envelope assemblies, the windows lead to the highest impact on the EUI with the SC of about 21% due to the high Window to Wall Ratio (WWR) of 38.4% in the model and the high thermal transmittance of fenestration when compared to walls and roofs. The second highest contributor in the building envelope variables is the wall thermal transmittance, with an SC of about 5%.

Amongst all input variables, the boiler efficiency leads to the highest magnitude SC of -54% due to the large contribution of the space heating end-use. The Chiller COP also leads to an important contribution in reducing the EUI, with an SC of about -9.0%. Among the auxiliary equipment (fans and pumps), the supply air fan has the highest impact with SC of about -8.4%. The fans run during all months of the year, for 5,350 hours out of a total of 6,280 hours in which heating or cooling loads happen.

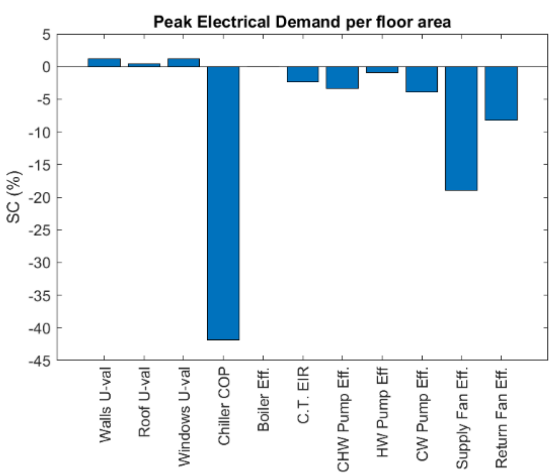

Figure 4: Sensitivity coefficient of the Peak Electrical Demand per floor area versus input variables (positive coefficients relate to an increase in the peak electrical demand).

In Figure 4, the SCs of the peak electrical demand for the selected input variables are presented. The chiller COP leads to the highest SC of about -42%. In the base case, the peak electrical load by the chiller alone corresponds to about 39% of the annual peak electrical demand. Supply and return air fans yield a SC of -19% and -8%, respectively.

In Figure 5, the SCs of the energy cost per energy consumption for the selected input variables are presented. The first relevant trend to be noticed is regarding the boiler efficiency. As the natural gas-fired boiler efficiency increases, the contribution of the natural gas as energy source relative to the total energy sources decreases. Given the fact that the natural gas is a less expensive energy source (4.70 ¢/kWh) when compared to electricity (10.1 ¢/kWh), using less of this source incurs in having a more expensive energy portfolio.

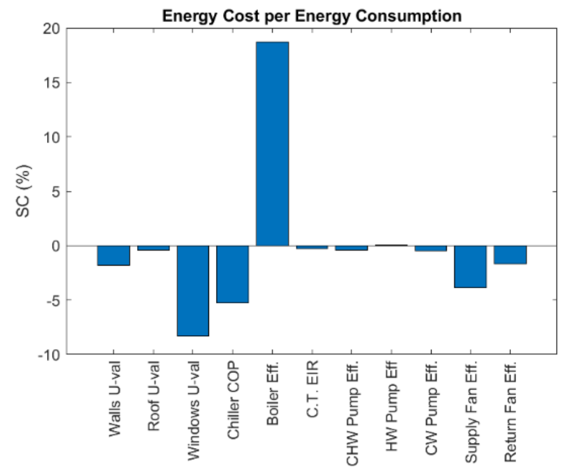

Figure 5: Sensitivity coefficient of the Energy Cost per Energy Consumption versus input variables (positive coefficients relate to an increase in the energy cost per unit of energy consumption).

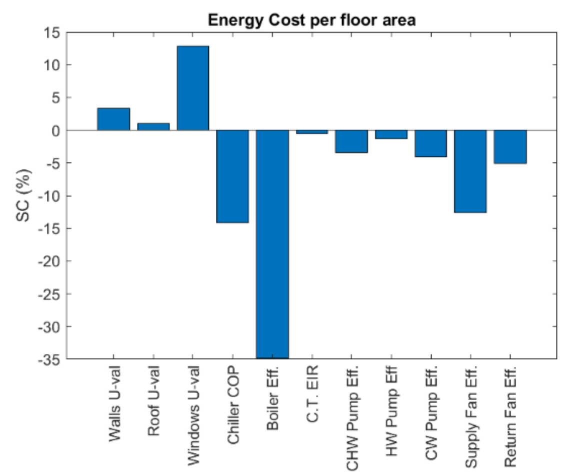

Figure 6: Sensitivity coefficient of the Energy Cost per floor area versus input variables (positive coefficients relate to an increase in the annual energy cost).

In Figure 6, the SCs of the annual energy cost per floor area for the selected input variables are presented. The same trend as the one seen in Figure 3 for the EUI is noticed. A slight change in the magnitude of the SCs is also noticed, due to the difference in the energy cost between natural gas and electricity. As seen in the referred figure, the window thermal transmittance leads to an SC approximately 13% of the annual energy cost. Building designers seeking to reduce the energy cost therefore could focus on reducing the thermal transmittance of windows. By comparing the magnitudes of the changes presented in the figure, if the same proportional change is applied to all input variables, comparatively the highest impact would be obtained by increasing the boiler efficiency. In this case, the boiler efficiency leads to an SC of -34.9%.

The interpretation of the sensitivity coefficients is highly dependent on the user's objective. Depending on the application, the user will select an individual KPI or a set of composite KPIs that better measure the intended outcome. Based on that selection, the user can then assert which input variable has the highest impact. In building energy code applications, in which usually either the EUI or the annual energy cost are the most used metrics, based on the case study data, one could assert that the boiler efficiency is the predominant factor. Looking from a different perspective, if one is focusing on reducing the peak electrical demand, one could assert that the chiller COP is the predominant factor.

There is a wide range of variables within a specific application and policymakers can benefit from prioritizing certain fields of research. Since only relative changes, which represent feasible values that can be achieved in practice, are used for comparison of input variables, different components (e.g. wall U-value and chiller COP) can be compared in order to assert their impact. As an example, the wall U-value leads to an SC of approximately 5.2% of the base case EUI, while the chiller COP leads to an SC of approximately -9.0%. In this scenario, prioritizing advancements in the chiller COP would be more effective than prioritizing advancements in the Wall U-value, given that achieving both advancements require a similar amount of research resources.

The proposed method provides a way to weigh the impact that various relevant components to the design and operation of a building have on a reference prototypical model. In order to showcase the proposed method, a single building case study was performed. The present research does not encompass the comparison of different sensitivity analysis methods, but it proposes a method that addresses important aspects when it comes to performing sensitivity analysis: the number of simulation models (and consequently, the time) needed to obtain useful sensitivity results, the ease to implement said methods in a computer code, the computational power needed to perform the analysis and the ease to interpret the final sensitivity coefficients. The method proved to be easy to implement using eQUEST native functionalities and an additional MATLAB code. Additionally, the method proved to be time and resource efficient. Using a standard portable computer, the total simulation time for all 65 simulation runs was 43 minutes, with the MATLAB post-processing code adding an extra minute at the end of the simulation runs.

The scope of the present work could be expanded in future works to encompass producing conclusions that could be readily implemented in the current stage of the NECB development. This expansion of scope would require applying the proposed method in a selection of statistically representative building models over a selection of statistically representative climate zones in Canada. In that case, a weighted average of the sensitivity coefficients obtained from each model run would indicate which areas in the future version of the code should be prioritized. This prioritization can come in the form of allocation of R&D resources in the development of improvements to critical building envelope and HVAC equipment components. Another application would be the comparison of different design alternatives by using their sensitivity coefficients and subsequent selection of which design alternatives should be implemented if the coefficients meet a certain threshold.

While the whole building KPIs are a summarized and holistic metric that encompass the combined effects of all design choices, they do not consider the initial investment necessary to implement the ECMs and how the system behaves over their entire lifetime. It is beyond the scope of the present research to explore the investment necessary to implement the changes studied in the input variables section or the net present value of the building operation throughout its lifetime. Given the availability of price and equipment performance degradation data, including the life cycle cost or life cycle energy consumption could prove beneficial to understand the long-term impact of proposed ECMs.

CONCLUSION

The proposed method is useful as a tool for energy code updates by assessing the potential increase of Key Performance Indicators (KPIs) due to changes in design input variables. Further updates of NECB-2017 prescriptive requirements should consider prioritizing modifications of design input values based on their impact on these KPIs.

The sensitivity analysis of the energy efficiency of the case study building indicate that the minimum energy performance requirements of HVAC equipment, such as chillers, boilers, fans and pumps have the highest impact amongst the studied variables. Applying these changes on NECB requirements would significantly modify the values of the KPIs at the whole-building, system and equipment levels.

Although the increase of annual building energy efficiency is an important goal, code updates should consider the life cycle cost, energy use and emissions. The proposed method can aid in allocation of R&D resources in the development of improvements to the building envelope and HVAC equipment. Policymakers can also benefit from this proposed method by having an extended understanding on the impact of changes in energy code's provisions on the prototypical building's energy consumption and/or cost.

Future work will include the generalization of the proposed method to different climates and other building types, and the addition of life-cycle related KPIs.

ACKNOWLEDGEMENTS

The authors acknowledge the financial support from Natural Sciences and Engineering Research Council of Canada and

the Faculty of Engineering and Computer Science of Concordia University.

REFERENCES

ASHRAE. (2013). *Energy Standard for Buildings Except Low-Rise Residential Buildings (Standard 90.1-2013).*

Bowley, W., Westermann, P., & Evins, R. (2018). Using Multiple Linear Regression to Estimate Building Retrofit Energy Reductions. *Proceedings of eSIM 2018: Building Simulation Conference*. Montréal (Canada), 9-10 May 2018.

CIBSE. (2004). *Guide F: Energy efficiency in buildings.*

Crawley, D. B., Hand, J. W., Kummert, M., & Griffith, B. T. (2005). Contrasting the capabilities of building energy performance simulation programs. *Building and Environment 43(4)*, 661-673.

Dincer, I., & Dost, S. (1996). Energy intensities for Canada. *Applied Energy, 53(3)*, 283–298.

EIA. (2019). *International Energy Outlook 2019.* IEA. Paris (France).

Feist, W., & Ebel, W. (1998). Low Electricity Houses - A Real Case: The Passive House in Darmstad-Kranichstein. In *Development with Sustainable Use of Electricity*. Springer. Dordrecht (Netherlands).

Girgis-McEwen, E., & Ullah, R. (2018). Energy efficiency measures for net-zero energy ready building codes. *Proceedings of eSIM 2018: Building Simulation Conference*. Montréal (Canada), 9-10 May 2018.

IEA. (2015). *Energy Balances of OECD Countries 2015*. OECD Publishing. Paris (France).

Irwin, R., Chan, J., & Frisque, A. (2016). Energy Performance for ASHRAE 90.1 Baselines for A Variety of Canadian Climates and Building Types. *Proceedings of eSIM 2016: Building Simulation Conference*. Hamilton (Canada), 3-4 May, 2016.

Isaacs, N. P. (1999). Performance-based Building Energy Efficiency Code. *Proceedings of Building Control Commission International Convention.* Melbourne (Australia), 12-15 April, 1999.

Lerond, J. (2017). *eQUEST Batch Processing Documentation.* Available: https://lymerej.gitbooks.io/equest-batch-processing-documentation/content/functioning.html

Madison, K. (2012). *Large Batch DOE-2 Modelling with eQUEST.* Available: https://docs.google.com/open?id=0B2_lyY0pvJmVZHgwd3lDR3VvU0E

Madison, K., Usibelli, T. J., & Harris, J. P. (1994). The Washington State Non-Residential Energy Code: A New Model Process for Code Development. *Proceedings from the 1994 ACEEE Summer Studies on Energy Efficiency in Buildings*. Washington, D.C. (U.S.A.), 28 August-3 September, 1994.

Mechri, H. E., Capozzoli, A., & Corrado, V. (2010). USE of the ANOVA approach for sensitive building energy design. *Applied Energy, 87(10)*, 3073–3083.

Ministère de l'Égalité des territoires et du Logement. (2011). *Réglementation thermique 2012: un saut énergétique pour les bâtiments neufs.*

Ministère de l'énergie et des ressources. (2019). *E-1.1, r. 1 - Regulation respecting energy conservation in new buildings.*

NRC. (2016). *Energy Use Data Handbook: 1990 to 2016.* Natural Resources Canada. Ottawa (Canada).

NRC. (2017). *National Energy Code of Canada for Buildings 2017.*

Rallapalli, H. S. (2010). *A Comparison of EnergyPlus and eQUEST Whole Building Energy Simulation Results for a Medium Sized Office Building (Master's thesis).* Arizona State University, Tempe, Arizona, U.S.A..

Rosenberg, M., Jonlin, D., & Nadel, S. (2017). A Perspective of Energy Codes and Regulations for the Buildings of the Future. *Journal of Solar Energy Engineering, 139(1)*, 1-6.

Ryan, E., Wild, O., Voulgarakis, A., & Lee, L. (2018). Fast sensitivity analysis methods for computationally expensive models with multi-dimensional output. *Geoscientific Model Development, 11(8)*, 3131–3146.

Saltelli, A., Ratto, M., Andres, T., Campolongo, F., Cariboni, J., Gatelli, D., Saisana, M., & Tarantola, S. (2008). *Global Sensitivity Analysis: The Primer.* John Wiley & Sons. Chichester (U.K.).

Song, J., Wei, L., Sun, Y., & Tian, W. (2014). Implementation of Meta-modelling for Sensitivity Analysis in Building Energy Analysis. *Proceedings of eSIM 2014: Building Simulation Conference*. Ottawa (Canada), 8-9 May 2014.

Statistics Canada. (2019a). *Table 18-10-0204-01 - Electric power selling price index, monthly*. Available: https://www150.statcan.gc.ca/t1/tbl1/en/tv.action?pid=1810020401

Statistics Canada. (2019b). *Table 18-10-0034-01 - Raw materials price index, monthly*. Available: https://www150.statcan.gc.ca/t1/tbl1/en/tv.action?pid=1810003401

Tian, W. (2013). A review of sensitivity analysis methods in building energy analysis. *Renewable and Sustainable Energy Reviews, 20*, 411–419.

USGBC. (2019). *LEED V4 for Building Design and Construction.*