A Sensitivity Analysis Method for the Update of the National Energy Building Code of Canada (NECB-2017)

Pedro Rafael Guaraldi da Silva

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By: Pedro Rafael Guaraldi da Silva

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Signed by the final Examining Committee:

____ Chair
Dr. M. Nik-Bakht

____ Examiner
Dr. M. Nik-Bakht

____ Examiner
Dr. M. Ouf

____ Supervisor
Dr. R. Zmeureanu

Approved by ____
Dr. Ashutosh Bagchi Chair of Department

__________ 2021 ____
Dr. Mourad Debbabi Dean of Faculty

ABSTRACT

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Pedro Rafael Guaraldi da Silva

An increasing trend in energy consumption can be seen worldwide. Projections for the world energy consumption indicate an increase of nearly 50% by 2050. In Canada, the electric power selling price has risen by 250% in the last four decades. The rising trend in energy consumption and cost is a pressing concern. Within that trend, residential, commercial, and institutional buildings are big contributors, accounting for 28% of the total secondary energy use in Canada. As a direct response to the increase of energy use in buildings, minimum energy efficiency requirements were proposed and compiled into energy standards, seeking to provide guidelines and instructions in the design, construction, and operation stages. These standards proved to be a powerful tool to improve energy efficiency, especially if adopted by state and federal legislators as mandatory requirements. Given the major role that such standards play, attention is drawn to the process used in updating these energy efficiency requirements. This research proposes a method for identifying the most impactful factors in the energy efficiency of buildings and for quantifying the impact that changes in these factors have on a range of energy related KPIs. This method can help policy makers and parties involved in the update of building energy code requirements by providing a metric to prioritize changes based on their impact. Additionally, the proposed method can aid in the allocation of R&D resources in the proposal of improvements to the building envelope and HVAC equipment, based on the impact of each of the studied improvements.

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To the great patriarchs and matriarchs of my family, who without seeing the end of their ventures, by paths as yet untrodden and through perils unknown, have paved the way for me today to imprint my mark upon the world.

To my immediate family, my father, my mother and my brother, who have, at the hardest of times, been a constant reminder of what I'm fighting for.

To my grandmother, who successfully raised two generations and exerted a tremendous positive influence on many others, which certainly adopted her as mother, sister and mentor.

To my aunt, who has set the example for me to enter Academia and has served as a fountain of wisdom, both temporally and spiritually, from which I draw to the present day.

To my uncle, who taught me how to achieve excellence in everything that I do and to hold myself accountable for all my actions and their consequences.

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At times, life can be challenging, and the success thereof appears to be the product of constant, mindful and conscientious struggle. I draw from the same words that Queen Elizabeth II used in her first Christmas Broadcast in 1957:

"Though with great difficulty I am got hither, yet now I do not repent me of all the trouble I have been at to arrive where I am. My sword I give to him that shall succeed me in my pilgrimage and my courage and skill to him that can get it. My marks and scars I carry with me, to be a witness for me that I have fought his battles who now will be my rewarder."

The Pilgrim's Progress by John Bunyan

The silver lining of enduring life's challenges lies in the development not only of the intellect, but also of the spirit. A morally sound and prepared spirit allows us to "*escape the deserved agonies of our moral failings and overcome the undeserved agonies of our mortal misfortunes*". What better can describe the fruits of the Spirit than the words of Parley P. Pratt?

"The gift of the Holy Ghost...quickens all the intellectual faculties, increases, enlarges, expands, and purifies all the natural passions and affections, and adapts them, by the gift of wisdom, to their lawful use. It inspires, develops, cultivates, and matures all the fine-toned sympathies, joys, tastes, kindred feelings, and affections of our nature. It inspires virtue, kindness, goodness, tenderness, gentleness, and charity. It develops beauty of person, form, and features. It tends to health, vigor, animation, and social feeling. It invigorates all the faculties of the physical and intellectual man. It strengthens and gives tone to the nerves. In short, it is, as it were, marrow to the bone, joy to the heart, light to the eyes, music to the ears, and life to the whole being."

Key to the Science of Theology by Parley P. Pratt

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CHAPTER 1 : Introduction and Motivation

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 [1].

An increasing trend in energy consumption can be seen worldwide. In Canada, the total final energy consumption increases by an average of approximately 13% from one decade to another, while the average for all the countries that are members of the Organisation for Economic Co-operation and Development (OECD) is approximately 7% [2]. Projections for the world energy consumption indicate an increase of nearly 50% between 2018 and 2050 [3].

An increasing trend in energy prices can also be observed. In Canada, the electric power selling price has risen by approximately 80% from January 2000 to January 2020 [4]. The crude energy products price (a category comprising crude oil and bitumen, natural gas and other energy products, such as coal, steam and heated or cooled water) has risen approximately by 83% in the same time frame. Despite presenting an overall increasing trend, the energy price can be significantly disrupted by and during certain events. The COVID-19 pandemic has triggered a historic price drop in crude energy products. In Canada, comparing April 2020 with January 2020, the conventional crude oil price has dropped approximately 70% and the natural gas price has dropped approximately 12%. Since the drop in April, the price of crude energy products has risen back again sharply and continues to increase. [5]

Within the context of buildings, the energy consumption follows the aforementioned increasing trends. In OECD countries, total building energy consumption is expected to increase by an additional 13% from 2018 to 2050 [3]. In Canada, according to the Energy Use Data Handbook, the set of residential, commercial and institutional buildings sectors combined accounted for 28% of the total secondary energy use (final demand) in the year of 2017. If the trends observed in the past three decades remain the same, the total building energy consumption is expected to increase by an additional 20% from 2017 to 2050 [6].

The dynamics of energy price and consumption have affected how buildings are designed, constructed and operated. Reducing energy consumption has become a research focus as a response to the environmental impact of buildings, financial expenditure with energy resources and to the volatility in energy prices. Building energy 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 [7].
- In the U.S., ASHRAE Standard 90.1, with its first edition in 1975 [8].
- In Canada, National Energy Code for Buildings (NECB), with its first edition in 1997 [9].
- In Québec, E-1.1, r.1 - Regulation respecting energy conservation in new buildings, with its first edition in 1983 [10].
- In the U.K., CIBSE Guide F, with its first edition in 1998 [11].

In addition to building energy codes, a number of sustainability and energy performance labels have been developed. Examples of these labels are the LEED certification, with its first pilot in 1998 [12], and the PassivHaus certification, with its first certified building in 1991 [13].

The development of building energy codes has had a great impact on the energy consumption of buildings. Compared with the 1975 baseline version, compliance with the ASHRAE 90.1-1989 Standard leads to a 15% reduction of the building energy use, compliance with the 2004 version leads to about 30% reduction, and compliance with the 2013 version leads to about 50% reduction. It is expected that the future versions of the ASHRAE 90.1 Standard will lead to a 70% reduction of building energy use by 2025 [14]. As for the Canadian counterpart, compliance with the NECB 2017 improves building energy efficiency by up to 15% when compared with the NECB-2011 version, and it is expected that future versions of NECB will reach the goal of Net Zero Energy Ready buildings by 2030 [9].

Given the major role that such standards play, attention is drawn to the process used in updating their energy efficiency requirements. The main steps used in the process of updating performance-based building energy efficiency codes are outlined, as follows [15]:

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, many of which are new technologies, 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 reasonable computational times for business and research applications [16]. 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 [17].

The goal of this research is the proposal of a multi-linear regression sensitivity analysis method to evaluate the impact of suggested ECMs on building energy related KPIs. The proposed method provides a solution for policymakers to prioritize suggested changes to future energy code versions base on their impact on building energy performance. Amongst the research objectives are the combination of a simulation program and sensitivity analysis method in order to produce a method that is easily implemented, time efficient, and that uses readily available computational resources. One of the results of the application of the method is obtaining a series of sensitivity coefficients that allow for a straightforward comparison between ECMs in different categories (e.g. lighting, HVAC, building envelope). These coefficients are then used to propose changes to minimum energy efficiency requirements that integrate NECB updates.

The assumptions of the proposed method are that the energy related KPIs compiled from the simulation outputs are linearly correlated with the input variables. Another assumption is that the input variables are independent. These assumptions imply that the model is dependant on the chosen dataset. It is important to validate the model before recommendations to code updates are made. The method is applied to a refence building modelled according to the prescriptive and performance requirements of NECB-2017. The results obtained from this application and subsequent code update recommendations benefit new buildings modelled according to the NECB. The method was validated in a case study institutional building, modelled to be compliant with NECB-2017. For the chosen set of input variables, with changes performed one at a time, it was verified that the KPIs are linearly correlated with the input variables. Conclusions were drawn for different climatic zones in Canada and recommendations for changes in the NECB were provided. These conclusions and recommendations are limited to a building with similar design characteristics to the chosen reference building. Future works include the generalization to other building types, covering a bigger portion of the Canadian building stock.

CHAPTER 2 : Literature Review

This chapter presents a critical literature review of publications related to the development of building energy codes or standards. Three main items that have contributed to the development of such codes/standards are investigated: Building Energy Modelling and Building Performance Simulation (BEM/BPS), Key Performance Indicators (KPI), and Sensitivity Analysis. This investigation is conducted by first providing from the literature a conceptual definition for each one of these items and how they are used in the field of building energy codes. Afterwards, a summary of studies within the broad context of building energy performance provide a *state-of-the-art* overview of these items. Lastly, another summary of studies demonstrates the current usage of these tools by researchers and policymakers within the specific context of building energy code development.

The goal of this investigation is building a foundational understanding of building energy performance simulation, how to measure energy performance in buildings, and how correlations between these performance metrics and the many input variables of the simulation can be found. This goal is achieved by providing a conceptual definition and a summary of studies, both in a broad building energy performance context and in the specific context of code development. Another goal of the present chapter is to outline how the application of these three tools together in the development of building energy codes can be improved. This is met by identifying research gaps in the studies and proposing solutions in the conclusion of the literature review.

2.1. Method

This section describes the procedure employed in gathering the publications that served as a base for the present study. The steps used to search, evaluate and organize the literature are listed below:

1. Selection of keywords in areas pertaining to the study;
2. Search the Google Scholar website with Harzing's Publish or Perish software [18];
3. Selection of most relevant papers for the preliminary review;
4. Detailed analysis of selected papers;
5. Expansion of search to other papers that are referenced in the first set of selected papers, altogether with papers recommended by ScienceDirect and Mendeley based on what other researchers explored, and
6. Organization of papers into a database using Mendeley software [19].

The keywords used in the search are chosen to be reliable descriptors of the methods and objectives planned for the study. These keywords are a combination of the author's choice and common keywords in related publications. Once defined, these keywords serve as the search strings that are used as inputs in the Harzing's Publish or Perish (PoP) program, an automated search software used for scholarly publications.

To perform a search in the literature, the user can select from publicly available data sources, such as Crossref, Google Scholar, Scopus and Web of Science. Once the data source is chosen, the user inputs main parameters to guide the search, such as author, title or keywords and year range. The resulting publications from this search are evaluated and ranked using citation and impact metrics. Google Scholar was chosen as the data source since it is free to use and it is estimated to cover over 99.3 million documents, or approximately 87% of the total number of scholarly documents found on the web [20].

Starting from the results listed by PoP, a preliminary review of the abstract, methodology and conclusions from each paper allow the selection of the most relevant publications to be analysed in detail. Once a publication has been thoroughly analysed, the search is expanded using ScienceDirect's website feature for recommended articles or Mendeley software feature for related documents.

ScienceDirect is a web-based database for scientific research publications. The Article Recommender feature suggests other articles that might be worth exploring, based on researchers' online search behavior. Mendeley is a free reference manager used to manage and share research papers and to generate bibliographies. Mendeley’s recommendations come from a mix of analysis based on the content of the selected paper and what other users with similar interests are reading.

After this process is done, the publications are organized into a database using Mendeley. The document database in Mendeley is a list of publications, ordered by authors, title, year, journal and date of inclusion on database. By clicking on each row of this list, more details of the publication are displayed, provided that such information is available and indexed in the chosen data source. Examples of these additional details are the abstract, keywords, URL to journal webpage containing the paper, and the DOI and/or ISSN.

2.2. Building Energy Modelling (BEM) and Building Performance Simulation (BPS)

The literature search related to this topic uses the following keywords: energy code optimization; building energy performance; code development; building energy modeling.

Building Energy Modelling (BEM) can be defined as the *"analysis of building energy performance through its simulation using predefined criteria describing building composition and utilisation"* [21]. Similarly, Building Performance Simulation (BPS) can be defined as *"the replication of aspects of the building performance using a computer-based, mathematical model created on the basis of fundamental physical principles and sound engineering practice"* [22]. Within the predefined criteria used to create a building model, one can find information describing the building shell, internal loads, HVAC systems and utility rates and economics. These criteria serve as inputs to model complex energy flow interactions within and between the building and its boundaries. As examples of these interactions, one can cite heat and moisture transfer through conditioned and unconditioned or outdoor spaces and heat generated within the conditioned spaces by lighting and equipment. The main output of the simulation is the use of energy and the utility cost of the building.

Although the terms simulation and model are commonly used as synonyms, Becker and Parker [23] brought attention to an important distinction that must be made with regards to these terms. According to the authors, *"a **simulation** enacts, or implements, or instantiates, a **model**. A **model** is a description of some **system** that is to be simulated, and that model is often a mathematical one. A **system** contains objects of some sort that interact with each other. A model describes the system in such a way that it can be understood by anyone who can read the description and it describes a system at a particular level of abstraction to be used."*

BEM/BPS is used extensively during the design and retrofit of individual buildings. Crawley [24] unveiled that another powerful use of this tool consists on assessing the impact of changes of energy standards requirements on the building energy performance. This assessment is done by evaluating changes in the energy use and utility cost of buildings (outputs of the simulation) as a function of changes in minimum performance requirements set out in these standards (inputs of the simulation). As an example to illustrate this idea, one study used BEM/BPS to evaluate how the whole-building annual energy use changes by improving the envelope thermal transmittance and HVAC equipment efficiency, with base requirement values taken from NECB-2015 [25].

This additional understanding supports the development of these regulations by providing policymakers with a tool to quantify and maximize the financial (e.g. through cost) and environmental (e.g. through energy use) benefits of improvements to these regulations. These benefits can be reaped in an individual building level when applied in specific case studies, and also in regional and national levels when simulation is applied to a set of building models covering statistically representative building types and locations (called building stocks) [15].

2.2.1. Overview of BEM/BPS Literature

Simulation programmes have been available since the 1960s, aiding in the design of buildings by providing load calculations and energy analysis. The drive for a more sustainable built environment has prompted the development and improvement of these programmes. Capabilities to model heat and mass transfer, airflow, daylighting and different types of system and components were successively appended. Improved graphical user interfaces have facilitated the use of complex features and have contributed to the success and widespread use of these tools [26].

Since its introduction and popularization in the building engineering field, BEM/BPS tools have been used in a broad spectrum of applications. These programs facilitate the modelling of building composition and utilisation and provide engineers with useful and easy-to employ energy diagnostics tools. Hong, Chou and Bong [27] listed some of the popular applications: (i) building heating/cooling load calculation; (ii) energy performance analysis for design and retrofitting; (iii) Building Energy Management and Control System (EMCS) design; (iv) compliance with building regulations, codes and standards; (v) cost analysis; (vi) study of passive energy saving options, and (vii) Computational Fluid Dynamics.

Amongst the objectives of using BEM/BPS programmes, one can cite: (i) to ensure requisite levels of comfort and indoor air quality; (ii) to devise energy efficiency and demand management solutions; (iii) to embed new and renewable energy technologies; (iv) to lessen environmental impact; (v) to ensure conformance with legislative requirements, and (v) to formulate energy action plans at any scale. One approach used to accomplish these objectives is to use BEM/BPS programmes to evaluate design variants iteratively and identify new potential directions in the development process. These programs can also be used to evaluate the robustness of a technology under different usage scenarios and operating conditions. Lastly, they provide an opportunity to assess materials, components and systems in a virtual environment without the need to build physical test prototypes. This equips engineers with a cost-effective method to explore different building design options and technologies. With uses exceeding the design phase of buildings, BEM programmes can also assist in the phases of building commissioning and operation. During these phases, comparisons between predicted and measured performance and evaluation of whole life performance aggregate robustness to the analysis [26].

Substantial energy savings during building operation can be achieved when conventional building design considers energy efficiency. Heating, Ventilating and Air Conditioning (HVAC) systems and lighting relate to a large portion of a building's energy use and are good candidates to be the focus of energy efficiency measures. BEM/BPS programmes can be used to model such systems individually and as parts of an integrated system, modelled to represent complex and dynamic interactions between the outdoor environment, the building envelope, the HVAC system, the lighting system, and control devices. [27]

There are several BEM/BPS programs available on the market with diverse sets of features that render different scopes. It is beyond the scope of this study to discuss the advantages and limitations of specific programs, as the list of available programs and related publications is substantial. Instead, a discussion of the criteria used for the selection of such programs is provided.

Crawley et al. [17] surveyed and compared the features of major building energy simulation programs. Examples of the programs analysed are DOE-2.1E, EnergyPlus, eQUEST, HAP and TRNSYS. The programs capabilities are compared in several categories, incorporating calculation of thermal and electric loads, simulation of HVAC system and plants and economic evaluation. Users are encouraged first to study their simulation needs and then choose from a suite of tools a program that would best suit the particularities of each case.

Rallapalli [16] reiterated that the choice of the simulation program is dependant on the usability and applicability of the program with respect to the user's needs. A comparison between eQUEST and EnergyPlus modelling process and simulation results for a medium sized office building is also presented. As main characteristics for eQUEST, a user-friendly graphical interface and rapid simulation times for a high number of spaces are pointed out. As for EnergyPlus, it is pointed out the capacity to model more complex systems, producing more accurate results, but with longer simulation times.

Hong, Chou and Bong [27] suggested that the user should be familiarized with the application scope of the program, more specifically by understanding the assumptions, simplifications, and approximations in the calculation procedures. The users understanding should also include knowing how the input files are structured and generated. Lastly, demonstration and validation examples, providing an opportunity to compare simulation results are recommended.

The authors explored four important factors that determine the robustness of a BEM/BPS program: (i) computing capability, (ii) usability, (iii) data exchange capability, and (iv) database support.

Computing capability is an important aspect covering the core algorithm, the application scope, computing speed and accuracy and user extensibility. The core algorithm refers to whether the energy simulation is linear or non-linear, steady state or transient, deterministic or stochastic. Also, if the computation is single-zone or multi-zone based and what types of boundary conditions, initial conditions and meshing scheme can be applied to each zone. The application scope refers to what types of buildings, weather, HVAC systems and control strategies can be modelled by the program. The computing speed and accuracy are linked to which core algorithm is used and to the processing speed of the computing platform chosen for the simulation. Lastly, user extensibility refers to the users being able to develop their own modules (computer codes) that can be linked and integrated to the simulation, providing extended or customized functions for special applications.

Usability is one of the main factors that limit the use of many developed programmes in building practice. Gaps between a scientific approach and an engineering approach contribute to that limitation. The usability performance of a simulation program can be divided by its stages of use, covering learning how to use the program, preparing input data, running the program an interpreting the results. A well written user manual or guide with a user-friendly interface should guide the user during the learning process. Demonstration and validation examples, convenient on-line help facilities, an after-sales service contact, Internet support and multimedia technology can be incorporated to the program to improve this process. The effort needed to prepare input data necessary for the simulation should be kept to a minimum, with the data itself ordered in a consistent format and with the least redundancy. A diagnostic tool that scans the input file and warns the user of possible errors, as well as identifying errors during the simulation without crashing is desirable. The ability to run steps of the simulation independently, without having to re-do the whole process from the beginning is also desirable. A modularized approach, with different modules (or steps of the simulation) exchanging data with one another is a solution to address this issue. Customization of the outputs, covering summary results, detailed results and intermediate results, with the ability to export the data either as text files or as multimedia resources (graphics, images, sounds, animations and videos) that can be later integrated into other documents provides robustness to the program.

Tian et al. [28] used the EnergyPlus program to carry out batches of building energy simulation. The program was chosen since the IDF files (input data files) for EnergyPlus are ASCII files (unformatted text file) that can be easily edited using computer languages such as R, MATLAB and Excel VBA. Programming codes created using these languages are used to automatically create hundreds or thousands of energy models that are variations of a base case IDF file. Variations of parameters in input files and the results obtained from the simulation of the energy models are then analysed to assert which parameters have the most importance in selected KPIs.

During the process of code development, sequential simulations to evaluate different scenarios are needed frequently. These scenarios encompass different design characteristics such as a range of building envelope thermal characteristics, building types and climatic regions. Regarding the process of creating building models and collecting the results, Tian [29] pointed out the need of an automated process due to sensitivity analysis requiring many simulation runs to be performed. Clarke and Hensen [26] highlighted that the computational burden of such studies rises with the need to perform multiple sequential simulations. Building simulation programs which provide flexibility, easily processed input files and satisfactory simulation runtimes, such as EnergyPlus, ESP-r, TRNSYS, DOE-2 and eQUEST can be used as tools to facilitate the creation of these models.

2.2.2. BEM/BPS in Building Energy Code Development

The Pacific Northwest National Laboratory (PNNL), under contracts issued by the U.S. Department of Energy (DOE), has developed several publications and reports addressing development and compliance of building energy codes. These publications and reports are divided into two main groups, according to the scope of each research and discussed in detail within each section. The two main groups are the impact of implementation of codes and code version comparison; and the evaluation of new EEMs to be included in standards.

A number of studies [30]–[34] were performed before or after the publication of standards, either to demonstrate the feasibility of achieving a certain level of energy reduction for certain types of buildings across a range of climatic zones or to evaluate in retrospect the level of energy reduction already achieved by the studied guidelines. Other studies [35]–[43] were published as supporting literature during the development of new standards and design guides under a direct contract from the policymakers or as a standalone research projects.

Impact of implementation of codes and comparison to previous version baselines

Determining the energy savings arising from the implementation of codes and from addenda to current code editions is a critical step in the follow-up of code development and it is useful for setting new energy performance targets [30]. The following publications contained in this subsection address code development with that objective in mind.

Livingston et al. [31] presented a method in which the EnergyPlus program is used to evaluate the impact of implementing ASHRAE 90.1 Standard requirements as mandatory in the design and operation of new and existing buildings on the whole U.S.. The impact is evaluated over estimated historical and projected energy savings, consumer cost savings, and avoided emissions, covering the different versions of the 90.1 Standards. The evaluation was conducted using prototype building models developed with the EnergyPlus program. A building stock of a total of 16 commercial building prototypes in 15 climate locations was developed, representing 75% of the commercial building floor area in the U.S.. The method consisted of first modeling a baseline building stock and an ASHRAE 90.1 compliant building stock. These building stocks represented, respectively, the commercial building scenario without the intervention of building energy efficiency codes, and with the adoption of building energy efficiency codes. Second, the simulations for the baseline and the compliant building stocks were performed, recording the

Energy Use Index (EUI) for each case. Lastly, the indicators were weighted over the floor area corresponding to each building model for the two scenarios and the savings are determined by comparing the indicators for the two scenarios. From 1975 to 2010, improvements in the ASHRAE Standard 90.1 potentially yielded a reduction of over 40% in the Energy Use Index (EUI) of compliant buildings. This method is important to evaluate the benefit of adopting building energy efficiency codes and can also be used to evaluate the impact of suggestions to future versions of the code.

The report also addressed another important aspect during the development of building energy codes: code compliance. Code compliance refers to whether a building meets the energy code criteria set out during the design phase. BEM/BPS programs can be used to evaluate if a certain building is compliant to the energy standard by comparing the energy performance indicators of the building in question to the performance indicators of a baseline building. The baseline building is modelled in compliance with the strict prescriptive requirements of the code. The use of these programs in code compliance enables builders, designers, and code inspectors to assess compliance of buildings with building energy codes and offers professional liability to those involved in the designing process.

In a similar report, Thornton et al. [32] evaluated the potential energy savings from the application of ASHRAE Standard 90.1-2010 compared to the 90.1-2004 baseline. A method for evaluating the energy savings impacts of change proposals, including the evaluation of already implemented codes was proposed. The method, called ‘Progress Indicator’ consisted of the following steps: (i) develop prototype building models; (ii) generate minimally compliant models for the Standard 90.1; (iii) apply models to selected climatic zones; (iv) develop construction weighting factors, and (v) calculate the national weighted energy use intensity and energy cost index. A total of 16 prototype building models were used from the DOE Commercial Prototype Building Models, representing 80% of the U.S. commercial building floor area and over 70% of the energy consumed in U.S. commercial buildings. These prototypes were simulated over 17 climate locations, used for the development of the ASHRAE standard. The energy usage statistics arising from the simulations were weighted over building type and climate related geographic areas in the U.S. using five years of recent construction data, obtaining national-weighted energy savings. The weighting factors are necessary to provide a national average that is statistically representative of distribution of building types in each of the climatic zones. The simulation results showed 32.7% site energy savings and 29.5% energy cost savings, excluding plug and process loads.

In a later study by Liu, Rosenberg and Athalye [30], the energy savings potential of the 90.1-2016 version was evaluated relative to the 90.1-2004 baseline using the same methodology. The buildings meeting the requirements of Standard 90.1-2016 exhibited a 34.2% energy and energy cost savings relative to the baseline. The authors also pointed out that this methodology can be used in other applications, such as DOE determination, support to states adopting energy codes and code development. Whenever a new version of the Standard 90.1 is published, the U.S. DOE is required to determine if the update would improve energy efficiency in buildings. The referred methodology can be used to show if buildings constructed according to new versions of the code will use less energy than those constructed using a previous version. When states consider adopting new versions of the code, energy savings impacts, and the cost effectiveness of the code adoption can be evaluated through the sequential simulations performed on a state-level statistically representative building stock. Lastly, in code development, the energy saving impact and the cost effectiveness of individual EEMs can be determined.

Mendon, Lucas and Goel [33] assessed the cost effectiveness of the 2009 and the 2012 International Energy Conservation Code (IECC) over the 2006 IECC baseline at the state level. The analysis focuses on family dwellings, townhomes, and low-rise multifamily residential buildings. The cost effectiveness analysis was performed by assembling construction cost data for the building elements that have changed between the baseline 2006 IECC version and the analysed code. A baseline building energy model was developed, altogether with variant models that incorporate the new building elements. The energy differences between the baseline and the variant models are used to aggregate the energy savings and incremental costs to state, climate-zone, and national levels and to calculate cost-effectiveness metrics. The 2009 IECC and the 2012 IECC present a national weighted energy cost saving of 10.8% and 32.1%, respectively. An earlier report by Lucas [34], compared the energy efficiency gains between the 2006 IECC and the 2003 IECC.

Evaluation of new EEMs to be included in Standards

A series of reports address the development of the ASHRAE Advanced Energy Design Guides (AEDGs). The AEDGs provide recommendations to achieve zero energy buildings or to achieve energy savings over the minimum code requirements of the ASHRAE Standard 90.1.

Thornton et al. [35] used the EnergyPlus program in the development of the ASHRAE AEDG aiming to achieve 50% in medium sized office buildings. Recommended packages of Energy Efficiency Measures (EEMs) were analysed and the savings results for a code compliant medium office prototype building model in all 16 U.S. climate locations were presented. The study evaluated the cost effectiveness of these new proposed energy conservation measures relative to the ASHRAE Standard 90.1-2004 energy standard baseline scenario. The recommendation of a primary package of energy measures comprising using radiant heating and cooling with DOAS was evaluated and compared to a second package comprising the use of a VAV system for HVAC. Additional prescriptive packages comprising new envelope, lighting, plug load, HVAC and service water heating requirements were also evaluated and presented. The cost effectiveness of these measures was measured using the average payback period, considering national averages for the implementation and the energy costs. The evaluation approach was described in a series of steps: (i) develop a prototypical medium office building description; (ii) create a baseline model from the prototype that is minimally code compliant for ASHRAE Standard 90.1-2004; (iii) create an advanced model based on the recommended energy-saving technologies in the Report; (iv) evaluate the energy savings arising from implementing the technologies compared to the baseline model in all 16 representative climate cities; (v) present the cost-effectiveness of the energy efficiency recommendations. The primary package demonstrated a national weighted average energy saving potential of 56.1%, with an average payback of 7.6 years, while the second package demonstrated a potential of 46.3%, with an average payback of 4.6 years.

A short summary of other relevant PNNL reports that use substantially the same approach is given. The EEMs often include a common set of recommendations, spanning envelope, lighting, plug load, HVAC and service water heating EEMs, and building type specific EEMs.

Thornton et al. [36] evaluated EEMs in small office buildings, including recommendations for the use of overhangs, cool roof and improved ductwork design. A similar report refers to the development of the 30% AEDG [37].

Jiang et al. [38] evaluated EEMs in highway lodging buildings, including recommendations for miscellaneous appliances. A similar report referred to the development of the 30% AEDG [39].

Zhang et al. [40] evaluated EEMs in quick-service restaurants, including recommendations for commercial kitchen appliances and refrigeration, and kitchen exhaust hoods, heat recovery equipment and economizers.

Liu et al. [41] evaluated EEMs in small warehouse and self-storage buildings, including recommendations for infiltration reduction technologies. The authors conducted an initial scoping study to determine which technologies will be the focus of the recommendations. In the scoping study, the impact of using various technologies considered in combination on the energy savings target was assessed using a sensitivity analysis method. Once the combination of the technologies was determined, the simulations were expanded to include more building prototypes and climatic zones. In that stage, further sensitivity analyses were employed as part of the envelope analysis.

Also using the initial scoping study approach, Liu et al. [42] evaluated EEMs in small retail buildings, including recommendations for unitary packaged and split HVAC equipment, building automation and control systems, service water heating for bathrooms and sinks, and building commissioning.

Athalye et al. [43] assembled a set of EEMs that could potentially deliver 20% energy savings over a range baseline model buildings. These EEMs were selected as part of the development of a voluntary code that could be implemented in stages at a city level to improve building energy efficiency. The set of assembled EEMs addressed opaque envelope and fenestration, air leakage, interior and exterior lighting power, occupancy sensors, fan power, HVAC equipment efficiency, HVAC controls, service hot water waste heat recovery, plug load control, daylighting, and others. Five building model prototypes were selected from the DOE Commercial Prototype Building Models, a set of models representing the national building stock in the United States and evaluated over a total of 15 climatic zones. With the proposed EEMs, savings of 20% or more were achieved in nearly all building types and climatic zones. The authors referred to this report as part of a larger effort to achieve net zero energy building ready codes.

Other research reports

Evans et al. [44] presented tools that can be used in energy code development and made reference to procedures that incorporate BEM/BPS programs in different stages of the development process. In the stage of code analysis, a suite of statistically representative prototype buildings can be developed using these programs, allowing for an estimation of the energy savings from adopting the energy code. These programs can also be used in cost-benefit analyses conducted at local, regional, or national levels to build rapport for the implementation of the energy codes.

2.3. Key Performance Indicators (KPIs)

The literature search related to this topic uses the following keywords: key performance indicators; building energy simulation; energy code development.

The term Key Performance Indicator (KPI) was firstly coined in the business field. KPIs can be defined as *"the physical values which are used to measure, compare and manage the overall organizational performance"* [45]. These physical values can be quantified to measure performance in diverse fields, such as quality, cost, financial, flexibility, safety and environment.

The term eventually spread to the field of BEM, where KPIs are used as *"simple numeric metrics ... associated with a building's energy performance (i.e. lower or higher energy use)"* [46]. Building energy performance KPIs are a result of the building's characteristics, design, equipment selection and overall operation. As such, they can be used at different stages in a building's lifecycle to optimize its construction and operation by providing a metric to compare different design scenarios.

Proper selection of KPIs aids in generating correct and meaningful insights that will help to improve the building energy performance. Output BEM simulation variables can be organized and derived into Key Performance Indicators (KPIs) that can be benchmarked with other sources to assess the current efficiency level of an equipment, system or building.

The use of KPIs is especially relevant in the context of performance-based building energy codes. In such codes, maximum/minimum allowable values of KPIs are set based on a compliant reference building. Examples of these KPIs are the annual energy use (also referred as the building energy target), used in NECB [9] and the annual energy cost budget, used in ASHRAE 90.1 [8]. The use of such annual building performance values allows the code users to freely design a building within allowable ranges covering the methods, materials, and processes to be employed, provided that the proposed building presents a better KPI and respects the same characteristics (total floor area, use of building spaces, etc.) of the reference building [47].

2.3.1. Overview of KPI Literature

Hussain et al. [48] conducted a literature review and formulate new KPIs divided into three categories: economical; environmental and reliability, and quality KPIs. Some of the KPIs presented in the study were applied in a case study of a large hotel building with different types of zones.

Lourenço, Pinheiro and Heitor [49] performed a case study in eight Portuguese school buildings and link energy and environmental KPIs with the user behaviour. Based on the KPIs, management strategies were proposed to potentially enhance the energy performance.

Balaras et al. [46] presented a series of indicators that are used during the design, construction and operation of buildings. A case study on Hellenic buildings based on energy performance certificates was conducted.

ALwaer and Clements-Croome [50] developed a conceptual model to aid in the selection of KPIs that take into account the stakeholders perception on the impact of such indicators. The study focused on the use of indicators in sustainable intelligent buildings, addressing environmental, social, economic and technological issues. A model was proposed for measuring the level of sustainability in these buildings.

The International Energy Agency (IEA) [51] published a report addressing building energy performance metrics, aiming to provide data necessary to gauge progress and identify opportunities for improvement in building energy performance. Key factors that drive building energy use, such as population, building sector size, economic activity and building energy policy were discussed. Metrics data for major economies over the period of 2000 to 2012 were provided, as well as forecasts for building energy use and savings potential up to the year of 2050.

Cole and Kernan [52] performed a case study of life-cycle energy use for a generic office building. The initial embodied energy in building materials (wood, steel and structural concrete) was considered in addition to the energy associated with maintenance, repair and operation of the building. For the case study, the operating energy comprised the largest component of the life-cycle energy use.

Sun and Lee [53] compared the energy performance of two data centers in commercial office buildings. The study employed metrics that are specific for measuring energy and power usage. The data centers were characterized as high energy consuming facilities with substantial potential for energy and cost savings. Due to the intense internal process load and the need for space cooling, the usage of only traditional energy indicators was not sufficient to fully identify and support action towards the savings potential.

Abu Bakar et al. [54] discussed the use of the Energy Efficiency Index (EEI) indicator, a broad concept comprising the ratio of energy input to any chosen factor related to the energy using component (e.g. floor area). The usage of this indicator to track building energy performance in previous works was discussed, amongst other related methods and indicators.

Yan et al. [55] presented a multi-level energy performance diagnosis method for buildings where limited energy use data are available. Performance indices for benchmarking were presented and divided by building, system and component levels. The proposed methodology was validated in a case study for a high-rise building in Hong Kong.

Jonlin, Rosenberg, and Goel [56] developed a new metric to measure the total system efficiency of an HVAC system, the Total System Performance Ratio (TSPR), as an amendment to the 2018 Washington State Energy Code. The metric consists of a ratio between the annual thermal load of a building to the annual energy cost of the entire HVAC system. The cost was used instead of the energy consumption to include upstream impacts of distribution and generation losses, as well as greenhouse gas emissions. These two effects are embedded into the cost that includes the state average utility price and a social cost of carbon. The use of such metric allows flexibility in the design of HVAC systems, while respecting a target TSPR. This promotes the design of complete integrated systems that consider the interaction between the various components that make up the whole system.

The U.S. DOE [57] developed a reference manual that supports the use of the eQUEST program in the analysis of energy consumption in buildings. To perform this analysis, eQUEST provides many useful metrics relating to energy consumption and energy performance of the building and its systems in the output reports. The manual described in detail the DOE-2 computer code, used to simulate the building and generate these performance metrics, including its components. These metrics are derived from the LOADS, SYSTEMS, PLANT and ECONOMICS programs, used to simulate the thermal loads, the operation of HVAC components and to perform economical and life cycle analysis, and coded to be output in the REPORT program, used to generate output reports.

ASHRAE [58] published a pocket guide for HVAC-R, including references for ventilation requirements for residential and non-residential occupancies, occupant thermal comfort, thermal storage, radiant-panel heating and cooling, air-to-air energy recovery, space air diffusion data, equipment heat load data and other topics. The guide contains cooling load check figures that contain average values for a range of building types of typical occupancy densities, lights and other electrical equipment power densities, cooling peak thermal load densities, and supply air rates per floor area. The values can be used as a benchmark check figures in the design and commissioning of new and existing buildings.

The National Research Council of Canada (NRC) [9], in the National Energy Code of Canada for Buildings (NECB) 2017, set out technical provisions to address energy efficiency in the design and construction of new and existing buildings. Some of these technical provisions comprised minimum energy efficiency requirements for specific HVAC components, measure through KPIs. Examples of such energy efficiency KPI requirements in NECB-2017 are: (i) design flow density for air circulating fans, setting out a minimum air flow rate per unit of floor area to be delivered by supply fans, (ii) pumping power demand, setting out a maximum amount of power drawn by water circulating pumps per unit of thermal load in the spaces served by the pumps, and (iii) a combined supply and return fan power demand, setting out a maximum amount of power drawn by the air circulating fans per unit of volume displaced by the fans.

The American Society of Heating Refrigerating and Air-Conditioning Engineers (ASHRAE) [59], in the Standard 90.1, established minimum energy efficiency requirements for buildings, covering the design, construction and a plan for operation and maintenance, and the utilization of on-site, renewable energy resources. The requirements addressed building envelope, HVAC systems and components, service water heating, power, lighting and other equipment. In the performance path, the KPI used to indicate compliance of a proposed building is the energy cost budget.

The International Code Council (ICC) [60], in the International Energy Conservation Code (IECC), established minimum requirements for energy-efficient commercial and residential buildings using prescriptive and performance-related provisions. Similar to the ASHRAE Standard 90.1, it addressed the same categories and uses the annual energy cost as the performance metric to determine compliance.

The whole-building, system and component level KPIs from the literature are compiled, described and presented in Table 2.1 through Table 2.3.

Table 2.1 - Whole-building level KPIs found in the literature

Key Performance Indicator	Example of unit	Description	Ref.
Whole-building level			
Total energy use and energy use intensity	(kWh; kWh/m²; kWh/m³; kWh/m²-HDD; kWh/m²-CDD; kWh/p)	Quantifies the total annual energy consumption from all energy sources in the operation of a building. It can be normalized usually by floor area, or by volume for comparing differently sized buildings and zones with significantly different ceiling heights. It can be additionally normalized by degree days, accounting for different weather conditions or variations from year-to-year. It can also be normalized by occupant.	[9], [46] [48], [49] [50], [51] [52], [53] [54], [55] [57]
Peak power demand	(kW, W/m²; W/m³; W/ft²; W/ft³)	Quantifies the instantaneous power demand of all building equipment. It can be normalized by floor area or by volume.	[46], [50] [53], [57]
Energy cost	($; $/kWh; $/GJ; $/kBtu; $/m²; $/ft²)	Quantifies the total cost of energy resources in a building. The annual energy cost is commonly used for purposes of benchmarking with other buildings. It can include the cost of periodic and reactive maintenance of the energy system, in addition to the cost of the energy resources. It can be normalized by energy unit per source (electricity, gas, steam, etc.) or by floor area.	[46], [48] [57], [59] [60]
Power demand cost	($; $/W)	Quantifies the total cost of the power demand in a building. The demand comprises a relevant portion of the utilities bill and is normally charged considering the peak instantaneous electrical power in a month.	[46], [57] [59], [60]

Table 2.2 - System level KPIs found in the literature

Key Performance Indicator	Example of unit	Description	Ref.
System level			
Total system energy consumption	(MWh; kWh/m²; MBtu; kBtu/ft²)	Quantifies the total energy consumed for each end-use during a period. The end-use can be divided in categories such as lights, task lights, miscellaneous equipment, space heating space cooling, heat rejection, pumps and auxiliaries, ventilation fans, refrigeration, domestic hot water and external usage It can also refer to a specific system, to a circulation loop or to the whole building. It can be normalized by floor area.	[57]
Peak system power demand	(kW, W/m²; W/m³)	Quantifies the instantaneous power demand of all building equipment in each system. Examples are lighting peak electric demand and miscellaneous equipment peak electric demand It can be normalized by floor area or by volume.	[46], [50] [53], [57] [58]
Total system thermal load (heating/cooling)	(kWh, Wh/m²)	Quantifies the accumulated thermal demand for heating or cooling over a period. Can be normalized by floor area. It can be further broken down into sensible and latent thermal demands, to be used as a benchmark to evaluate different design scenarios or as an estimator for the building energy consumption.	[28], [55] [57], [61]
Peak system thermal load (heating/cooling)	(kW, W/m²; kBtu/hr; kBtu/hr-ft²; kBtu/hr-ft³)	Quantifies the maximum thermal demand for heating or cooling. Can be normalized by floor area. It can be further broken down into sensible and latent thermal demands, to be used for system selection and or as a benchmark to evaluate different design scenarios.	[46], [55] [57]
System Capacity Density	(m²/kW; ft²/RT)	Quantifies the total heating or cooling capacity of a system or circulation loop, or the nominal supply capacity or demand load of heating or cooling equipment, normalized by the floor area. It can be used as a benchmark for a preliminary comparison of cooling or heating loads with other systems, circulation loops or equipment.	[58]

System Coefficient of Performance (SCOP)	(kW/kW; Btu/Btu; Btu/kW)	Quantifies the coefficient of performance of the whole HVAC system, i.e. the amount of thermal output of the system divided by the amount of energy input of the system. Includes energy consumption of all equipment necessary to operate the system (e.g. chillers, boilers, pumps, fans)	[55]
Total System Performance Ratio (TSPR)	(kWh/$; kBtu/$)	Quantifies the economic performance of the whole HVAC system, i.e. the sum of the annual heating and cooling load divided by the sum of the annual cost of energy consumed by the HVAC system.	[56]

Table 2.3 - Component level KPIs found in the literature

Key Performance Indicator	Example of unit	Description	Ref.
Component level			
Annual Thermal Load	(MWh; MBtu)	Quantifies the annual total cooling, heating or heat rejection load in a given component (e.g. chiller, boiler, cooling tower)	[57]
Annual Energy Consumption	(MWh; MBtu)	Quantifies the annual total electrical load consumed by a given component (e.g. chiller, boiler, cooling tower, water circulating pumps, air circulation fans)	[57]
Coefficient of Performance (COP)	(W/W; Btu/Btu; Btu/h-W)	Quantifies the performance of a single component (e.g. chiller) as a ratio of the desired output energy produced to the energy input.	[9], [55] [57], [59] [60]
Boiler Efficiency	(W/W; Btu/Btu)	Quantifies the ratio of electric or fuel heat input to boiler heating capacity at full load (i.e., at the rated conditions).	[9], [57] [59], [60]
Cooling Tower Performance	(W/W; Btu/Btu)	Quantifies the ratio of electric input to nominal capacity for the cooling tower cell fan and recirculating pumps. The cell capacity is the heat rejection capacity of the cell.	[9], [57] [59], [60]
Design Flow Density	(L/s; gpm; cfm; L/s-m^2; cfm/ft^2)	Quantifies the design flow capacity of water circulating pumps or air circulating fans. It can be normalized by floor area.	[9], [58]
Pumping Power Demand	(W/kW; Btu/Btu)	Quantifies the amount of power drawn by water circulating pumps per unit of thermal load of the systems served by the pumps.	[9]
Peak combined supply and return fan power demand	(W/L-s; HP/cfm)	Quantifies the total amount of power drawn by both the supply and the return air circulating fans per unit of volumetric flow rate displaced by the fans.	[9], [59] [60]

Other BEM KPIs found in the literature cover whole-building level [46], [50], [52]–[54], system level (HVAC, lighting) [46], [50], [55], component level [46], economical [46], [48], environmental [46], [48]–[50], reliability [48], and Indoor Environmental Quality (IEQ) [46], [48], [50] KPIs.

2.3.2. KPIs in Building Energy Code Development

In the context of energy code development, KPIs are used to compare the performance of a baseline scenario and a proposed or alternate scenario. In the baseline scenario, a building energy model is used to represent (i) the current minimum energy efficiency requirements set out by energy codes, or (ii) the statistically representative performance of the actual building stock of the country. In the proposed or alternate scenario, the same model, or set of models, is adapted to incorporate new EEMs or to represent what-if scenarios, for example, if a certain requirement hadn't been put into practice. In these studies, a proposed change to the code or an alternate scenario is deemed effective if it presents a better KPI when compared to the baseline scenario. To perform these comparisons, the majority of the publications concentrate on whole-building KPIs relating to two categories: energy consumption and energy cost.

In publications that use the energy consumption as the base for comparison, the whole-building annual energy consumption is a popular choice, since it is a concise metric that covers the interactions of the proposed changes between all the modelled systems of a building over a range of climate conditions. Some studies include the life-cycle energy consumption in order to cover the energy impacts during the lifetime of the building. In publications that use the energy cost as the base for comparison, the whole-building annual energy cost is a popular choice, representing whole-building energy interactions, while also bringing to the table the main concern for building owners and operators: how much money will be spent to operate and maintain the building at the end of the year. In some studies, the payback period, internal return rate and life-cycle cost are used. Less commonly, environmental impact indicators are also used to evaluate how beneficial a proposed change is, or to serve as a tiebreaker factor when competing changes with similar energy or cost outcomes are obtained.

Livingston et al. [31] estimated the impact of adoption of the ASHRAE Standard 90.1 by obtaining the total site energy savings for U.S. buildings by weighting the whole-building annual energy consumption over the total applicable floor area subject to the code for a range of prototype models over a range of climatic zones. Finally, the total site energy savings were multiplied by the average expected lifetime of buildings to provide a more complete impact evaluation. The values were presented in the order of quadrillion Btus (Quads). After determining the total site energy savings, the energy cost savings were then determined by multiplying the total site energy savings by the national average energy price. Since the estimation was provided over the lifetime of the building, the net present value (NPV) indicator was used to represent the energy cost savings. The study also provided a summary of historical and projected emissions savings. For some greenhouse gases, the emissions were presented in equivalent metric tons of CO_2.

In a similar study, Thornton et al. [32] compared the ASHRAE Standard 90.1-2010 to the 90.1-2004 baseline. The whole-building annual energy consumption and energy cost were normalized by the floor area and were used as the indicators to compare the performance of the two code versions. Site energy and energy cost savings were presented in percent terms. A later study by Liu, Rosenberg and Athalye [30] used the same method and indicators to compare the 90.1-2016 version to the 90.1-2004 baseline.

Mendon, Lucas and Goel [33] assessed the cost effectiveness of the 2009 and the 2012 International Energy Conservation Code (IECC) over the 2006 IECC baseline at the state level. The annual energy consumption metric was extracted for each case. The energy use was then converted to energy cost using fuel costs in the different states and complemented with building upgrades and construction costs. Three cost-effectiveness metrics were computed: Life-cycle Cost (LCC), simple payback, and annual consumer cash flow. National weighted energy cost savings were also presented in percent values.

During the development of the ASHRAE AEDG, recommendations to increase energy efficiency were given in forms of new EEMs targeting the minimum code requirements of the ASHRAE Standard 90.1. These EEMs were evaluated over a range of prototype building models in different climates using a series of economic and energy KPIs.

Thornton et al. [35] evaluated new EEMs to be incorporated into the 50% AEDG for medium sized office buildings, presenting the percent energy savings for each climatic zone. The cost-effectiveness of packages of recommendations was also analysed using the simple playback metric. Reports PNNL-18773 [38] and PNNL-19809 [40] also used the same metrics.

Report PNNL-16250 that addressed the development of the 30% AEDG for medium sized office buildings presented only the average percent energy savings of the recommended EEMs [37]. Reports PNNL-17874 [39], PNNL-17056 [41], PNNL-16031 [42], and PNNL-26824 [43] also used the same metrics.

Other studies found in the literature regarding code development comprise a sensitivity analysis, with the objective of identifying the input variables that are most influential on a certain

KPI. A common practice in these studies is to obtain the sensitivity coefficients for different climatic zones, since the codes are developed to encompass a range of different locations.

Mechri, Capozzoli and Corrado [62] used the heating and cooling energy needs as the KPIs in a study to determine the variability of that KPI as a function of the variability of some building envelope design variables. The sensitivity coefficients were studied in a prototypical office building for various Italian climatic zones.

Girgis-McEwen & Ullah [25] used the whole-building annual energy use as the KPI, in a study where sensitivity analysis was applied to evaluate the impact of Energy Conservation Measures (ECMs) on an NECB-2015 compliant prototypical office building. The simulation was evaluated in six climatic zones in Canada.

Irwin, Chan and Frisque [63] also used the whole-building annual energy use as the KPI, in a study where sensitivity analysis was applied to evaluate the impact of changes in the chiller and boiler efficiency and in the Solar Heat Gain Coefficient (SHGC) of the envelope fenestration. The models used comprised a series of ASHRAE 90.1 compliant baseline models for different building types and Canadian climatic zones.

In another study, Bowley, Westermann and Evins [64] used the whole-building annual energy use, fuel and electricity cost and carbon emission as the KPI. The study applied a sensitivity analysis method to evaluate the impact of retrofits on a building stock of Victoria, BC, Canada.

2.4. Sensitivity Analysis

The literature search related to this topic uses the following keywords: sensitivity analysis, energy code optimization; building energy performance; code development; building energy modelling.

Sensitivity analysis can be defined as the study of how changes in the output of a model (numerical or otherwise) can be apportioned to different sources of changes in the model input [65]. When applied in a building energy analysis context, sensitivity analysis plays an important role in identifying the key design variables by assessing their impact on building energy performance [29]. This process allows decision makers to prioritize Energy Conservation Measures (ECM) [28] and to reveal patterns that can be used in energy optimization [66].

One way of identifying the key design variables is by quantifying the impact that changes in design variables has on selected KPIs. Local and/or global sensitivity analysis 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 [29], [67].

2.4.1. Overview of Sensitivity Analysis Literature

The methods of application of sensitivity analysis can be divided into two groups with distinct scopes: local sensitivity analysis and global sensitivity analysis.

The local sensitivity analysis, also called differential sensitivity analysis, is a derivative-based approach, in which the sensitivity of an output variable versus an input variable is explored around a base point in which a partial derivative with respect to that variable is computed [67]. In order to eliminate undesired influence between the observed input variable and other input variables, this method works by varying one factor at a time, while all the other factors are fixed [29].

The global sensitivity analysis comprises a series of methods that are based on exploring the space of the input variables and/or the combination of the spaces of the input variables. This approach of exploring the whole domain differs from the local approach, where the derivatives are estimated at a single data point, or at small, independent spaces of input variables. Using the whole space of input variables and combinations thereof enables more robust and informative analyses [67]. As analysts seek to improve the reliability of proposed ECMs and computational resources become more readily available, global sensitivity analysis methods in building energy assessment are more and more being gradually implemented [66].

The methods of application of the global sensitivity analysis can be further divided into groups with distinct calculation methodologies and interpretation of the sensitivity coefficients. As part of a comprehensive literature review of sensitivity analysis methods in building energy analysis, Tian [29] summarized the four major groups: regression method, screening-based method, variance-based method and meta-model based method. Each method is evaluated over its advantages, disadvantages and applicability and the choice of the method is dependant on the research purpose, computational cost of energy models, the number of input variables, the analyst's time for the project and the familiarity with the sensitivity methods.

The regression method is pointed out as a first alternative due to its moderate computational cost and easy to interpret and compare sensitivity indexes. This choice is conditional on the goodness of the fitting process, or in other words how linear the output and input variables are correlated, and the independence of input variables. Saltelli et al. [65] recommended a coefficient of determination R^2 to be at least 0.7 for acceptance of a regression model. If the regression method yields an uncertain fit, the meta-model analysis can be used without running an extra number of simulations. These two approaches can also be applied in observational studies, where a limited number of measurements are available. For high computational energy models and many input variables, the screening-based method can be used to provide a qualitative comparison between the input variables. Lastly, variance-based methods provide more reliable results at the cost of increased computational time.

Tian [29] also discussed how the numerical values (and distributions of these values) for the input variables can be generated. These are mainly dependant of the research purpose of the sensitivity analysis. If the objective of the analysis is to study actual monitored energy consumption, the numerical values can be generated using a normal distribution. A normal distribution encompasses the natural variations that occur in the building envelope, such as the construction, aging and actual condition of the building. If the objective of the analysis is to identify effective energy saving measures by studying design variables, a uniform distribution can be used.

Once these distributions have been generated, sampling methods can be used to combine sets of numerical values of input variables for the creation of building energy models. The Latin-hypercube sampling is pointed out as being an efficient and widely used method in building performance analysis.

Yang et al. [66] compared the advantages and drawbacks of each one of the four global sensitivity analysis methods as tools for building energy assessment in a case study retail building in China. A methodology flowchart used to describe the process of creating the energy models and using the simulation results for sensitivity analysis was provided. The steps used in the methodology are the following: (1) defining a range for the variation of input factors; (2) creating a combination of these inputs; (3) creating energy models based on these combinations; (4) running the energy models; (5) collecting the energy results; (6) conducting a sensitivity analysis, and (7) analysing the results of the sensitivity analysis. The authors suggested using at least two fundamentally different methods for sensitivity analysis to obtain more robust results when assessing building energy simulations.

Tian et al. [28] applied the regression and meta-modelling global sensitivity analysis methods in an office building. The study analysed the effect of changing the batch size (number of simulations) and checking the convergence of the sensitivity indicators before running additional simulations. The proposed sequential approach with increasing batch sizes could avoid non-convergence of sensitivity indicators due to an insufficient number of simulations or over-convergence due to a larger than required number of simulations. The authors pointed out that studies in the literature do not properly diagnose the sensitivity analysis using formal statistical methods. As a result, the reliability and correctness of the ranking of importance of variables can be improved by using the described method. The authors recommended that if within the scope of the study, statistical analysis programs such as Simlab and R can be used to perform sensitivity analysis for assessing variable importance in building performance analysis.

In a recent study, Kristensen and Petersen [68] compared the local, screening-based and variance-base sensitivity analysis methods in two ISO 13790 thermal building energy models. The authors outlined the steps of choosing and using an appropriate sensitivity analysis method for building energy model investigations. The steps were divided as: (i) defining model input distributions in either uniform or non-uniform distributions; (ii) sampling the model input using ether One-At-a-Time (OAT) discrete sampling, OAT Morris sampling or Latin Hypercube Sampling (LHS); (iii) running building energy models; (iv) applying the appropriate sensitivity analysis method, and (v) ranking the parameter by analysing the results. The authors pointed out that the three evaluated methods were able to identify the same cluster of most sensitive parameters. The final parameter ranking provided by the local sensitivity analysis method is different than the one provided by the global sensitivity analysis methods. This difference is due to the local sensitivity analysis method not being able to uncouple the effects from correlated inputs or from non-linear and non-additive model behavior in its sensitivity indices. The two global sensitivity analysis methods used yielded very similar ranking of influential parameters.

Menberg, Heo and Choudhary [61] compared the regression, screening-based and variance-based methods of global sensitivity analysis in a case study studio building using a TRNSYS simulation model. The performance of these methods was evaluated with different simulation batch sizes (also called trajectories in the screening-based method) with respect to input parameter ranking and identification of important and non-influential parameters. The authors found that for influential input parameters, the ranking and identification of influential parameters from all three methods were in very good agreement. For a quantitative analysis of parameter ranking, the authors used methods that investigate higher-order effects and parameter interactions.

Song et al. [69] applied the meta-modelling global sensitivity analysis method to evaluate the impact of ECMs on a case study office building model. The input parameters analysed in the study can be grouped in three categories: changes in the thermal characteristics of building envelope, internal heat gains and HVAC system. The impact of the ECMS was evaluated over the annual heating and cooling energy use, and the annual carbon emissions.

For the building in question, the authors recommended using heat recovery units, slightly decreasing the heating temperature setpoint and improving window thermal performance as the most relevant ECMs to reduce heating energy needs. To reduce cooling energy needs, installing low SHGC windows or external shading, using daylighting control on lighting, increasing the cooling temperature setpoint and reducing lighting and equipment peak heat gains were pointed out as the most relevant ECMs. The authors verified a linear relationship between all studied output variables and the most relevant input variables for the interval chosen and state that linear models could be used to approximate the relationship between inputs and outputs.

More robust sensitivity analysis methods, such as the variance-based method also require substantially increased model runs, typically ranging in the thousands or tens of thousands. More elaborate methods, such as Monte Carlo or LHS input sampling become necessary to properly obtain the sensitivity indices, increasing computational effort and technical expertise needed to perform the analysis. A trend is seen in the reviewed studies where for a more robust analysis, the authors tend to employ simpler energy models, such as the one prescribed by ISO 13790 instead of full-fledged computer programs, such as eQUEST or EnergyPlus. When such computer programs are used, parallel computing, either with multiple processing cores in a single computer or with a cluster of computers is employed to achieve feasible computational times. The importance of this effect is exponentially increased with the desired number of input variables to be studied. This observation reiterates that the choice of the sensitivity analysis method not only depends on the robustness of the analysis itself, but on what resources (e.g. computational, technical knowledge) are available to the analyst.

Several studies available in the literature follow a conventional approach of performing the analysis on a case study building. These studies evaluated the energy or environmental impact of alternative solutions or design options on a base case reference scenario. A range of building types in different climates, varying common design variables can be found as the baseline configuration. Examples of design variables commonly explored are climatic, building envelope and building energy use data. By comparing these studies, it is seen that the critical input variables can change from building to building depending on the climate region, constructive and operational characteristics.

2.4.2. Sensitivity Analysis in Building Energy Code Development

Although many papers found in the literature discussed sensitivity analysis in building energy simulation, only a few of these papers proposed methods that can be used in a generalized way in energy code development. The studies found in the literature that directly discuss applications of sensitivity analysis in energy code development are summarized below.

Mechri, Capozzoli and Corrado [62] proposed a method in which a variance-based global sensitivity analysis method is used to analyze the change in heating and cooling energy needs based on the variability of some design variables. The study hinted that policymakers could benefit from using such method by providing adequate information on the impact of the control parameters on the building energy needs. The authors substantiated this claim by presenting generalized conclusions for rectangular office buildings, obtained from studying a multi-story case study office building over five climatic zones in Italy. The case study building was modelled with its characteristics set according to the limits present on the prescriptive and performance requirements of the Italian building energy regulation. The impact of the variability of design variables on code compliance for different climatic zones was discussed and the most influential input parameters were identified. The authors suggested that the Italian energy code should formulate office building energy consumption as a function of the window to wall ratio. Future steps for the work comprised analysing how different shapes for the same type of building affect the obtained results.

Girgis-McEwen & Ullah [25] applied local sensitivity analysis to evaluate the impact of Energy Conservation Measures (ECMs) on the whole-building annual energy use of an NECB-2015 compliant prototypical office building in six climatic zones in Canada. The scope of the study was to evaluate potential savings arising from ECMs proposed by the Pan-Canadian Framework on Clean Growth and Climate Change. The proposed ECMs were suggestions that could be incorporated in future versions of NECB with the objective of achieving Net Zero Energy Ready (NZER) building codes by 2030. Amongst the ECMs evaluated, there were changes in the fenestration area, envelope thermal transmittance, lighting system, and energy efficient equipment and strategies. The study pointed out that not all proposed ECMs could be evaluated due to the simulation program (CanQUEST) not having the option to model the technology used by these ECMs.

Irwin, Chan and Frisque [63] applied the local sensitivity analysis over a series of ASHRAE 90.1 compliant baseline models for different building types and Canadian climatic zones. The method was used to evaluate the impact of code change decisions on a northern, heating-dominated climate such as the Canadian one. The 2007 version of the ASHRAE Standard 90.1 was used to generate the baseline models. The baseline models were then modified to incorporate the new requirements present in the 2010 version of the code. The differences in the efficiency requirements between the 2010 and the 2007 version were evaluated in the study.

The change in Energy Use Intensity (EUI) for each model was presented for three ECMs: the increase of chiller COP, boiler efficiency, and a reduction of the Solar Heat Gain Coefficient (SHGC) of windows. The authors concluded that the building type has a higher influence on the EUI than the climatic zone itself. For the Canadian climate, comparing code changes from the 2007 version to the 2010 version, including a modest increase in the boiler efficiency would have been more effective than increasing the chiller efficiency with respect to the building energy consumption. Regarding changes to the SHGC, a decrease in heating energy needs was followed by an increase in the cooling energy needs. This trade-off did not allow for an assertive recommendation of higher or lower SHGCs. Passive design principles can be used to overcome this challenge.

Bowley, Westermann and Evins [64] applied the multiple-linear regression sensitivity analysis method to evaluate the impact of retrofits on a building stock of Victoria, BC, Canada. The authors pointed out that using relative changes (percent change from baseline cases) instead of using the absolute values of the output variables leads to a better model accuracy. The regression coefficients were tested for statistical significance and input variables were removed from the model if the indicators are below a certain threshold. In addition, the model was trained using a training dataset and verified over a smaller test dataset. The study relied on a Natural Resources Canada (NRC) database containing pre-retrofit and post-retrofit energy audits performed in residential buildings. The retrofits were grouped into building shell and heating system. The impact analysis focused on the annual energy consumption, operating cost and carbon emissions, and the initial investment for the selected retrofits. Installing more efficient heating systems was indicated as the most effective retrofit option in terms of energy consumption. Installing better envelope insulation was also pointed out as a good strategy. The authors suggested that the proposed method could be applied to create municipal policies for retrofit incentives seeking to reduce energy consumption and carbon emissions.

2.5. Conclusions

General remarks from the literature

BEM/BPS programs have been used extensively in code development, as tools to evaluate the impact of code implementation, to compare updated and previous code versions and to evaluate new EEMs to be included in future code versions. In these applications, simulation programs are commonly used to create a baseline building energy model, or a series of models, which serve as a reference to compare variants incorporating changes reflecting new or proposed scenarios. Batches of simulations are conducted over a range of climatic zones, including these models, or series of models, developed to be statistically relevant building representations. These results of the batches of simulation are compared using energy or cost performance KPIs and conclusions are drawn to further the objective of reducing energy consumption or financial expenditure. In CHAPTER 3 : Building Energy Model Development, the development process of the baseline building energy model using the eQUEST program according to the latest version of NECB is described in detail. This model that represents a Canadian institutional building can be used as a reference for future studies on code development and compliance.

Due to the nature of the batch simulation process, hundreds or thousands of models representing specific building types and weather scenarios are generated. The need arises for a tool that can perform batch simulations with a user-friendly interface and that is capable of collecting and presenting energy performance results that can be interpreted intuitively through the comparison of KPIs. The present research identifies a gap in the literature as to how to perform batch simulation by using the eQUEST program. A thorough and detailed description of the batch processing feature is developed in CHAPTER 4 : Batch Processing Feature, with examples of input files generated in a spreadsheet file and the steps necessary to run the batch simulations. The present research contributes to the documentation of the eQUEST program and elevates the usage of the program to new applications, such as energy performance studies and code development, in a reliable and easy-to-use way.

In most energy analyses, whole-building indicators, such as the Energy Use Index (EUI), are used to measure building performance. This approach is limited since no information of the performance of the systems that operate within a building is provided. Although this approach is useful for building benchmarking and compliance purposes, no insights regarding how these systems could be improved can be drawn solely from these indicators. This research reviews energy related KPIs used in the current practice of building energy performance analysis and in code development. In CHAPTER 2 : Literature Review, a complete list of KPIs is compiled and filtered from the literature and divided in three levels: whole-building, system and component. Building designers and code developers, armed with this additional set of KPIs, are better prepared to understand the cause and effect relationship between the building performance and its systems and components. These indicators can be used to quantify how much each system and component contributes to the performance of the minimally compliant energy code building model.

Sensitivity analysis has been used in preliminary scoping studies to focus the efforts of researchers into the most cost-effective solutions to improve energy efficiency. The focus of these studies was to determine which EEMs were the most cost-effective and the discussion covers mostly the energy saving results. Other studies span the usage of quick, simple local sensitivity analysis to complex, resource-intensive variance-based methods that can explore combinations of inputs. Within the context of code development, there is room for a detailed discussion and presentation of a method that is simple to apply, requires average computational resources and provides an intuitive quantifiable metric to help determine which are the most relevant factors in a code performance. In CHAPTER 5 : Sensitivity Analysis of an Institutional Building in Montréal, QC, Canada, a sensitivity analysis method tailored for code development is discussed and validated in a case study. The discussion includes the energy related KPIs compiled from the literature.

Building energy codes are constantly under revision and improvement, seeking to push the minimum energy efficiency requirements of buildings and to achieve net zero energy buildings in the following decades. This research contributes to the literature addressing the National Energy Code of Canada for Buildings (NECB) by first performing the case study of the institutional building in the Canadian climatic zone of Montréal, QC, and later extending the study to multiple climatic zones in CHAPTER 6 : Sensitivity Analysis Applied to the Climatic Zones of Canada. The effects of climate on the sensitivity coefficients are studied and generalizations are drawn. 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. In CHAPTER 7 : Proposed

Changes to NECB-2017, a set of proposed changes to the current version of the code is developed based on the results of the extended sensitivity analysis study.

Scope and means of the present research

In order to address the gaps discussed in the previous paragraphs, this research presents a method for evaluating the sensitivity of KPIs on building energy performance. The proposed method is applied to the NECB-2017 in a range of climates, using as starting point the minimum prescriptive and performance requirements of the code. The analysis of results aids 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 update of the energy efficiency requirement of such codes.

The proposed method is comprised of three main steps: (i) modelling and simulation; (ii) selection and calculation of KPIs, and (iii) sensitivity analysis and conclusions.

For the modelling and simulation step, a case study (reference) building energy model is created using the eQUEST program, developed to be compliant to NECB-2017. The eQUEST program was chosen due to its capacity to model the technologies included in NECB-2017, respecting to the calculation requirements present in the code. In addition, the program is easy to use and time efficient due to, respectively, its user-friendly graphical interface and reduced runtimes for projects with a high number of spaces.

The selection and calculation of KPIs provide a quantifiable metric of the building energy performance and allow insights to be drawn as to what aspects of the minimum code requirements can be improved. This study contributes to the literature by selecting a set of energy KPIs spanning across the whole-building, system and equipment levels, complementing the traditional building Energy Use Intensity (EUI).

Lastly, a sensitivity analysis is performed and recommendations of changes to the NECB-2017 minimum energy efficiency requirements are provided. The analysis yields sensitivity coefficients that correlate the final energy efficiency of the building and its systems to the input minimum energy efficiency requirements. The application of this method is useful in updating the NECB as it provides a ranking of the most impactful requirements on energy efficiency, aiding policymakers to focus on more effective changes for the next code editions.

The proposed sensitivity analysis method uses the EUI and the annual energy cost as the main KPIs to determine which solutions are more effective in saving energy and reducing cost.

The initial cost of equipment and building materials are not included in the present study, as they are susceptible to market and technology variations that happen year to year. These results obtained with the proposed method do not encompass the optimum life cycle cost design option; but rather focus only on the operation energy use and cost. Starting from these results, future studies must include the initial costs of changing code's prescriptions, in order to provide a holistic view of the impact of these changes.

CHAPTER 3 : Building Energy Model Development

This chapter describes the procedure and the premises employed in setting up the building energy model. The building envelope, loads and systems are modelled in such a way that they fully embody the energy efficiency requirements of the National Energy Code of Canada for Buildings (NECB) 2017 [9]. The objective of this development is to create a fully compliant reference building model that serves as a benchmark to evaluate the impact of the aforementioned requirements on some Key Performance Indicators (KPI) regarding energy efficiency, such as the annual building energy consumption.

There are many building energy simulation programs available to develop the model, each one varying in number and extension of features and capabilities. A study has been published contrasting the capabilities of twenty major programs, including DOE, EnergyPlus and TRNSYS. One of the conclusions is that users would benefit from having a suite of tools from which they could choose, having in mind specific simulation tasks or technologies needed to be approached by the simulation at hand [17].

In the current study, attention must be paid to what tasks and technologies are present in the model. The energy efficiency requirements found in NECB 2017 focus on: determining compliance of acceptable solutions (Part 1 of NECB); prescriptive requirements to the building envelope (Part 3 of NECB), lighting (Part 4 of NECB), HVAC systems (Part 5 of NECB), service water systems (Part 6 of NECB) and electrical power systems and motors (Part 7 of NECB); or compliance to the building energy performance as a whole (Part 8 of NECB).

Another important aspect that needs to be observed when choosing the program is that there are some specifications that the energy model calculations should conform to. NECB 2017 and ASHRAE Standard 90.1 [8] (one of the referenced codes in NECB) present some requirements for the modelling to be compliant, such as: processes that must be included in thermal load calculations, energy consumption of electrical systems, time interval used in the simulation, operating schedules and climatic data and number of unmet hours for the temperature setpoint. A complete test method to evaluate building energy analysis using computer programs is described in ASHRAE Standard 140 [70].

The technologies included in the aforementioned Parts of NECB 2017, as well as the energy model calculation requirements that are applicable to the present study can all be modeled using eQUEST. In addition to its wide range of application, eQUEST is easy to use due to having a user-friendly graphical interface that allows users to edit DOE-2 text files in a straightforward manner and quick in producing results due to presenting reduced runtimes for projects with a high number of spaces. All of this contributes to eQUEST popularity as one of the widely used energy modelling tools [16]. Since in the present study the analysis of the impact of each energy efficiency requirement is performed through batch simulations of a multi-space model, these factors weigh-in for the choice of eQUEST as the modelling software.

The next step is to define the building to be used for the sensitivity analysis. The chosen building is the Centre for Structural and Functional Genomics building, a research facility subject to Concordia University. This research facility building comprises mainly office and laboratory spaces served by ancillary conference rooms, storage rooms and corridor spaces. The eQUEST model was developed from a base file [71] and modified to comply to NECB 2017.

A thorough description of the model discussing the building shell, internal loads and the water-side and air-side HVAC system is provided in the Sections 3.1 to 3.5 of the thesis.

3.1. Project & Site Info

The building is located on 7141 Rue Sherbrooke Ouest, Montréal, QC, H4B 1R6 (Lat 45.4586, Lon -73.6427, Alt 52 m). For visualization purposes, a satellite rendering from Google Maps and the 3-D geometry view from eQUEST are presented in Figure 3.1 and Figure 3.2, respectively.

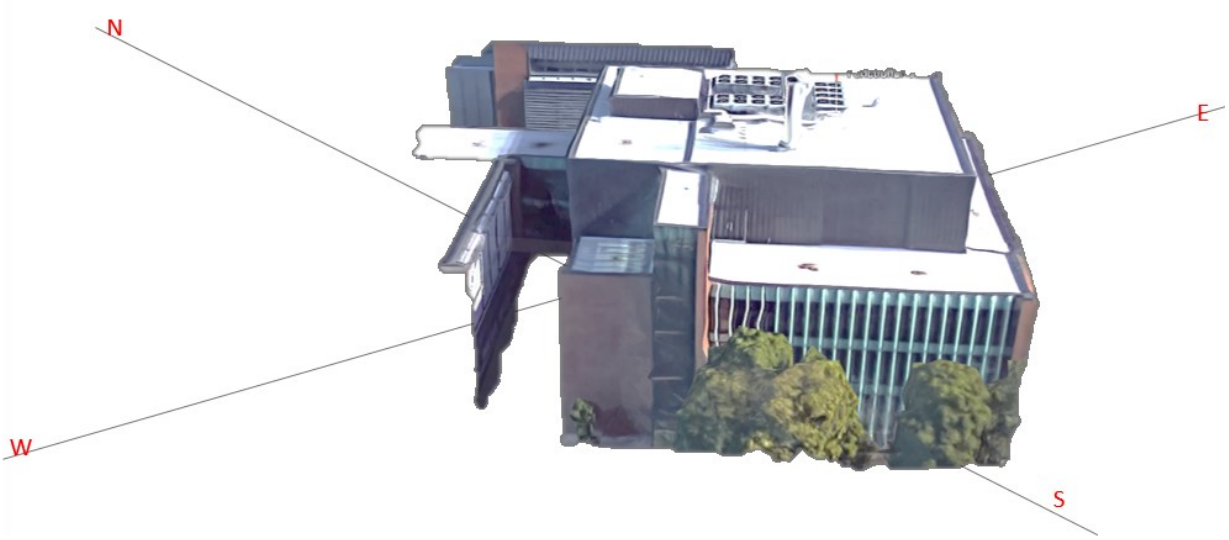


Figure 3.1 - 3-D Rendering of Satellite imagery of Genomics Building (extracted from Google Maps on May 24th, 2019)

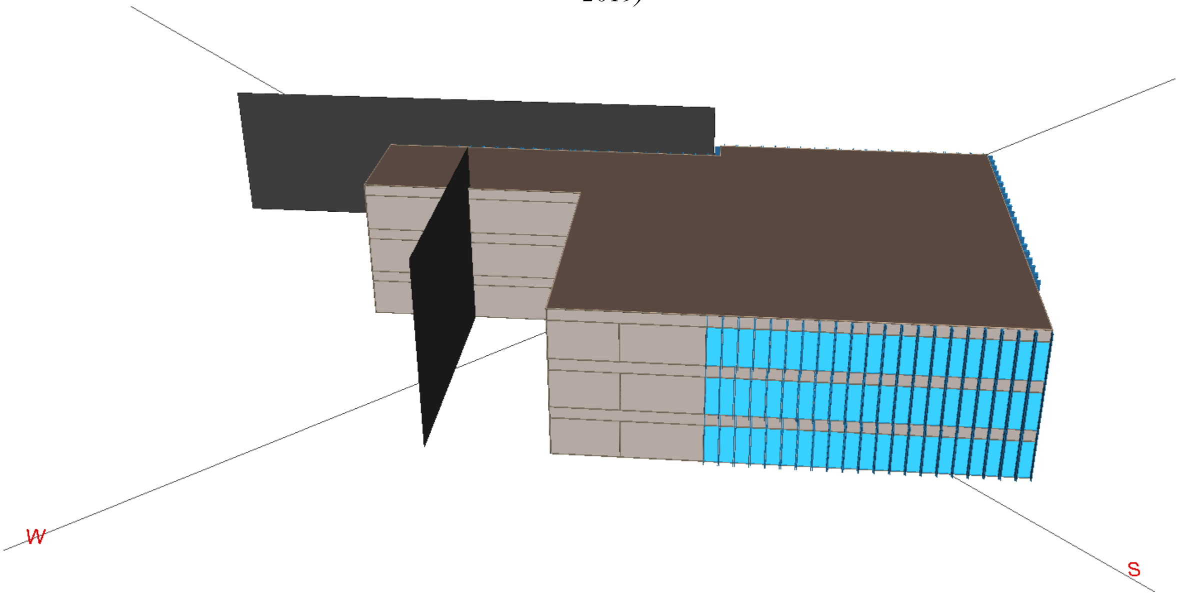


Figure 3.2 - 3-D Geometry view of the Genomics Building (extracted from eQUEST model)

For the present study, compliance to climatic data provisions in Part 8 of NECB 2017 is required. Sentence 8.4.2.3.(1) requires climatic data to be a good representation of the climate, when compared to the average of at least 10 years of measured data. A compliant hourly weather file is available directly from the DOE-2 website for the Montréal region. The file itself comes from the Canadian Weather Year for Energy Calculation (CWEC) database, a group of datasets created by joining twelve Meteorological Months extracted from a database of, typically, 30 years of weather data. The CWEC database is also pointed out as an acceptable source in Note A-8.4.2.3.

3.2. Building Shell

The building shell is comprised of three storeys, identical in floor plan, but having some distinctions regarding the space type. A 2-D representation of the building is provided in Figure 3.3.

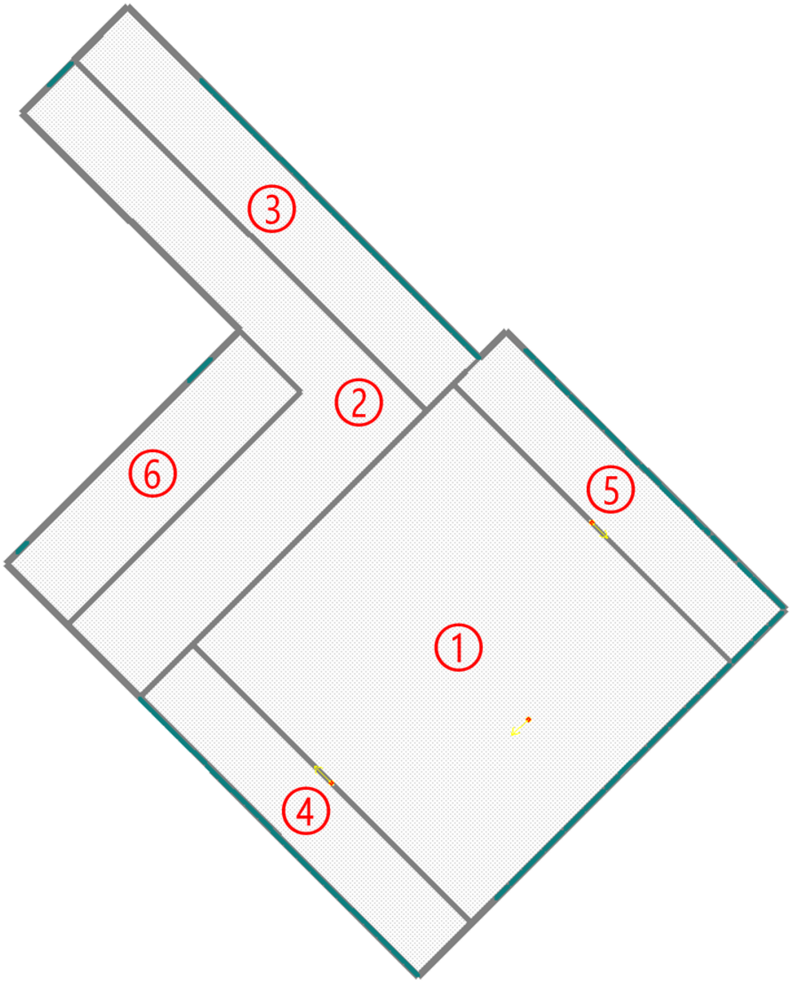


Figure 3.3 - 2-D Geometry view of the Genomics Building (extracted from eQUEST model)

The basement level of the building is occupied by a conditioned data center, subject to its own temperature control with a separate HVAC system. For this reason, this level was not considered in the model. The ground floor is in contact with this conditioned space and for purposes of simplification is considered to be adiabatic.

The activity descriptions of the space types with a nomenclature matching NECB 2017 broken down by floor and surface area and referring to the numbers in Figure 3.3 are presented in Table 3.1.

Table 3.1 - Space names, activity description and areas

#	Space Name	Activity Description	Area m² (ft²)
EL1 Ground Floor			
①	EL1 SE Perim Spc (G.SE3)	Conference/Meeting/Multi-purpose room	100.1 (1077.7)
②	EL1 SW Perim Spc (G.SW6)	Storage room ≥ 5 m²	100.1 (1077.7)
③	EL1 NE Perim Spc (G.NE4)	Corridor/Transition area	489.4 (5268.3)
④	EL1 SW Perim Spc (G.SW1)	Office	126.2 (1358.2)
⑤	EL1 NE Perim Spc (G.NE2)	Corridor/Transition area	96.6 (1040.3)
⑥	EL1 WNW Perim Spc (G.WNW5)	Storage room ≥ 5 m²	239.1 (2573.5)
EL1 Mid Floor			
①	EL1 SE Perim Spc (M.SE10) A	Laboratory (other)	100.1 (1077.7)
②	EL1 SW Perim Spc (M.SW13)	Corridor/Transition area	100.1 (1077.7)
③	EL1 NE Perim Spc (M.NE11)	Office	489.4 (5268.3)
④	EL1 SW Perim Spc (M.SW8)	Office	126.2 (1358.2)
⑤	EL1 NE Perim Spc (M.NE9)	Office	96.6 (1040.3)
⑥	EL1 WNW Perim Spc (M.WNW12)	Storage room ≥ 5 m²	239.1 (2573.5)
EL1 Top Floor			
①	EL1 SE Perim Spc (T.SE17) A	Laboratory (other)	100.1 (1077.7)
②	EL1 SW Perim Spc (T.SW20)	Corridor/Transition area	100.1 (1077.7)
③	EL1 NE Perim Spc (T.NE18)	Office	489.4 (5268.3)
④	EL1 SW Perim Spc (T.SW15)	Office	126.2 (1358.2)
⑤	EL1 NE Perim Spc (T.NE16)	Office	96.6 (1040.3)
⑥	EL1 WNW Perim Spc (T.WNW19)	Storage room ≥ 5 m²	239.1 (2573.5)
Total Surface Area			**3,454.5 (37,187.1)**

All spaces listed in Table 3.1 are conditioned. The total conditioned floor area in this case is equal to the total surface area of 3,454.5 m² (37,187.1 ft²).

3.2.1. Walls, Floors and Roofs

Since all the spaces are conditioned at a temperature difference not greater than 10 ºC, there are no energy efficiency requirements for internal ceilings, walls and floors (refer to Sentence 3.1.1.1.(1) for requirement and Sentence 1.4.1.2.(1) for definition of building envelope). The assemblies separating these internal spaces were simplified to a single construction of each type: ceiling, wall and floor.

For the walls, floors and roofs separating the interior conditioned spaces from the exterior, requirements are set forth in Tables 3.2.2.2 and 3.2.3.1, depending if the assemblies are above-ground or in contact with the ground, respectively. Three compliant constructions were created and assigned to the corresponding assemblies in the model. According to NECB 2017, the requirements for the thermal transmittance of the assemblies can be harsher or lighter, depending on the climatic zone.

The climatic zones are defined as a function of the number of heating degree-days. According to the Climatic Information for Building Design in Canada Part in NECB 2017, the Montréal Region (City Hall) has a total of 4,200 heating degree-days (HDD) below 18 ºC. This value places the Montréal Region in Zone 6, which covers all the regions with HDDs between 4,000 and 4,999. The maximum overall thermal transmittance of the external building assemblies assigned to the model are presented in Table 3.2, as well as a comparison between the values of NECB 2017 and the previous edition (NECB 2015).

Table 3.2 - Overall Thermal Transmittance of Building Assemblies

Building Assembly	**Maximum Overall Thermal Transmittance W/m².K (Btu/h.ft².°F)** ***NECB 2015***	**Maximum Overall Thermal Transmittance W/m².K (Btu/h.ft².°F)** ***NECB 2017***
Above-ground Opaque Walls	0.247 (0.044)	Same as NECB 2015
Above-ground Opaque Roofs	0.183 (0.032)	0.156 (0.0278)
Floors in Contact with the Ground	0.757 (0.133)	Same as NECB 2015

3.2.2. Fenestration

In a similar manner, fenestration, a term that covers windows and their frames, was modeled according to Sentence 3.2.2.3.(3). NECB 2017 prescriptions cover the thermal transmittance of fenestration. Other relevant characteristics, such as the shading coefficient, visible transmittance and outside emissivity need not to comply to a specific minimum/maximum requirement. In practice, this implies that multiple NECB compliant fenestration components are achievable, with each component having significantly different thermal performances.

In order to create a compliant component, a new glass type was created using the simplified method in eQUEST. This simplified method requires the shading coefficient, the glass conductance and the visible transmittance to be set. The glass thermal conductance was adjusted to the required guideline value for Zone 6, while the shading coefficient and the visible transmittance were preserved from the glass type present in the base building model. The glass doors were simplified to the same glass type of the windows, due to its small number of components (5) when compared to the total number of fenestration components (307). The characteristics of the new compliant glass type are presented in Table 3.3 and Table 3.4, as well as a comparison between the values of NECB 2017 and the previous edition of NECB 2015.

Table 3.3 - NECB Glass type Properties of the custom window assembly

Building Assembly	**Maximum Overall Thermal Transmittance, W/m².K (Btu/h.ft².°F)** ***NECB 2015***	**Maximum Overall Thermal Transmittance, W/m².K (Btu/h.ft².°F)** ***NECB 2017***
All fenestration	2.2 (0.39)	1.9 (0.33)

Table 3.4 - Custom Glass type Properties of the custom window assembly

Custom Glass Type Properties	**Value**
Shading Coefficient	0.81
Visible Transmisttance	0.78

3.2.3. Maximum Fenestration Ratio

According to Sentence 3.2.1.4.(1), there is a maximum allowable total vertical fenestration and door area to gross wall area ratio (FDWR), defined by the following formula:

$$\begin{cases} FDWR = 0.40 \; for \; HDD \leq 4000 \\ FDWR = \frac{2000-0.2*HDD}{3000} \; for \; 4000 < HDD < 7000 \\ FDWR = 0.2 \; for \; HDD \geq 7000 \end{cases} \tag{1}$$

In this formula, the fenestration and door areas are calculated to using the rough opening in the wall, including all related frame and sash members, as stated in Sentence 3.1.1.6.(1). The gross wall area is calculated as the sum of the areas of all above-ground wall assemblies including fenestration and doors, as stated in Sentence 3.1.1.6.(3).

Considering that the Montréal (City Hall) region has 4,200 HDDs, the maximum FDWR is 38.7%. Upon running the base file, the total window area indicated in the Details of Exterior Surfaces Report (LV-D report) from eQUEST is 883.04 m² (9,504.99 ft²) and the total gross wall area is 1,946.38 (20,950.80 ft²), resulting in a FDWR of 45.4%. In order to bring the building shell into compliance, 41 windows out of a total of 307 were removed proportionally along each orientation, respecting the recommendations in Sentence 8.4.4.3.(3). After this modification, a total window area of 748.33 m² (8,054.69 ft²) remained, resulting in a FDWR of 38.4%.

3.2.4. Air Leakage

Subsection 3.2.4 establishes requirements for air leakage control in the building envelope. In Articles 3.2.4.2 to 3.2.4.5, a maximum air leakage rate as a function of the pressure differential in the air barrier assembly is given. The rate is expressed as volumetric flowrate divided by the area of the assembly. For opaque building assemblies and fenestration (fixed windows and skylights), the air leakage rate shall be no greater than 0.2 L/s-m^2 (per unit of surface area of the whole air barrier assembly) at a pressure differential of 75 Pa, according to Clause 3.2.4.2.(2).(b) and to Sentence 3.2.4.3.(3), respectively. It is important to remark that the term air leakage (air being expelled outward from within the building) and infiltration (air being sucked up inward from outside of the building) in this part of the thesis are used interchangeably, due to the direction of the flow being a function of the pressure differential between the internal and external environment.

In eQUEST, there are five infiltration models available. The difference between the inputs of these models is the type and number of variables needed to perform the calculations. Among these input variables are wind speed and direction, outside air dry-bulb temperature and specific coefficients that depend on the model chosen. A simplified model provides an option to input the air leakage rate per unit of gross external wall area.

For the base case model, the Detailed Data Edit mode was used to set up the air-change model for each zone. The inputs of this model are the number of air changes per hour for the zone or the infiltration flow per floor area, or both. This allows the infiltration rate to be calculated by performing the following steps:

1. Obtaining the wall and window area of each space;
2. Multiplying the wall and window area of each space by the maximum air leakage rate, obtaining as a result the total air leakage rate for each zone;
3. Dividing the result by the floor area of each space, and
4. Applying the air leakage rate per floor area to each space in the model.

The rates are summarized in Table 3.5.

Table 3.5 - Air Leakage Calculation for each space

Space Name	Wall + Windows Area m² (ft²)	Air Leakage rate L/s (cfm)	Floor Area m² (ft²)	Air Leakage rate per floor area L/s-m² (cfm/ft²)
EL1 Ground Floor				
EL1 SW Perim Spc (G.SW1)	83.1 (894.5)	16.62 (35.22)	100.1 (1077.7)	**0.166 (0.0327)**
EL1 NE Perim Spc (G.NE2)	89.8 (967)	17.96 (38.06)	100.1 (1077.7)	**0.1794 (0.0353)**
EL1 SE Perim Spc (G.SE3)	65.2 (701.5)	13.04 (27.63)	489.4 (5268.3)	**0.0266 (0.0052)**
EL1 NE Perim Spc (G.NE4)	101.3 (1090)	20.26 (42.93)	126.2 (1358.2)	**0.1605 (0.0316)**
EL1 WNW Perim Spc (G.WNW5)	73.9 (795.5)	14.78 (31.32)	96.6 (1040.3)	**0.153 (0.0301)**
EL1 SW Perim Spc (G.SW6)	85.8 (923.5)	17.16 (36.36)	239.1 (2573.5)	**0.0718 (0.0141)**
EL1 Plnm (G.7)	149.7 (1611.6)	29.94 (63.44)	1151.6 (12395.7)	**0.026 (0.0051)**
EL1 Mid Floor				
EL1 SW Perim Spc (M.SW8)	83.1 (894.5)	16.62 (35.22)	100.1 (1077.7)	**0.166 (0.0327)**
EL1 NE Perim Spc (M.NE9)	89.8 (967)	17.96 (38.06)	100.1 (1077.7)	**0.1794 (0.0353)**
EL1 SE Perim Spc (M.SE10)	65.2 (701.5)	13.04 (27.63)	489.4 (5268.3)	**0.0266 (0.0052)**
EL1 NE Perim Spc (M.NE11)	101.3 (1090)	20.26 (42.93)	126.2 (1358.2)	**0.1605 (0.0316)**
EL1 WNW Perim Spc (M.WNW12)	73.9 (795.5)	14.78 (31.32)	96.6 (1040.3)	**0.153 (0.0301)**
EL1 SW Perim Spc (M.SW13)	85.8 (923.5)	17.16 (36.36)	239.1 (2573.5)	**0.0718 (0.0141)**
EL1 Plnm (M.14)	149.7 (1611.6)	29.94 (63.44)	1151.6 (12395.7)	**0.026 (0.0051)**
EL1 Top Floor				
EL1 SW Perim Spc (T.SW15)	83.1 (894.5)	16.62 (35.22)	100.1 (1077.7)	**0.166 (0.0327)**
EL1 NE Perim Spc (T.NE16)	89.8 (967)	17.96 (38.06)	100.1 (1077.7)	**0.1794 (0.0353)**
EL1 SE Perim Spc (T.SE17)	65.2 (701.5)	13.04 (27.63)	489.4 (5268.3)	**0.0266 (0.0052)**
EL1 NE Perim Spc (T.NE18)	101.3 (1090)	20.26 (42.93)	126.2 (1358.2)	**0.1605 (0.0316)**
EL1 WNW Perim Spc (T.WNW19)	73.9 (795.5)	14.78 (31.32)	96.6 (1040.3)	**0.153 (0.0301)**
EL1 SW Perim Spc (T.SW20)	85.8 (923.5)	17.16 (36.36)	239.1 (2573.5)	**0.0718 (0.0141)**
EL1 Plnm (T.21)	149.7 (1611.6)	29.94 (63.44)	1151.6 (12395.7)	**0.026 (0.0051)**
TOTAL	**1946.4 (20950.8)**	**389.28 (824.84)**	**6909.5 (74374.2)**	**0.0563 (0.0111)**

In addition to the rates presented for each space, there is also the infiltration through the roof building assembly, presented in Table 3.6.

Table 3.6 - Air Leakage Calculation for the Roof Space

Space Name	**Wall + Windows Area m² (ft²)**	**Air Leakage L/s (cfm)**	**Floor Area m² (ft²)**	**Air Leakage rate per floor area L/s-m² (cfm/ft²)**
EL1 Plnm (T.21) - Wall + Windows	149.7 (1611.6)	29.94 (63.44)	1151.6 (12395.7)	**0.026 (0.0051)**
EL1 Plnm (T.21) - Roof	1151.6 (12395.69)	230.32 (488.02)	1151.6 (12395.7)	**0.2 (0.0394)**
TOTAL	**1301.3 (14007.3)**	**260.26 (551.46)**	**1151.6 (12395.7)**	**0.226 (0.0445)**

3.3. Internal Loads

All the parameters used to calculate the internal space loads are described in this section.

3.3.1. Occupancy and Equipment Load

The space properties were adjusted to the ones specified as being representative of each space type in NECB 2017, replacing the custom values in the base file. Part of Table A-8.4.3.2.(2)-B is reproduced for the spaces of interest in Table 3.7.

Table 3.7 - Modeling Guidance for Loads and Operating Schedules by Space Type

Space Type	**Occupant Density m²/occupant (ft²/occupant)**	**Peak Receptacle Load W/m² (W/ft²)**	**Operating Schedule**
Conference/Meeting/Multi-purpose room	5 (54)	1 (0.093)	C
Corridor/Transition area	100 (1,076)	0 (0)	*
Laboratory (other)	20 (215)	10 (0.929)	A
Office	20 (215)	7.5 (0.697)	C
Storage room ≥ 5 m²	100 (1,076)	1 (0.093)	*

**An asterisk (*) in this column indicates that there is no recommended default schedule for the space type listed. In general, such space types will be simulated using a schedule that is similar to the adjacent spaces served: e.g. a corridor space serving an adjacent office space will be simulated using a schedule that is similar to that of the office space.*

3.3.2. Lighting

The interior lighting power was modelled according to Clause 4.2.1.6.(1).(b), using the space-by-space method. Each space was assigned a specific lighting power density (LPD) for the exact space type. Table 3.8 summarizes the densities used, extracted from Table 4.2.1.6, as well as a comparison between the values of NECB 2017 and the previous edition of NECB 2015.

Table 3.8 - Lighting Power Densities (LPDs) per space type

Space Type	**Lighting Power Density W/m² (W/ft²) *NECB 2015***	**Lighting Power Density W/m² (W/ft²) *NECB 2017***
Conference/Meeting/Multi-purpose room	13.3 (1.24)	11.5 (1.06)
Corridor/Transition area (other)	7.1 (0.660)	Same as NECB 2015
Laboratory (other)	19.5 (1.81)	15.6 (1.45)
Office (enclosed, > 25m²)	12.0 (1.11)	10.0 (0.929)
Storage Room (>= 5 m²)	6.8 (0.632)	Same as NECB 2015

Automatic daylight responsive controls for side lighting or top lighting are provisions required by NECB 2017. In Table 4.2.1.6, the types of spaces that require such controls are listed. All the space types in the model are present in the referred table and require daylighting controls. In eQUEST, a modification on the base file was made to include this calculation in all zones that have windows.

3.3.3. Heat Gain per Occupants

As for the heat gain per occupant, the sensible and latent heat gains were obtained from the ASHRAE Fundamentals Handbook [72] and are reproduced in Table 3.9.

Table 3.9 - Representative Rates of Heat Gain by Human Beings

Degree of Activity	Considered Applicable Space Types	Sensible Heat W (Btu/h)	Latent Heat W (Btu/h)
Seated, very light work	Conference Room	70 (245)	45 (155)
Walking, standing	Corridor	75 (250)	70 (250)
Moderately active office work	Laboratory, Office	75 (250)	55 (200)
Light bench work	Storage Room	80 (275)	140 (475)

3.3.4. Operating Schedules

The operating schedules A and C can be found in NECB-2017 [9].

3.4. Water-Side HVAC

The objective of developing the building energy model is to simulate the impact of the provisions laid out in the Prescriptive Path on the energy target of a reference building. To accomplish such objective, the model and simulation thereof shall comply to NECB by applying the provisions of the Building Energy Performance Compliance Path (Part 8) on a reference building model designed respecting the Prescriptive Path.

An important remark is that the Performance Path thoroughly addresses energy model premises and calculations, while the Prescriptive Path thoroughly addresses performance requirements used in the design of the Building Envelope (Section 3.2), Lighting (Section 4.2), HVAC systems (Section 5.2), Service Water Systems (Section 6.2) and Electrical Power Systems (Section 7.2). Precedence of the provisions in Part 8 over the other Sections is permitted, as stated in Clauses 8.1.1.1.(a) and (b).

The issue of HVAC System Selection and a method for such are discussed in Article 8.4.4.7. A relationship between the system type and the space or building type and size is established in Table 8.4.4.7.-A and a description of the types of HVAC systems is provided in Table 8.4.4.7.-B. The building type considered for the reference building is an office building (General Area with more than 2 storeys). The corresponding system for this building type is System – 6, which is described in Table 3.10.

Table 3.10 - Description of HVAC System (NECB 2017)

System Number	Type of HVAC System	Fan Control	Type of Cooling System	Type of Heating System
System – 6	Multi-zone built-up system with baseboard heating	Variable-volume	Water-cooled water chiller	Baseboards: electric resistance or hydronic with fuel-fired boiler

A representation of the water-side system modelled in eQUEST is presented in Figure 3.4. 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 boiler, a hot water (HW) pump, a central heating coil and a set of baseboard heaters and reheat coils installed in each zone.

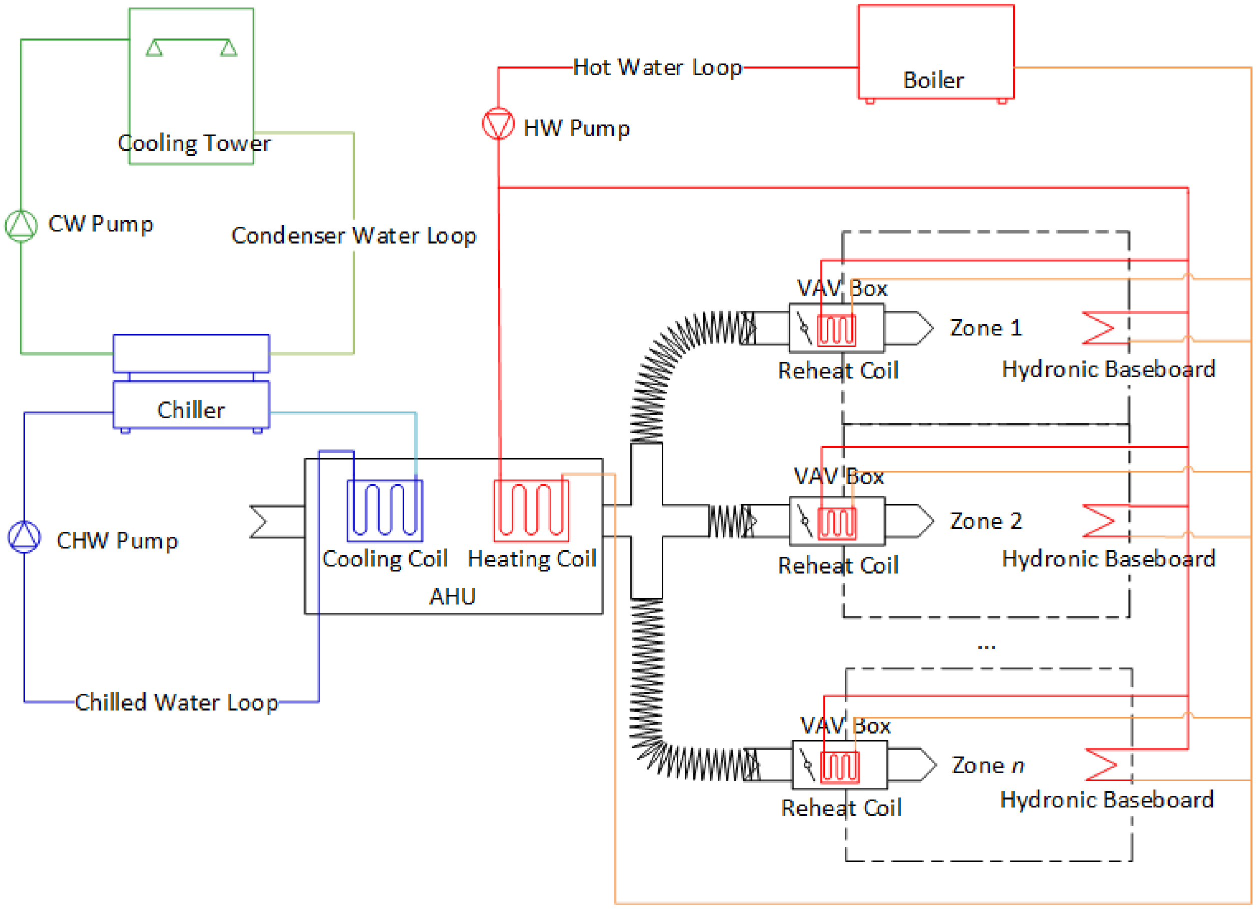


Figure 3.4 - Water-side HVAC System Representation

3.4.1. Pumping System Design

Regarding pumping system design, two main issues are covered by the HVAC Systems Part (Part 5 in NECB): design for variable fluid flow and maximum pumping power demand. The requirements on pumping system design are triggered by conditions and can have exceptions.

A summary of when to use and when not to use variable fluid flow is provided in Table 3.11.

Table 3.11 - Conditions triggering Variable-Flow Pumping Systems

Conditions (if)
• **System serves control valves modulating as a function of thermal load, and** • **Total pump system motor nameplate power ≥ 7.5 kW**
Effects (then)
• **System shall be designed for variable fluid flow, and** • **System shall be capable of reducing system flow to 50% or less of design flow**
Exceptions
• **Flow greater than 50% of design flow is required for proper operation of equipment, or** • **System serves a single control valve, or** • **System includes controls to reset fluid temperature based on OA temperature or system loads**
References
• **Sentence 5.2.6.1 (Application), and** • **Sentence 5.2.6.2 (Variable-Flow Pumping Systems)**

In Table 3.11, total pump system motor nameplate power means the sum of the design power of all pumps required to properly provide thermal energy to an HVAC system, equipment, appliance or to a conditioned space.

When comparing the provisions that cover variable speed pumps in Part 5 with the provisions in Part 8, a conflict appears. Clauses 8.4.4.9.(6).(e) and 8.4.4.10.(6).(d) and Sentence 8.4.4.11.(4) all prescribe that the pumping system shall be modeled as constant speed operation for Heating, Cooling and Cooling Tower Systems, respectively.

In constant speed operation, the pump runs at maximum power and the flow becomes a function of the total static head in the loop imposed by the opening and closing of the control valves. This causes a constant speed system to be more energy demanding than a variable speed pumping system, since in the latter pump shaft rotating speed, and consequently power, are varied through a variable speed drive, seeking to maintain a constant head across the pump loop.

In practice, this means that if the Performance Path is chosen for compliance, the constant speed operation provision in Part 8 takes precedence over the variable speed operation in Part 5 for simulating the reference building target energy consumption and there is additional room for the HVAC system designer to conceptualize a more efficient pumping system in the proposed building.

Sentence 5.2.6.3.(1) addresses pumping power demand and dictates a maximum combined pumping power demand of pump motors for each type of hydronic system: heating, heat rejection, cooling and water-source heat pump. The value is expressed as a ratio of the combined power of the pump motors over the peak thermal demand of the space at design conditions and is given for each case in Table 3.12.

Table 3.12 - Maximum Combined Pumping Power Demand of Pump Motors for each Type of Hydronic System

Type of Hydronic System	**Maximum Combined Pumping Power Demand of Pump Motors, $W_{motorpower}/kW_{thermalpeak}$**
Heating	4.5
Heat Rejection	12
Cooling	14
Water-source heat pump	22

Two questions arise from using this method: what the definition of the peak thermal demand of the space at design conditions is; and how to determine the power demand of the pump before knowing the peak thermal demand.

Answering the first question, there are two possible interpretations of the peak thermal demand of the space. The first one is derived from the Fundamentals Handbook. The space load is defined as *"the amount of energy that must be added to or extracted from a space to maintain thermal comfort"*. The boundary for analysing this amount of energy is the space (or zone) and therefore internal heat gains or losses from sources such as lights, people, appliances, and equipment are included. Thermal energy spent in system loads that happen outside of the space such as cooling or heating outdoor air and heat exchange in reheat coils, fans and pumps are not included in the space load.

The second possible interpretation is understanding the term space as the full building and therefore considering the peak thermal demand that occurs in the loop, including all types of heat gain or loss. According to this interpretation, thermal energy spent in system loads are indeed included in the peak thermal demand.

The argument in favor of the second interpretation is being able to answer the second question posed before. A ratio of the pump power over the thermal demand is able to be deducted using an algebraic approach, since the thermal demand in the loop is defined simply as the product of the fluid flow and the temperature drop or rise in the loop and not as a function of numerous variables arising from the sum of different heat gain types in the space. Pump power is also defined algebraically as the product of the flow, the total static pressure and a combined electrical and mechanical efficiency of the pump. All of these variables are well defined during the design phase of the HVAC system and compliance values for these variables for the reference building can be found in Part 8.

A summary of the steps needed to define the pump characteristics for compliance is given:

1. Write equation for pump power demand, $W = f(F, SP, \eta)$;
2. Write equation for the peak thermal demand in the loop, $Q = f(F, \rho, c_p, \Delta T)$;
3. Divide the equations to obtain the ratio;
4. Define maximum pump power demand and other constants, and
5. Solve for the differential pressure across the pump.

Each step described above is performed, with nomenclature and symbols matching the ones in NECB 2017.

The pump power is defined as a function of the flow, the total differential pressure and the pump efficiency:

$$W = F.\frac{SP}{\eta} \tag{2}$$

Where

W = power demand, in W,

F = design flow rate, in m³/s,

SP = design differential pressure across the pump, in Pa, and

η = combined impeller-motor efficiency, expressed as a decimal fraction

The peak thermal load in the circulation loop is defined as a function of the flow, fluid density and specific heat and temperature rise or drop:

$$Q = F.\rho.c_p.\Delta T \qquad (3)$$

Where

Q = heat transfer rate gained or lost by the circulation loop fluid, in W

F = design flow rate, in m^3/s

ρ = fluid density, in kg/m^3

c_p = fluid specific heat at constant pressure, in J/kg-ºC

ΔT = temperature drop or rise in the circulation loop, in ºC

Dividing the equations, the pumping power demand relationship is defined:

$$\frac{W}{Q} = \frac{SP}{\rho.c_p.\Delta T.\eta} \qquad (4)$$

And the last step is solving the pumping power demand equation for SP:

$$SP = \left(\frac{W}{Q}\right).\rho.c_p.\Delta T.\eta \qquad (5)$$

With the pump efficiency written as:

$$\eta = \eta_{motor}.\eta_{impeller} \qquad (6)$$

Where

η = combined impeller-motor efficiency, expressed as a decimal fraction

η_{motor} = motor efficiency, expressed as a decimal fraction

$\eta_{impeller}$ = impeller efficiency, expressed as a decimal fraction

Table 3.13 summarizes the inputs and references thereof, as well as the calculated differential pressure for each loop.

Table 3.13 - Calculations of Differential Pressure to respect Pumping Power Demand

Input	**Unit**	**Hot Water Loop**	**Condenser Water Loop**	**Chilled Water Loop**	**Reference**
Fluid Density (ρ)	kg/m³ (lb/ft³)	1,000 (62.42)			**STP (0 ºC, 1 atm)**
Fluid Specific Heat (c_p)	J/kg-°C (Btu/lb-°F)	4,186 (1.000)			
Fluid temperature change (ΔT)	°C (°F)	16 (28.8)	6 (10.8)	6 (10.8)	**8.4.4.9.(6).(f).(iii), 8.4.4.11.(5).(c) and 8.4.4.10.(6).(e).(iii), respectively**
Motor Efficiency (η_{motor})	%	85.5	90.2	87.5	**DOE-2 [57], [73]**
Impeller Efficiency ($\eta_{impeller}$)	%	77	77	77	
Maximum Pumping Power Demand $\left(\frac{W}{Q}\right)$	W/kW	4.5	12	14	**Table 5.2.6.3**
Differential Pressure (SP)	**Pa (ft H_2O)**	**198,421 (66.4)**	**209,329 (70.0)**	**236,907 (79.3)**	

3.4.2. System Oversizing

With regards to equipment oversizing, Clauses 8.4.4.8.(1).(b) and 8.4.4.8.(2).(b) state respectively that the heating equipment can be modeled using an oversizing factor of between a chosen amount and a maximum of 30%, and the cooling equipment by a factor of between a chosen amount and a maximum of 10%. The referred clauses can be particularly useful for covering unexpected peaks in heating or cooling loads that can happen in practical applications. No oversizing was applied to the model in question due to the deterministic nature of the simulation performed by eQUEST and the fact that all systems are auto-sized to respect the calculated peak loads.

3.4.3. Heating System

NECB-2017 provides criteria for HVAC system selection to be used in the reference building. These recommended HVAC system concepts detail the type of the heating and cooling system to be used, as well as the fan control strategy. The systems described in NECB-2017, if applied in accordance with the remaining code prescriptions, would result in an energy efficient building built in accordance with best engineering practices. The definition of which concept is used to model a reference building is relevant, since the annual energy consumption of the reference building serves as a target to determine if a building is compliant or not.

Accordingly, the heating system used in the reference building of the present study was modeled according to Article 8.4.4.9 of the Performance Path method. The characteristics are summarized in Table 3.14.

Table 3.14 - Characteristics of Heating System

Characteristic	Attribute	Reference
Heating system type	Hydronic with fuel-fired boiler	System 6 Table 8.4.4.7.-A Table 8.4.4.7.-B
Boiler type	Gas-fired Boiler	Refer to part 3.6 of the thesis
Boiler efficiency	$E_t^{(1)} \geq 83.0\%$	Table 5.2.12.1
Number of Boilers	Two boilers of equal capacity	*"Heating capacity greater than 176 kW and not greater than 352 kW"* Clause 8.4.4.9.(6).(b)
Pumping System	Primary system with constant speed operation	Clause 8.4.4.9.(6).(e)
Temperature Drop	A 16 °C temperature drop	Subclause 8.4.4.9.(6).(f).(iii)
Hot water supply temperature	82 ºC for an outdoor air temperature of -16 ºC, and 60 ºC for an outdoor air temperature of 0 ºC	Subclauses 8.4.4.9.(6).(h).(i) and (ii)

(1) E_t = thermal efficiency, in %

The choice of the type of heating system is addressed in Section 3.6 of the thesis.

3.4.4. Cooling System

In accordance with the guidelines disposed in NECB-2017 for the modelling of a reference building, the cooling system was modeled according to Article 8.4.4.10 of the Performance Path. The characteristics are summarized in Table 3.15.

Table 3.15 - Characteristics of Cooling System

Characteristic	Attribute	Reference
Cooling system type	Water-cooled water chiller	System 6 Table 8.4.4.7.-A Table 8.4.4.7.-B
Chiller type	Water-cooled, centrifugal	-
Chiller efficiency	COP = 5.547	CAN/CSA-C743 in NECB-2017 [9]
Number of Chillers	One water chiller	*"cooling capacity is not greater than 2,100 kW"* Clause 8.4.4.10.(6).(b)
Pumping System	Primary system with constant speed operation	Clause 8.4.4.10.(6).(d)
Temperature Rise	A 6 °C temperature rise	Subclause 8.4.4.10.(6).(e).(iii)
Chilled water supply temperature	Set at 7 °C	Clause 8.4.4.10.(6).(g)
Chiller modulation	Fully modulating down to 25% of the capacity	Clause 8.4.4.10.(6).(h)

Although the HVAC System type 6 requires a water-cooled water chiller for the cooling system, it doesn't directly specify which type of chiller is required to be used. CAN/CSA-C743 is the referenced standard for energy performance requirements for chillers. In it are listed the types of water-cooled chillers covered and efficiency requirements specific for each type of chiller. The centrifugal chiller type has a better coefficient of performance for the chiller capacity range and is chosen for the present study.

3.4.5. Cooling Tower System

The cooling tower system was modeled according to Article 8.4.4.11. The characteristics are summarized in Table 3.16.

Table 3.16 - Characteristics of Cooling Tower System

Characteristic	Attribute	Reference
Cooling Tower type	Axial-fan, direct-contact cooling tower	Sentence 8.4.4.11.(1)
Inlet and Outlet Water Temperature	35 ºC and 29 ºC, respectively	Clause 8.4.4.11.(1).(b)
Inlet Outside Air Wet Bulb Temperature	24 °C	Clause 8.4.4.11.(1).(c)
Cooling Tower efficiency	$kW_{ele}/kW_{th} = 0.013$	Table 5.2.12.2
Number of Cooling Towers	One cell	*"cooling tower capacity is not greater than 1,750 kW"* Sentence 8.4.4.11.(2)
Pumping System	Constant speed operation	Sentence 8.4.4.11.(4)
Temperature Drop	A 6 °C temperature drop	Clause 8.4.4.11.(5).(c)
Cooling Tower modulation	A cycling control to maintain an outlet water temperature of 29 ºC	Sentence 8.4.4.11.(6)

3.4.6. Service Water Systems

It is not mandatory to incorporate service water heating and pumping systems in all building designs. If they are included however, in regions where standards are enforced, the design of such systems should be compliant to the provisions set out in these standards. With respect to service water systems, NECB 2017 sets out provisions that cover service water heating equipment performance, piping insulation, temperature controls and other relevant requirements for showers, lavatories, swimming pools and pressure booster systems.

For purposes of simplification, the modelled building does not incorporate service water systems.

3.4.7. Piping Insulation

When considering the effects of piping insulation, one must know the length and diameter of the piping, as well as the temperature difference between the fluid and the exterior. It is not possible to accurately estimate these dimensions of the piping without having in possession the technical drawings of the building HVAC system.

In addition, installation and maintenance are subject to diverse factors (e.g. handling of insulating material, provision of vapour barrier protection, provision of mechanical and weathering protection) that, in practice, make the overall health of the insulation hard to predict. If the insulation material is installed in accordance with good practice, the effects of thermal loss are reduced to their maximum extent.

For these reasons, the effect of thermal loss due to piping insulation was not considered in the simulation.

3.5. Air-Side HVAC

As previously discussed in the Water-Side HVAC part of the thesis, the building type considered for the reference building is an office building (General Area with more than 2 storeys). The corresponding HVAC system for this building type is System – 6, described in Tables 8.4.4.7-A and B. This selection follows the procedure laid out in NECB-2017 to model the reference building according to the Performance Path.

System number 6 requires a multi-zone built-up system with baseboard heating and variable-volume fans. For air distribution, the Variable Air Volume System (VAVS) type was selected. This system comprises a main chilled water coil and a main heating coil, supply and return variable airflow fans and hydronic baseboard heaters and reheat coils in every thermal zone attached to the hot water loop. In addition, 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.

A representation of the air-side system modelled in eQUEST is presented in Figure 3.5.

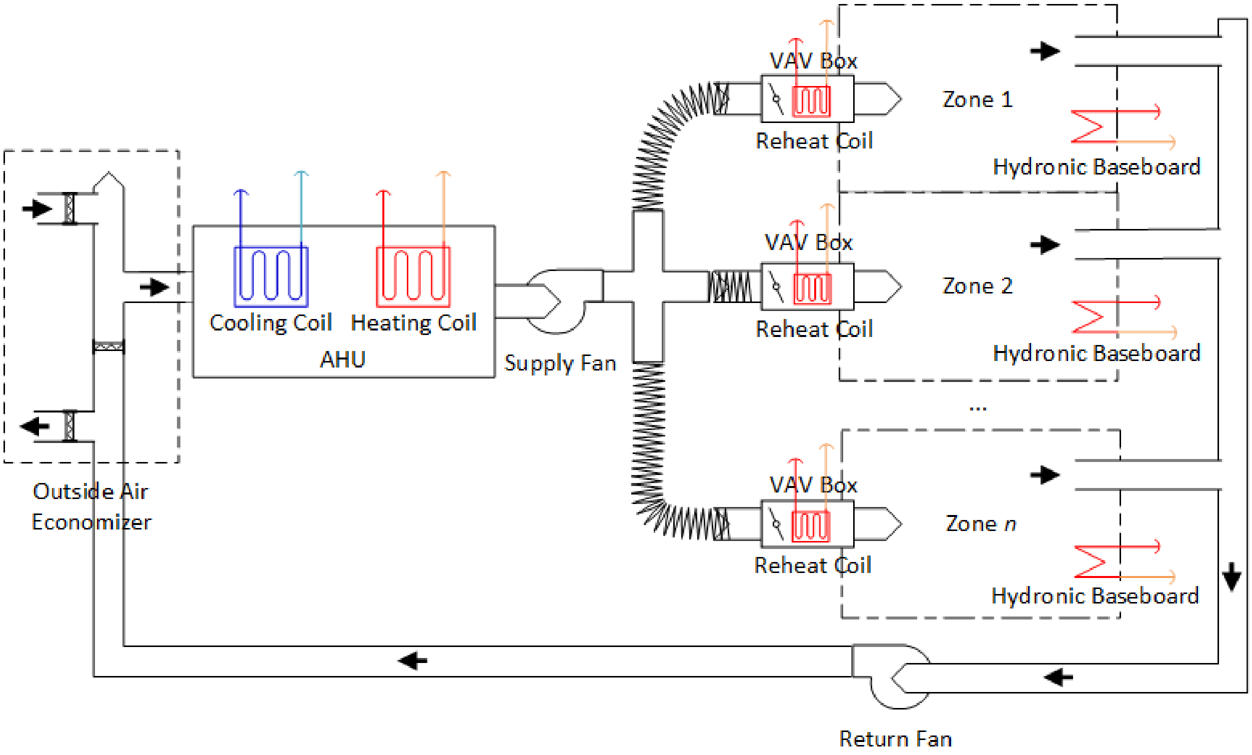


Figure 3.5 - Air-side HVAC System Representation

3.5.1. Cooling with Outdoor Air

The cooling with outdoor air system was modeled according to Article 8.4.4.12. The characteristics are summarized in Table 3.17.

Table 3.17 - Characteristics of Cooling with Outdoor Air System

Characteristic	Attribute	Reference
Cooling with Outdoor Air	Yes	Sentence 8.4.4.12.(1) Article 5.2.2.7 "*each system that … has an air-handling capacity of more than 1,500 L/s or a cooling capacity of more than 20 kW"*
Type of cooling	Cooling by direct use of outdoor air (Air Economizer System)	Article 5.2.2.8
Control option	Fixed dry bulb temperature sensor	Sentence 5.2.2.8.(2)
Temperature setpoint	21.1 °C (70 °F)	Note A-5.2.2.5.(2) ASHRAE 90.1-2016, Table 6.5.1.1.3

In Sentence 5.2.2.8.(2), two control options are described: temperature-based and enthalpy-based. Both control strategies described refer to comparing either the air temperature or the enthalpy of the return air to the outdoor air.

A simulation study using the DOE-2.2 engine compared the performance of the many alternatives for control, including the combination of fixed (comparing a sensor measurement with a fixed constant) or differential (comparing indoor and outdoor sensor measurements) approaches over a combination of dry-bulb, dew point and enthalpy sensors. The study also considered the measurement error inherent to each type of sensor. The main conclusion is that fixed dry-bulb temperature controls are the preferred high limit device for all climatic zones due to their very low first costs, inherently high energy efficiency, minimal sensor error, minimal energy impact even when there is sensor error, and low maintenance costs [74].

By using a fixed dry-bulb temperature control, a fixed temperature setpoint must be selected to guide the operation of the air economizer damper. Note A-5.2.2.5.(2) describes a setpoint range between 21 ºC and 24 ºC depending on the climate type. More specifically, the range varies based on the humidity of each climatic zone during the cooling season. ASHRAE

90.1 (one of the referenced codes in NECB 2017), expands the discussion of the control settings for Air Economizers and provides a table with the high-limit shutoff set points for the economizers.

3.5.2. Fan System Design

The fan system was modeled according to Sentence 8.4.4.18.(4). The characteristics are summarized in Table 3.18.

Table 3.18 - Characteristics of Fan System

Characteristic	Attribute	Reference
Space temperature control throttling range	+- 1 °C (+- 1.8 °F)	Sentence 8.4.3.7.(1)
Supply air temperature	Constant at 13 °C (55.4 °F)	Clause 8.4.4.18.(4).(a)
Supply fan static pressure	1,000 Pa (4.01 inH_2O)	Clause 8.4.4.18.(4).(b)
Supply fan combined fan-motor efficiency	55%	Clause 8.4.4.18.(4).(b)
Return fan static pressure	250 Pa (1.00 in H_2O)	Clause 8.4.4.18.(4).(c)
Return fan combined fan-motor efficiency	30%	Clause 8.4.4.18.(4).(c)
Minimum supply airflow rate	2.0 L/s-m² (0.39 cfm/ft²), when occupied	Subclause 8.4.4.18.(4).(d).(i)

The Prescriptive Path, in Subsection 5.2.3.1, also discusses fan system design characteristics. Within this Subsection, according to Sentence 5.2.3.2.(1), the power demand required by the motors for the combined supply and return fan system at design conditions can be calculated using the following equation:

$$W = 0.001\ .\ F\ .\frac{SP}{\eta} \tag{7}$$

Where

W = power demand, in W,

F = design flow rate, in L/s,

SP = design static pressure across the fan, in Pa, and

η = combined fan-drive-motor efficiency, expressed as a decimal fraction

The formula can be modified to express the ratio of the power demand over the design flow rate, becoming:

$$\frac{W}{F} = 0.001\,.\frac{SP}{\eta} \quad (8)$$

As stated in Sentences 5.2.3.2.(1) and 5.2.3.3.(1), in Constant-Volume Fan Systems, this rate shall not exceed 1.6 W/L-s of supply air delivered to the conditioned space at design conditions and in Variable-Air-Volume Fan Systems, this ratio shall not exceed 2.65 W/L-s, respectively. Applying the limits described, a new relationship is established:

$$\frac{SP}{\eta} \leq 1{,}600 \text{ (Pa) for constant-volume fan systems} \quad (9)$$

$$\frac{SP}{\eta} \leq 2{,}650 \text{ (Pa) for variable-air-volume fan systems} \quad (10)$$

This relationship can be applied when designing new systems or when evaluating the parameters used when existing systems were designed. To apply this relationship, one could obtain the design static pressure across the fan from the pressure loss in the duct network and then set an efficiency for the fans such that the final ratio will remain below the recommended threshold. An existing system can be evaluated for compliance in the same manner, by measuring the pressure drop across the fan or by taking the nameplate pressure drop values and by measuring the fan efficiency or by taking the nameplate efficiency and plugging the values in the formula.

3.5.3. Outdoor Air Ventilation Rates

Sentence 8.4.3.6.(1) of the NECB-2017 states that for purposes of compliance calculations, the peak outdoor air ventilation rates shall be set to minimum values required by the applicable ventilation standards. Furthermore, ASHRAE Standard 62.1 is cited in the referenced documents as a source of the latest best practice for ventilation calculations.

Table 3.19 summarizes the combined outdoor air rates for all space types.

Table 3.19 - Combined Outdoor Air Rates for All Space Types

Space Type	Combined Outdoor Air Rate L/s-person (cfm/person)
Conference/Meeting/Multi-purpose room	(6)
Corridor/Transition area	5.5 (11)
Laboratory (other)	8.5 (17)
Office	8.5 (17)
Storage room ≥ 5 m²*	23.6 (50)

**The combined outdoor air rate for this space was corrected to use NECB-2017 occupancy densities.*

3.5.4. Duct Leakage and Insulation

When considering the effects of duct leakage, one must know the leakage class and the shape of the ducts, as well as the maximum operating static pressure. These parameters are used to calculate the maximum permitted leakage as a function of the duct surface area. When considering the effects of duct insulation, one must know the duct surface area and the temperature difference between the fluid and the exterior. It is not possible to accurately estimate these characteristics without having in possession the technical drawings of the building HVAC system. In addition, predicting air leakage to unwanted areas when plenums are used is not practical.

Furthermore, installation and maintenance are subject to diverse factors (e.g. handling of insulating material, provision of vapour barrier protection, provision of mechanical and weathering protection, duct construction and sealing) that, in practice, make the overall health of the duct system hard to predict. If the construction, installation, sealing and insulation are in accordance with good practice, the effects of thermal loss and leakage are reduced to their maximum extent.

For these reasons, the effect of thermal loss and leakage due to duct insulation and sealing were not considered in the simulation.

3.5.5. Energy Recovery

As stated in Sentence 5.2.10.1.(1), when the exhaust air system's design supply fan airflow rate meets or exceeds a threshold value, it shall be equipped with an energy recovery system. This requirement is dependent on the ventilation system's continuous or non-continuous operation and the percentage of outdoor air it uses at design airflow conditions, as well as the climatic zone of the building location.

For a system to be considered non-continuously operating, the ventilation systems must operate less than 8,000 hours per year. In a preliminary run of the base case simulation, it was verified that 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. This puts the referred system in the non-continuously operating scenario. It was also verified in the preliminary run from the system design parameters that the outside air ratio of the VAVS system was 15.6%, with a total supply airflow capacity of 7,344 L/s (15,560 cfm).

According to Table 5.2.10.1.-A, for the climatic zone 6 (Montréal zone), with a percentage of outdoor air at design airflow conditions of between ≥ 10% and < 20%, the maximum design supply airflow rate threshold value for an airside system without recovery systems is 12,270 L/s (25 999 cfm). The referred system does not achieve that threshold value and for that reason, was not modelled with an energy recovery system.

3.6. Comparison of Heating System Types

In Table 3.10, the recommended types of heating systems powering baseboard heaters are either electric resistance or fuel-fired boiler. This definition seems to apply directly to the baseboard heaters, leaving the central heating coil heating system type without any apparent restriction. In practice, in order to simplify the design of the heating system, one can assume a single heating system type for all the HVAC system.

It is interesting to notice the recommendation of fuel-fired boilers and no mention of electric boilers. This recommendation is likely to be aligned with common practice, where fuel-fire systems are commonly used in regions where fuel costs are cheaper than electricity costs. In the case of fuel-fired HVAC systems, not only the total electrical consumption is reduced but also the peak electrical demand. As these components comprise a big part of the utilities bill, attention is paid to reduce them.

A comparison of three possible embodiments of heating systems is performed to illustrate the attractiveness of each system type. In Embodiment 1, the heat source of the central heating coils, reheat coils and baseboard heaters is Electric Resistance. In Embodiment 2, the heat source of the coils is hydronic with the Hot Water Loop being powered by an Electric Boiler. In Embodiment 3, the heat source of the coils is hydronic with the Hot Water Loop being powered by a fuel-fired boiler.

3.6.1. Gas-Fired vs. Oil-Fired Boilers

NECB 2017 does not specify for the heating system of HVAC System 6 which fuel source is recommended to be used in the boiler (gas-fired, oil-fired, residual and other oils), leaving the choice open for the designer. It does specify, however, efficiency requirements specific for each fuel source that must be respected. Gas-fired boilers and oil-fired boilers have very similar minimum performance requirements according to NECB 2017. For oil-fired boilers, the minimum performance requirement for the same equipment heating capacity range as in the studied embodiments is of $E_t \geq 83.4\%$, compared to the $E_t \geq 83.0\%$ for the gas-fired alternative.

Another important factor when it comes to deciding the source of the energy of the fuel-fired is the cost of the fuel itself. A comparison between the cost of natural gas and oil is made.

The natural gas price is calculated from the data of the natural gas distributor Énergir. The natural gas price is composed of multiple components, obtained from the website of the Régie de l'énergie of Québec, an economic regulation agency operating in the energy market of Québec [75] and from the website of Énergir [76]. In Énergir's website, the calorific power for the natural gas can be found [77].

The oil prices refer to the rack prices, that is, the price paid for the fuel at the refinery to be delivered to a particular client, including the cost of the fuel itself, as well as transportation, overhead, and profit costs. The data covers the minimum prices paid in the region of Montréal and is also obtained from the Régie de l'énergie of Québec [78]. The calorific power of the oil is obtained from an NRC publication [79].

Table 3.20 summarizes the comparison between natural gas and oil.

Table 3.20 - 2018 Average Weighted Price for Energy from Fuel Sources

Source of fuel	Volume Unit SI (non-SI)	2018 Average Weighted Price for the fuel ¢/volume unit	Calorific Power MJ/volume unit (Btu/volume unit)	2018 Average Weighted Price for the energy ¢/MJ ($/Therm)
Natural gas	m^3 (ft^3)	49.534 (1.4026)	37.892 (1017.0)	1.3072 (1.3792)
Light Oil - Mazout léger	L (gallon)	84.430 (319.57)	38.510 (138,150)	2.1924 (2.3132)

Given that thermal efficiency requirement for the boilers is approximately the same independent of the source of the fuel, the natural gas option is much more attractive financially since its fuel energy cost is 40.4% lesser than the oil.

In addition, it is useful to compare the emission factors, that is how many grams of pollutants are emitted per unit of energy released when the fuel is burned, between the natural gas and the oil-fired boilers. The uncontrolled emission factors, that is, when no emission control devices, such as electrostatic precipitators, filters and scrubbers are used, for oil-fired boilers are many times higher than the ones for natural gas-fired boilers. According to an EPA publication, the oil-fired boiler emission factors are roughly 2 to 3 times the value for natural gas-fired boilers for pollutants such as hydrocarbons (HC), carbon monoxide (CO), nitrogen oxides (NO_x) and particulate matter (PM); 10 to 50 times the value for sulfur dioxide (SO_2); and lastly oil-fired boilers also emit lead (Pb), while natural gas-fired boilers don't emit it [80].

Both the cost and the pollutant emission factors qualify natural gas as the best option for the Embodiment 3 of the comparison.

3.6.2. Performance Requirements for Heating Equipment

The minimum performance requirements used in this comparison are summarized in Table 3.21.

Table 3.21 - Heating Equipment Performance Requirements

Embodiment	Equipment Heating Capacity Range, kW (Btu/h)	Standard	Minimum Performance	Reference
1 - All Electric Resistance(1)	-	-	100%	DOE-2.2
2 - Hydronic w/ Electric Boiler(2)	Any (Instantaneous electric water heater)	10 CFR Part 430	93%	ASHRAE 90.1-2016
3 - Hydronic w/ Gas-fired Boiler	≥ 88 (300,000) and < 733 (2,500,000)	ANSI Z21.13/CSA 4.9	E_t(3) ≥ 83.0%	NECB 2017 Table 5.2.12.1

(1) NECB 2017 does not specify efficiency requirements for resistances. The premise is that all electricity consumed by the resistance is converted into heat (Joule effect). When the Electric Resistance option is chosen in eQUEST, also there is no input field for the efficiency of the resistances. The program uses a built-in 100% efficiency for all resistances.

(2) For Electric boilers, Table 5.2.12.1 states that no standards address the performance efficiency of electric boilers; however, their efficiency typically approaches 100%. In the absence of a specific guideline value, the recommendations in ASHRAE 90.1-2016 were used.

(3) E_t = thermal efficiency, in %

3.6.3. Utility Rates & Economics

The electricity rate was obtained from Hydro-Québec, a public power utility that manages the generation, transmission and distribution of electricity in the province of Québec, Canada [81]. The rate considered was the general rate for medium-power customers (Rate M), under the business customers section. This rate applies to the contracts in which the maximum power demand has been at least 50 kilowatts (kW) during a consumption period included in the last 12 monthly periods. If the maximum power demand surpassed 5000 kilowatts (kw) during any month, the best rate would be the general rate for large-power customers (Rate L).

The structure of this rate is summarized in Table 3.22.

Table 3.22 - Structure of Rate M (extracted from Hydro-Québec website on August 8th, 2019)

Component	**2017 Rate (Effective April 1, 2017)**		**2018 Rate (Effective April 1, 2018)**	
Demand ($/kW)	14.43		14.46	
Consumption (¢/kWh)	For the first 210,000 kWh	For the remaining consumption	For the first 210,000 kWh	For the remaining consumption
	4.97	3.69	4.99	3.70
Minimum Monthly Bill(1) ($)	36.99		36.99	
Credit for Supply at medium or high voltage ($/kW)	*Not considered*		*Not considered*	
Adjustment for transformation losses (¢/kW)	*Not considered*		*Not considered*	

(1) three-phase electricity delivery considered

Since Hydro-Québec rates are updated once a year, in the beginning of April, the year of 2018 is covered by two rates: the one effective April 1, 2017 and the one effective April 1, 2018. The first one is applied to the months of January through March and the second one is applied to the months of April through December. It is possible to assign a qualification schedule to each utility rate in eQUEST, specifying which period of time is covered by each desired rate. The schedules can be applied in an hourly, weekly and annual basis, making this a powerful tool to manage the way the billing calculations are performed.

There is an option to have the electricity supplied at medium or high voltage (over 5 kV) and have a transformer in the building to convert to a lower voltage. The advantage of this is to have a cost reduction on the demand charge. Voltage information is not included in the building energy model and neither is within the scope of this comparison and therefore this option was not explored.

The gas rate was obtained from Énergir, a utility that produces electricity from wind and distribute traditional and renewable natural gas in the province of Québec, Canada [75], [76]. The business customers rate was considered, and the structure of this rate is summarized in Table 3.23.

Table 3.23 - Énergir's gas bill components and prices

Component	Unit	Rate
Natural Gas Supply	¢/m³	13.090
Transportation	¢/m³	3.414
Load-balancing	¢/m³	7.042
Inventory-related Adjustments	¢/m³	*Not considered*
Cap and Trade Emission Allowances Service	¢/m³	3.659
Distribution - Basic Fee	¢/Metering device/Day	110.420
Distribution - Volume Withdrawn Fee	¢/m³	20.875
Yearly Weighted Average Price (with all the above listed components)	**¢/m³**	49.418

The load-balancing component of the gas bill require applying formulas that depend on the last twelve months gas volume consumption. So far, eQUEST does not support entering inputs that depend on the outputs of the simulation. To overcome this, the simulation is performed once to obtain the monthly gas volume consumption and the rates are then calculated manually. Once the total cost is calculated, it is divided by the total gas volume consumed during the year to obtain a virtual rate that is simply a yearly weighted average price.

Since the focus of the comparison is to determine the best Embodiment in terms of energy consumption during operation, initial investment costs related to each option were not considered. The initial investment is otherwise important to evaluate the best system financially over the course of their lifespan.

3.6.4. Results and Discussion

The results of the comparison of three possible embodiments of heating systems are provided in this section. The attractiveness of each system type is compared through energy and cost indicators. In Embodiment 1, the heat source of the central heating coils, reheat coils and baseboard heaters is Electric Resistance. In Embodiment 2, the heat source of the coils is hydronic with the Hot Water Loop being powered by an Electric Boiler. In Embodiment 3, the heat source of the coils is hydronic with the Hot Water Loop being powered by a fuel-fired boiler. These three models encompassing all the premises described in the previous sections were created in eQUEST. The results of each run are summarized and compared in Table A.1 through Table A.4, presented in APPENDIX A.

Analyzing the results in Table A.2, we see an increase in electric energy consumption comparing Embodiment 2 with Embodiment 1. This happens due to the decrease in efficiency of the heating equipment. The electric boiler used in Embodiment 2 has an efficiency of 93%, while the conversion from electricity to heat in the electric resistance (Joule effect) used in Embodiment 1 is considered to be 100% efficient. Since Embodiment 2 uses water as the heat transfer fluid, there is an additional energy consumption for pumping the fluid in the Hot Water Loop.

Since Embodiment 2 and Embodiment 3 consider the same premises in their modelling, their end-use energy consumptions are the same, except for space heating. The difference in the space heating happens because Embodiment 2 uses electricity instead of natural gas as the main heat source. In general, Embodiment 3 presents substantial electric energy reduction due to having natural gas as the heat source. When compared to Embodiment 1, a reduction in the annual energy consumption of 45.5% is seen. When compared to Embodiment 2, a reduction of 48.7% is seen.

Analyzing the results in Table A.3, we see an increase in electric energy demand comparing Embodiment 2 with Embodiment 1. This happens due to the decrease in efficiency of the heating equipment and to the need for additional pumping power, following the same reasoning in the electric energy consumption.

Comparing the peak demand for each end-use in Embodiment 3 with Embodiments 1 and 2, we notice an increase in all categories, except for space heating, pumps and auxiliary equipment and the total monthly demand. This happens because the hour when the peak demand occurs changes between the Embodiments. In Embodiments 1 and 2, space heating is a major component of the electricity demand, since the heating itself is performed either by the electric resistances or the electric boiler. During the peak hour, that is mostly determined by the peak space heating demand, other end-uses are not at their highest value. Differently, in Embodiment 3, since space heating is not done using electricity, the other end-use components have a higher contribution in the peak hour in terms of amount and when it occurs.

The main factor used to determine which Embodiment is the best financially is the annual utility bill. The annual utility bill embodies the savings from the reduction in electricity consumption and demand, as well as the additional expenses related to natural gas consumption. Analyzing the results in Table A.4, we see an increase in the annual utility bill comparing Embodiment 2 with Embodiment 1. This happens due to the decrease in efficiency of the heating equipment and to the need for additional pumping power, following the same reasoning of the previous paragraphs.

Table 3.24 - Summary of comparison between all embodiments

KPI	Unit	Embodiment 1 - All Electric Resistance	Savings of #3 compared to #1	Embodiment 2 - Hydronic w/ Electric Boiler	Savings of #3 compared to #2	Embodiment 3 - Hydronic w/ Gas-fired Boiler
Annual Electric Consumption	kWh	496.2	45.6%	526.6	48.7%	270.4
Peak Monthly Electric Demand	kW	243.9	60.6%	256.8	62.6%	96.2
Annual Gas Consumption	MWh	-	-	-	-	298.7
Peak Monthly Gas Demand	kW	-	-	-	-	219.5
Annual Utility Bills	**$**	**57,277**	**27.9%**	**59,696**	**30.8%**	**41,282**

Table 3.24 compares the main KPIs between the three proposed embodiments. Embodiment 3 presents substantial financial savings when compared to the other Embodiments. When compared to Embodiment 1, a reduction in the annual monthly bill of 27.9% is seen. When compared to Embodiment 2, a reduction of 30.8% is seen. Since the main source of the savings is

the reduction of electricity consumption and demand due to the use of natural gas as the main heat source, the cost of the gas plays an important role in determining the feasibility of gas-fired boilers. **Given that Embodiment 3 performed best in terms of annual utility bills, the gas-fired boiler is chosen to be the compliant base case for the current study.**

As additional remarks, by analyzing the results in Table A.1, higher gas consumption in the winter due to lower outside air temperatures is seen. In terms of gas demand, a threshold for high demands can be set ranging from October through April. Such high demands for a period of many months contrast with the sharp decrease in the gas consumption for the period of time. The explanation lies in the occurrence of exceptionally cold days during all of that period, decreasing however in frequency progressively until the summer arrives.

3.7. Running the Compliant Base Case

The original base case eQUEST file was modified to achieve full compliance to NECB 2017 code, both in the prescriptive path and in the performance path [71]. Where applicable, parameters for the building envelope, internal loads and the water-side and air-side HVAC systems were adjusted to the requirements presented in the code. For the specific vales used in each part of the model, refer to the previous sections of the thesis. The run period of the simulation was set to one year (365 days with 24-hour days, resulting in 8760 hours of simulation).

General building characteristics are presented in Table 3.25. Benchmark values for the base case model are also presented in Table 3.26. The performance of the base case was evaluated through a range of KPIs, presented in Table 3.27. These KPIs refer to the performance at the whole building, system and equipment level.

Table 3.25 - General Building Characteristics

Variable	Unit	Value
Total Floor Area	m² (ft²)	3,454.5 (37,187)
Maximum Occupants	person (person)	197
Occupancy	m²/person (ft²/person)	17.54 (188.8)
Total Gross Wall Area	m² (ft²)	1,946.38 (20,950.80)
Total Window Area	m² (ft²)	748.30 (8,054.69)
Total Roof Area	m² (ft²)	1,151.59 (12,395.69)

Table 3.26 – Benchmark Values extracted from the Base Case Model Simulation Results

Variable	Unit	Value
Whole Building Check Figures		
Energy Use[1]	MWh (MBtu)	569.6 (1942.2)
Peak Electric Demand	kW_{ele}	96.2
Annual Energy Cost	$	41,267
Lighting Peak Electric Demand	kW_{ele}	32.4
Miscellaneous Equipment Peak Electric Demand	kW_{ele}	14.8
FDWR	%	38.4
Heating and Cooling Check Figures		
Peak Space Cooling Load	kW_{th} (kBtu/hr)	98.5 (336.1)
Peak Space Heating Load	kW_{th} (kBtu/hr)	87.4 (298.1)
Peak Building HVAC Cooling Load	kW_{th} (kBtu/hr)	202.8 (692.1)
Peak Building HVAC Heating Load	kW_{th} (kBtu/hr)	183.1 (624.9)
Peak Circulation Loop Cooling Load	kW_{th} (kBtu/hr)	205.3 (700.5)
Peak Circulation Loop Heating Load	kW_{th} (kBtu/hr)	182.4 (622.4)
Chilled Water Loop Capacity	kW_{th} (TR)	206 (58.7)
Cooling Capacity per floor area	m^2/kW_{th} (ft^2/TR)	16.7 (634)
Hot Water Loop Capacity	kW_{th} (kBtu/hr)	182 (619)
Heating Capacity per floor area	m^2/kW_{th} (ft^2/kBtu)	19.0 (60.1)
Condenser Water Loop Capacity	kW_{th} (kBtu/hr)	247 (841)
Pumping Check Figures		
CHW Loop Pump Power	kW_{ele} (HP)	2.855 (3.829)
CHW Loop Pump Design Flow	L/s (gpm)	8.126 (128.8)
HW Loop Pump Power	kW_{ele} (HP)	0.819 (1.10)
HW Loop Pump Design Flow	L/s (gpm)	2.72 (43.1)
CW Loop Pump Power	kW_{ele} (HP)	3.155 (4.231)
CW Loop Pump Design Flow	L/s (gpm)	10.49 (166.2)
Air Distribution Check Figures		
Supply Fan Power Demand	kW_{ele} (HP)	13.179 (17.673)
Return Fan Power Demand	kW_{ele} (HP)	6.025 (8.080)
Fan Airflow Capacity	L/s (cfm)	7,341.1 (15,555)
Supply Airflow per floor area	L/s-m^2 (cfm/ft^2)	2.1249 (0.41829)

1 - Includes both electricity and natural gas energy

2 - "ele" refers to electrical load and "th" refers to thermal load

Table 3.27 - Base Case Model KPIs

Variable	Unit	Value
Whole Building KPIs		
Energy Use Intensity[1]	GJ/m² (kBtu/ft²)	0.59313 (52.227)
Peak Electric Demand per floor area	W_{ele}/m² (W/ft²)	27.852 (2.5875)
Annual Energy Cost per floor area	\$/m² (\$/ft²)	11.95 (1.11)
Lighting Peak Electric Demand per floor area	W_{ele}/m² (W/ft²)	9.377 (0.871)
Miscellaneous Equipment Peak Electric Demand per floor area	W_{ele}/m² (W/ft²)	4.287 (0.398)
HVAC System KPIs		
System Performance Ratio (Heating)	W_{th}/W_{ele} (Btu/Btu)	0.658
System Performance Ratio (Cooling)	W_{th}/W_{ele} (Btu/Btu)	1.446
System Performance Ratio (Both)	W_{th}/W_{ele} (Btu/Btu)	0.876
Total System Performance Ratio	kWh_{th}/\$ (kBtu/\$)	9.322 (31.81)
Equipment KPIs		
Chiller COP (Yearly Average)	W_{th}/W_{ele} (Btu/Btu)	3.407
Boiler Efficiency (Yearly Average)	W_{th}/W_{ele} (Btu/Btu)	0.780
Cooling Tower Performance (Yearly Average)	W_{ele}/W_{th} (Btu/Btu)	0.00735
Auxiliary Equipment KPIs		
Heating Pumping Power Demand	W_{ele}/kW_{th} (Btu/Btu)	4.515
Heat Rejection Pumping Power Demand	W_{ele}/kW_{th} (Btu/Btu)	12.80
Cooling Pumping Power Demand	W_{ele}/kW_{th} (Btu/Btu)	13.84
Combined supply and return fan power demand	W_{ele}/L-s (10^{-3} HP/cfm)	2.616 (1.656)

1 - Includes both electricity and natural gas energy

2 - "ele" refers to electrical load and "th" refers to thermal load

A summary of the end-uses of the Energy Use Intensity (EUI) is illustrated in Figure 3.6.

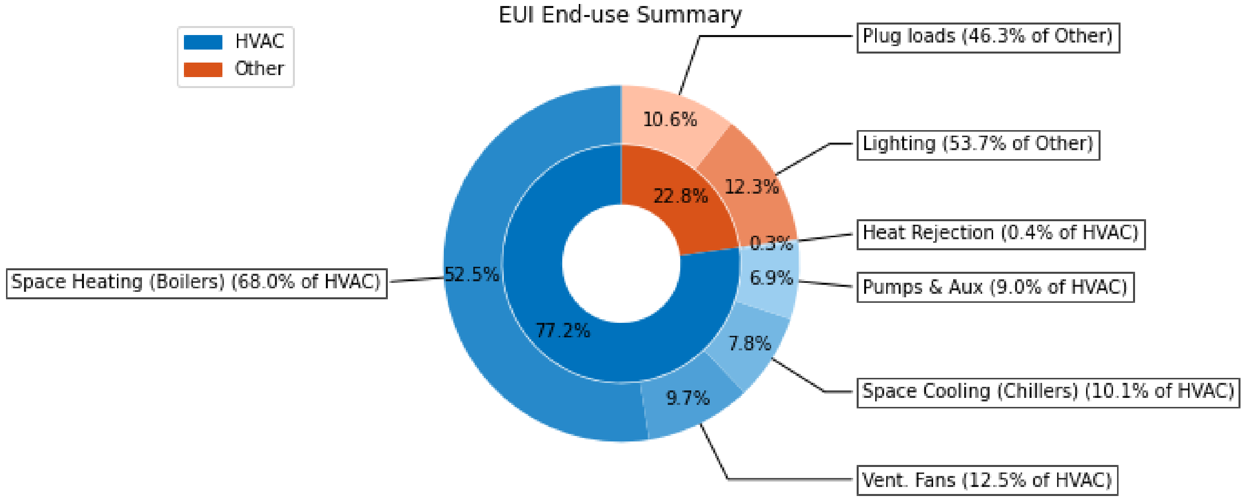


Figure 3.6 - EUI End-use Summary Sunburst plot

Table 3.28 – EUI End-use Summary Table

System	**HVAC**					**Other**	
Annual Energy Consumption (kWh)	439,194					129,908	
Percent of EUI (%)	77.2					22.8	
End-use	**Space Heating (Boilers)**	**Ventilation Fans**	**Space Cooling (Chillers)**	**Pumps & Aux**	**Heat Rejection**	**Lighting**	**Plug loads**
Annual Energy Consumption (kWh)	298,700	54,963	44,537	39,340	1,654	69,750	60,158
Percent of System (%)	68.0	12.5	10.1	9.0	0.4	53.7	46.3
Percent of EUI (%)	**52.5**	**9.7**	**7.8**	**6.9**	**0.3**	**12.3**	**10.6**

In the base case scenario, HVAC related energy consumption amounts to 77.2% of the EUI. This high contribution is due primarily to energy spent in space heating, by the natural gas fired boilers, which amount to 68.0% of the HVAC system energy and 52.5% of the building EUI. The low efficiency in energy conversion from the combustion process in the boiler as compared to the high efficiency in the vapor compression cycle of the chiller, coupled with the heating dominated climate in the building's location explain the disproportional contribution of this end-use to the EUI. The ventilation fans, chiller and pumps and auxiliary equipment consume considerably less, with each of them amounting to approximately 10% of the HVAC system energy and 8% of the building EUI. The energy spent by the cooling tower fans is negligible.

The remaining 22.8% is caused by lighting and plug loads, with both components exhibiting similar expenditures. Plug loads amount to 46.3% of the energy consumption other than by the HVAC system and it amounts to 10.6% of the EUI. Lighting amount to 53.7% of the energy consumption other than by the HVAC system and it amounts to 12.3% of the EUI.

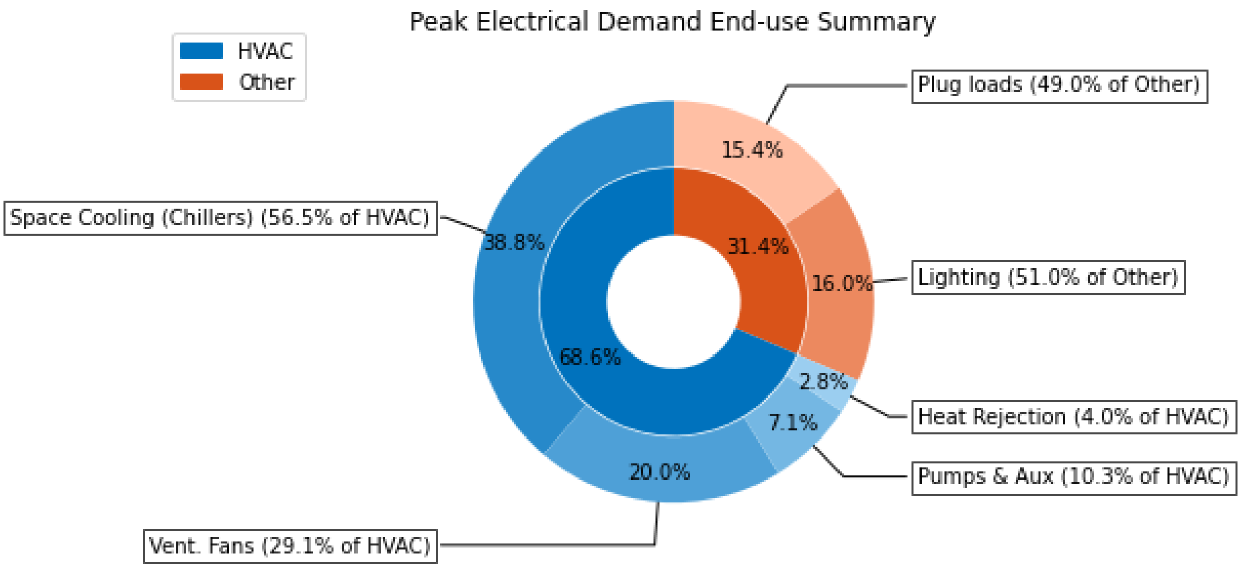


Figure 3.7 – Peak electrical demand End-use Summary Sunburst plot

Table 3.29 – Peak Electrical Demand End-use Summary Table

System	**HVAC**					**Other**	
Peak Electrical Demand (kW)	66.021					30.229	
Percent of PED (%)	68.6					31.4	
End-use	**Space Cooling (Chillers)**	**Ventilation Fans**	**Pumps & Aux**	**Heat Rejection**	**Space Heating (Boilers)**	**Lighting**	**Plug loads**
Peak Electrical Demand (kW)	37.313	19.211	6.830	2.667	0	15.420	14.809
Percent of System (%)	56.5	29.1	10.3	4.0	0	51.0	49.0
Percent of PED (%)	**38.8**	**20.0**	**7.1**	**2.8**	**0**	**16.0**	**15.4**

While space heating is performed by a natural gas fired boiler, space cooling, an end-use that takes up a considerable amount of energy, is performed by an electric chiller. In the base case scenario, the chillers are responsible for 38.8% of the whole-building peak electrical demand and 56.5% of the HVAC peak electrical demand. The next biggest contributors are the ventilation fans, comprising 20.0% of the whole-building demand and 29.1% of the HVAC demand. Smaller contributors are the pumps and auxiliary equipment and the heat rejection equipment. Lighting and plug loads require roughly the same power demand and combined represent roughly a third of the whole building electric demand.

Benchmarking the whole building KPIs against median values taken from the literature demonstrates the benefits of using NECB 2017 during the design and construction of new buildings. A comparison between the values obtained for the base case simulation and benchmark median values from literature or benchmark example buildings provides an idea of the order of magnitude of the savings that can be achieved. The results are compiled in Table 3.30, with the respective percent difference and references used for the comparison.

Table 3.30 - Comparison of Whole Building KPIs of the base case scenario with literature benchmarks

Variable	Value	Benchmark	Diff.	Ref.
Whole Building KPIs				
Energy Use Intensity in GJ/m² (kBtu/ft²)	0.593 (52.2)	0.99 (87.2)	-40.1%	[82]
Peak Electric Demand per floor area in W_{ele}/m^2 (W/ft²)	27.9 (2.59)	36.6 (3.4)	-23.8%	[83]
Annual Energy Cost per floor area in \$/m² (\$/ft²)	11.95 (1.11)	31.10 (2.89)	-61.6%	[83]
Lighting Peak Electric Demand per floor area in W_{ele}/m^2 (W/ft²)	9.38 (0.871)	6.84 (0.635) to 14.8 (1.374)	+37.7% to -36.6%	[84]
Miscellaneous Equipment Peak Electric Demand per floor area in W_{ele}/m^2 (W/ft²)	4.287 (0.398)	5.382 (0.50)	-20.4%	[85]

A reduction of 40.1% in the Energy Use Intensity was observed when comparing the results of the base case annual building energy consumption with the Canadian National Median Reference Values for office buildings taken from the ENERGY STAR Portfolio Manager database [82]. This reduction can be likely explained by the contrast of the elevated energy efficiency requirements of the latest version of NECB (2017), compared to the median values being samples composed of both new and existing buildings. Existing buildings were designed according to older standards and operate with reduced performance due to equipment efficiency depreciation with time. The building envelope design also plays an important role in the reduction of energy consumption. In the newer versions of NECB, tighter building envelope design, resulting in less infiltration and exfiltration of outdoor air, and better thermal insulation are factors that reduce the heating and cooling thermal loads of the spaces.

There is an overall reduction in the peak electric demand per floor area of 23.8% when compared with an example office tower [83]. The benchmark building is located in Toronto, ON, Canada and was built in the 1990s and recommissioned in 2012. This reduction can be likely explained by the increased energy efficiency of all electrical equipment considered in NECB when compared to the equipment already in use in the office tower. This more efficient equipment encompasses a whole group of area and task lighting, miscellaneous (plug loads), exterior usage, pumps and auxiliaries, ventilation fans, water heating, heat pumps, space heating, refrigeration, heat rejection and space cooling equipment. In addition, as mentioned before, better envelope design can contribute to the reduction of cooling loads, usually handled by an electrical chiller.

The compounded effects of more energy efficient equipment and tighter and better insulated envelope amount to a reduction in the annual energy cost of 61.6% when comparing the base case simulation with the example benchmark office building [83]. The comparison considers improvements in energy consumption expenses with electricity consumption (kWh), maximum electrical demand (kW) and natural gas consumption.

Comparing the lighting peak electric demand with the median installed wattage from the 2015 U.S. Lighting Market Characterization yields a range from an increase of 37.7% to a reduction of 36.6%, depending on the building space type [84]. Although the base case building is made up of office spaces (which corresponds to a lighting power density of 0.797 W/ft^2 in the Market Characterization report), it also encompasses a substantial area of conference/multi-purpose rooms and laboratories used for educational purposes (which corresponds to a lighting power density of 1.374 W/ft^2 in the Market Characterization report) . It’s valid then to consider a difference range instead of a single value.

Lastly, by comparing the miscellaneous equipment (plug loads) peak electric demand with the average peak plug for offices (without laboratories or data centers) in a study conducted by NREL, a reduction of 20.4% can be verified [85]. This reduction also reflects the ongoing trend of energy consumption reduction in miscellaneous equipment used in conference/meeting/multi-purpose room, laboratory and offices for more recent building energy standards.

CHAPTER 4 : Batch Processing Feature

This chapter describes the batch processing feature in eQUEST: a native functionality that allows users to execute limitless consecutive simulations. Tools that automatize the simulation process are of paramount importance in Building Energy Modelling/Building Performance Simulation (BEM/BPS) due to the need of exploring the relationship between inputs and outputs through numerous simulations for a large range of scenarios. This implies the availability of hundreds or thousands of simulated models representing different combinations of input parameters. The approach developed, based on scarcely available documentation, and presented in this chapter is a contribution to batch processing that is needed for increasing the simulation productivity in eQUEST. The step-by-step process of set-up and utilization is explained with accompanying illustrations and example files.

This feature relies on an 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 case model file. The feature that is launched within eQUEST native interface will use the external database file to create the new models and launch the simulation runs automatically. By using this feature, the effort otherwise required to generate numerous simulation models representing different design scenarios is considerably reduced. After the models are generated and simulated, an automatically generated Comma Separated Value (.csv) output file containing some main building performance indicators and check figures is created. This automated model generation, simulation and result extraction feature allows users to analyze the impact of many permutations of design decisions on the building energy performance in a time and resource-efficient way.

One of the shortcomings of the batch processing feature is that up to the current version (eQUEST 3.65, build 7175), there is no official documentation available on how to set up and run the feature. Users rely on experimentation and expertise from other users to develop proficiency in using this tool [86]. To address this shortcoming, the step by step process of setting up eQUEST to perform the batch processing is detailed in this chapter.

A general overview of the tool approach is illustrated in Figure 4.1.

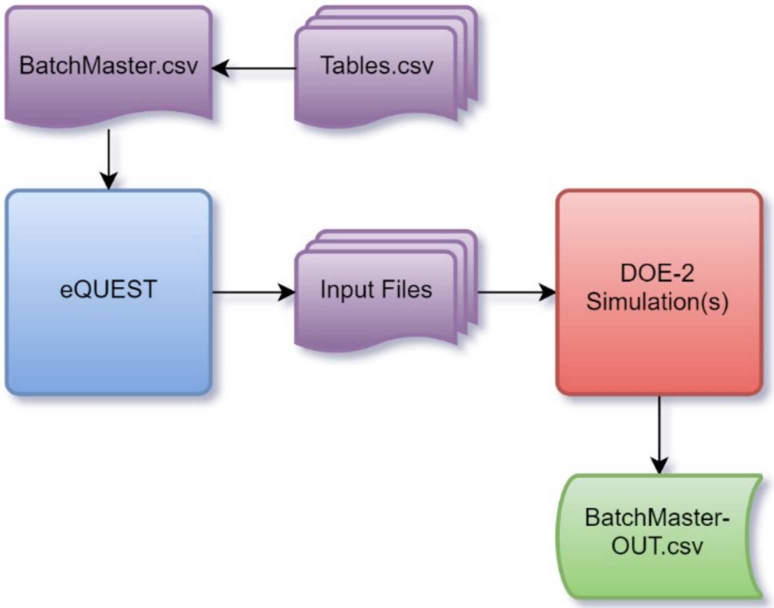
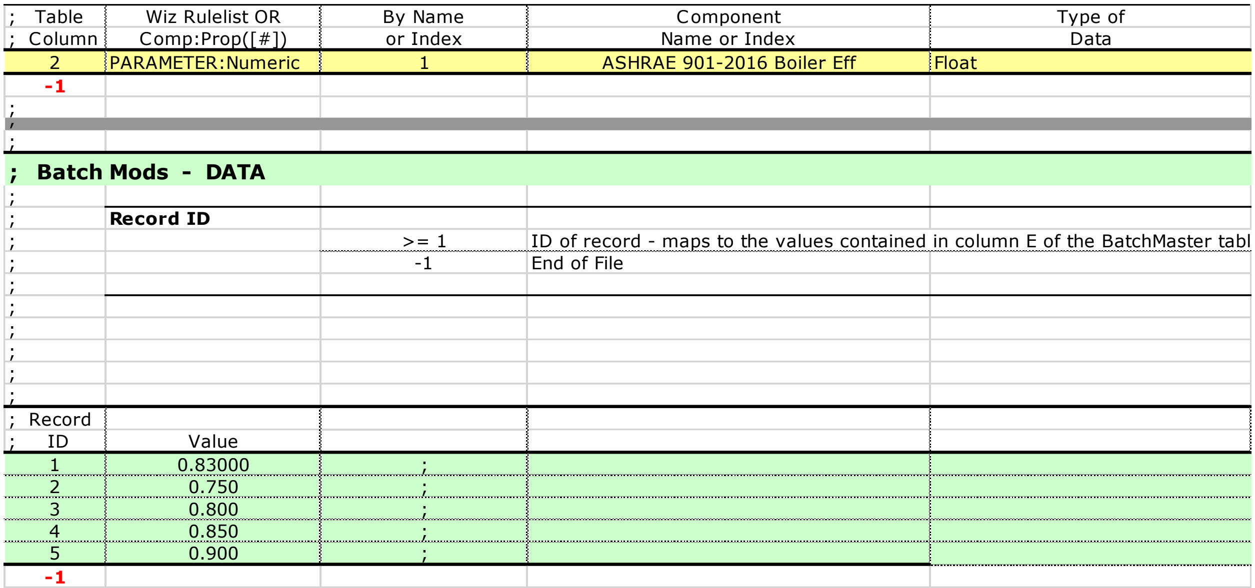


Figure 4.1 - Batch Processing Work-flow [87]

The process starts with a series of .csv tables ("Tables.csv"), called data modification tables, that contain specific instructions on what properties or parameters are to be modified to generate each new model, and to which values these properties and parameters should be modified to. As an example, in the first row of a data modification table, a user could find the number "2" referring to which column in that table contains the parameter to be passed on to the new model. In the next columns of the first row, the user could find the string *"PARAMETER:Numeric"*, followed by the string *"BlrEff"*, indicating that this file contains instructions to change the numeric parameter that quantifies the boiler efficiency in the base case model file. In subsequent rows, the user could find in each row a numeric value, such as *"0.85"*, *"0.80"*, or *"0.75"* representing the actual value that will be assigned as the boiler efficiency in each new model created from the base file. These "slave" tables of data modifications are then passed on to a "master" batch directives table.

A screenshot exemplifying a data modification table is shown in Figure 4.2.

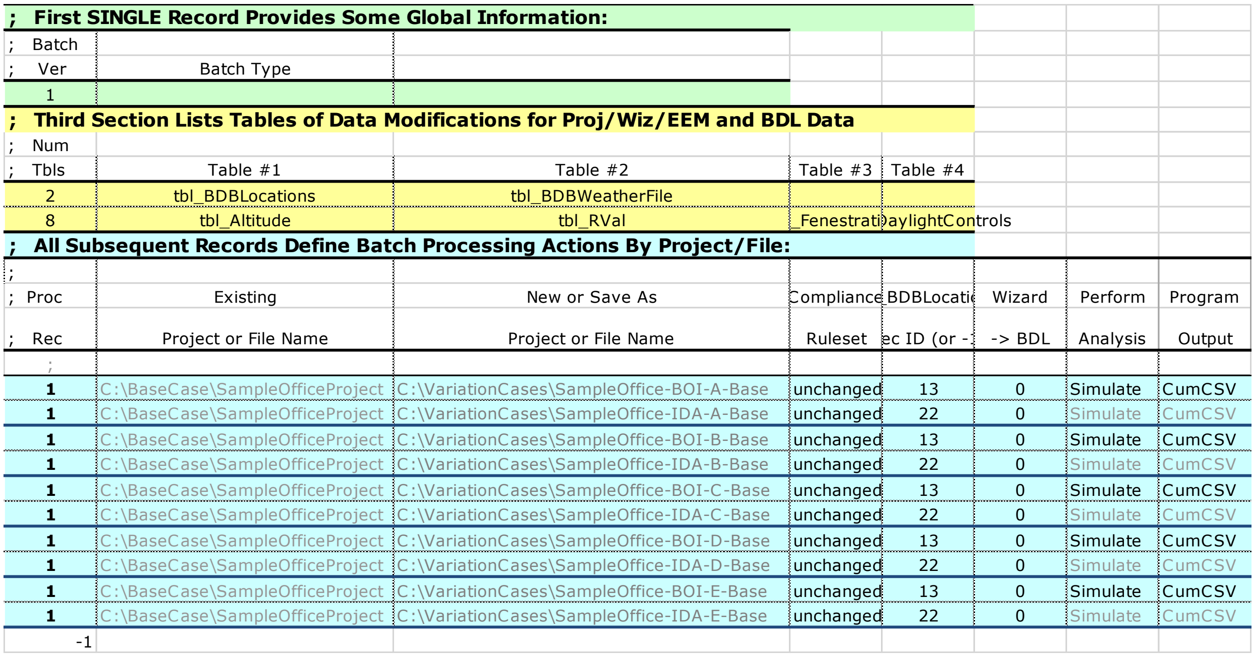


; Table ; Column	Wiz Rulelist OR Comp:Prop([#])	By Name or Index	Component Name or Index	Type of Data
2	PARAMETER:Numeric	1	ASHRAE 901-2016 Boiler Eff	Float
-1				
;				
;				
;				
; Batch Mods - DATA				
;				
;	**Record ID**			
;		>= 1	ID of record - maps to the values contained in column E of the BatchMaster tabl	
;		-1	End of File	
;				
;				
;				
;				
;				
;				
; Record ; ID	Value			
1	0.83000	;		
2	0.750	;		
3	0.800	;		
4	0.850	;		
5	0.900	;		
-1				

Figure 4.2 - Screenshot of an example of a data modification table created on Excel

The master batch directives table (“BatchMaster.csv”) contains global information on the batch simulation run. It indicates what type of processing is to be performed (simulation, ranked efficiency measure runs, etc.), what is the measure analysis information (building type, climatic zone, etc.), which tables of data modifications are to be used, and contains the file locations of the existing and new model simulations to be executed. As an example, in the first row of a master batch directives table, a user could find the string “1” representing the batch version and type, with this value corresponding to the type of processing that allows performing the simulations without any advanced post processing of the output data. In subsequent rows, the user could find in each row the strings *“C:\BaseCase”*, followed by *“C:\VariationCases*”, indicating the file location of the base case and where the variation cases will be saved, and a series of values such as “1”, “3”, “2”, indicating which rows from the data modification tables (e.g. BlrEff table, ChillerCOP table, etc.) are to be used to create the new variation case models.

A screenshot exemplifying a master batch directives table is shown in Figure 4.3.



; First SINGLE Record Provides Some Global Information:								
; Batch								
; Ver	Batch Type							
1								
; Third Section Lists Tables of Data Modifications for Proj/Wiz/EEM and BDL Data								
; Num								
; Tbls	Table #1	Table #2	Table #3	Table #4				
2	tbl_BDBLocations	tbl_BDBWeatherFile						
8	tbl_Altitude	tbl_RVal	_Fenestrati	aylightControls				
; All Subsequent Records Define Batch Processing Actions By Project/File:								
;								
; Proc	Existing	New or Save As	Compliance	BDBLocati	Wizard	Perform	Program
; Rec	Project or File Name	Project or File Name	Ruleset	ec ID (or -	-> BDL	Analysis	Output
;								
1	C:\BaseCase\SampleOfficeProject	C:\VariationCases\SampleOffice-BOI-A-Base	unchanged	13	0	Simulate	CumCSV	
1	C:\BaseCase\SampleOfficeProject	C:\VariationCases\SampleOffice-IDA-A-Base	unchanged	22	0	Simulate	CumCSV	
1	C:\BaseCase\SampleOfficeProject	C:\VariationCases\SampleOffice-BOI-B-Base	unchanged	13	0	Simulate	CumCSV	
1	C:\BaseCase\SampleOfficeProject	C:\VariationCases\SampleOffice-IDA-B-Base	unchanged	22	0	Simulate	CumCSV	
1	C:\BaseCase\SampleOfficeProject	C:\VariationCases\SampleOffice-BOI-C-Base	unchanged	13	0	Simulate	CumCSV	
1	C:\BaseCase\SampleOfficeProject	C:\VariationCases\SampleOffice-IDA-C-Base	unchanged	22	0	Simulate	CumCSV	
1	C:\BaseCase\SampleOfficeProject	C:\VariationCases\SampleOffice-BOI-D-Base	unchanged	13	0	Simulate	CumCSV	
1	C:\BaseCase\SampleOfficeProject	C:\VariationCases\SampleOffice-IDA-D-Base	unchanged	22	0	Simulate	CumCSV	
1	C:\BaseCase\SampleOfficeProject	C:\VariationCases\SampleOffice-BOI-E-Base	unchanged	13	0	Simulate	CumCSV	
1	C:\BaseCase\SampleOfficeProject	C:\VariationCases\SampleOffice-IDA-E-Base	unchanged	22	0	Simulate	CumCSV	
-1								

Figure 4.3 - Screenshot of an example of a master batch directives table created on Excel

After these two tables are created, the location of the master table file is passed on to eQUEST, which then uses the instructions contained in that table to generate input files that will be used for the simulation of the new variation case models from the base case model. These new variation case models are then passed on as input files to the DOE-2.2 simulation engine. Once the simulations are performed, some main performance indicators and check figures are compiled into an output table file (“BatchMaster-OUT.csv”).

The scope of this research also encompasses providing a more comprehensive understanding of the cause and effect relationship between the building performance and its systems and components. For this reason, a MATLAB code was implemented in order to extract and calculate additional KPIs and check figures from the simulations output files. These additional indicators span three levels: whole-building, system and component and can be used to quantify how much each system and component contributes to the performance of the minimally compliant energy code building model.

4.1. Using the Tool

Once a base case model file is opened in the eQUEST graphical interface, the feature can be accessed under “*Tools* → *Batch Processing…*”, as illustrated in Figure 4.4.

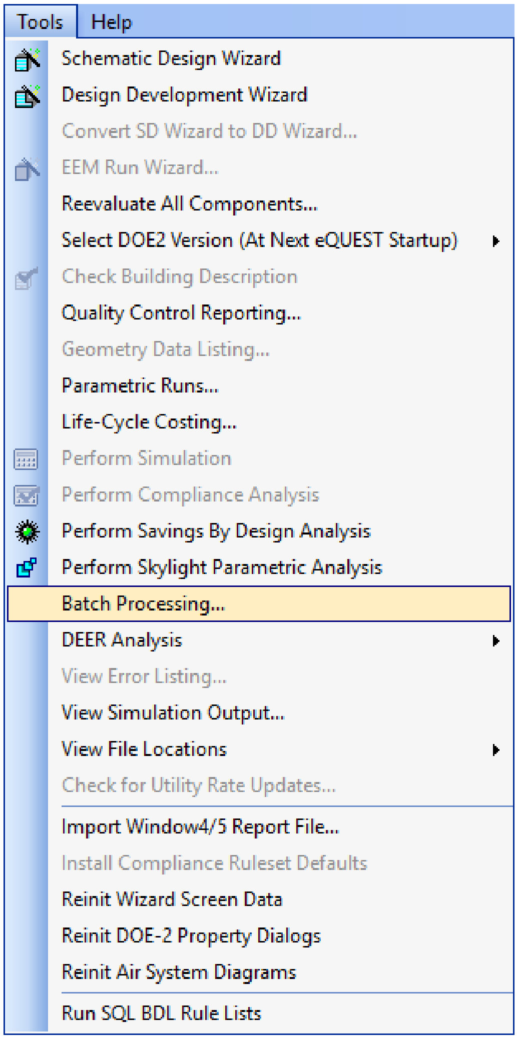


Figure 4.4 - eQUEST Tools Menu with Batch Processing option highlighted

Once the feature is selected, a prompt, reproduced in Figure 4.5, is shown requesting the user to provide two inputs: the Batch Directives and the Batch Output Results file locations. The Batch Output Log file is saved in the same location as the Batch Output Results File.

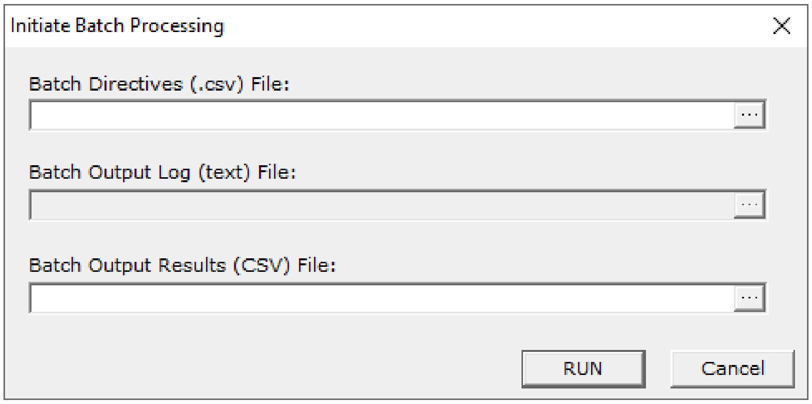
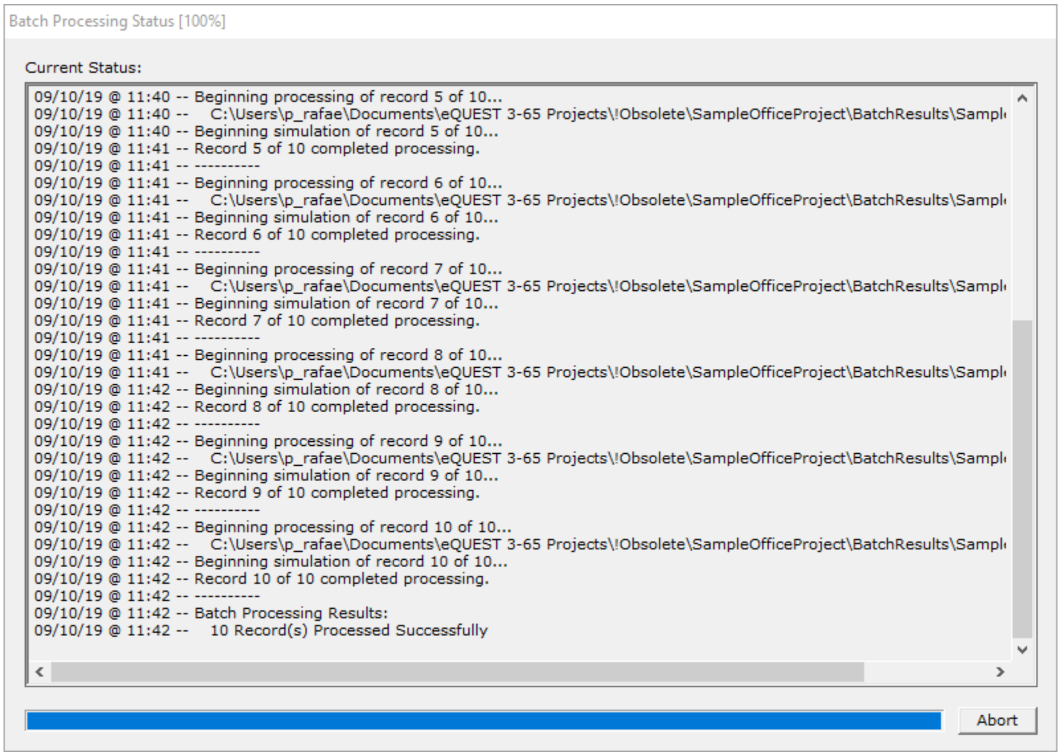


Figure 4.5 - Initiate Batch Processing prompt

The accepted file format for the Batch directives file is the CSV format. For ease of use, these files can be created using a spreadsheet format with an appropriate program, such as Microsoft Excel and saved with the appropriate file extension. Once the file locations have been provided, the user can start the batch processing by clicking on the *"Run"* button.

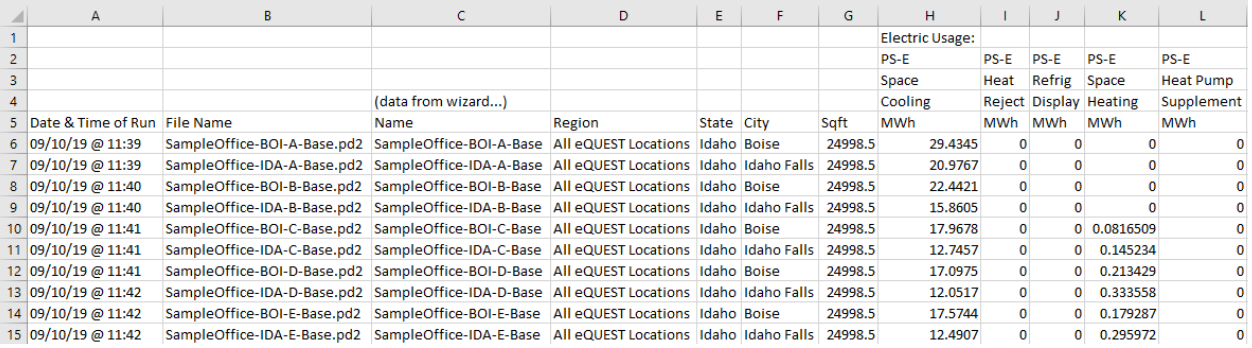
The batch processing status screen is shown when the process is started. In this screen, the progress of the batch simulations can be monitored. An example screen is illustrated in Figure 4.6. In each run, a new set of DOE-2.2 input files (with file extensions .inp and .pd2) and all their supporting files are created and saved into a previously defined location in the master batch directives table. This new set of files is comprised of a modified version of the base case file according to the instructions in the master table file that reference the tables of data modification (e.g. with different geographical locations, wall thermal transmittances, equipment efficiencies, etc.). Then, the simulation itself for the newly created model is performed. All of these events are recorded in the status screen, preceded by a time stamp.



```
09/10/19 @ 11:40 -- Beginning processing of record 5 of 10...
09/10/19 @ 11:40 --    C:\Users\p_rafae\Documents\eQUEST 3-65 Projects\!Obsolete\SampleOfficeProject\BatchResults\Sampl
09/10/19 @ 11:40 -- Beginning simulation of record 5 of 10...
09/10/19 @ 11:41 -- Record 5 of 10 completed processing.
09/10/19 @ 11:41 -- ----------
09/10/19 @ 11:41 -- Beginning processing of record 6 of 10...
09/10/19 @ 11:41 --    C:\Users\p_rafae\Documents\eQUEST 3-65 Projects\!Obsolete\SampleOfficeProject\BatchResults\Sampl
09/10/19 @ 11:41 -- Beginning simulation of record 6 of 10...
09/10/19 @ 11:41 -- Record 6 of 10 completed processing.
09/10/19 @ 11:41 -- ----------
09/10/19 @ 11:41 -- Beginning processing of record 7 of 10...
09/10/19 @ 11:41 --    C:\Users\p_rafae\Documents\eQUEST 3-65 Projects\!Obsolete\SampleOfficeProject\BatchResults\Sampl
09/10/19 @ 11:41 -- Beginning simulation of record 7 of 10...
09/10/19 @ 11:41 -- Record 7 of 10 completed processing.
09/10/19 @ 11:41 -- ----------
09/10/19 @ 11:41 -- Beginning processing of record 8 of 10...
09/10/19 @ 11:41 --    C:\Users\p_rafae\Documents\eQUEST 3-65 Projects\!Obsolete\SampleOfficeProject\BatchResults\Sampl
09/10/19 @ 11:42 -- Beginning simulation of record 8 of 10...
09/10/19 @ 11:42 -- Record 8 of 10 completed processing.
09/10/19 @ 11:42 -- ----------
09/10/19 @ 11:42 -- Beginning processing of record 9 of 10...
09/10/19 @ 11:42 --    C:\Users\p_rafae\Documents\eQUEST 3-65 Projects\!Obsolete\SampleOfficeProject\BatchResults\Sampl
09/10/19 @ 11:42 -- Beginning simulation of record 9 of 10...
09/10/19 @ 11:42 -- Record 9 of 10 completed processing.
09/10/19 @ 11:42 -- ----------
09/10/19 @ 11:42 -- Beginning processing of record 10 of 10...
09/10/19 @ 11:42 --    C:\Users\p_rafae\Documents\eQUEST 3-65 Projects\!Obsolete\SampleOfficeProject\BatchResults\Sampl
09/10/19 @ 11:42 -- Beginning simulation of record 10 of 10...
09/10/19 @ 11:42 -- Record 10 of 10 completed processing.
09/10/19 @ 11:42 -- ----------
09/10/19 @ 11:42 -- Batch Processing Results:
09/10/19 @ 11:42 --    10 Record(s) Processed Successfully
```

Figure 4.6 - Example of Batch Processing Status Screen

At the end of a successful batch simulation run, the status screen concludes the processing with a message stating the total number of records processed successfully. An output .csv file summarizing the results of the batch simulations is then automatically generated. A snippet of this output file is shown in Figure 4.7. Each row refers to a specific record, and each column refers to a property of said record.



	A	B	C	D	E	F	G	H	I	J	K	L
1								Electric Usage:				
2								PS-E	PS-E	PS-E	PS-E	PS-E
3								Space	Heat	Refrig	Space	Heat Pump
4			(data from wizard...)					Cooling	Reject	Display	Heating	Supplement
5	Date & Time of Run	File Name	Name	Region	State	City	Sqft	MWh	MWh	MWh	MWh	MWh
6	09/10/19 @ 11:39	SampleOffice-BOI-A-Base.pd2	SampleOffice-BOI-A-Base	All eQUEST Locations	Idaho	Boise	24998.5	29.4345	0	0	0	0
7	09/10/19 @ 11:39	SampleOffice-IDA-A-Base.pd2	SampleOffice-IDA-A-Base	All eQUEST Locations	Idaho	Idaho Falls	24998.5	20.9767	0	0	0	0
8	09/10/19 @ 11:40	SampleOffice-BOI-B-Base.pd2	SampleOffice-BOI-B-Base	All eQUEST Locations	Idaho	Boise	24998.5	22.4421	0	0	0	0
9	09/10/19 @ 11:40	SampleOffice-IDA-B-Base.pd2	SampleOffice-IDA-B-Base	All eQUEST Locations	Idaho	Idaho Falls	24998.5	15.8605	0	0	0	0
10	09/10/19 @ 11:41	SampleOffice-BOI-C-Base.pd2	SampleOffice-BOI-C-Base	All eQUEST Locations	Idaho	Boise	24998.5	17.9678	0	0	0.0816509	0
11	09/10/19 @ 11:41	SampleOffice-IDA-C-Base.pd2	SampleOffice-IDA-C-Base	All eQUEST Locations	Idaho	Idaho Falls	24998.5	12.7457	0	0	0.145234	0
12	09/10/19 @ 11:41	SampleOffice-BOI-D-Base.pd2	SampleOffice-BOI-D-Base	All eQUEST Locations	Idaho	Boise	24998.5	17.0975	0	0	0.213429	0
13	09/10/19 @ 11:42	SampleOffice-IDA-D-Base.pd2	SampleOffice-IDA-D-Base	All eQUEST Locations	Idaho	Idaho Falls	24998.5	12.0517	0	0	0.333558	0
14	09/10/19 @ 11:42	SampleOffice-BOI-E-Base.pd2	SampleOffice-BOI-E-Base	All eQUEST Locations	Idaho	Boise	24998.5	17.5744	0	0	0.179287	0
15	09/10/19 @ 11:42	SampleOffice-IDA-E-Base.pd2	SampleOffice-IDA-E-Base	All eQUEST Locations	Idaho	Idaho Falls	24998.5	12.4907	0	0	0.295972	0

Figure 4.7 - Batch Processing Output File Snippet

This standardized output file contains information concerning each simulation run, compiled from the DOE-2.2 reports. The DOE reports that are used in this process are listed below:

- **PS-E Report (Energy End-Use Summary for all Meters)**
    - ***Electric Usage and Non-Coincident Peak Electric Demand, Fuel Usage and Non-Coincident Peak Fuel Demand for:***
        - Space Cooling, Heat Rejection, Refrigeration Display, Space Heating, Heat Pump Supplement, Domestic Hot Water, Ventilation Fans, Pumps & Auxiliary, Exterior Usage, Miscellaneous Equipment, Task Lights, Ambient Lights, and Total.
- **SS-D Report (Building HVAC Load Summary)**
        - Peak Cooling Coil Load, and Multi-hour Electric Demand.
- **BEPS Report (Building Energy Performance)**
        - Zone Outside Throttling Range, Plant Load Not Met, Cooling Loads Not Met, and Heating Loads Not Met.
- **ES-E Report (Utility Bills - sums by rate type)**
        - Steam, Chilled Water, Electric, Natural Gas, LPG, Fuel Oil, Diesel Oil, Coal, Methanol, Other Fuel, Electric Sale, and Total.

The detailed process used to create the batch directives file and the table of data modification files is described in the following sections.

4.2. Batch Directives File Creation Process

In this section, the process of creating the batch directives file is further explained, accompanied by a flowchart illustrated in Figure 4.8. In section 4.3, an example of the file is given.

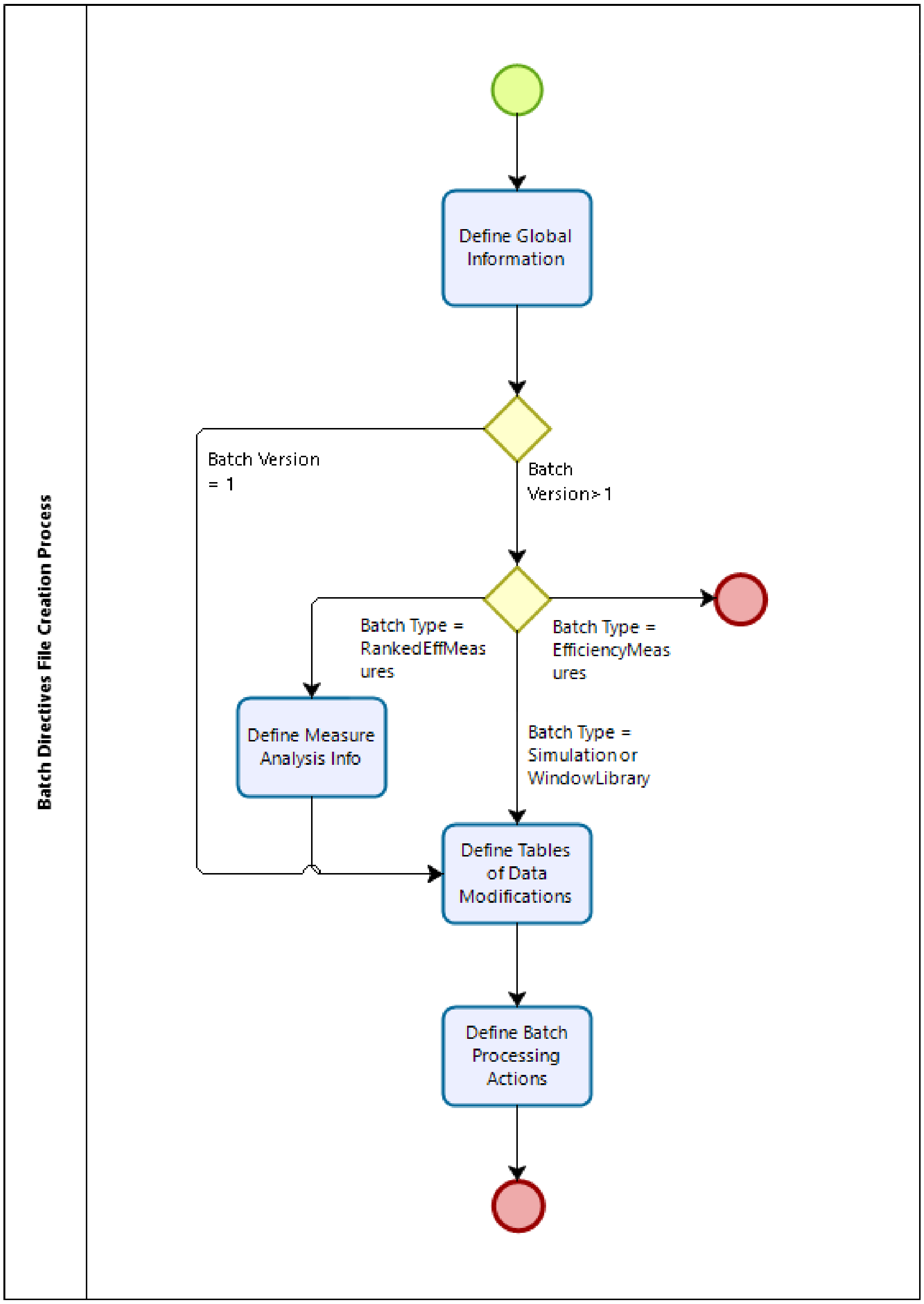


Figure 4.8 - Flowchart illustrating the process flow of the batch directives file creation

The first sub-process in the process flow of the batch directives file creation is the **Define Global Information**.

In this sub-process the batch version and type properties are defined. The batch version is a number denoting which version of the batch processing mechanism the file is written in. The batch type is only specified for batch versions higher than “1” and determines what type of processing is to be performed. For versions higher than “1”, it is possible to perform more advanced analyses.

Options for these more advanced analyses include performing one or more DOE-2 simulations including wizard-generated models and compliance analysis (*Batch Type = Simulation*), generating a Building Description Language (BDL) library of different components (*Batch Type = WindowLibrary*), and performing efficiency measure runs in which each baseline model is run with different measures to rank the impact of the measures on the energy performance of the building (*Batch Type = RankedEffMeasures*). If the user wishes to perform these analyses, additional information must be provided in the second sub-process, named **Define Measure Analysis Info**. Other batch types (*Batch Type = EfficiencyMeasures)* that were under development and had not been yet implemented at the time the supporting literature was published might be available.

In the present study, the focus of the analysis is to determine the sensitivity indices of the output variables related to the input variables. The baseline model was created beforehand, alongside with the data modification tables necessary for creating the variation cases for the sensitivity analysis. For this reason, the batch version “1” was chosen since it comprises all the necessary tools.

In the third sub-process **Define Tables of Data Modifications,** information concerning the instructions to generate the variant models is provided. The variant models are generated from a base case model file after performing changes in two categories: changes to the Project/Wizard/Energy Efficiency Measures component (stored in the *.pd2* file of the model) and changes to the BDL component (stored in the *.inp* file of the model).

The *.pd2* file contains all properties that regard either the building geometry or the project description. Examples of these properties are the weather file, the location of the building and geometrical positions of floors, walls and windows. The *.inp* file contains all the information regarding the building description and is written in the Building Description Language (BDL). Examples of these properties are global parameters used in the simulation, materials, layers and constructions used in the building shell, glass types and schedules.

During this sub-process, in each row of the batch directives file the number of *.pd2* file data modification tables and the number of *.inp* file data modification tables are written, alongside with the names of these tables. With these parameters defined, the batch directives file is able to reference the other data modification tables and modify the base case model to generate the new variant model files.

The fourth and last sub-process is the **Define Batch Processing Actions**. In this sub-process, properties are defined for each desired combination of modifications. Each row in this part of the table contains information regarding a new record and represents a new variant building model to be generated from the base case model and simulated.

In each row a process record flag, determining if the record should or should not be processed is defined. Then, a '*new or existing*' flag is defined, with the option to either create and save a new set of project files or merely use the current one. For both options, the file location must be provided. If the user wishes to perform compliance analysis using a compliance ruleset file, the user can provide the name of the ruleset or use the '*unchanged'* property not to do compliance analysis. Following these steps, a number of columns is created, one for each property defined in the tables of data modification. For each column, a number is given that points to the row containing the value in the table of data modification the user wishes this property to be set to. Next, a wizard to BDL conversion flag is defined, determining whether inputs converted from the wizard data should be used based on if they were previously edited using the table of modifications data. The type of the analysis to be performed is defined and lastly, the way the output file is generated is defined.

Additional information found in the supporting literature is available in APPENDIX B.

4.3. Example of Batch Directives File

An example of a batch directives CSV file generated according to the instructions presented in the previous section is reproduced in its entirety in the greyed text box below.

```
1
2,tbl_BDBLocations,tbl_BDBWeatherFile
3,tbl_Altitude,tbl_RVal,tbl_Fenestration
1,C:\SampleBaseProject,C:\SampleModifiedProject-A,unchanged,2,4,3,1,5,0,Simulate,CumCSV
1,C:\SampleBaseProject,C:\SampleModifiedProject-B,unchanged,1,3,5,2,4,0,Simulate,CumCSV
-1
```

Each field in the file presented above is delimited by commas. The explanation of these fields is given in the greyed text box below, with each field from the above table corresponding to the same field in the table below in green font color.

```
Batch Ver
Num Tbls, Proj/Wiz/EEM mod Table #1, Proj/Wiz/EEM mod Table #2
Num Tbls, BDL mod Table #1, BDL mod Table #2
Proc Rec, Existing File Name, New File Name, Compliance Ruleset, tbl_BDBLocations Rec ID,
tbl_BDBWeatherFile Rec ID, tbl_Altitude Rec ID, tbl_RVal Rec ID, tbl_Fenestration Rec ID,
Wizard -> BDL, Perform Analysis, Program Output
Proc Rec, Existing File Name, New File Name, Compliance Ruleset, tbl_BDBLocations Rec ID,
tbl_BDBWeatherFile Rec ID, tbl_Altitude Rec ID, tbl_RVal Rec ID, tbl_Fenestration Rec ID,
Wizard -> BDL, Perform Analysis, Program Output
End of File Flag
```

In the first row, the number "1" defines the Batch Version. Since the version is not bigger than 1, no further definition is required for the Batch Type is required.

In the second row, the number "2" defines the number of Project/Wizard/Energy Efficiency Measures modification tables. Following this number of tables is an equivalent number of strings that refer to the name of these modification tables. The strings "*tbl_BDBLocations*" and "*tbl_BDBWeatherFile*" refer to the modification tables that contain respectively the geographical locations and the weather files that will be used to generate the new building models.

In the third row, the number "3" defines the number of BDL modification tables. Following this number of tables is an equivalent number of strings that refer to the name of these modification tables. The strings "*tbl_Altitude*", "*tbl_RVal*", and "*tbl_Fenestration*" refer to the modification tables that contain respectively the altitudes, thermal resistance values and fenestration characteristics that will be used to generate the new building models.

In the fourth row, the number "1" defines the process record flag that identifies that this simulation record is to be performed indeed. The opposite would be the number "0" that would cause the simulation to skip the current simulation record and proceed to the next row. Following this flag are the file locations of the base case model used to generate the new models and where the new models will be saved represented respectively by the strings "*C:\SampleBaseProject*" and "*C:\SampleModifiedProject-A*". Next, a string defines the compliance ruleset that is to be used in the simulation. In this case, the "*unchanged*" string defines that no compliance analysis is to be performed, since it's not within the scope of this example or within the scope of the present research. After this, the record IDs of the data modification tables is defined, that is, which row of these data modification tables is to be used to generate the new model in question. The numbers "2", "4", "3", "1", and "5" instruct the DOE engine to capture the second, fourth, third, first and fifth rows of the data modification tables to generate the new model. Each one of these numbers refer to a different data modification table. The order used is the same order passed on in the second and third rows of this file, that is, in this example, the data modification tables that will be used as sources are respectively "*tbl_BDBLocations*", "*tbl_BDBWeatherFile*", "*tbl_Altitude*", "*tbl_RVal*", and "*tbl_Fenestration*". The following flag refers to how the program edits the input file with respect to the options previously edited in the Wizard. The number "0" instructs DOE only to modify the base case model parameters if these parameters have already been edited using the Wizard within eQUEST. Lastly, the string "*Simulate*" defines which type of analysis is to be performed, amongst the options of performing a regular simulation, a building Wizard simulation, an Energy Efficiency Measure run or a compliance analysis. The last field contains the string "*CumCSV*" that defines the program output. In this case, this string refers to a cumulative CSV approach, in which the results of each new simulation run are added after the last row of the output file without rewriting previously recorded simulation outputs.

The fifth row contains the same sort of instructions as the ones used in the fourth row. In this row, a new simulation run with different characteristics are defined. The user can subsequently add new rows to generate as many variation cases as he wishes.

The sixth and last rows contains the number “-1” identifying that this is the end of the file.

4.4. Tables of Data Modifications Creation Process

In this section, the process of creating the tables of data modifications file is further explained, accompanied by a flowchart illustrated in Figure 4.9. In section 4.5, an example of the file is given.

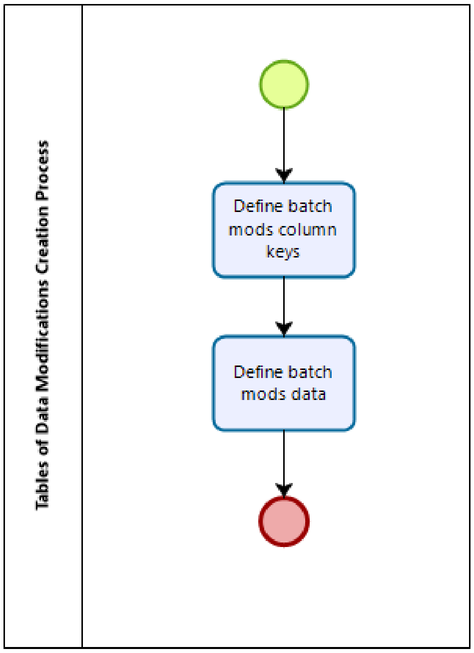


Figure 4.9 - Flowchart illustrating the process flow of the Tables of Data Modifications Creation Process

The first sub-process in the process flow of the tables of data modifications file creation is the **Define Batch Mods Column Keys**.

In this sub-process, numeric identifiers that indicate which columns of the current data table contain the parameters to be passed on to create the variant models are defined.

After this step, the property and the component being changed are also defined, separated by a colon (e.g. *Component:Property*). It can be either a property from the .pd2 file, such as the *WeatherFile* property under the *Proj* (Project) component, or a property from the .inp file, such as the *Type* property under the *Boiler* component. Another possibility is to use this field to modify global parameters, either symbolic or numeric instead of changing a specific property of a specific component of the model input files. A rulelist can also be used to evaluate which properties are to be changed.

Next, the referencing of the components must be defined. Components to be changed can be referenced either by their component name, identified by the flag "1" or by index, representing the order of occurrence, identified by the flag "0". In the column immediately after this one, the user informs the component name (e.g. *Boiler1, Boiler2, etc.)* or order of occurrence (e.g. *1, 2, etc.)*. Lastly, the type of data being modified is informed among four options: integer, float, string or symbol. The procedure is repeated, and rows are added to the file until the user no longer wishes to change properties under that specific component or global parameter.

The second and last sub-process is the **Define Batch Mods Data**. In the previous sub-process, instructions regarding to the type of data being modified were passed. In this sub-process, the actual numeric or text data to which the parameters will be modified to are defined. First, an index is provided for each entry. This index starts with the number "1" for the first row and each next row added will be the index of the previous row increased by one unit. Within each row, in the subsequent columns, the desired values for the property or properties to be changed are defined. The number of columns filled will be equivalent to the number properties to be changed defined in the Define Batch Mods Column Keys sub-process.

Additional information found in the supporting literature is available in APPENDIX C.

4.5. Example of Table of Data Modification

An example of a table of data modification CSV file generated according to the instructions presented in the previous section is reproduced in its entirety in the greyed text box below.

```
2,BOILER:TYPE,1,Boiler1,Symbol
3,BOILER:HEAT-INPUT-RATIO,1,Boiler1,Float
-1
1,HW-BOILER,1.330
2,HW-BOILER,1.250
3,HW-BOILER-W/DRAFT,1.250
4,HW-CONDENSING,1.120
5,HW-CONDENSING,1.070
-1
```

Each field in the file presented above is delimited by commas. The explanation of these fields is given in the greyed text box below, with each field from the above table corresponding to the same field in the table below in green font color.

```
Table Column, Wiz Rulelist OR COM:KEY[#], By Name or Index, Component/Variable Name or Index, Type of Data
Table Column, Wiz Rulelist OR COM:KEY[#], By Name or Index, Component/Variable Name or Index, Type of Data
End of Batch Mods - Column Key
Idx;TYPE;HIR
Idx;TYPE;HIR
Idx;TYPE;HIR
Idx;TYPE;HIR
Idx;TYPE;HIR
End of File Flag
```

In the first row, the number “2” defines that this property will draw from the values contained in the second column of the rows that follow the end of the column key section of the current file. Next, the string “BOILER:Type” defines that the “Type” property of the “BOILER” component will be modified to the values present in the next section of the file. The number "1" defines that the component to be changed will be searched by its name, rather than by its order of occurrence (index). After this, the string "Boiler1" defines the name of the component that is to be searched and modified. Lastly, the string "Symbol" defines that the data type of the "Type" property is a symbol.

In the second row, the same logic of construction used in the first row is used. The number "3" defines that this property will draw from the values contained in the third column of the rows that follow the end of the column key section of the current file. Similarly, the string "BOILER:HEAT-INPUT-RATIO" defines that the "HEAT-INPUT-RATIO" property of the "BOILER" component will be modified. This step can be repeated, and rows are added to the file until the user no longer wishes to change properties under that specific component or global parameter.

In the third row, the flag "-1" defines the end of the batch modification column keys. This begins a new section of the file that contains the values that will be assigned to the properties listed in the first and second rows.

In the fourth row, the number "1" defines this row as the first entry in the index of available rows containing values to be passed on to the properties. In the second column of the fourth row, the string "HW-BOILER" defines that the "Type" property of the "BOILER" component is a Hot Water Boiler. In the third column of the fourth row, the number "1.330" defines the "HEAT-INPUT-RATIO" of the "BOILER" component. Notice how the second column (column 2) and the third column (column 3) of this row contain the same information as defined respectively by the numbers "2" and "3" in the batch mods column key section, in the first and second rows of the file.

In the fifth row, the same logic of construction used in the fourth row is used. The index number is increased by one unit and subsequent values for the "Type" and for the "HEAT-INPUT-RATIO" properties are defined. This step can be repeated, and rows are added to the file until the user no longer wishes to change properties under that specific component or global parameter.

In the ninth row, the flag "-1" defines the end of the table of data modifications file.

4.6. Data Extraction and Compilation

In this section, the process of data extraction and compilation is further explained, accompanied by a flowchart illustrated in Figure 4.10. This process is performed by a MATLAB code that is executed after the batch simulations have been run and all the output files have been generated. In APPENDIX D, the code incorporating this process is reproduced.

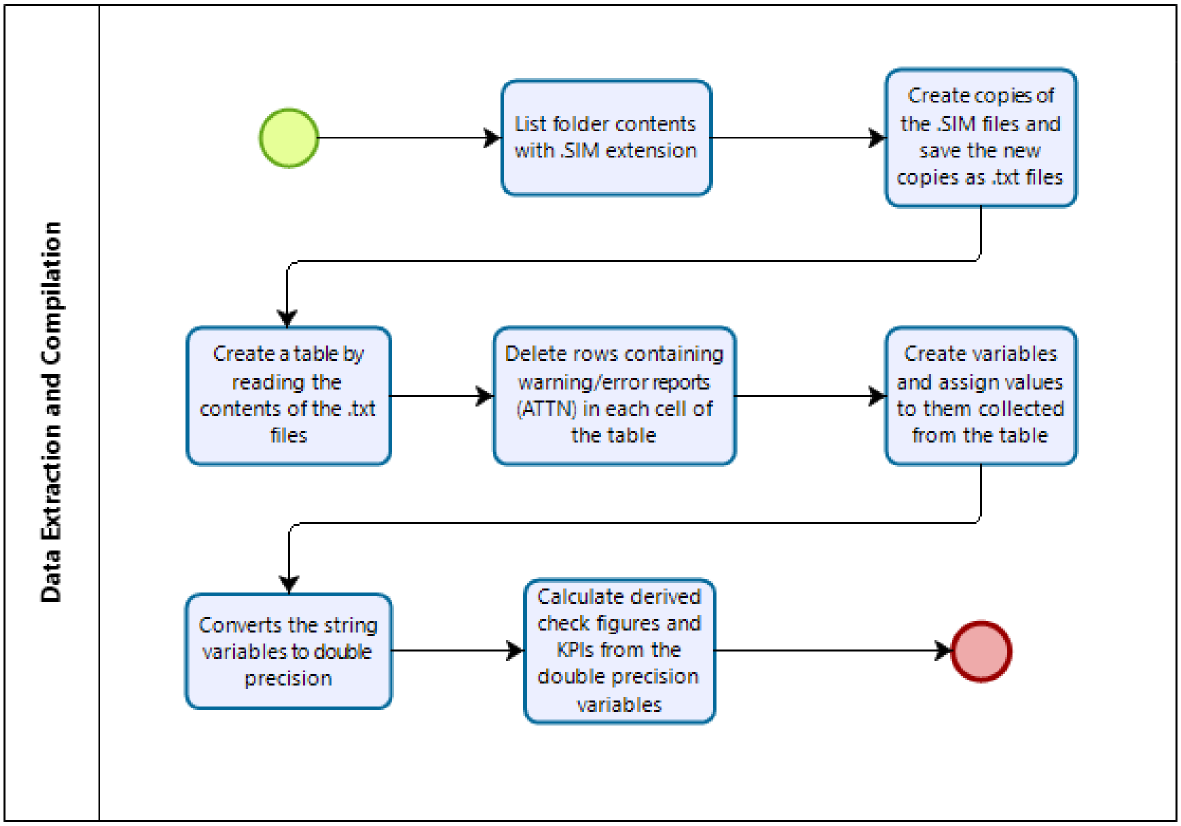


Figure 4.10 - Flowchart illustrating the process flow of the Data Extraction and Compilation Process

The general approach of the MATLAB code is to import the information contained in the .SIM files of the simulations and use the imported values to calculate the desired parameters. The .SIM files contain all the output reports generated by the DOE program, including error and warning reports and pre-programmed hourly reports. Within the selected output folder, after the batch simulations are run, the user can find one .SIM file for each one of the variant models. One of the aspects that make working with the .SIM files so convenient is that they are structed using delimited-separated values, using as the delimiter the space character and are able to be opened using any text editor.

In order to import the values from the .SIM file into a table using the native *readtable* command, first these files have to be available to MATLAB in a .txt, .dat or .csv file extension. The first two sub-processes address this requirement: **List folder contents with .SIM extension** and **Create copies of the .SIM files and save the new copies as .txt files**. Following this step, the sub-process **Create a table by reading the contents of the .txt files** employs the *readtable* command to import all contents from the delimited output files into a MATLAB table. Each cell of this table contains an individual table that contains the rows and columns with information imported from each simulation output file.

At this step, a correction to make each table cell the same length needs to be applied. Each table cell (corresponding to a single simulation run) has a different length due to a report that is added by the DOE program at the beginning of each simulation run. This report, named '*Report ATTN - Simulation Messages For Review HVAC'* contains warning, caution and error messages alerting the user to possible inconsistencies in the input files that may generate unwanted or out of the range outputs. Since each simulation is comprised of different inputs, the length of each ATTN report is different. To address this, the sub-process **Delete rows containing warning/error reports (ATTN) in each cell of the table** searches for the headers "ATTN" and "SV-A", with the latter being the first report after the ATTN report and marks the corresponding rows that contain these headers. Next, all the rows between ATTN and the SV-A reports are deleted, making all table cells have the same length.

This correction is necessary since in the next sub-process **Create variables and assign values to them collected from the table**, additional variables are assigned to values that are stored specifically in a certain row and in a certain column of this table cell. If each cell had a different length, different information would be assigned to variables that should contain the same information. Since these variables are collected from a text file, they are initially saved in a string format. The sub-process **Converts the string variables to double precision** changes the variable type from string to double for them to be used in further calculations.

The last sub-processes **Calculate derived check figures and KPIs from the double precision variables** uses the values collected and assigned to the variables created in the previous step and calculates the remaining desired KPIs and check figures. These indicators are calculated from the simulation results at three levels: whole-building, systems and equipment and cover various end-uses, such as building energy use intensity, electric power, building cooling and heating loads, and individual equipment efficiency and sizing.

CHAPTER 5 : Sensitivity Analysis of an Institutional Building in Montréal, QC, Canada

This chapter describes the procedure and the premises employed in performing a sensitivity analysis of a selection of design and operating parameters on a selection of Key Performance Indicators (KPIs) pertaining to building energy efficiency. These parameters serve as inputs for batch simulations ran in eQUEST on a benchmark building (Concordia Genomics Building). Once the batch processing is done, output variables are collected from the simulation files and the KPIs are calculated with the aid of a MATLAB code. The sensitivity analysis is performed, and the sensitivity coefficients are analysed.

The scope is to compare the impact of changes in input variables on select KPIs by means of a sensitivity analysis. The objective of this comparison is obtaining a rank of the most critical provisions of NECB, in terms of energy efficiency. Building this rank across multi-level KPIs (whole building, system and equipment level) allows interested parties to have a holistic view on how the input variables regulated by NECB impact the performance of the system.

The following steps summarize the method used in this chapter:

1. Selection of the design input variables, and assignment of numerical value ranges for each variable.
2. Selection of the KPIs.
3. 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, and the batch mode simulations.
4. Extraction and organization of the results.
5. Calculation of the derived KPIs.
6. Calculation of the sensitivity coefficients.
7. Result analysis and conclusions.

5.1. Selection of Design and Operating Input Variables

The prescriptive and performance path provisions in NECB contain both quantified (quantitative) requirements and non-quantified (qualitative) requirements.

Examples of quantified requirements are the maximum overall thermal transmittance for building assemblies, where the requirement is given in W/m²-K and its value depends on the climatic zone, and the chiller COP, where the requirement is given as the minimum COP and its value depends on the equipment size and compressor type.

Examples of non-quantified requirements are the provision of vapour barrier protection to prevent condensation on insulated cold-air supply ducts or provision of protection against mechanical damage or weathering on insulated ducts. Requirements such as these reflect the best engineering practice and can have a great influence in the overall performance of the building, impacting thermal comfort, indoor air quality, energy efficiency and maintenance and operation routines. It is hard to estimate the direct impact that the qualitative requirements have on the building energy efficiency due to its non-determinist nature. The eQUEST program does not feature the capacity to include these effects in the simulation. Given this reason, this study will focus on the quantified variables.

The design and operating variables to be used as inputs in the sensitivity analysis are listed in Table 5.1. The base case corresponds to a model designed in accordance with the prescriptive and performance requirements relating to the building envelope (Part 3 of NECB-2017), HVAC Systems (Part 5 of NECB-2017) and compliance to the whole-building energy performance (Part 8 of NECB-2017). These 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 their relevance in the building operation and their contribution to the building energy consumption.

In Table 5.1, the values recommended by NECB either in the prescriptive or the performance path are presented in the column entitled Base Case.

Table 5.1 - Table of Input Data for the Sensitivity Analysis Cases

#	**Variable**	**Unit**	**Base Case**	**Case 1 (-2)**	**Case 2 (-1)**	**Case 3 (+1)**	**Case 4 (+2)**
Envelope							
1	Above-ground Zone 6 Walls Thermal Transmittance (NECB 2017)	W/m²-K	0.247	0.200	0.225	0.275	0.300
2	Above-ground Zone 6 Roofs Thermal Transmittance (NECB 2017)	W/m²-K	0.156	0.050	0.100	0.200	0.250
3	Zone 6 Fenestration Thermal Transmittance (NECB 2017)	W/m²-K	1.9	1.5	1.7	2.1	2.3
Water-Side System							
4	Chiller Rated COP (CAN/CSA-C743)	kW_{th}/kW_{ele}	5.547	4.5	5.0	6.0	6.5
5	Boiler Rated Efficiency (ASHRAE 90.1-2016)	kW_{th}/kW_{ele}	83%	75%	80%	85%	90%
6	Cooling Tower EIR (NECB 2017)	kW_{ele}/kW_{th}	0.013	0.009	0.011	0.015	0.017
7	Heating Pump Combined Efficiency (NECB 2017)	%	66%	55%	60%	70%	75%
8	Heat Rejection Pump Combined Efficiency (NECB 2017)	%	69%	55%	60%	70%	75%
9	Cooling Pump Combined Efficiency (NECB 2017)	%	67%	55%	60%	70%	75%
Air-Side HVAC System							
10	Supply Fan Total Efficiency (NECB 2017)	%	55%	45%	50%	60%	65%
11	Return Fan Total Efficiency (NECB 2017)	%	30%	20%	25%	35%	40%
Space							
12	Occupied Zone Heating Setpoint Temperature (NECB 2017)	°C	22	20	21	23	24
13	Occupied Zone Cooling Setpoint Temperature (NECB 2017)	°C	24	22	23	25	26

The chosen model input sampling method is a One-At-a-Time (OAT) discrete sampling. This method of selection of input variables aims to identify the most effective energy saving measures in building design and operation by varying the NECB requirements between a feasible minimum and maximum range that corresponds to values seen in engineering practice.

With this sampling method, each of the 13 variables are varied one at a time for 5 different values, creating an input space of 65 models. The 5 different values assigned to each variable are the base case value, plus 4 other variations, represented by Cases 1 through 4 in Table 5.1. The variation building energy models are obtained by modifying the base case model to include the change in that particular variable.

A constant numerical step (e.g. +-5%, +-1°C) was used from Cases 1 though 4 to generate the input space. Discussion in the literature can be found regarding whether constant steps applied to a starting/ending value, or a normal distribution with an average and standard deviation should be used to generate the input space [29], [68]. In the context of building energy codes, the choice of the input variable value is a design choice and is not subject to unpredictable variations that are found in the construction and operational stages of the building. In such cases, these unpredictable variations are well modelled by normal distributions and further discussion regarding uncertainty analysis is a necessary step. Since the proposed method explores the impact of changes made to the prescriptive requirements of NECB based on the parameter ranking obtained from the sensitivity analysis, applying a constant step is appropriate to explore a chosen input variable range.

5.2. Selection of Key Performance Indicators

The KPIs are evaluated 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 in Table 5.2. Other than the KPIs selected for evaluating this institutional building, an additional collection of KPIs and check figures commonly used during the design phase and energy performance evaluation of the building is presented in APPENDIX E.

Table 5.2 - Key Performance Indicators used in Sensitivity Analysis

#	Variable	Unit
	Whole-building KPIs	
a.	Energy Use Intensity per floor area (EUI)	GJ_{en}/m^2 ($kBtu/ft^2$)
b.	Peak Electric Demand per floor area	W_{en}/m^2 (W/ft^2)
c.	Energy Cost per Energy Consumption[1]	$\$/GJ_{en}$ ($\$/kBtu$)
d.	Energy Cost per floor area	$\$/m^2$ ($\$/ft^2$)
	System KPIs	
a.	COP of Heating System[2]	W_{th}/W_{en} (Btu/Btu)
b.	COP of Cooling System[2]	W_{th}/W_{en} (Btu/Btu)
c.	COP of both Heating and Cooling Systems[2]	W_{th}/W_{en} (Btu/Btu)
d.	Peak Cooling Coils Load per floor area	kW_{th}/m^2 ($kBtu/hr\text{-}ft^2$)
e.	Peak Heating Coils Load per floor area	kW_{th}/m^2 ($kBtu/hr\text{-}ft^2$)
f.	Total Building Heating and Cooling Loads per Total HVAC Energy Consumption	W_{th}/W_{en} (Btu/Btu)
g.	Supply Airflow Rate per floor area	$L/s\text{-}m^2$ (cfm/ft^2)
h.	Combined Supply and Return Air Fans Power Demand per Supply Airflow Rate[3]	$W_{en}/L\text{-}s$ (10^{-3} HP/cfm)
	Equipment KPIs	
a.	Chiller COP	W_{th}/W_{ele} (Btu/Btu)
b.	Boiler Efficiency	W_{th}/W_{gas} (Btu/Btu)
c.	Cooling Tower Performance[4]	W_{en}/W_{th} (Btu/Btu)
d.	Heating Pumping Power Demand[5]	W_{en}/kW_{th} (Btu/Btu)
e.	Heat Rejection Pumping Power Demand[5]	W_{en}/kW_{th} (Btu/Btu)
f.	Cooling Pumping Power Demand[5]	W_{en}/kW_{th} (Btu/Btu)

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 coefficient of performance 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 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).

5.3. Sensitivity Analysis

In the sensitivity analysis method applied in this study, the sensitivity of an output variable is defined as how much that output variable changes as a function of the change of one input variable at a time, explored around a base (reference) point.

The multi-linear regression (MLR) method is a widely used method in building energy analysis since it is easy to implement, fast to compute and easy to interpret the results [29]. A matrix form implementation of the regression method is used, where the Sensitivity Coefficient (SC) that measures the impact of an input variable X on a KPI Y is given by [88]:

$$SC = (X^T X)^{-1} X^T Y \tag{11}$$

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 obtained in the simulation of the baseline case, described in CHAPTER 3.

$$Y = \frac{Y_n - Y_{base}}{Y_{base}} \tag{12}$$

$$X = \frac{X_n - X_{base}}{X_{base}} \tag{13}$$

The normalization process transforms the units of independent into percent changes over the base case, making it possible for their values to be directly comparable giving a measurement of the relative importance of each input factor.

An exception was used for Sensitivity Coefficients (SCs) relating to the heating and cooling temperature setpoints. For these variables, the SCs relate to percent changes in the output variable relative to an increase/decrease of one degree Celsius in the input variable.

The sensitivity analysis method used in this study is comprised of a multiple linear regression performed over an input space with variables sampled one at a time. The sensitivity coefficients obtained from this method represent first-order interactions inputs and outputs. Studying higher-order interactions between the variables is beyond the scope of this study.

Additionally, the multiple linear regression already presents a high coefficient of determination for the studied domain of input-output variables.

If NECB-compliant building model stocks are explored, a large number of input variables with a large number of output results are likely to arise. In such cases, understanding higher-order interactions is an important step to allow for generalization of conclusions from analysing the resulting sensitivity coefficients and to support the proposition of correlations that would cover the entire building model stocks in the entire input variable domain.

This research focuses on aiding in the prioritization of improvements to the prescriptive requirements of NECB by providing a ranking of which variables are the most significant. In practice, each code cycle incorporates changes to specific clauses and rarely incorporates a complete revamp of all prescriptive requirements. This fact decreases the likelihood of substantial interactions between multiple input parameters (in this case, the prescriptive requirements) happening at each code cycle. All of this supports the proposition of a method that is able to evaluate the impacts of changes accurately and intuitively to the prescriptive requirements in a time and resource efficient manner.

The MLR sensitivity analysis method presents the advantage of an intuitive interpretation based on the comparison of the SCs and a simple implementation through the referenced matrix form. However, it must be applied with caution since it is model dependant. The linearity of the modelled output against the inputs and the goodness of the fit must be verified, if necessary, using statistic indicators, such as the coefficient of determination (R^2).

5.4. Results and Discussion

The SCs obtained for all selected KPIs are presented in Table 5.3. These SCs represent a percent increase in the selected KPI given a unit increase (100% or 1°C) in the input variable.

Table 5.3 - Sensitivity coefficients for all KPIs

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**
SCs	**%**	**%**	**%**	**%**	**%**	**%**	**%**	**%**	**%**	**%**	**%**	**% per °C**	**% per °C**
Whole-building KPIs													
a.	5.16	1.41	21.02	-9.01	-54.1	-0.39	-2.95	-1.21	-3.55	-8.41	-3.21	9.06	-2.2
b.	1.23	0.44	1.19	-41.8	-	-2.35	-3.35	-0.9	-3.94	-18.9	-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	-14.1	-34.8	-0.52	-3.44	-1.29	-4.05	-12.5	-5.04	6.41	-2.13
System KPIs													
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	-	-	-	-	-	-	-	-	-70.6	-34.7	-	-
Equipment KPIs													
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	-	-84.8	-	-	-	0.38	0.13	0.01	0.09
d.	-0.06	-	-0.32	-	-	-	-	-106.	-	0.16	-	0.01	0.09
e.	-0.16	0.05	0.19	0.15	-	-	-	-	-120.	-0.18	-0.01	-	-
f.	0.24	-0.01	0.04	-	-	-	-113.	-	-	0.14	0.11	-	-

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 of the whole building. This section focuses on the result analysis of the whole-building KPIs, since these are the most used indicators in building energy code development, as pointed out 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.

Out of all SCs presented in in Table 5.3, a selection of the most relevant ones in building energy code development was made and plotted in bar charts to be further analysed. The SCs for the selected whole-building KPIs are presented in Figure 5.1 through Figure 5.4, followed by a discussion on the impact of the input variables on these KPIs.

The SC values portrayed in the following figures represent the change in the KPI for one unit (i.e. 100% or 1 °C) 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. Given this linear behaviour, decreasing the value of the input variable by one unit would result in a change with the same magnitude of increasing the value of the input variable also by one unit, but with an opposite sign.

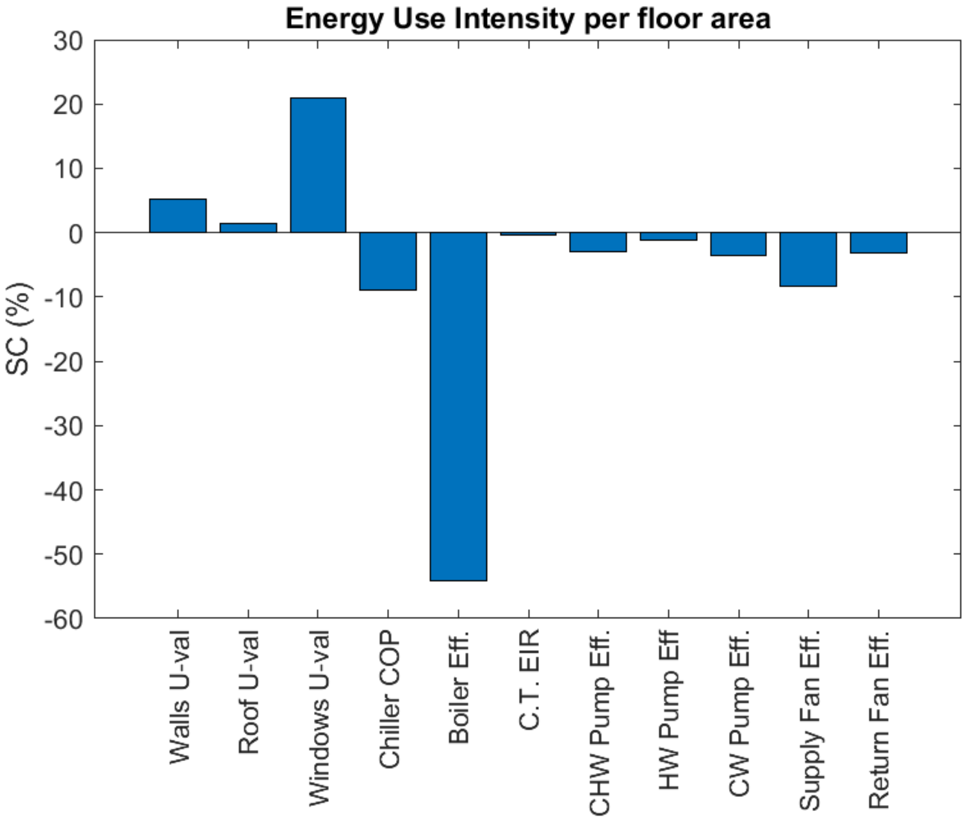


Figure 5.1 - Sensitivity coefficient of the Energy Use Intensity per floor area versus input variables (positive coefficients relate an increase in energy consumption).

In Figure 5.1, the SCs of the EUI are presented for the selected input variables.

Among the envelope assemblies, the windows lead to the highest impact on the EUI with the SC of about 21%. This high impact is due to the high Window to Wall Ratio (WWR) of 38.4% in the reference building model and the high thermal transmittance of fenestration when compared to walls and roofs (1.9 W/m²-K to 0.247 W/m²-K and 0.183 W/m²-K, respectively). The second highest contributor in the building envelope variables is the thermal transmittance of walls that leads to the increase of EUI with an SC of about 5%.

Among all input variables, the boiler efficiency leads to the highest magnitude SC of -54%. This is due to the large contribution of the space heating end-use to the EUI. In the base case scenario, boilers consume 52.5% of the total energy used by the building. The Chiller COP also leads to an important contribution in reducing the EUI, with an SC of about -9.0%. Its contribution to the total EUI is also considerable, with a total of 7.8% being consumed by the chillers for space cooling purposes in the base case scenario.

Among the auxiliary equipment (fans and pumps), the supply air fan has the highest impact with SC of about -8.4%. Although the fans don't have a very high peak power demand, they 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. This makes them the second highest HVAC end-use, with a total of 9.7% of the energy being consumed by the ventilation vans in the base case scenario.

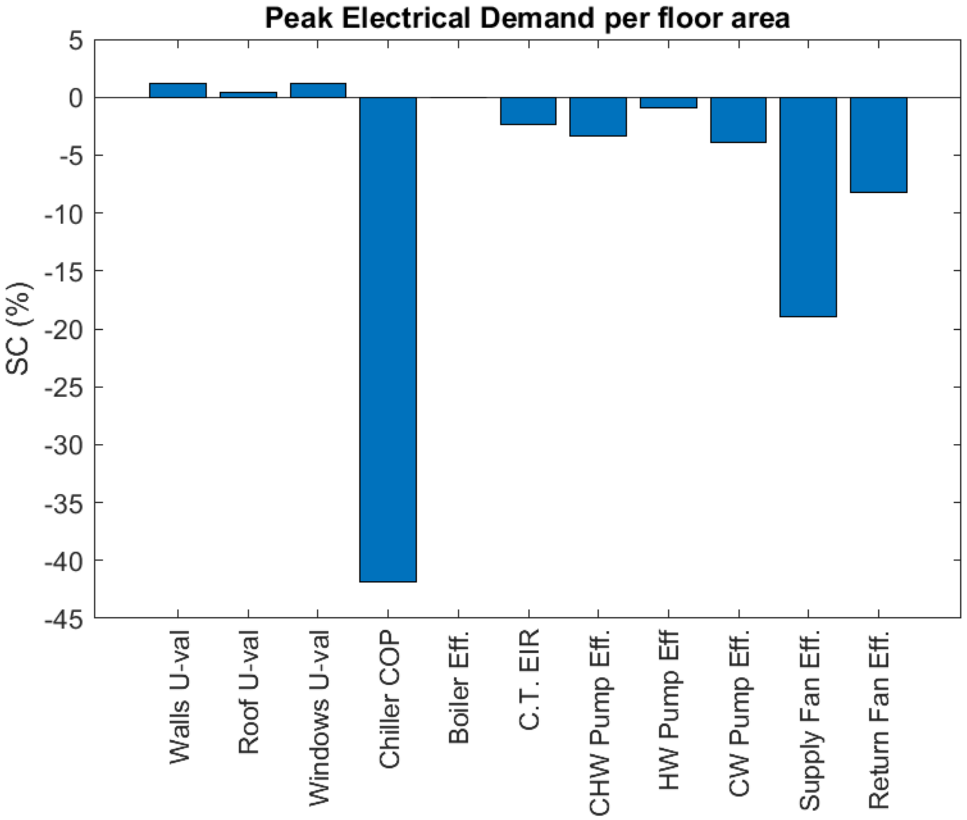


Figure 5.2 - Sensitivity coefficient of the Peak Electrical Demand per floor area versus input variables (positive coefficients relate an increase in energy consumption).

In Figure 5.2, 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 modelled building, electricity is consumed by HVAC equipment, more specifically for the purposes of space cooling, heat rejection and ventilation, and by plug loads and lighting. Since the chiller is an electric centrifugal chiller that is dedicated to space cooling, this equipment has a high impact on the peak electrical demand of the building. In the base case, the peak electrical load by the chiller alone corresponds to 38.8% of the annual peak electrical demand.

Following the chiller COP, the supply and return air fan efficiencies have a high impact on the peak electrical demand, yielding SCs of -19% and -8%, respectively. The ventilation fans also take up a considerable part of the base case scenario peak electrical demand, consuming about 20.0% of the peak power.

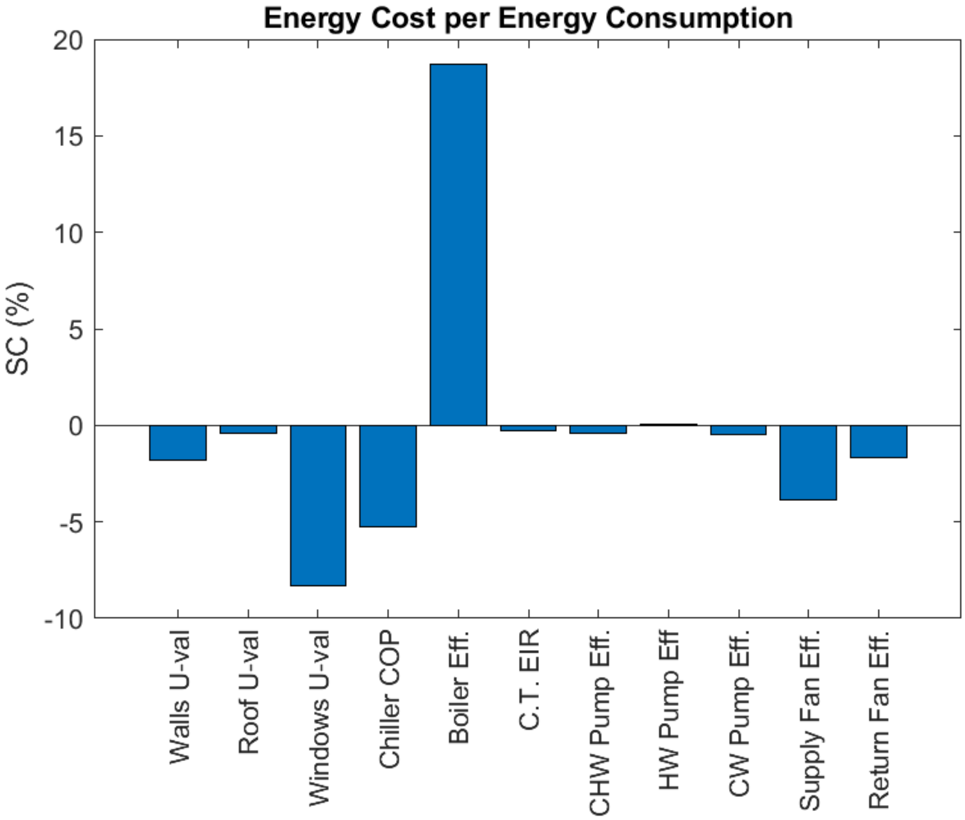


Figure 5.3 - Sensitivity coefficient of the Energy Cost per Energy Consumption versus input variables (positive coefficients relate an increase in energy consumption).

In Figure 5.3, the SCs of the energy cost per energy consumption for the selected input variables are presented.

Among the primary equipment, the boiler efficiency presents a high impact on the energy cost per energy consumption, with an SC of 18.7%. 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 natural gas incurs in having a more expensive energy portfolio overall. The chiller COP is also a major factor driving the energy cost per energy consumption, with an SC of -5.3%, due to its significant contribution both to the energy consumption and to the energy cost.

Among the envelope assemblies, the thermal transmittance of walls yields a high SC of -8.3%. In this case, increasing the thermal transmittance of walls would decrease the energy cost per energy consumption. This is likely due to a bigger increase in the heating loads compared to the increase in the cooling loads due to the extra conduction heat transfer in the walls in a heating dominated climate, such as the one of Montréal. With the increase in the heating loads, more energy from the natural gas energy source is used, making the energy cost per energy consumption proportionally cheaper.

Lastly, among the auxiliary equipment, the supply fan efficiency yields an SC of -3.8%. Increasing the fan efficiencies impacts directly the amount of electricity consumed and the peak electrical demand of the building.

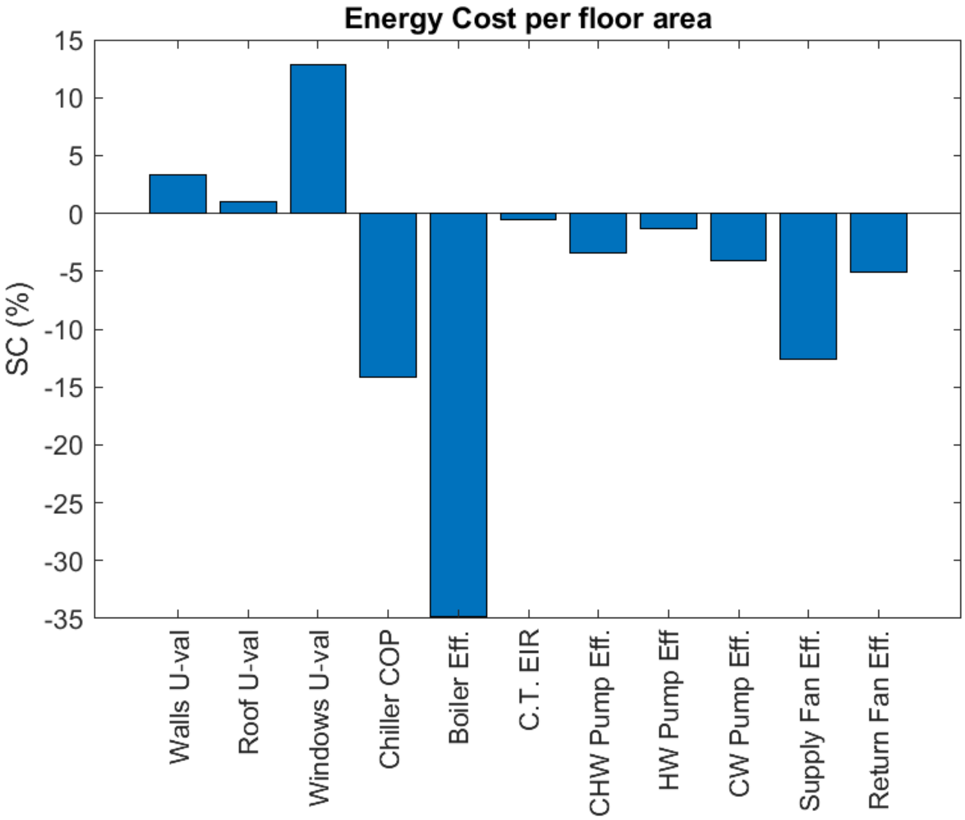


Figure 5.4 - Sensitivity coefficient of the Energy Cost per floor area versus input variables (positive coefficients relate an increase in energy consumption).

In Figure 5.4, the SCs of the annual energy cost per floor area for the selected input variables are presented.

The same trends as the one seen for the EUI are 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 of 12.9% 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 -34.8%.

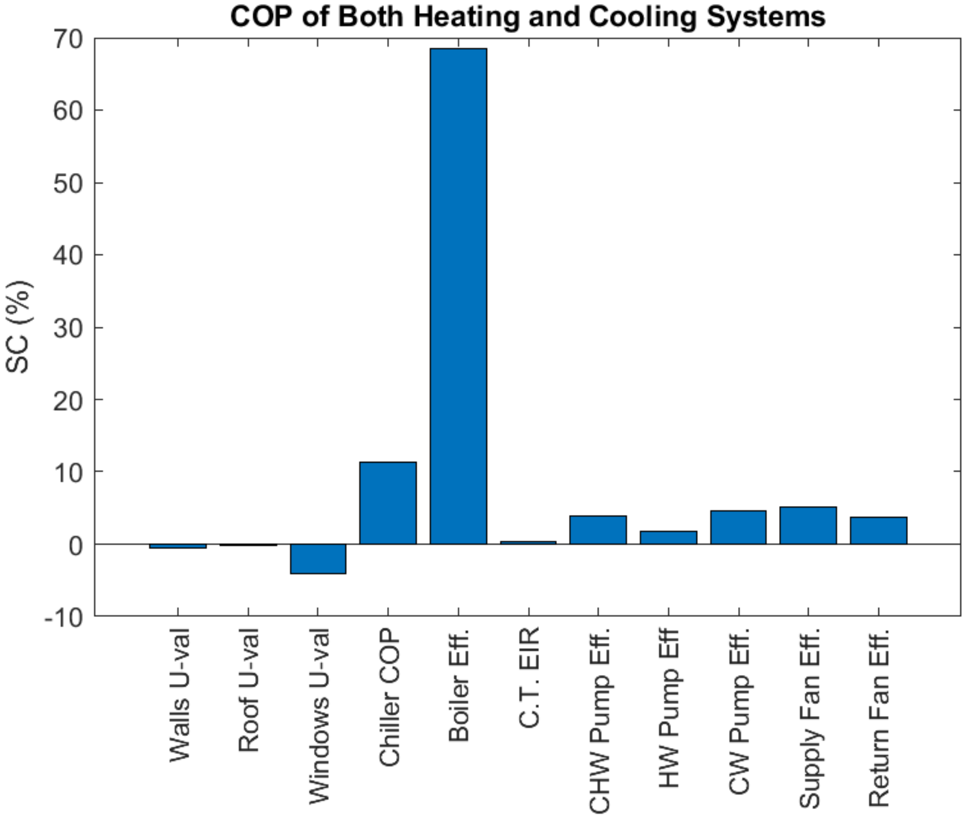


Figure 5.5 - Sensitivity coefficient of the COP of Both Heating and Cooling Systems versus input variables (positive coefficients relate an increase in energy consumption).

In Figure 5.5, the SCs of the COP of both heating and cooling systems for the selected input variables are presented.

The highest impact is observed for the boiler efficiency, with an SC of 68.5%. This high impact is explained by the significant energy consumption contribution of the natural gas fired boilers in providing space heating. The boilers account for 68.0% of the energy consumed by the HVAC system in the base case scenario. Following the high impact of the boiler, the chiller COP is also an important factor, with an SC of 11.4%. In the base case scenario, the chillers take up 10.1% of the HVAC energy consumption. With lesser contributions, we find the efficiency of the fans and pumps and the thermal transmittance of walls.

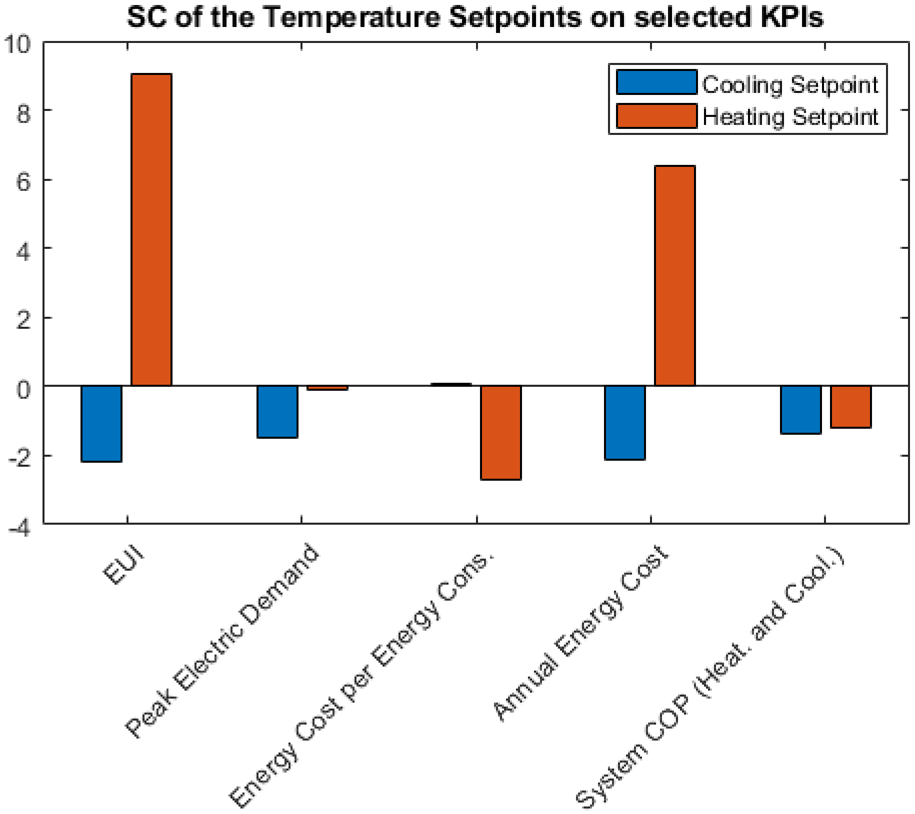


Figure 5.6 - Sensitivity coefficient of the temperature setpoints on selected KPIs (positive coefficients relate an increase in energy consumption).

In Figure 5.6, the SCs of the temperature setpoints for the selected KPIs are presented.

These setpoints impact directly in the thermal load by increasing or decreasing the amount of heat exchanged through the building envelope and in the ventilation system. The heating temperature setpoints have a high impact on the EUI and on the annual energy cost, with an SC of 9.1% and 6.4% respectively. The heating setpoint has a smaller impact on the annual system COP and the energy cost per energy consumption and a negligible impact on the peak electric demand. The cooling temperature setpoint has a similar effect on the EUI, peak electric demand, annual energy cost and the system COP. It has a negligible impact on the energy cost per energy consumption.

While it is important to understand the impact that the temperature setpoints have on the energy performance of the building, these variables also directly impact the thermal comfort of the indoor environment. It is important not to restrict the operation of these parameters looking only through the perspective of saving energy, since it can severely disrupt the ability of a building to serve its main activity type. There are standards, such as the ASHRAE Standard 62.1 [89], which treat about ventilation for acceptable indoor air quality, that provide operative ranges of indoor temperature and humidity to provide thermal comfort for the occupants. These choice of the temperature setpoints should then be left to the building operators, provided the observance of such standards.

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 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 could benefit from using the proposed method as a tool for prioritizing modifications of design input values based on their impact on these KPIs. The method weighs 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. To obtain generalized conclusions that would allow for policymakers to make more informed decisions, it is important to evaluate these sensitivity coefficients under a range of conditions. This would require applying the proposed method over a selection of statistically representative locations for all climatic zones in Canada.

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. Should future versions of the NECB consider applying changes on these NECB requirements, the values of the KPIs at the whole-building, system and equipment levels would be significantly modified.

The scope of the present work could be expanded by applying the proposed method in a selection of statistically representative building models over a selection of statistically representative climatic 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. 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 energy consumption and/or cost of prototypical buildings. Another application would be the comparison of multiple 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.

The main scope of the NECB is to improve the energy efficiency of new buildings and reduce greenhouse gas emissions, providing long-term benefits for both Canada's economy and the environment. The main metrics used to measure the code’s contributions are the annual energy use and the annual energy cost. This traditional approach can be expanded to include life cycle performance indicators focusing on cost, energy use and emissions. These would provide a more holistic view on the impact of proposed changes throughout the lifetime of a building.

CHAPTER 6 : Sensitivity Analysis Applied to the Climatic Zones of Canada

This chapter describes the procedure and the premises employed in applying the sensitivity analysis method presented in CHAPTER 5 over all climatic zones of Canada. The same selection of design and operating parameters and Key Performance Indicators (KPIs) pertaining to building energy efficiency presented in CHAPTER 5 was used. The selection of values assigned to the envelope thermal transmittance variables was expanded to create a stock of reference models that are compliant to the NECB requirements of each climate zone.

The simulation was performed with aid of the batch processing feature of eQUEST presented in CHAPTER 4, using as reference the newly created stock of base case models for each climate zone, created using as a template the Concordia's Genomics building energy model presented in CHAPTER 3. Output variables are collected from the simulation files and the KPIs are calculated with the aid of a modified MATLAB code, adapted to calculate the Sensitivity Coefficients (SCs) for each climatic zone separately. The coefficients are illustrated in a boxplot using a complementary Python code.

The scope of performing the sensitivity analysis is to determine the variation of the SCs in a number of cities selected to represent the different climatic zones of Canada. The objective of this comparison is to improve the ranking process of the most critical provisions of NECB in terms of energy efficiency by covering a range of weather conditions present in Canada. This improvement allows the user to draw generalized conclusions for the studied building type.

The following steps, in addition to the steps presented in CHAPTER 5, summarize the method used in this chapter:

1. Selection of representative locations for the climatic zones of Canada;
2. Selection of design input variables for each climatic zone in compliance with NECB-2017;
3. Selection of energy prices for each climatic zone;
4. Preparation of box plots illustrating the effect of the climatic zones on the sensitivity coefficients, and
5. Result analysis and conclusions.

6.1. Selection of Representative Locations for the Climatic Zones

NECB's provisions fall into groups prescribing stricter or less strict requirements based on how harsh the weather is at the building's location. The metric used to classify these groups is the Heating Degree Days, an indicator that is proportional to the temperature difference between the outside temperature and a reference temperature, usually set at 18 °C, for a given period, usually one year.

The zones chosen in this study are consistent with the thermal criteria and climatic zones used in the NECB-2017 and used as a basis to determine performance and operation requirements. For each zone, a city was selected based on its population and its importance in that geographical region. Table 6.1 summarizes the locations chosen.

Table 6.1 – List of locations chosen to be representative of each Canadian climatic zone

Climatic Zone	Heating Degree Days	Location Chosen
Zone 4	HDD < 3,000	Victoria (HDD = 2,650)
Zone 5	3,000 ≤ HDD ≤ 3,999	Toronto (HDD = 3,520)
Zone 6	4,000 ≤ HDD ≤ 4,999	Montréal (HDD = 4,200)
Zone 7A	5,000 ≤ HDD ≤ 5,999	Edmonton (HDD = 5,120)
Zone 7B	6,000 ≤ HDD ≤ 6,999	Whitehorse (HDD = 6,580)
Zone 8	HDD ≥ 7,000	Yellowknife (HDD = 8,170)

6.2. Selection of Design and Operating Input Variables for Each Climate Zone

In CHAPTER 5, a series of values were proposed for the design input variables that make up the sensitivity analysis study. The base case values represented the minimum performance requirements for a reference building located in Montréal, QC. In order to generalize the sensitivity analysis to encompass all climate zones in Canada, the reference model needs to be adapted: (i) to comply with NECB requirements for different climatic zone, and (ii) to use the electricity and natural gas prices for each location.

These changes result in not a single reference model, but a stock of six reference building model, each model for one of the six studied climatic zones. All of the reference building models are compliant to NECB's prescriptions of their respective climatic zones. The sensitivity analysis is then performed for each climatic zone, respecting each base case model. Table 6.2 presents the input data for the sensitivity analysis cases for each climatic zone, and the values used to generate each base case model.

All other variables relating to the energy performance of the water-side and air-side HVAC systems, as well as the temperature setpoints, presented in Table 5.1 were also used in this sensitivity analysis study. NECB's prescriptions relating to these variables is not dependent on the climatic zone and therefore the numeric values assigned to these input variables were also used in the present chapter. The table was not presented to avoid duplication of content.

Table 6.2 - Table of Input Data for the Sensitivity Analysis Cases for Each Climate Zone

#	**Variable**	**Unit**	**Base Case (NECB-2017)**	**Case 1 (-2)**	**Case 2 (-1)**	**Case 3 (+1)**	**Case 4 (+2)**
Envelope – Zone 4							
1	Walls Thermal Transmittance	W/m²-K	0.315	0.275	0.300	0.350	0.375
2	Roofs Thermal Transmittance	W/m²-K	0.193	0.150	0.175	0.225	0.250
3	Fenestration Thermal Transmittance	W/m²-K	2.1	1.7	1.9	2.3	2.5
Envelope – Zone 5							
4	Walls Thermal Transmittance	W/m²-K	0.278	0.225	0.250	0.300	0.325
5	Roofs Thermal Transmittance	W/m²-K	0.156	0.100	0.125	0.175	0.200
6	Fenestration Thermal Transmittance	W/m²-K	1.9	1.5	1.7	2.1	2.3
Envelope – Zone 6							
7	Walls Thermal Transmittance	W/m²-K	0.247	0.200	0.225	0.275	0.300
8	Roofs Thermal Transmittance	W/m²-K	0.156	0.100	0.125	0.175	0.200
9	Fenestration Thermal Transmittance	W/m²-K	1.9	1.5	1.7	2.1	2.3
Envelope – Zone 7A							
10	Walls Thermal Transmittance	W/m²-K	0.210	0.150	0.175	0.225	0.250
11	Roofs Thermal Transmittance	W/m²-K	0.138	0.100	0.125	0.175	0.200
12	Fenestration Thermal Transmittance	W/m²-K	1.9	1.5	1.7	2.1	2.3
Envelope – Zone 7B							
13	Walls Thermal Transmittance	W/m²-K	0.210	0.150	0.175	0.225	0.250
14	Roofs Thermal Transmittance	W/m²-K	0.138	0.100	0.125	0.175	0.200
15	Fenestration Thermal Transmittance	W/m²-K	1.9	1.5	1.7	2.1	2.3
Envelope – Zone 8							
16	Walls Thermal Transmittance	W/m²-K	0.183	0.125	0.150	0.200	0.225
17	Roofs Thermal Transmittance	W/m²-K	0.121	0.075	0.100	0.150	0.175
18	Fenestration Thermal Transmittance	W/m²-K	1.4	1.0	1.2	1.6	1.8

6.3. Selection of Energy Prices for Each Climate Zone

A commonly used methodology to obtain impact of changes to code's prescription that are representative of multiple locations is to use the national average energy price [35], [36], [40]. One of the shortcomings of using the national average is not considering the difference between states or provinces of the availability of the different energy sources used to operate a building. This effect can be illustrated in the example of a building that has high heating loads supplied by a gas fired boiler. The impact of changing the boiler efficiency on the annual energy cost is severely dependant on the cost of the natural gas. The same can be said for a building with high cooling loads supplied by an electric centrifugal chiller. The impact of changing the chiller COP on the annual energy cost in these conditions would be severely dependant on the cost of electricity.

In order to improve that is representative of each location, it is important to consider the regional variations of energy price. Using a localized energy price allows a more accurate representation of the annual utility cost of each reference building, with the annual cost being a driver in determining the feasibility of implementing changes in building design and operation.

NRC provides for each province in Canada the end-use prices for electricity, natural gas and oil [90]. These end-use prices reflect the average price paid by the final consumers in residential, commercial, industrial and transportation sectors. These end-use prices include transport, balancing, distribution, inventory-related adjustments, emission taxes and other relevant bill components and taxes. By doing so, these end-use prices provide a good estimation of the price paid by building owners to operate their buildings.

The prices used in the simulations are summarized in Table 6.3, by provincial average.

Table 6.3 – Provincial Average Energy Price

Climatic Zone	Location Chosen	Provincial Average Electricity Price ($/GJ)	Provincial Average Natural Gas Price ($/GJ)
Zone 4	Victoria, BC	28.60	11.31
Zone 5	Toronto, ON	44.50	8.72
Zone 6	Montréal, QC	24.75	12.94
Zone 7A	Edmonton, AB	20.80	3.60
Zone 7B	Whitehorse, YT	35.62	9.07
Zone 8	Yellowknife, NWT	41.36	9.69

The provincial average electricity price for Québec is \$24.75 per GJ, while with the utility provider Hydro-Québec for Montréal, the electricity virtual rate (including both demand and energy components) is \$28.02 per GJ for the base case model described in CHAPTER 3. The electricity price in Montréal is 13.5% higher than the provincial average.

The provincial average natural gas price for Québec is \$12.94 per GJ, while with the utility provider Énergir for Montréal, the natural gas price is \$13.04 per GJ for the base case model described in CHAPTER 3. The natural gas price in Montréal is 0.8% higher than the provincial average.

6.4. Preparation of the box plots

A robust graphical representation is required to consolidate results obtained from multiple batches of simulation runs, with each batch representing a climate location. To perform this task, a box plot was used. This plot captures the numerical variations of a studied variable within a dataset and portrays them in box and whiskers that reflect statistically significant ranges for the plotted dataset.

The datasets are comprised of sets of series of arrays of sensitivity coefficients, with each array being populated with the coefficients obtained for each climatic zone. Different arrays of sensitivity coefficients contain information on different input variables. Different sets of these series of array refer to specific KPIs. A selection of whole-building KPIs provide a holistic understanding of the impact of the input variables on the overall performance of the building in a range of climatic zones.

An example box plot with an explanation of its graphical features is illustrated in Figure 6.1.

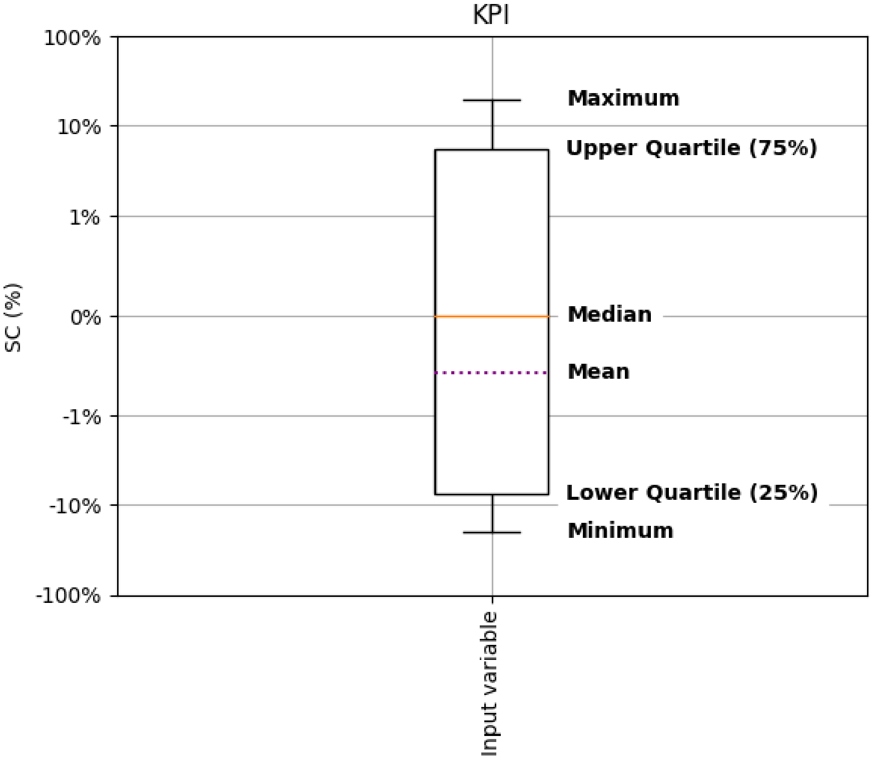


Figure 6.1 - Example box plot with an explanation for the graphical features

Each single boxplot contains the sensitivity coefficients for all six climate zones for a given input variable.

The **top and the bottom whiskers** in the box plot represent the highest and the lowest sensitivity coefficients in that array of coefficients, respectively. These whiskers often reflect the most extreme climatic conditions, obtained in either the warmest or the coldest zone of Canada. It is important to mention that while the zones in Canada are classified by increasing ranges of HDDs, with zones further north representing increasingly colder zones, the same logic does not apply to cooling. Preliminary results of this chapter show that certain locations which have a lower HDD classification than others can incur in lower annual cooling energy consumption; for example, comparing Victoria (Zone 4) and Montréal (Zone 6) yields these results.

The **top and bottom limits of the box** represent the 75th and the 25th quantiles of the array of sensitivity coefficients, respectively. These limits delimit a range that is statistically representative of the variation of the sensitivity coefficients for most of the climatic zones of Canada.

The **mean of all sensitivity coefficients** obtained for the six climatic zones is illustrated by a purple dotted line. Lastly, **the median value**, represented by an orange line, represents the average between the climatic zones that captures the climate in Canada’s most populated geographical regions (Zone 6, or Montréal, and Zone 7A, or Edmonton). Refer to the gray and purple colored zones in Figure 6.2 for a representation of these regions.

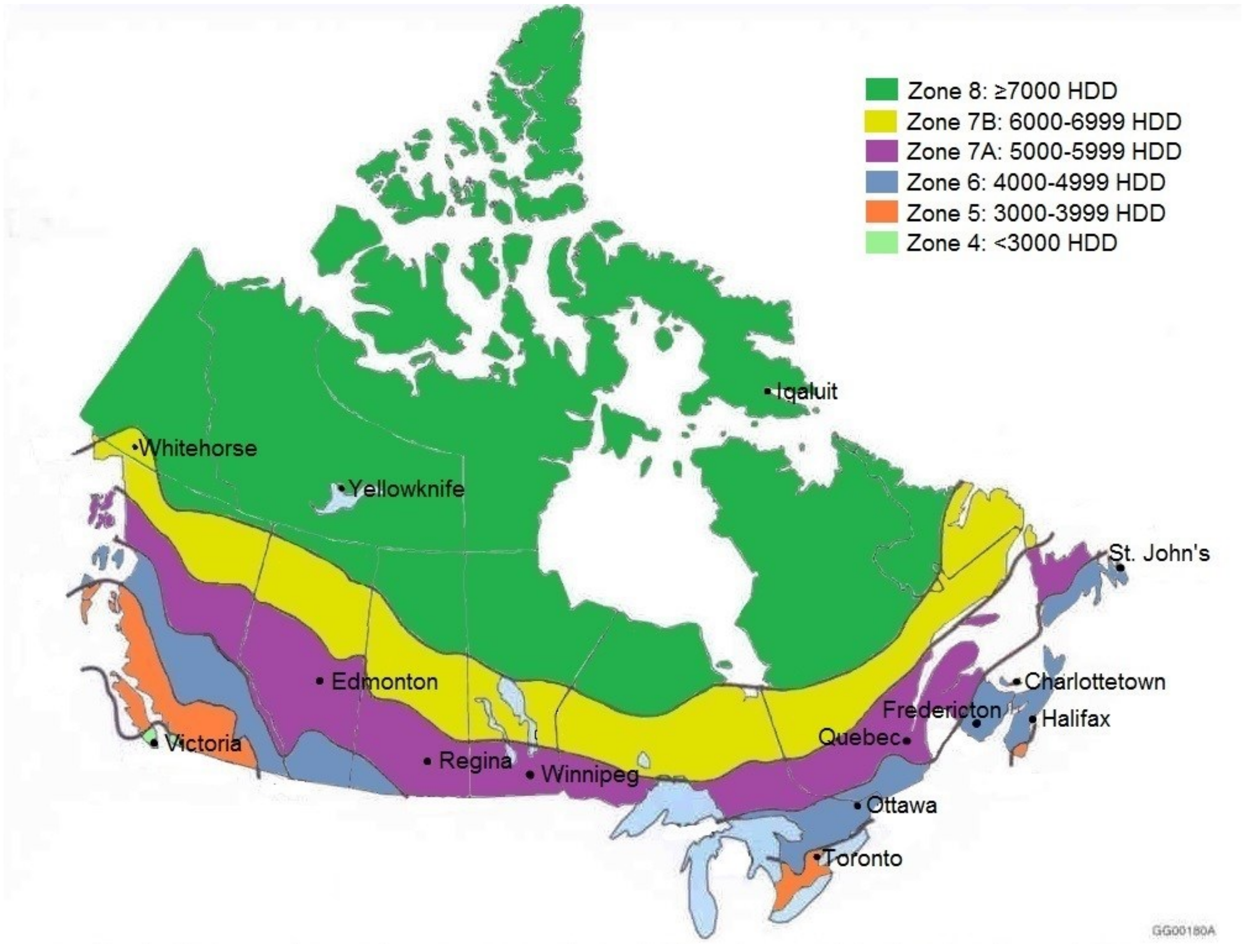


Figure 6.2 - Color coded climatic zones of Canada [91]

The sensitivity coefficients can take up values of opposite signs and with significantly different magnitudes and variances, as seen in Figure 6.3, in the box plot of the SCs of the COP of both heating and cooling. In this example, the same variable (thermal transmittance of windows) can vary from -5% to 5%, while others stay in the range of 60% to 80% (boiler efficiency).

A transformation of the y-axis scale is recommended to improve the display of the results. To perform this task, a symmetric log transformation was applied in the box plot. In addition, to facilitate comparison between the different variables, the boxes were sequenced based on their mean, starting from the highest value to the lowest value.

6.5. Results and Discussion

In CHAPTER 5, a selection of 13 input variables was presented, with each input variable being assigned five different values: a base case value and four variation case values. In that setting, the total number of simulation runs was 65. In this chapter, these simulation runs were repeated for six different climatic zones, resulting in a total of 390 simulation runs.

All the SCs are presented in Table 6.4 and color coded based on the magnitude of their impact. The input variables were grouped based on the magnitude of their impact on the studied KPIs. Results for the 3 impact groups, negligible impact ($|SC| < 1\%$), low impact ($1\% < |SC| < 10\%$), and high impact ($|SC| \geq 10\%$). Additionally, the results are presented graphically in Figure 6.4 to Figure 6.9. Following the box plots, Table 6.5 to Table 6.10 provide the statistic indicators of each array of sensitivity coefficients.

An additional indicator, the percent relative range, defined as the difference between the maximum and minimum value divided by the mean was added at the end of each table. The calculation procedure of the percent relative range for negligible impact input variables does not yield relevant conclusions due to the very small, often close to each other and unrepresentative results of the impact of those variables on the selected KPI. These SC results, in the range of 0.1% to 1.0%, can often be explained by consecutive rounding in the calculation procedures.

Table 6.4 - Sensitivity coefficients for all KPIs for all climatic zones

KPI	Zone	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
	SCs	%	%	%	%	%	%	%	%	%	%	%	% per °C	% per °C
EUI	4	5.3	1.2	17.4	-7.4	-53.3	0.0	-3.0	-1.4	-3.6	-8.4	-3.6	11.5	-1.8
	5	5.7	1.5	21.5	-8.2	-53.7	-0.2	-2.9	-1.4	-3.6	-8.7	-3.8	9.3	-2.0
	6	5.0	1.4	21.8	-9.0	-54.4	-0.2	-3.4	-1.4	-3.7	-8.4	-3.4	9.1	-2.2
	7A	5.5	1.5	27.0	-6.2	-57.6	0.0	-2.9	-1.2	-3.2	-8.6	-3.3	8.5	-2.1
	7B	6.2	1.8	26.2	-3.5	-65.6	0.0	-2.4	-1.6	-2.8	-5.9	-2.5	7.1	-1.3
	8	6.2	1.9	24.9	-4.1	-65.7	0.0	-2.3	-1.2	-2.6	-6.5	-2.7	6.5	-1.3
Peak Electrical Demand	4	1.1	0.3	-1.7	-34.7	0.0	-1.3	-3.4	-0.8	-4.0	-21.4	-9.5	0.4	-2.5
	5	0.3	0.0	-2.2	-41.0	0.0	-2.1	-3.0	-0.9	-3.6	-18.7	-7.0	0.4	-1.7
	6	1.2	0.4	1.2	-41.5	0.0	-2.3	-3.4	-0.9	-3.9	-19.0	-8.2	-0.1	-1.5
	7A	0.8	0.3	-1.1	-37.3	0.0	-1.7	-3.5	-1.1	-4.1	-20.9	-8.8	0.1	-1.6
	7B	0.8	0.3	0.8	-34.6	0.0	-1.1	-3.3	-1.2	-3.9	-20.8	-9.5	0.1	-1.4
	8	0.3	0.2	-2.9	-34.8	0.0	-1.3	-3.5	-1.2	-4.1	-20.8	-9.1	-0.1	-1.1
Energy Cost per Energy Consumption	4	-2.3	-0.4	-8.6	-3.2	22.0	-0.1	-1.3	-0.5	-1.6	-3.9	-1.6	-3.9	-0.3
	5	-3.9	-0.7	-15.7	-5.9	34.9	-0.2	-1.9	-0.9	-2.2	-6.4	-2.7	-4.6	-0.5
	6	-1.7	-0.3	-7.8	-2.9	16.0	-0.1	-1.0	-0.4	-1.2	-3.0	-1.2	-2.0	-0.2
	7A	-4.0	-0.9	-20.1	-5.2	38.3	-0.1	-2.4	-1.2	-2.9	-7.6	-3.0	-4.0	-0.5
	7B	-3.4	-0.8	-17.0	-3.1	33.0	0.0	-2.0	-1.2	-2.4	-5.9	-2.5	-2.4	-0.4
	8	-3.3	-0.9	-14.6	-3.8	34.8	-0.1	-2.1	-1.1	-2.5	-7.6	-3.3	-2.0	-0.5
Energy Cost per floor area	4	2.9	0.9	9.0	-10.3	-31.0	-0.2	-4.3	-1.7	-5.1	-12.7	-5.0	8.0	-2.1
	5	1.9	0.7	5.7	-14.2	-18.1	-0.4	-4.5	-2.2	-5.3	-15.2	-6.3	5.0	-2.5
	6	3.3	1.0	13.8	-11.7	-37.7	-0.3	-4.0	-1.8	-4.8	-11.7	-4.5	7.1	-2.4
	7A	1.6	0.6	7.1	-11.4	-18.5	-0.2	-5.3	-2.6	-6.2	-16.0	-6.3	4.7	-2.6
	7B	2.8	1.0	9.4	-6.5	-31.8	-0.1	-4.3	-2.6	-5.0	-11.6	-5.0	4.8	-1.7
	8	2.7	1.0	10.3	-7.9	-29.9	-0.1	-4.3	-2.3	-5.1	-13.9	-6.0	4.5	-1.8
COP of Both Heating and Cooling Systems	4	0.0	-0.2	-1.2	9.4	69.9	0.2	3.9	1.6	4.6	3.6	4.4	0.3	-1.5
	5	-0.8	-0.2	-5.0	10.7	68.9	0.3	3.4	1.7	4.0	4.9	4.0	-1.4	-1.5
	6	-0.5	-0.2	-4.1	11.2	68.5	0.3	3.9	1.7	4.6	5.1	3.7	-1.2	-1.3
	7A	0.3	-0.1	-0.2	7.8	72.4	0.1	3.6	1.8	4.2	5.2	4.0	0.3	-1.2
	7B	1.2	0.2	6.0	4.3	80.2	0.0	2.8	1.7	3.3	5.4	3.3	0.6	-0.3
	8	0.6	0.1	2.2	4.9	78.6	0.1	2.7	1.5	3.2	5.6	3.8	0.0	-0.6

Legend: ☐ *Negligible impact* 🟧 *Low impact* 🟥 *High impact*

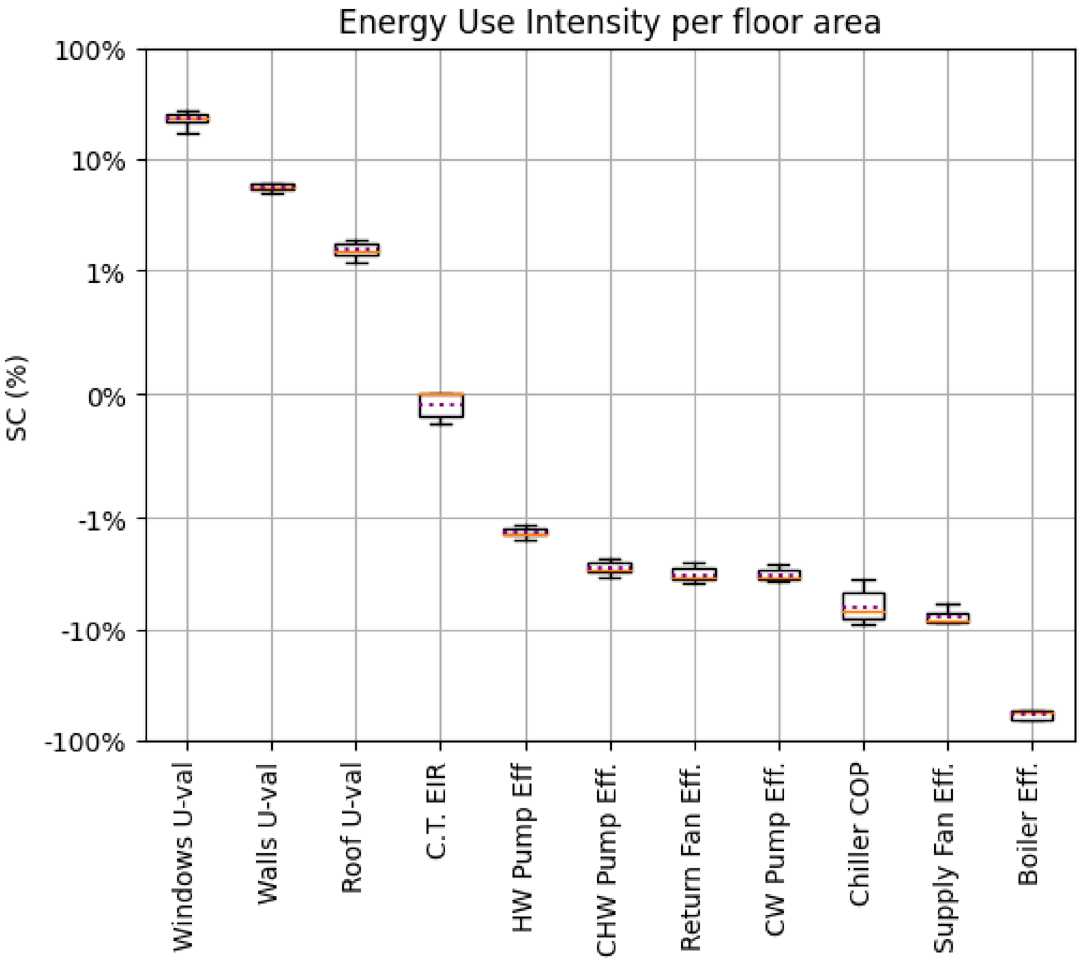


Figure 6.4 - Box plot of the sensitivity coefficients of the Energy Use Intensity per floor area versus input variables for all climatic zones (positive coefficients relate an increase in energy consumption).

Table 6.5 - Details of the Energy Use Intensity boxplot

Variable (%)	**Windows U-val**	**Walls U-val**	**Roof U-val**	**C.T. EIR**	**HW Pump Eff**	**CHW Pump Eff.**	**Return Fan Eff.**	**CW Pump Eff.**	**Chiller COP**	**Supply Fan Eff.**	**Boiler Eff.**
Minimum	17.4	5.0	1.2	-0.2	-1.6	-3.4	-3.8	-3.7	-9.0	-8.7	-65.7
Lower quartile	21.6	5.4	1.4	-0.2	-1.4	-3.0	-3.6	-3.6	-8.0	-8.5	-63.6
Median	23.3	5.6	1.5	0.0	-1.4	-2.9	-3.4	-3.4	-6.8	-8.4	-56.0
Mean	23.1	5.6	1.6	-0.1	-1.3	-2.8	-3.2	-3.2	-6.4	-7.7	-58.4
Upper quartile	25.9	6.0	1.7	0.0	-1.2	-2.5	-2.8	-2.9	-4.6	-7.0	-53.9
Maximum	27.0	6.2	1.9	0.0	-1.2	-2.3	-2.5	-2.6	-3.5	-5.9	-53.3
Percent relative range	**41.4**	**21.0**	**48.8**	**304.4**	**30.4**	**39.9**	**41.4**	**35.1**	**86.3**	**35.2**	**21.2**

Summary

In the **high impact** category were grouped the thermal transmittance of windows and the boiler efficiency. The boiler efficiency presents the highest impact with a negative correlation with the EUI, with its SCs varying between -65.7% and -53.3%, with a mean value of -58.4%. In the sequence, with a positive correlation with the EUI, the thermal transmittance of windows presents SCs that vary between 17.4% and 27.0%, with a mean value of 23.1%. In the **low impact** category were grouped the thermal transmittance of the walls and of the roof as well as the pump and fan efficiencies and the chiller COP. In the **negligible impact** category, the cooling tower energy input ratio is found.

Influence of climatic zones on the SCs

The impact of most variables on the EUI is considerably affected by the weather conditions, with most percent relative ranges in the 30% to 50%. The impact of chiller COP on the EUI is the most affected by the weather conditions, with a percent relative range of 86.3%. The impacts of the boiler efficiency and the thermal transmittance of walls on the EUI are the least affected by the weather conditions, with a percent relative range of 21.2% and 21.0%, respectively.

There is no significant difference between all climate zones in relation to the magnitude of the impact of the SCs. Performing changes in the input variables of the high impact category would be effective in all climate zones.

Changing the boiler efficiency would be the most effective in Zone 8 - Yellowknife (SC = -65.7%), and slightly less effective in Zone 4 – Victoria (SC = -53.3%).

The same applies to the thermal transmittance of windows. Zone 8 – Yellowknife (SC = 24.9%) is the most sensitive to changes in that variable, while Zone 4 – Victoria (SC = 17.4%) is slightly less sensitive.

Result analysis and discussion

The high SC values for the boiler efficiency can be explained by its important participation in the building EUI. In the base case scenario, where the natural gas fired boiler is responsible for the building space heating needs, its energy consumption comprises 52.5% of the total EUI. As for the high SC values of the thermal transmittance of windows, its contribution to the conduction heat losses, which are particularly high during the winter, is an important factor to be considered. When compared to the walls, the thermal transmittance of windows is considerably higher: approximately 6.7 times more. Since the building has an elevated total vertical fenestration and door area to gross wall area ratio (FDWR) of 38.5%, increasing the thermal transmittance of the windows incurs in additional heat losses, which are translated in an increase in the EUI through the space heating end-use.

The percent relative ranges of the chiller COP and the boiler efficiency, which differ from most other values in the table, evidence a connection between the weather conditions and the primary HVAC equipment performance. The impact of the weather conditions on the performance of most equipment can be explained in part due to an increase or decrease in the HVAC thermal load, which in turn causes an increase or decrease in the average part load ratio of the equipment, mostly designed to operate at peak efficiency on nominal conditions. Another factor tied to weather conditions that affects performance is the operating temperature of airside and waterside fluids. The efficiency of the primary HVAC equipment, especially of chillers and cooling towers, is strongly tied to these temperatures, which are important variables in the heat transfer between systems and the outdoor air.

Given these interactions, the high percent relative range in for chiller COP SCs can be explained by the strong correlation between the weather conditions and the performance of the chiller. In a water-cooled chiller, with colder outdoor air temperatures and lower relative humidity, the cooling tower is able to provide colder entering condensing water temperatures to the chiller condenser, which greatly reduces compressor power. A relatively lower percent relative range in the boiler efficiency SCs for the same parameters can likely be explained by the fact that the boiler doesn't interact directly with the outdoor air. Its performance depends mostly on the hot water temperature setpoint and the part load ratio.

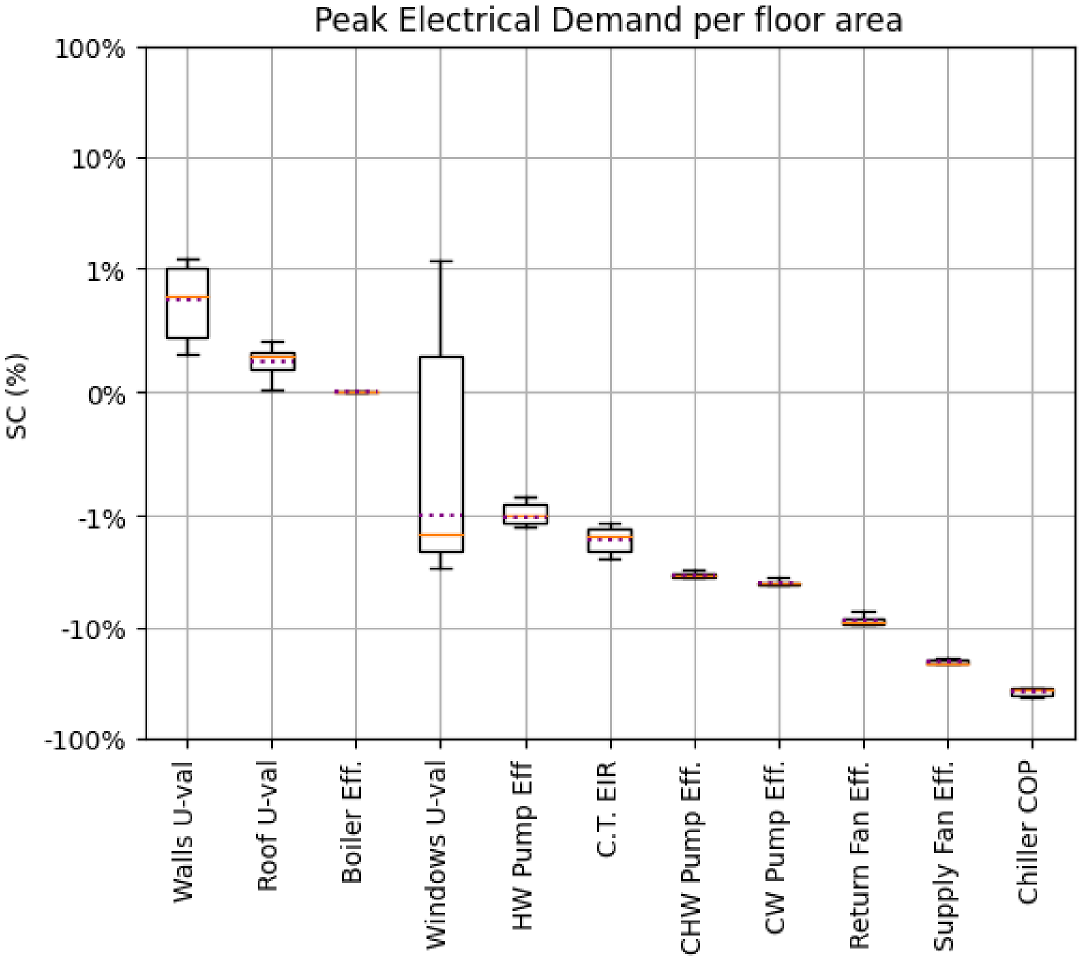


Figure 6.5 - Box plot of the sensitivity coefficients of the Peak Electrical Demand per floor area versus input variables for all climatic zones (positive coefficients relate an increase in energy consumption).

Table 6.6 - Details of the Peak Electrical Demand boxplot

Variable (%)	**Walls U-val**	**Roof U-val**	**Boiler Eff.**	**Windows U-val**	**HW Pump Eff**	**C.T. EIR**	**CHW Pump Eff.**	**CW Pump Eff.**	**Return Fan Eff.**	**Supply Fan Eff.**	**Chiller COP**
Minimum	0.3	0.0	0.0	-2.9	-1.2	-2.3	-3.5	-4.1	-9.5	-21.4	-41.5
Lower quartile	0.5	0.2	0.0	-2.1	-1.1	-2.0	-3.5	-4.1	-9.4	-20.9	-40.0
Median	0.8	0.3	0.0	-1.4	-1.0	-1.5	-3.4	-4.0	-9.0	-20.8	-36.0
Mean	0.8	0.3	0.0	-1.0	-1.0	-1.7	-3.3	-3.9	-8.7	-20.3	-37.3
Upper quartile	1.0	0.3	0.0	0.3	-0.9	-1.3	-3.3	-3.9	-8.3	-19.4	-34.7
Maximum	1.2	0.4	0.0	1.2	-0.8	-1.1	-3.0	-3.6	-7.0	-18.7	-34.6
Percent relative range	**120**	**151**	**-**	**415**	**36.6**	**72.6**	**14.4**	**14.4**	**28.5**	**13.2**	**18.3**

Summary

In the **high impact** category were grouped the supply fan efficiency and the chiller COP. The chiller COP presents the highest impact with a negative correlation with the peak electrical demand, with its SCs varying between -41.5% and -34.6%, with a mean value of -37.3%. In the sequence, also with a negative correlation with the peak electrical demand, the supply fan efficiency presents SCs that vary between -21.4% and -18.7%, with a mean value of -20.3%. In the **low impact** category were grouped the thermal transmittance of walls and windows, the pumps efficiency, the return fan efficiency, and the cooling tower EIR. In the **negligible impact** category were grouped the thermal transmittance of the roof and the boiler efficiency.

Influence of climatic zones on the SCs

The impact of most variables on the peak electrical demand is considerably affected by the weather conditions, with most percent relative ranges in the 10% to 40%. The impact of the thermal transmittance of windows on the peak electrical demand is the most affected by the weather conditions, with a percent relative range of 415%, followed by the high values of 151% for the thermal transmittance of the roof, 120% for the thermal transmittance of the walls and 72.6% for the cooling tower EIR.

There are some differences between climate zones in relation to the magnitude of the impact of the SCs, specially in variables that have a low impact.

Changing the thermal transmittance of walls has a low impact on Zone 4 – Victoria (SC = 1.1%) and on Zone 6 – Montréal (SC = 1.2%), while on all other zones, the impact is negligible.

Changing the thermal transmittance of windows has a negligible impact on Zone 7B – Whitehorse (SC = 0.8%), while on all other zones, the impact is low.

Changing the hot water pump efficiency has a negligible impact on Zone 4 – Victoria, Zone 5 – Toronto, and Zone 6 – Montréal, while it has a low impact on Zone 7A – Edmonton (SC = -1.1%), Zone 7B – Whitehorse (SC = -1.2%), and Zone 8 – Yellowknife (SC = -1.2%).

Performing changes in the input variables of the high impact category would be effective in all climate zones.

Changing the chiller COP would be the most effective in Zone 6 - Montréal (SC = -41.5%), and slightly less effective in Zone 7B – Whitehorse (SC = -34.6%).

The same applies to the supply fan efficiency. Zone 4 – Victoria (SC = -21.4%) is the most sensitive to changes in that variable, while Zone 5 – Toronto (SC = -18.7%) is slightly less sensitive.

Result analysis and discussion

Given the configuration of the system with an electrical chiller serving the chilled water loop, the peak electrical demand of the building is highly correlated with space cooling needs. The hot water loop is served by natural gas fired boilers, taking care of the building's space heating needs. For this reason, the SCs of the boiler efficiency on the peak electrical demand are null.

The highest contributors to the peak electrical demand are the supply fan efficiency and the chiller COP. At the time of peak, the supply fan and the chiller COP require a high electrical power to provide adequate ventilation and space cooling to the zones. In the base case scenario, the ventilation fans and the chiller are the highest end-use contributors to the annual peak electrical power demand. The chiller COP comprises 38.8% of the whole building annual peak electrical power demand and 56.5% of the HVAC system building annual peak electrical power demand, while the ventilation fans comprise 20.0% and 29.1% to the same KPIs, respectively.

The impact of changing the thermal transmittance of windows on the peak electrical demand can be positive or negative depending on the climatic zone. In certain climates, a thermal balance between the indoor and outdoor conditions can be achieved depending on the characteristics of the building thermal zones and the outdoor temperature. In the design stage, building engineers can be take advantage of this thermal balance to save electrical energy.

As seen in the results, depending on the climatic zone, increasing the insulation of the windows will have a negative effect. This is most likely due to the thermal balance being upset by less than desired outward heat flux in the windows caused by unnecessary additional thermal resistance. In particularly cold climates however where the heating needs far exceed the cooling needs for most of the year, increasing window insulation can prove to be beneficial. The effects of weather conditions on the impact of the thermal transmittance of the walls on the peak electrical demand is not as severe. This can be partially explained by the reduced conduction heat transfer through the walls when compared to the windows, due to its high thermal resistance. In addition, the windows take up a considerable portion of the building envelope.

The impact of the cooling tower EIR on the peak electrical demand is higher than its impact on the EUI, as well as being more dependant on the weather conditions. This arises from the peak electrical demand being highly correlated with the cooling loads, taken on by the electrical chiller, and the chiller COP dependency on the condenser water temperature.

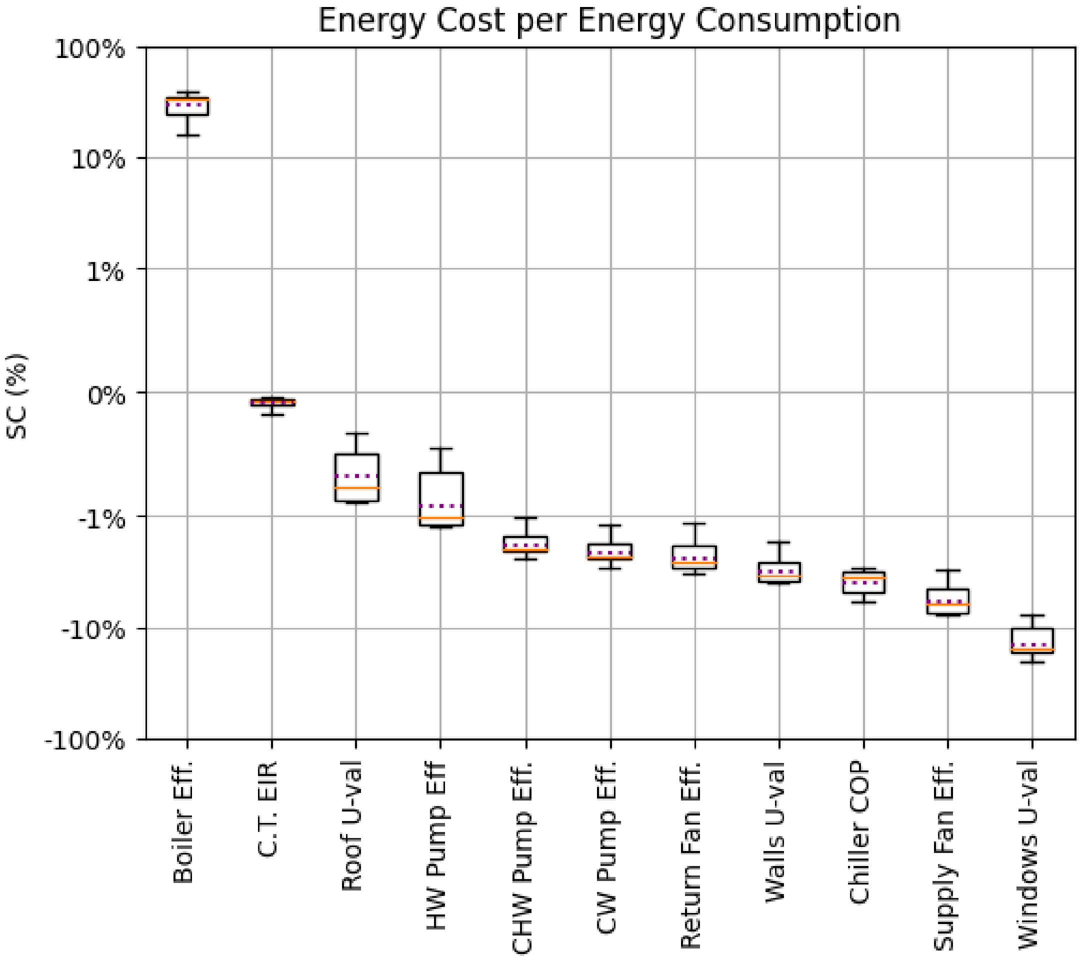


Figure 6.6 - Box plot of the sensitivity coefficients of the Energy Cost per Energy Consumption versus input variables for all climatic zones (positive coefficients relate an increase in energy consumption).

Table 6.7 - Details of the Energy Cost per Energy Consumption boxplot

Variable (%)	Boiler Eff.	C.T. EIR	Roof U-val	HW Pump Eff	CHW Pump Eff.	CW Pump Eff.	Return Fan Eff.	Walls U-val	Chiller COP	Supply Fan Eff.	Windows U-val
Minimum	16.0	-0.2	-0.9	-1.2	-2.4	-2.9	-3.3	-4.0	-5.9	-7.6	-20.1
Lower quartile	24.8	-0.1	-0.9	-1.2	-2.1	-2.4	-2.9	-3.8	-4.9	-7.3	-16.7
Median	33.9	-0.1	-0.8	-1.0	-2.0	-2.3	-2.6	-3.4	-3.5	-6.2	-15.2
Mean	29.8	-0.1	-0.7	-0.9	-1.8	-2.1	-2.4	-3.1	-4.0	-5.7	-14.0
Upper quartile	34.9	-0.1	-0.5	-0.6	-1.5	-1.7	-1.8	-2.6	-3.1	-4.4	-10.1
Maximum	38.3	0.0	-0.3	-0.4	-1.0	-1.2	-1.2	-1.7	-2.9	-3.0	-7.8
Percent relative range	**74.6**	**168**	**82.9**	**84.7**	**78.8**	**79.1**	**89.8**	**73.1**	**74.4**	**80.3**	**88.1**

Summary

In the **high impact** category, the boiler efficiency and the thermal transmittance of windows are found. The boiler efficiency presents the highest impact with a positive correlation with the energy cost per energy consumption, with its SCs varying between 16.0% and 38.3%, with a mean value of 29.8%. The thermal transmittance of windows presents a negative correlation with the energy cost per energy consumption, with its SCs varying between -20.1% and -7.8%, with a mean value of -14.0%. In the **low impact** category were grouped the pump efficiencies, the fans efficiency, the thermal transmittance of walls, and the chiller COP. In the **negligible impact** category were grouped the cooling tower EIR and the thermal transmittance of the roof.

Influence of climatic zones on the SCs

The impact of most variables on the energy cost per energy consumption is considerably affected by the weather conditions, with most percent relative ranges in the 70% to 90%.

There are some differences between climate zones in relation to the magnitude of the impact of the SCs.

Changing the thermal transmittance of windows has a high impact on Zone 5 – Toronto (SC = -15.7%), Zone 7A – Edmonton (SC = -20.1%), Zone 7B – Whitehorse (SC = -17.0%), and on Zone 8 – Yellowknife (SC = -14.6%), while it has a low impact on Zone 4 – Victoria (SC = -8.6%), and Zone 6 – Montréal (SC = -7.8%).

Changing the hot water pump efficiency has a negligible impact on Zone 4 – Victoria, Zone 5 – Toronto, and Zone 6 – Montréal, while it has a low impact on Zone 7A – Edmonton (SC = -1.2%), Zone 7B – Whitehorse (SC = -1.2%), and Zone 8 – Yellowknife (SC = -1.1%).

Performing changes in the input variables of the high impact category would be effective in almost all climate zones.

Changing the thermal transmittance of windows be the most effective in Zone 7A - Edmonton (SC = -20.1%), and less effective in Zone 6 – Montréal (SC = -7.8%).

With regards to the boiler efficiency, Zone 7A – Edmonton (SC = 38.3%) is the most sensitive to changes in that variable, while Zone 6 – Montréal (SC = 16.0%) is slightly less sensitive.

Result analysis and discussion

This variable represents the annual utility cost for all energy sources divided by the building site EUI, i.e. the sum of the energy consumption from all energy sources in the building.

In the reference building, two energy sources are used: natural gas and electricity. The value of this variable reflects a balance between these energy sources with different costs under different weather conditions.

The boiler efficiency is the variable with the highest impact on the energy cost per energy consumption. This is due to its elevated contribution both to the utility cost and to the whole building energy consumption. In the base case scenario, the energy consumption of the natural gas fired boiler comprises 52.5% of the total EUI and 34.0% of the annual utility cost.

Natural gas is a cheap energy source that brings the overall utility cost per site EUI down. As the boiler efficiency is increased, the proportion energy consumed from natural gas to all energy sources is reduced. This causes the energy cost to increase with the boiler efficiency. The conversion of natural gas into usable energy to provide space heating or cooling is relatively inefficient when compared to other heat transfer equipment (e.g., electrical chiller, DX cooling coils, heat pumps). However, the price of natural gas energy is considerably lower than the electrical energy counterpart required to operate the other heat transfer equipment alternatives. This price difference justifies the utilization of fuel fired boilers, gas fired boilers in particular, as the main heat source for commercial buildings.

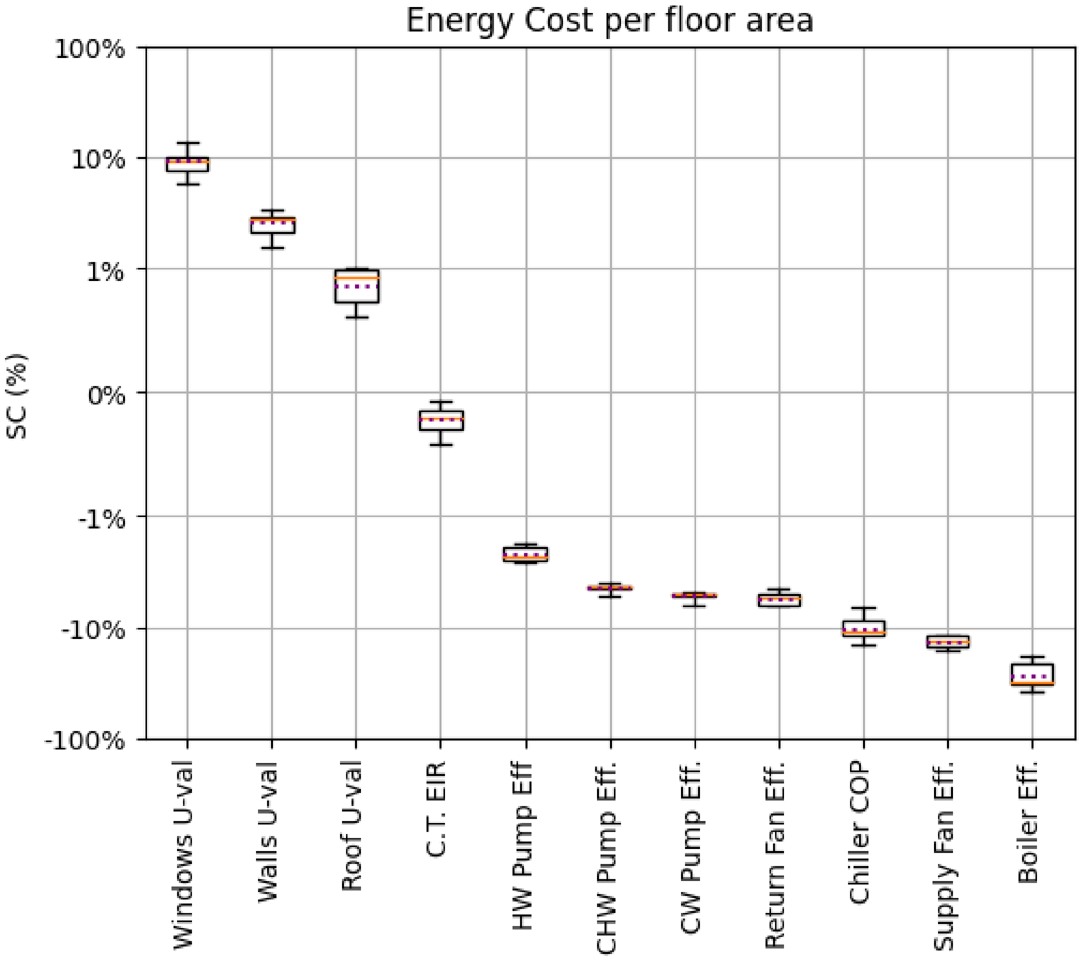


Figure 6.7 - Box plot of the sensitivity coefficients of the Energy Cost per floor area versus input variables for all climatic zones (positive coefficients relate an increase in energy consumption).

Table 6.8 - Details of the Annual Energy Cost boxplot

Variable (%)	**Windows U-val**	**Walls U-val**	**Roof U-val**	**C.T. EIR**	**HW Pump Eff**	**CHW Pump Eff.**	**CW Pump Eff.**	**Return Fan Eff.**	**Chiller COP**	**Supply Fan Eff.**	**Boiler Eff.**
Minimum	5.7	1.6	0.6	-0.4	-2.6	-5.3	-6.2	-6.3	-14.2	-16.0	-37.7
Lower quartile	7.5	2.1	0.7	-0.3	-2.5	-4.5	-5.3	-6.2	-11.6	-14.8	-31.6
Median	9.2	2.8	0.9	-0.2	-2.3	-4.3	-5.1	-5.5	-10.8	-13.3	-30.5
Mean	9.2	2.5	0.9	-0.2	-2.2	-4.4	-5.2	-5.5	-10.3	-13.5	-27.8
Upper quartile	10.1	2.9	1.0	-0.1	-1.9	-4.3	-5.0	-5.0	-8.5	-11.9	-21.3
Maximum	13.8	3.3	1.0	-0.1	-1.7	-4.0	-4.8	-4.5	-6.5	-11.6	-18.1
Percent relative range	**87.4**	**69.5**	**47.1**	**157**	**39.6**	**27.4**	**27.5**	**32.8**	**74.4**	**32.7**	**70.5**

Summary

In the **high impact** category were grouped the thermal transmittance of windows, the chiller COP, the supply fan efficiency and the boiler efficiency. The boiler efficiency presents the highest impact with a negative correlation with the annual energy cost, with its SCs varying between -37.7% and -18.1%, with a mean value of -27.8%. In the sequence, with a positive correlation, the thermal transmittance of windows presents SCs that vary between 5.7% and 13.8%, with a mean value of 9.2%. With a negative correlation, the supply fan efficiency presents SCs that vary between -16.0% and -11.6%, with a mean value of -13.5%; followed by the chiller COP that presents SCs that vary between -14.2% and -6.5%, with a mean value of -10.3%. In the **low impact** category were grouped the thermal transmittance of walls and roof, the pumps efficiency and the return fan efficiency. In the **negligible impact** category, the cooling tower EIR is found.

Influence of climatic zones on the SCs

The impact of most variables on the annual energy cost is considerably affected by the weather conditions, with most percent relative ranges in the 30% to 70%. The SCs of the CHW and the CW pump efficiencies are particularly less affected by weather conditions compared to the SCs of other variables, with a percent relative range of approximately 27%. The SCs of the chiller COP and the thermal transmittance of the windows are the most affected by the weather conditions, with a percent relative range of 74.4% and 87.4%, respectively.

There are some differences between climate zones in relation to the magnitude of the impact of the SCs.

Changing the thermal transmittance of windows has a high impact on Zone 6 – Montréal (SC = 13.8%) and Zone 8 – Yellowknife (SC = 10.3%), while it has a low impact on Zone 4 – Victoria (SC = 9%), Zone 5 – Toronto (SC = 5.7%), Zone 7A – Edmonton (SC = 7.1%), and Zone 7B – Whitehorse (SC = 9.4%).

Changing the chiller COP has a high impact on Zone 4 – Victoria (SC = -10.3%), Zone 5 – Toronto (SC = -14.2%), Zone 6 – Montréal (SC = -11.7%), and on Zone 7A – Yellowknife (SC = -11.4%), while it has a low impact on Zone 7B – Whitehorse (SC = -6.5%), and Zone 8 – Yellowknife (SC = -7.9%).

Changing the thermal transmittance of the roof has a negligible impact on Zone 4 – Victoria, Zone 5 – Toronto, and Zone 7A – Edmonton, while it has a low impact on Zone 6 –

Montréal (SC = 1.0%), Zone 7B – Whitehorse (SC = 1.0%), and Zone 8 – Yellowknife (SC = 1.0%).

Performing changes in the input variables of the high impact category would be effective in almost all climate zones.

Changing the thermal transmittance of windows be the most effective in Zone 6 - Montréal (SC = 13.8%), and less effective in Zone 5 – Toronto (SC = 5.7%).

With regards to the chiller COP, Zone 5 – Toronto (SC = -14.2%) is the most sensitive to changes in that variable, while Zone 7B – Whitehorse (SC = -6.5%) is less sensitive.

With regards to the boiler efficiency, Zone 6 – Montréal (SC = -37.7%) is the most sensitive to changes in that variable, while Zone 5 – Toronto (SC = -18.1%) is less sensitive.

With regards to the supply fan efficiency, Zone 7A – Edmonton (SC = -16.0%) is the most sensitive to changes in that variable, while Zone 7B – Whitehorse (SC = -11.6%) is less sensitive.

Result analysis and discussion

The same reasoning used to explain the high impact of some variables on the EUI can be used to explain the high impact of these variables on the annual energy cost. In this case, however, the equipment that consumes electricity has an increased impact. This is due to the annual energy cost being composed of a natural gas component and an electricity component, divided into electricity consumption and peak power demand. The costs associated with the peak power demand can be substantial, taking up to half of the total electricity cost in the base case scenario. Since these two components come into play to determine the annual energy cost, improvement in performance for equipment that consumes electricity usually causes a reduction in both the annual energy consumption and peak power demand. For example, as explained previously, the performance of the chiller is considerably affected by the weather conditions, impacting both the energy consumption and the peak power demand required by the chiller to provide cooling to the zones.

The lower impact of the weather conditions on the SCs of the pumps efficiencies is most likely due to the independence of the pump operation with regards to the weather condition. In all climates, the pumps operate for the same number of hours in a year, according to the schedules set out in NECB-2017 and operate under a constant speed setting.

The large surface area of the windows and the difference of the minimum thermal transmittance between the climatic zones are a likely contributor to the elevated impact of the weather on the SCs of the thermal transmittance of the windows on the annual energy cost. This impact is also likely correlated to the heat load induced by colder climates in the form of additional conduction heat losses from conditioned spaces to the outdoor space.

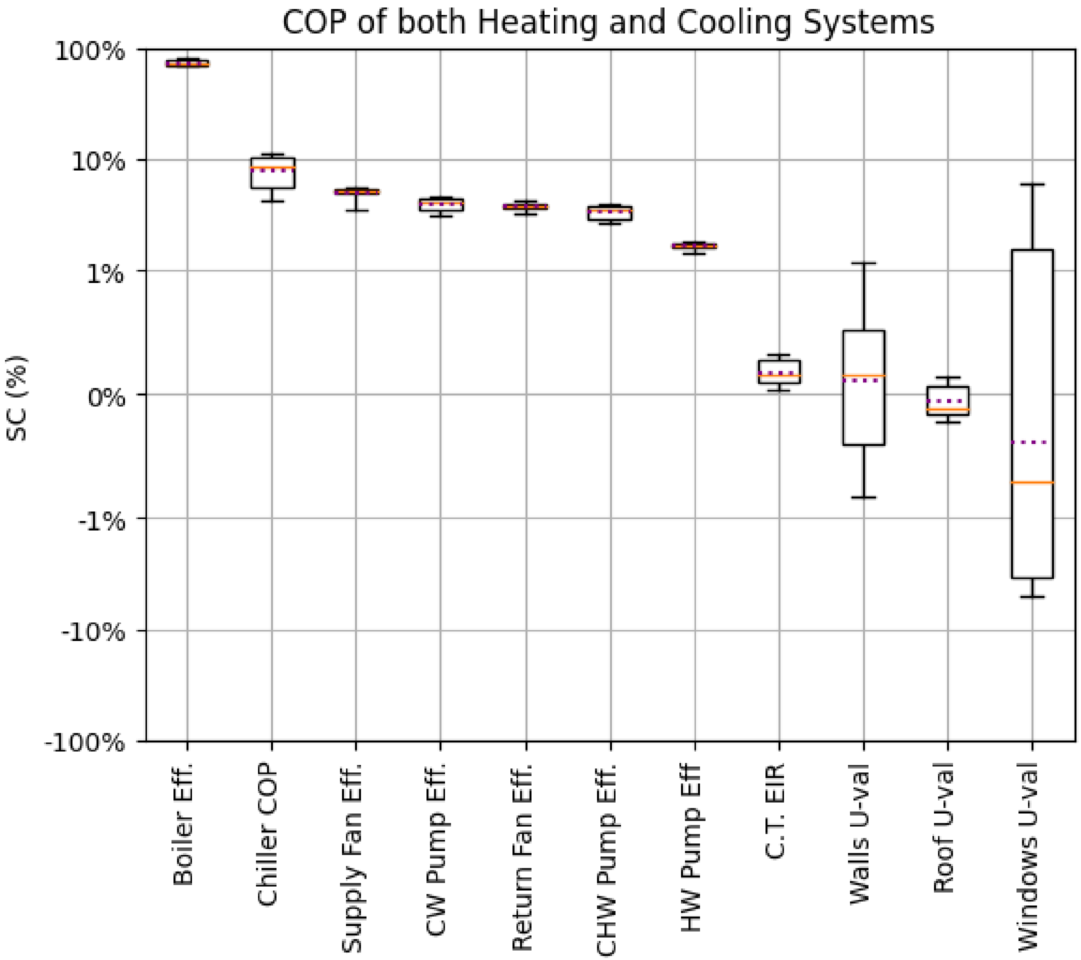


Figure 6.8 - Box plot of the sensitivity coefficients of the COP of both Heating and Cooling Systems versus input variables for all climatic zones (positive coefficients relate an increase in energy consumption).

Table 6.9 - Details of the COP of both Heating and Cooling Systems boxplot

Variable (%)	**Boiler Eff.**	**Chiller COP**	**Supply Fan Eff.**	**CW Pump Eff.**	**Return Fan Eff.**	**CHW Pump Eff.**	**HW Pump Eff**	**C.T. EIR**	**Walls U-val**	**Roof U-val**	**Windows U-val**
Minimum	68.5	4.3	3.6	3.2	3.3	2.7	1.5	0.0	-0.8	-0.2	-5.0
Lower quartile	69.2	5.7	5.0	3.5	3.7	3.0	1.6	0.1	-0.4	-0.2	-3.4
Median	71.2	8.6	5.1	4.1	3.9	3.5	1.7	0.2	0.2	-0.1	-0.7
Mean	73.1	8.1	5.0	4.0	3.8	3.4	1.7	0.2	0.1	-0.1	-0.4
Upper quartile	77.0	10.4	5.3	4.5	4.0	3.8	1.7	0.3	0.5	0.1	1.6
Maximum	80.2	11.2	5.6	4.6	4.4	3.9	1.8	0.3	1.2	0.2	6.0
Percent relative range	**16.0**	**86.4**	**41.9**	**36.2**	**28.3**	**36.3**	**21.5**	**154**	**1657**	**659**	**2820**

Summary

In the **high impact** category were grouped the boiler efficiency and the chiller COP. The boiler efficiency presents the highest impact with a positive correlation with the COP of both heating and cooling systems, with its SCs varying between 68.5% and 80.2%, with a mean value of 73.1%. In the sequence, also with a positive correlation, the chiller COP presents SCs that vary between 4.3% and 11.2%, with a mean value of 8.1%. In the **low impact** category were grouped the pumps efficiency, the fans efficiency and the thermal transmittance of walls and windows. In the **negligible impact** category were grouped the cooling tower EIR and the thermal transmittance of the roof.

Influence of climatic zones on the SCs

The impact of most variables on the COP of both heating and cooling systems is considerably affected by the weather conditions, with most percent relative ranges in the 20% to 50%. The SCs of the boiler efficiency are particularly less affected by weather conditions compared to the SCs of other variables, with a percent relative range of 16.0%. The SCs of the chiller COP are considerably affected by the weather conditions, with a percent relative range of 86.4%. Depending on the weather conditions, the SCs of some variables can take positive or negative values of different magnitudes. That is the case of the thermal transmittance of walls and windows, with a percent relative range of 1,657% and 2,820%, respectively.

There are some differences between climate zones in relation to the magnitude of the impact of the SCs, specially in variables that have a low impact.

Changing the chiller COP has a high impact on Zone 5 – Toronto (SC = 10.7%) and Zone 6 – Montréal (SC = 11.2%), while it has a low impact on Zone 4 – Victoria (SC = 9.4%), Zone 7A – Edmonton (SC = 7.8%), Zone 7B – Whitehorse (SC = 4.3%), and Zone 8 – Yellowknife (SC = 4.9%).

Changing the thermal transmittance of walls has a low impact on Zone 7B – Whitehorse (SC = 1.2%), while on all other zones, the impact is negligible.

Changing the thermal transmittance of windows has a negligible impact on Zone 7A – Edmonton (SC = -0.2%), while on all other zones, the impact is low.

Performing changes in the input variables of the high impact category would be effective in almost all climate zones.

Changing the chiller COP would be the most effective in Zone 6 - Montréal (SC = 11.2%), and less effective in Zone 7B – Whitehorse (SC = 4.3%).

The same applies to the boiler efficiency. Zone 7B – Whitehorse (SC = 80.2%) is the most sensitive to changes in that variable, while Zone 6 – Montréal (SC = 68.5%) is slightly less sensitive.

Result analysis and discussion

This variable reflects the average efficiency of the whole HVAC system, considering the respective contribution of each individual equipment to the system energy consumption. The equipment with the highest individual contributions are the boiler and the chiller. In the base case scenario, they each account for 68.0% and 10.1% of the HVAC system consumption, respectively. Implementing improvements in the efficiency of these equipment would lead to a considerable increase in the system COP.

Depending on weather conditions, the SCs of the thermal transmittance of the walls, windows and roof can be positive or negative. The thermal transmittance of the envelope impacts the conduction heat loss through its elements, and consequently the part-load ratio of the heating and cooling equipment. The inversion in the sign of the SCs is likely due to a change in the thermal balance established between the perimeter indoor spaces and the outdoor space during some months of the year. Depending on the weather conditions and the value of the thermal transmittance the part load ratio of the equipment can be positively or negatively affected. These variables present the highest percent relative range among all variables.

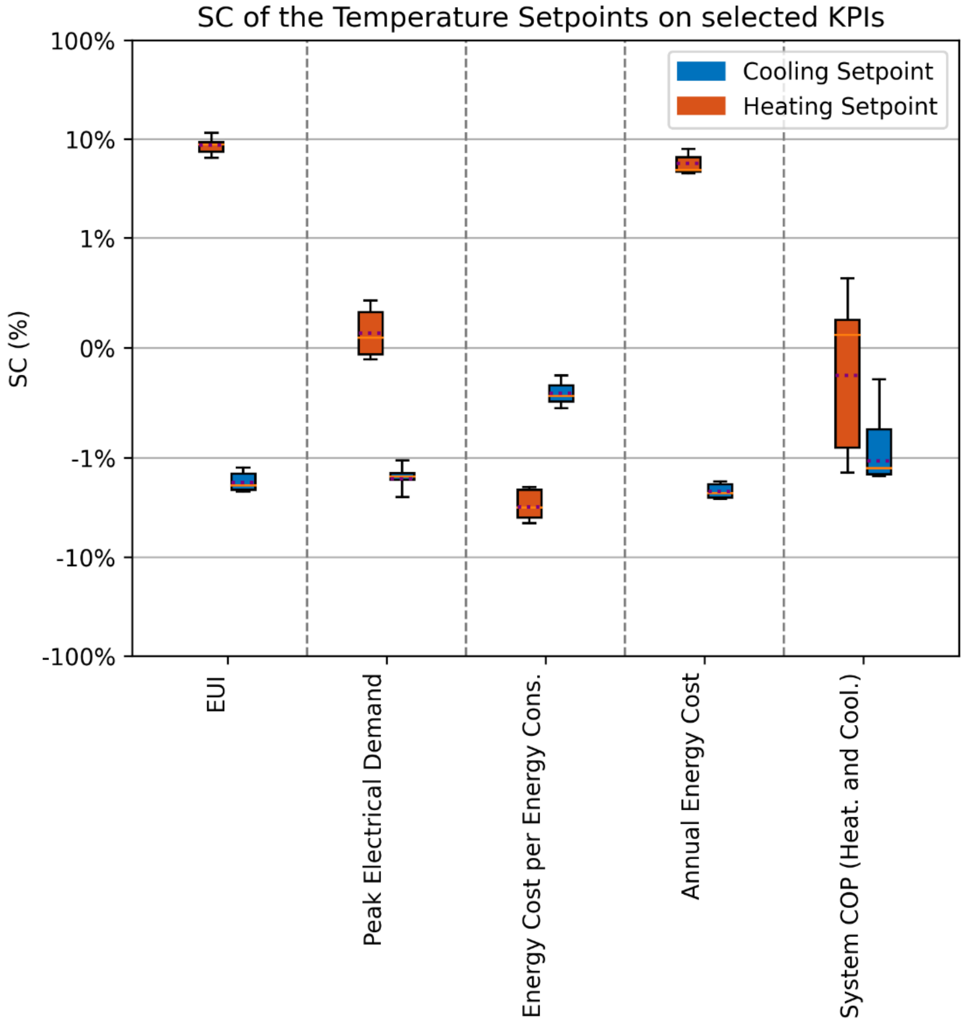


Figure 6.9 - Box plot of the sensitivity coefficients of the heating and cooling temperature setpoints over the selected KPIs (positive coefficients relate an increase in energy consumption).

Table 6.10 - Details of the heating and cooling temperature setpoints boxplot

Variable (%/°C)	Heating SP	Cooling SP	Heating SP	Cooling SP	Heating SP	Cooling SP	Heating SP	Cooling SP	Heating SP	Cooling SP
Minimum	6.5	-2.2	-0.1	-2.5	-4.6	-0.5	4.5	-2.6	-1.4	-1.5
Lower quartile	7.5	-2.1	-0.1	-1.7	-4.0	-0.5	4.7	-2.5	-0.9	-1.5
Median	8.8	-1.9	0.1	-1.5	-3.2	-0.4	4.9	-2.3	0.1	-1.3
Mean	8.7	-1.8	0.1	-1.6	-3.2	-0.4	5.7	-2.2	-0.2	-1.1
Upper quartile	9.2	-1.4	0.3	-1.4	-2.1	-0.3	6.6	-1.8	0.3	-0.7
Maximum	11.5	-1.3	0.4	-1.1	-2.0	-0.2	8.0	-1.7	0.6	-0.3
Percent relative range	**58.3**	**53.0**	**397**	**87.9**	**82.3**	**71.8**	**61.4**	**38.7**	**822**	**115**

Summary

Table 6.10 summarizes the indicators used to build the box plot presented in Figure 6.9. In the other box plots presented so far, the sensitive coefficients represent a percent increase in the selected KPI given a unit increase (100%) in the input variable. When studying the SCs of the temperature setpoints, a percent increase over a unit increase in the input variables is hard to interpret and doesn't translate very well into practical applications when compared to a percent increase over an increase of 1 °C in these temperature setpoints. A proper conversion from % to % per °C was applied to obtain the presented SCs.

With regards to the heating temperature setpoint, this variable presents a **high impact** on the EUI, with SCs varying between 6.5% and 11.5% and a mean value of 8.7%; a **low impact** on the energy cost per energy consumption, the annual energy cost and the system COP for both heating and cooling; and a **negligible impact** on the peak electrical demand.

With regards to the cooling temperature setpoint, this variable presents a **low impact** on the EUI, the peak electrical demand, the annual energy cost and the system COP for both heating and cooling; and a **negligible impact** on the energy cost per energy consumption.

Influence of climatic zones on the SCs

The SCs of the temperature setpoints on the selected KPIs is considerably affected by the weather conditions, with most percent relative ranges in the 50% to 90%. The SCs of the heating setpoint over the system COP for both heating and cooling is considerably affected by the weather conditions, with a percent relative range of 822%. The SCs of the cooling setpoint over the system COP for both heating and cooling is also considerably affected by the weather conditions, with a percent relative range of 115%. Depending on the weather conditions, the SCs of some variables can take positive or negative values. That is the case of the SCs of the heating and cooling setpoints over the system COP.

There are some differences between climate zones in relation to the magnitude of the impact of the SCs.

When looking at the SCs of the EUI, changing the heating setpoint has a high impact on Zone 4 – Victoria (SC = 11.5%), while on all other zones, the impact is low. Performing changes in this variable of the high impact category would be effective in almost all climate zones, with Zone 4 being the most affected one and Zone 8 – Yellowknife (SC = 6.5%) being the least affected one.

When looking of the SCs of the COP of both heating and cooling systems, changing the heating setpoint has a low impact on Zone 5 – Toronto (SC = -1.4%) and Zone 6 – Montréal (SC = -1.2%), while on all other zones, the impact is negligible. Changing the cooling setpoint has a low impact on Zone 4 – Victoria (SC = -1.5%), Zone 5 – Toronto (SC = -1.5%) and Zone 6 – Montréal (SC = -1.3%), and Zone 7A – Edmonton (SC = -1.2%), while on all other zones, the impact is negligible.

Result analysis and discussion

In general, the magnitude of the SCs of the heating temperature setpoint over the selected KPIs is higher than the cooling temperature setpoint counterparts. One of the likely explanations for this effect is the temperature difference in winter conditions compared to summer conditions.

Under cooling mode, the cooling system must extract heat from the zones at a rate that is equal to or higher than the heat gain from the outside through conduction in the building envelope and infiltration of outdoor air, and cool down the outdoor air flow rate being brought into the zones due to ventilation needs for indoor air quality. Under heating mode, the system performs the same task, but provides necessary heat instead of cool to overcome heat losses to the outside and to heat up the ventilation air. Both modes of heat gain/loss are proportional to the temperature difference between the zones and the outdoor space.

In the base case scenario, during the winter, the peak temperature difference between the outdoor air temperature and the indoor air temperature setpoint at a time of maximum heating load is approximately 45 °C (-23 °C to 22 °C). For the summer counterpart, the value is approximately 7 °C (31 °C to 24 °C). In the base case, the annual cooling energy was 546.1 GJ, with an annual maximum cooling load of 202.9 kW, while the annual heating energy was 839.7 GJ, with an annual maximum heating load of 183.1 kW. In heating dominant climates, these characteristics count as a factor that explains the high impact of the heating temperature setpoint on the EUI.

Changing the temperature setpoint can lead to an increase or decrease of the system COP for both heating and cooling depending on the weather conditions. The performance of the HVAC equipment can be impacted directly by the temperature setpoint by causing the system to respond changing waterside or airside operating temperatures and flows to achieve the new desired temperature setpoint. Changes in the heat load, particularly in the ventilation and thermal balance between the indoor and the outdoors, also impacts the part-load ratio of the equipment. This change then translates itself to a change in the system COP based on the part-load efficiency curves of each equipment.

Table 6.11 summarizes the classification of the overall impact of each input variable on the selected KPIs for all climate zones into three categories: negligible impact (max(|SC|) < 1%), low impact (1% < max(|SC|) < 10%), and high impact (max(|SC|) ≥ 10%).

Table 6.11 - Classification of the impact of each input variable on the studied KPIs

KPI	**Variable (%)**	**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.**	**Cooling SP**	**Heating SP**
Energy Use Intensity	Negligible Impact	-	-	-	-	-	N	-	-	-	-	-	-	-
	Low Impact	L	L	-	L	-	-	L	L	L	L	L	L	-
	High Impact	-	-	H	-	H	-	-	-	-	-	-	-	H
Peak Electrical Demand	Negligible Impact	-	N	-	-	N	-	-	-	-	-	-	-	N
	Low Impact	L	-	L*	-	-	L	L	L	L	-	L	L	-
	High Impact	-	-	-	H	-	-	-	-	-	H	-	-	-
Energy Cost per Energy Consumption	Negligible Impact	-	N	-	-	-	N	-	-	-	-	-	N	-
	Low Impact	L	-	-	L	-	-	L	L	L	L	L	-	L
	High Impact	-	-	H	-	H	-	-	-	-	-	-	-	-
Annual Energy Cost	Negligible Impact	-	-	-	-	-	N	-	-	-	-	-	-	-
	Low Impact	L	L	-	-	-	-	L	L	L	-	L	L	L
	High Impact	-	-	H	H	H	-	-	-	-	H	-	-	-
System COP Both Heating and Cooling	Negligible Impact	-	N	-	-	-	N	-	-	-	-	-	-	-
	Low Impact	L*	-	L*	-	-	-	L	L	L	L	L	L*	L*
	High Impact	-	-	-	H	H	-	-	-	-	-	-	-	-

N – Negligible impact, L – Low Impact, H – High Impact

** - Impact can be positive or negative depending on climatic zone*

The main KPIs concerning building operation and energy code development are the EUI and the annual energy cost. Building operators often seek for solutions that can reduce the operational cost, by increasing the energy efficiency of building service systems [92]. Building energy codes provide these solutions in a generalized manner, usually comparing the annual energy consumption of a proposed building to the energy consumption of a reference building, modelled in accordance with the code's provisions. NECB-2017 focuses on the target energy consumption of a building to accomplish its objective of improving the energy efficiency of new buildings and reducing greenhouse gas emissions.

This study demonstrated the application of the proposed sensitivity analysis method over a range of Canadian climate zones. A list of locations (cities) was selected based on their population and importance in that geographical region to be representative of each climatic zone. Reference building models were developed for each climatic zone, with respect to the minimum energy efficiency requirements of NECB for each climatic zone. With the locations selected, the batch processing feature of eQUEST was used to perform the sequential simulations of the selected design input variables. Lastly, the sensitivity analysis was performed with the aid of a MATLAB code, which together with a Python code outputted the results in illustrations.

The sensitivity analysis has demonstrated that the thermal transmittance of windows, the chiller COP, the boiler efficiency, and the supply fan efficiency have the highest impact on the energy performance and operating cost of the building. Differences of the magnitude of the impact of certain variables on the selected KPIs were detected between climatic zones and quantified using the SCs. Focusing on the EUI and on the annual energy cost, in terms of the envelope, the **thermal transmittance of windows** presents a high impact on the EUI for all climatic zones and on the annual energy cost for Zone 6 – Montréal and Zone 8 - Yellowknife. In terms of the primary HVAC equipment, the **boiler efficiency** presents a high impact on both the EUI and the annual energy cost for all climatic zones. The **chiller COP** presents a high impact on the annual energy cost for Zone 4 – Victoria, Zone 5 – Toronto, Zone 6 – Montréal and Zone 7A - Edmonton. In terms of secondary equipment, the **supply fan efficiency** presents a high impact on the annual energy cost for all climatic zones. In terms of operational parameters, the **heating temperature setpoint** presents a high impact on the EUI for Zone 4 - Victoria. Future code updates should prioritize changes in the energy efficiency requirements for these variables to maximize the savings from proposed code alterations.

With respect to the temperature setpoint, it’s important to consider that there are requirements for indoor air quality and thermal comfort that effectively reduce the operational range of that variable. In addition, temperature control should be at disposal of the building operator since thermal comfort can affect customer satisfaction at the building’s premises.

It was verified that the weather conditions can significantly alter the impact of variables on the selected KPIs. The percent relative range found for the studied variables was between 10% and

90% for most cases. In some of these cases, namely in the thermal transmittance of walls and windows and in the heating and cooling temperature setpoints to the system COP, the impact can be positive or negative depending on climatic zone. Given this effect, even though the overall energy consumption of a building could be reduced through the implementation of ECMs, the annual system COP for both heating and cooling would be reduced, depending on the climate.

The generalization of the conclusions presented in the previous chapter are an answer to important questions in the evaluation of the impact of NECB's provisions: How do the weather conditions affect code's provisions? And, which code's provisions present the highest impact given the effect of weather conditions? The proposed analysis using box plots allow for a quick and intuitive comparison of the SCs for each variable on selected KPIs and how much they vary with the weather conditions. The ranking of variables into negligible impact, low impact and high impact provides an intuitive system to determine which variables should become a priority of future code updates.

The proposed method is computationally efficient and time efficient. The sequential simulations and the MATLAB/Python code were performed using a standard laptop, equipped with an Intel Core i5 CPU and 12 GB DDR4 Memory. The total elapsed time for the 390 simulation runs in eQUEST was 281 minutes (3h 11m), with the sensitivity analysis MATLAB code adding 3 minutes of post-processing. With these figures, the average time per simulation run is 44 seconds for a building with 21 spaces divided in 3 floors, totalling 64 exterior surfaces, 63 interior surfaces and 266 windows. This demonstrates the capacity of upscaling the proposed method to include a winder range of building types, ECMs and KPIs.

An important remark can be made in regard to what NECB-2017 understands as an energy efficient building. Given how the code is structured, an energy efficient building would be one that presents a smaller annual energy consumption than a reference building modelled in accordance with the code’s provisions. This does not imply necessarily that the system operates with a high coefficient of performance of that its individual components are highly efficient in converting energy from one form into another. For example, in the base case model, more than half of the EUI consists of space heating energy consumption, with this end-use being served by a natural gas fired boiler. The efficiency of the boiler, its efficiency in converting natural gas energy into usable space heating energy, is merely 83%, while the chiller COP, its capacity to convert electricity into usable space cooling energy, is 5.547.

It would be interesting to have improving the system efficiency as a secondary focus of the code. This would represent complementing the traditional focus of reducing the overall energy expenditure with also reducing the entropy of the whole system. This could potentially relieve stress for Canada’s necessity to provide high density energy sources such as carbon-based fuels and would bring long-term benefits for both Canada's economy and the environment. In practice, this complementary focus can be achieved easily by focusing on changes to input variables that are aligned also with reducing the annual energy consumption and cost. As an example, in this study, it is verified that the boiler efficiency and the chiller COP fall into that category.

CHAPTER 7 : Proposed Changes to NECB-2017

This chapter describes a series of proposed changes to the NECB-2017 to be integrated into the next code update, chosen based on their impact on energy related KPIs. Three tiers of changes are presented, with each tier having increasing fenestration thermal resistance, chiller COP, boiler efficiency, and supply fan efficiency. The impact of the changes is evaluated using the energy and cost savings. In addition, the change in the system COP is presented, the identification of measures which present energy and cost savings (e.g. through reduction of the thermal load), but also reduce the overall efficiency of the HVAC system.

The following steps summarize the method used in this chapter:

1. Identification of most impactful code's provisions, performed in CHAPTER 6;
2. Proposal of changes to the minimum efficiency requirements of the identified code's provisions, and
3. Results and discussion followed by conclusions.

7.1. Proposed changes to the minimum efficiency requirements

The proposed sensitivity analysis method was applied in CHAPTER 5 for an institutional building located in Montréal and the results were generalized to all Canadian climate zones in CHAPTER 6. The input variables used for the sensitivity analysis were ranked according to the order of magnitude of their impact on the EUI and the annual energy cost KPIs. The highest impact input variables were the thermal transmittance of windows (envelope), the boiler efficiency and the chiller COP (HVAC primary equipment), and the supply fan efficiency (HVAC secondary equipment).

Following the identification of the most impactful code's provisions in the previous chapters, three proposals for changes to the minimum efficiency requirements for these input variables were proposed. These proposals integrate measures that reflect the *state of the art* in energy efficient envelope assemblies and equipment, taken from references in energy efficiency standards and in commercially available and certified HVAC equipment.

The proposed changes are summarized in Table 7.1 and Table 7.2 with the respective relative percent changes from the base case scenario for each proposal. The final impact of implementing these proposals was evaluated in all Canadian climate zones.

Table 7.1 - Proposed changes to the envelope minimum efficiency requirements for each climatic zone

Case	Thermal transmittance of windows (W/m².K) (Btu/h.ft².°F)											
	Zone 4	Δ (%)	Zone 5	Δ (%)	Zone 6	Δ (%)	Zone 7A	Δ (%)	Zone 7B	Δ (%)	Zone 8	Δ (%)
Base Case	2.10 (0.37)	-	1.90 (0.33)	-	1.90 (0.33)	-	1.90 (0.33)	-	1.90 (0.33)	-	1.40 (0.25)	-
Prop. 1	2.00 (0.35)	-4.8	1.80 (0.32)	-5.3	1.80 (0.32)	-5.3	1.80 (0.32)	-5.3	1.80 (0.32)	-5.3	1.30 (0.23)	-7.1
Prop. 2	1.85 (0.33)	-11.9	1.65 (0.29)	-13.2	1.65 (0.29)	-13.2	1.65 (0.29)	-13.2	1.65 (0.29)	-13.2	1.15 (0.20)	-17.9
Prop. 3	1.70 (0.30)	-19.0	1.50 (0.26)	-21.1	1.50 (0.26)	-21.1	1.50 (0.26)	-21.1	1.50 (0.26)	-21.1	1.00 (0.18)	-28.6

In the changes proposed to the thermal transmittance of windows that apply for Zones 5 to 7B in NECB, proposal 2 incorporates the minimum energy efficiency requirement for fixed vertical fenestration present in ASHRAE 90.1-2019 [93] for climatic zone 7. A requirement proposal of lower thermal resistance and one of higher thermal resistance were also included in proposals 1 and 3, respectively. Improvements of similar magnitude were applied to Zone 4 and Zone 8.

Table 7.2 - Proposed changes to the HVAC minimum efficiency requirements for all climatic zones

Case	Chiller COP (kW_t/kW_e)	Δ (%)	Boiler efficiency (%)	Δ (%)	Supply fan efficiency (%)	Δ (%)
Base Case (NECB-2017)	5.547	-	83	-	55	-
Proposal 1	6.0	8.2	85	2.4	60	9.1
Proposal 2	6.5	17.2	90	8.4	65	18.1
Proposal 3	7.0	26.2	95	14.5	70	27.3

In the changes proposed to the chiller COP, proposal 3 incorporates the most strict minimum energy efficiency requirement for water cooled, electrically operated centrifugal chillers present in ASHRAE 90.1-2019 [93].

In the changes proposed to the boiler efficiency, proposal 3 incorporates top boiler efficiencies for ENERGY STAR Certified Boilers [94] based on a list of the most efficient products of 2020.

In the changes proposed to the supply fan efficiency, proposal 3 incorporates top overall fan efficiencies seen in AMCA Fan Energy Index (FEI) metric proposal paper [95]. This new metric was adopted by ASHRAE Standard 90.1 as the minimum efficiency requirement for fans and it is defined as the ratio of the actual fan efficiency to a baseline fan efficiency, both calculated at a given airflow and pressure point.

7.2. Results and Discussion

Each code update proposal is simulated for all climate zones in Canada, resulting in a total of 96 simulation runs (4 cases per measure group, times 4 measure groups, times 6 climatic zones). All results are presented in Table 7.3. In addition, results for climate specific proposals for the envelope requirements are presented graphically from Figure 7.1 to Figure 7.3. Results for primary and secondary HVAC equipment that applies to all climatic zones are presented in box plots from Figure 7.4 to Figure 7.6. Following the box plots, Table 7.4 to Table 7.6 provide the statistic indicators of each array of sensitivity coefficients.

Table 7.3 – Savings for all KPIs for all climatic zones

KPI	Zone	Thermal transmittance of Windows			Chiller COP			Boiler Efficiency			Supply fan efficiency		
		Proposal 1	Proposal 2	Proposal 3	Proposal 1	Proposal 2	Proposal 3	Proposal 1	Proposal 2	Proposal 3	Proposal 1	Proposal 2	Proposal 3
	SCs	%	%	%	%	%	%	%	%	%	%	%	%
EUI	**4**	0.8	2.1	3.5	0.4	1.0	1.4	1.2	4.1	6.6	0.6	1.2	1.9
	5	1.2	2.8	4.5	0.6	1.2	1.7	1.3	4.2	6.7	0.8	1.3	1.9
	6	1.1	2.9	4.6	0.6	1.1	1.7	1.3	4.1	6.7	0.7	1.3	1.7
	7A	1.5	3.7	5.9	0.4	0.9	1.3	1.4	4.5	7.2	0.7	1.3	1.6
	7B	1.5	3.6	5.9	0.3	0.5	0.6	1.6	5.1	8.3	0.5	0.8	1.1
	8	1.8	4.4	7.2	0.3	0.5	0.7	1.6	5.3	8.6	0.5	0.8	1.2
Energy Cost per floor area	**4**	0.5	1.1	1.8	0.7	1.4	2.0	0.7	2.4	3.8	1.0	1.9	2.6
	5	0.3	0.8	1.2	1.0	1.9	2.7	0.4	1.4	2.3	1.2	2.2	3.1
	6	0.7	1.8	3.0	0.8	1.6	2.2	0.9	3.0	4.8	0.9	1.7	2.4
	7A	0.4	0.9	1.5	0.8	1.5	2.2	0.4	1.5	2.4	1.3	2.3	3.3
	7B	0.6	1.5	2.5	0.4	0.9	1.2	0.8	2.5	4.0	0.9	1.7	2.3
	8	0.7	1.8	2.8	0.5	1.0	1.4	0.8	2.6	4.2	1.1	1.9	2.7
COP of Both Heating and Cooling Systems	**4**	0.1	0.2	0.3	0.7	1.3	1.9	1.7	5.7	9.6	0.3	0.6	0.8
	5	0.3	0.7	1.2	0.7	1.5	2.1	1.7	5.7	9.6	0.4	0.7	1.0
	6	0.2	0.6	0.9	0.8	1.5	2.2	1.7	5.7	9.6	0.4	0.8	1.1
	7A	0.0	0.0	0.1	0.5	1.0	1.5	1.8	6.0	10.1	0.4	0.8	1.1
	7B	-0.3	-0.7	-1.1	0.3	0.6	0.8	2.0	6.7	11.4	0.4	0.8	1.1
	8	-0.1	-0.4	-0.8	0.3	0.6	0.8	2.0	6.7	11.4	0.4	0.8	1.1

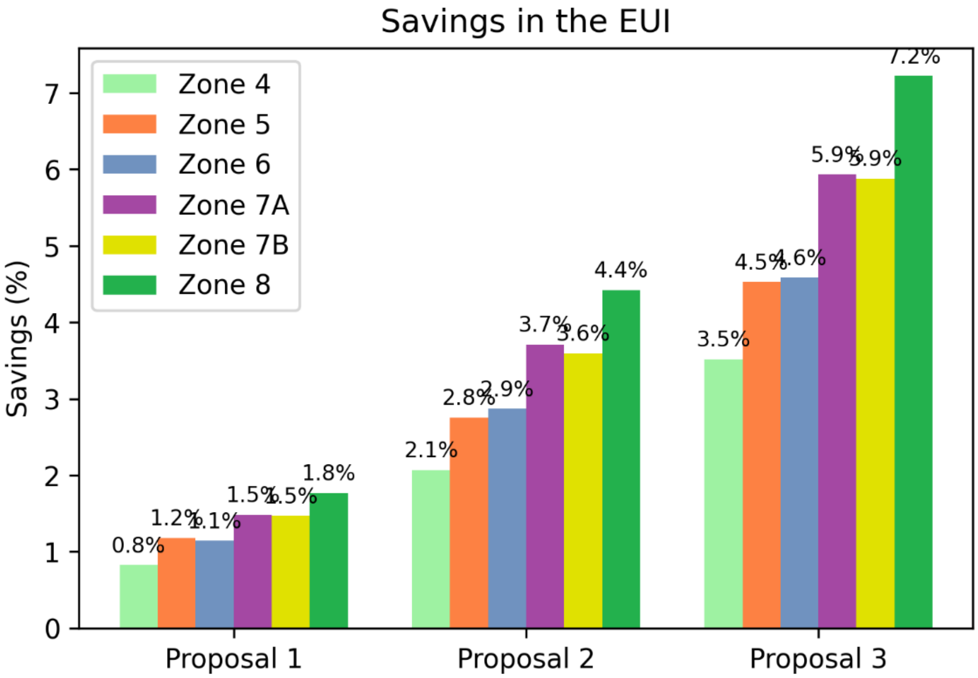


Figure 7.1 - Savings in the EUI from improvements in the thermal transmittance of windows

Improving the thermal transmittance of windows is beneficial in all climate zones, with savings in the EUI ranging from:

a) 0.8% to 1.8% with proposal 1;

b) 2.1% to 4.4% with proposal 2, and

c) 3.5% to 7.2% with proposal 3, depending on the climate zone.

Zone 8 – Yellowknife benefits the most of these improvements, while Zone 4 – Victoria benefits the least. The savings become more substantial as the number of Heating Degree Days (HDDs) increase. This is most likely due to the increasing temperature difference in colder climates between the indoor and outdoor spaces, separated by the fenestration assemblies.

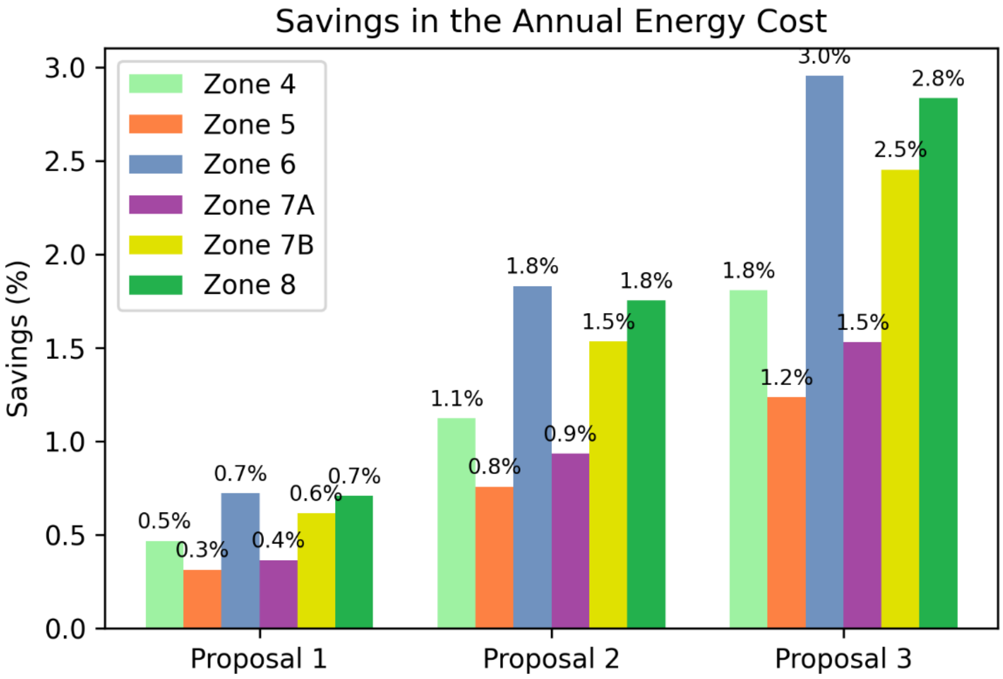


Figure 7.2 - Savings in the Annual Energy Cost from improvements in the thermal transmittance of windows

With regards to savings in the annual energy cost, improving the thermal transmittance of windows is still beneficial for all climate zones. Observed savings range from:

a) 0.3% to 0.7% with proposal 1;
b) 0.8% to 1.8% with proposal 2, and
c) 1.2% to 3.0% with proposal 3, depending on the climate zone.

The savings in the annual energy cost are not only proportional to the number of HDDs but are mainly affected by the energy price in each climatic zone. Because of regional differences in the energy price, Zone 6 – Montréal and Zone 8 – Yellowknife are the climatic zones that observe the most savings in energy cost, while Zone 5 – Toronto and Zone 7A – Edmonton are the ones that observe the least savings.

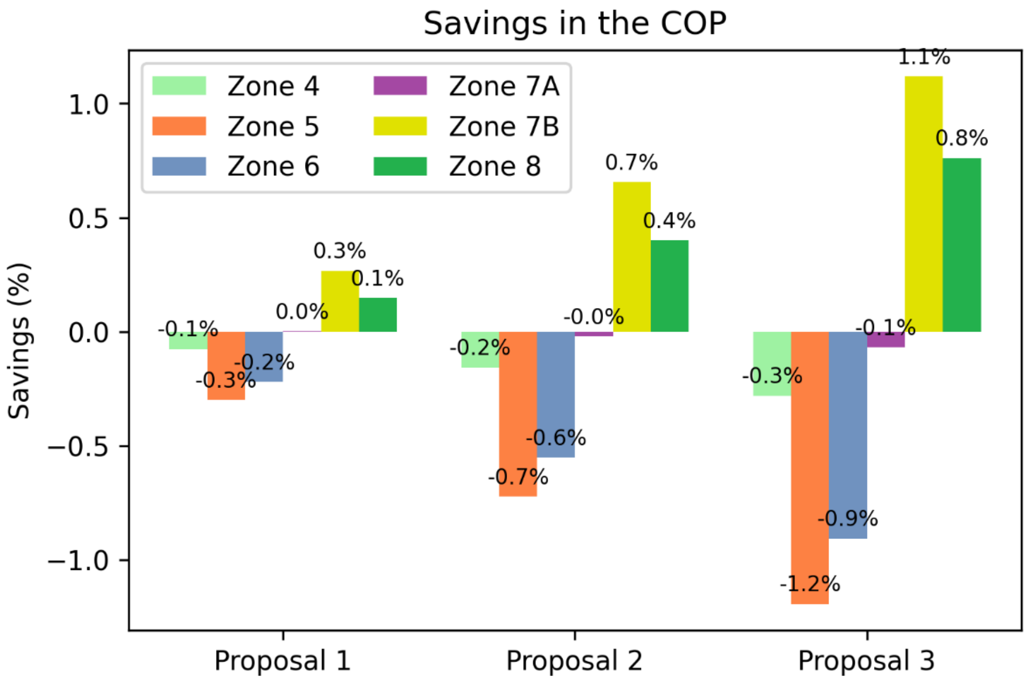


Figure 7.3 - Savings in the annual system COP from improvements in the thermal transmittance of windows

Depending on the climatic zone, improving the thermal transmittance of windows can be either beneficial or detrimental to the simulated annual system COP. This effect is explained by: (a) a change in the building thermal load, impacting in the part-load ratio of HVAC equipment and ultimately their performance, and (b) a change in the proportion of heating loads to cooling loads, with each load being addressed by a system (heating or cooling) of different efficiency, ultimately impacting the annual system COP.

Zone 4 to Zone 7A lose performance in the HVAC system as the thermal transmittance of windows is decreased, while Zone 7B and 8 gain performance. Zone 5 – Toronto and Zone 6 – Montréal are the most negatively affected by these changes, while Zone 7B - Whitehorse and Zone 8 - Yellowknife are the most positively affected.

This effect that is dependant on the climatic zone is likely a balance between the decrease of equipment efficiency and the increase of proportional participation of cooling equipment (more efficient equipment) in the energy end-uses as compared to heating equipment. The decrease of equipment efficiency is due to reduced part loads from lower thermal load in envelope heat transfer through conduction. This leads to an overall decrease in the system COP. The increase of proportional participation of cooling equipment is due to better insulation in perimeter thermal zones, which exchanges considerable heat in very cold climates. Some core zones still require cooling all year long. Given that the design COP of the chiller is 5.547 in the base case scenario, while the boiler efficiency is merely 83%, increasing the proportional participation of space cooling elevates the system COP.

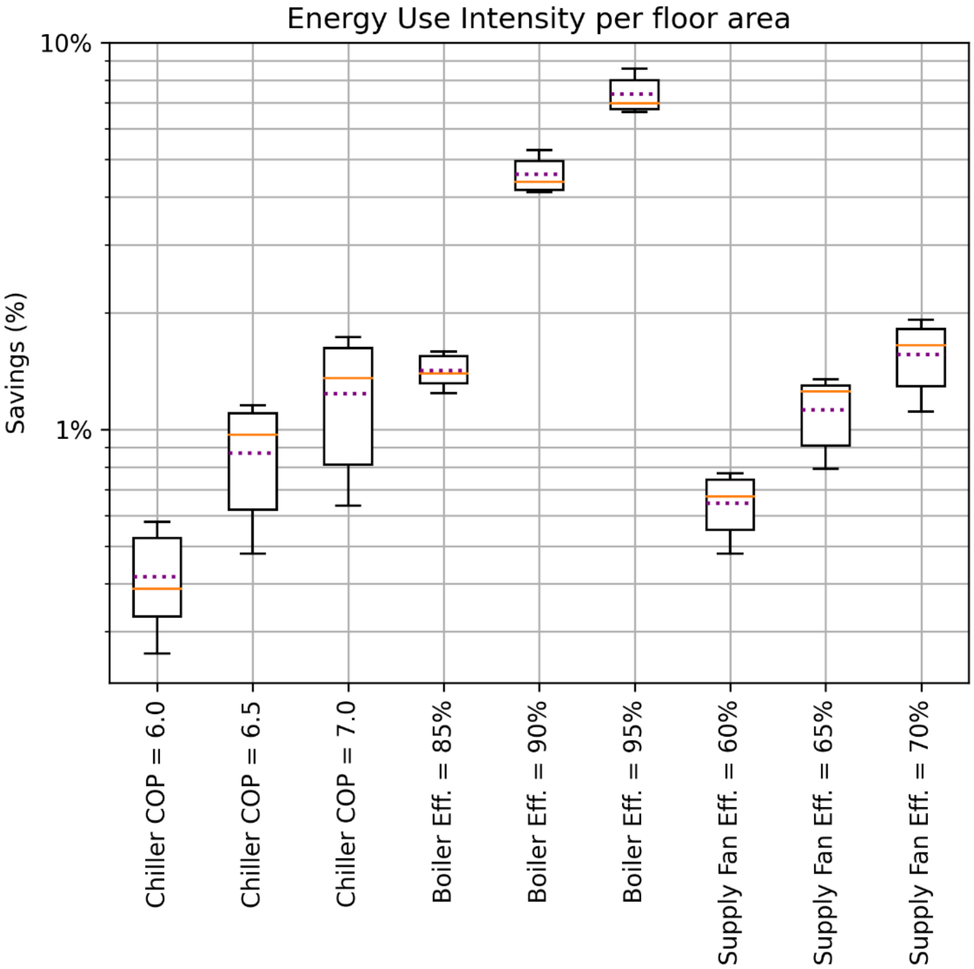


Figure 7.4 - Box plot of the savings in the Energy Use Intensity per floor area versus proposed code updates for all climatic zones (positive coefficients relate a decrease in energy consumption).

Table 7.4 - Details of the Energy Use Intensity boxplot

Variable (%)	Chiller COP 6.0	Chiller COP 6.5	Chiller COP 7.0	Boiler Eff. 85%	Boiler Eff. 90%	Boiler Eff. 95%	Sup Fan Eff 60%	Sup Fan Eff 65%	Sup Fan Eff 70%
Minimum	0.3	0.5	0.6	1.2	4.1	6.6	0.5	0.8	1.1
Lower quartile	0.3	0.6	0.8	1.3	4.2	6.7	0.6	0.9	1.3
Median	0.4	1.0	1.4	1.4	4.4	7.0	0.7	1.3	1.7
Mean	0.4	0.9	1.2	1.4	4.6	7.4	0.6	1.1	1.6
Upper quartile	0.5	1.1	1.6	1.5	4.9	8.0	0.7	1.3	1.8
Maximum	0.6	1.2	1.7	1.6	5.3	8.6	0.8	1.3	1.9
Percent relative range	**75.4**	**77.8**	**88.5**	**24.5**	**25.4**	**26.4**	**45.4**	**49.4**	**51.8**

Comparing all 4 groups of proposed changes, the group that presents the highest mean energy savings is the boiler efficiency improvements group with mean savings ranging from 1.4% to 7.4% depending on how substantial the improvement is. The chiller COP and the supply fan efficiency present a lower impact that is similar in magnitude, ranging from 0.4% to 1.2% and 0.6% to 1.6%, respectively depending on how substantial the improvement is.

Most variables are considerably impacted by the weather conditions, with a percent relative range of approximately 40% to 90%. The chiller COP is the input variable that is most affected by the weather conditions, with a percent relative range of approximately 70% to 90%.

The boiler efficiency is the input variable that is least affected by weather conditions, with a percent relative range of approximately 20% to 30%. This is a positive factor if suggestions to boiler improvements are implemented. Due to their performance not being severely dependent on weather conditions, the improvements in boiler efficiency would provide similar benefits under a range of climates.

With regards to improvements in the chiller COP, Zone 4 – Victoria, Zone 5 – Toronto, Zone 6 – Montréal and Zone 7A - Edmonton enjoy the most benefits while Zone 7B – Whitehorse and Zone 8 – Yellowknife enjoy lesser benefits. The same effects are observed for improvements in the supply fan efficiency.

With regards to improvements in the boiler efficiency, Zone 7B – Whitehorse and Zone 8 – Yellowknife enjoy the most benefits, while the other zones enjoy lesser benefits.

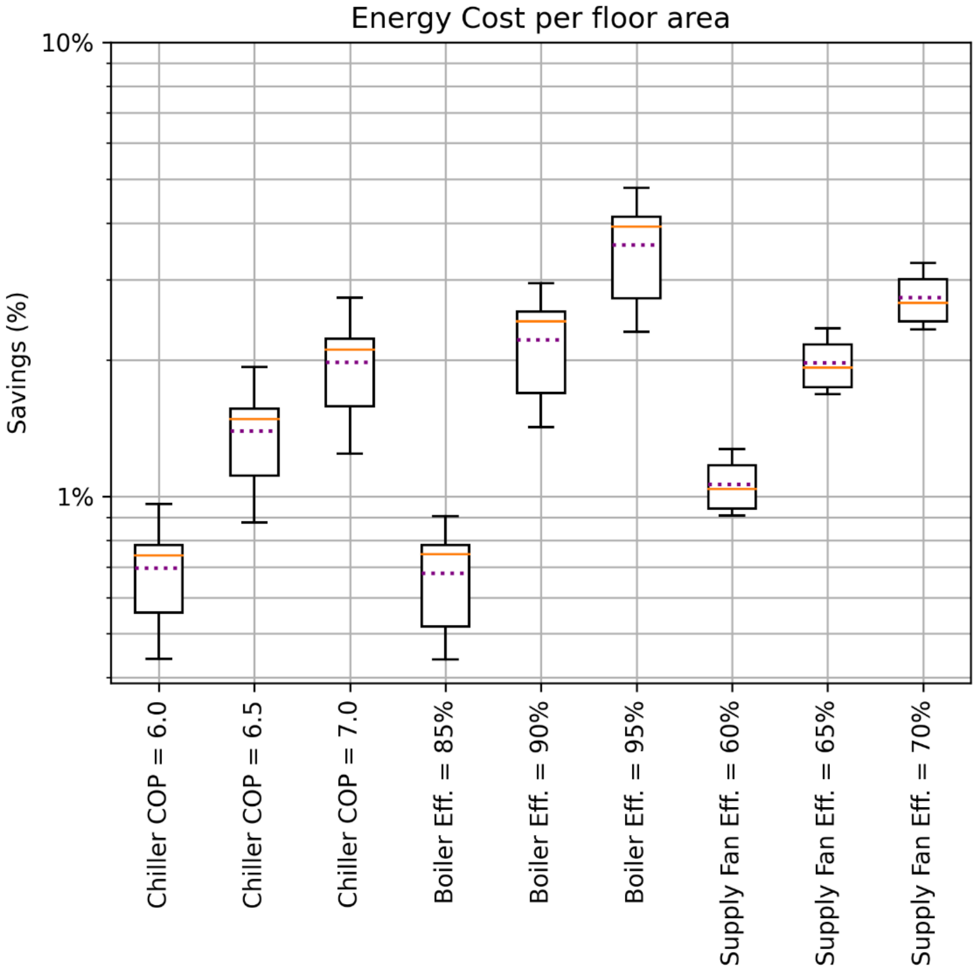


Figure 7.5 - Box plot of the savings in the Annual Energy Cost per floor area versus proposed code updates for all climatic zones (positive coefficients relate a decrease in energy cost).

Table 7.5 - Details of the Annual Energy Cost boxplot

Variable (%)	**Chiller COP 6.0**	**Chiller COP 6.5**	**Chiller COP 7.0**	**Boiler Eff. 85%**	**Boiler Eff. 90%**	**Boiler Eff. 95%**	**Sup Fan Eff 60%**	**Sup Fan Eff 65%**	**Sup Fan Eff 70%**
Minimum	0.4	0.9	1.2	0.4	1.4	2.3	0.9	1.7	2.3
Lower quartile	0.6	1.1	1.6	0.5	1.7	2.7	0.9	1.7	2.4
Median	0.7	1.5	2.1	0.7	2.4	3.9	1.0	1.9	2.7
Mean	0.7	1.4	2.0	0.7	2.2	3.6	1.1	2.0	2.7
Upper quartile	0.8	1.6	2.2	0.8	2.6	4.1	1.2	2.2	3.0
Maximum	1.0	1.9	2.7	0.9	3.0	4.8	1.3	2.3	3.3
Percent relative range	**75.3**	**75.5**	**75.6**	**68.7**	**69.1**	**69.1**	**34.2**	**34.0**	**34.3**

In terms of magnitude and ranking of most impactful changes, the results obtained for the annual cost savings are similar to the results obtained for the EUI savings. There are differences in the individual values that arise from variations of the energy price from climatic zone to climatic zone.

Comparing all groups of proposed changes, the group that presents the highest mean annual cost savings is the boiler efficiency improvements group with mean savings ranging from 0.7% to 3.6% depending on how substantial the improvement is. The chiller COP and the supply fan efficiency present a lower impact that is similar in magnitude, ranging from 0.7% to 2.0% and 1.1% to 2.7%, respectively depending on how substantial the improvement is.

Most variables are considerably impacted by the weather conditions, with a percent relative range of approximately 70% to 75%. The boiler efficiency is less affected by weather conditions, with a percent relative range of approximately 45%. The supply fan efficiency is the input variable that is least affected by weather conditions, with a percent relative range of approximately 34%.

With regards to the chiller COP, Zone 5 – Toronto enjoys the most benefits, Zone 4 – Victoria, Zone 6 – Montréal and Zone 7A – Edmonton enjoy less benefits, while Zone 7B – Whitehorse and Zone 8 – Yellowknife enjoy the least benefits.

With regards to improvements in the boiler efficiency, Zone 6 – Montréal enjoys the most benefits, Zone 4 – Victoria, Zone 7B – Whitehorse and Zone 8 – Yellowknife enjoy less benefits, while Zone 5 – Toronto and Zone 7A – Edmonton enjoy the least benefits.

With regards to improvements in the supply fan efficiency, Zone 5 – Toronto and Zone 7A – Edmonton enjoy the most benefits, while the other zones enjoy lesser benefits.

Compared to the results obtained for the EUI, electricity consuming equipment will have their contributions enlarged due to high cost of electric energy. Natural gas consuming equipment will have their contributions diminished due to the low cost of natural gas.

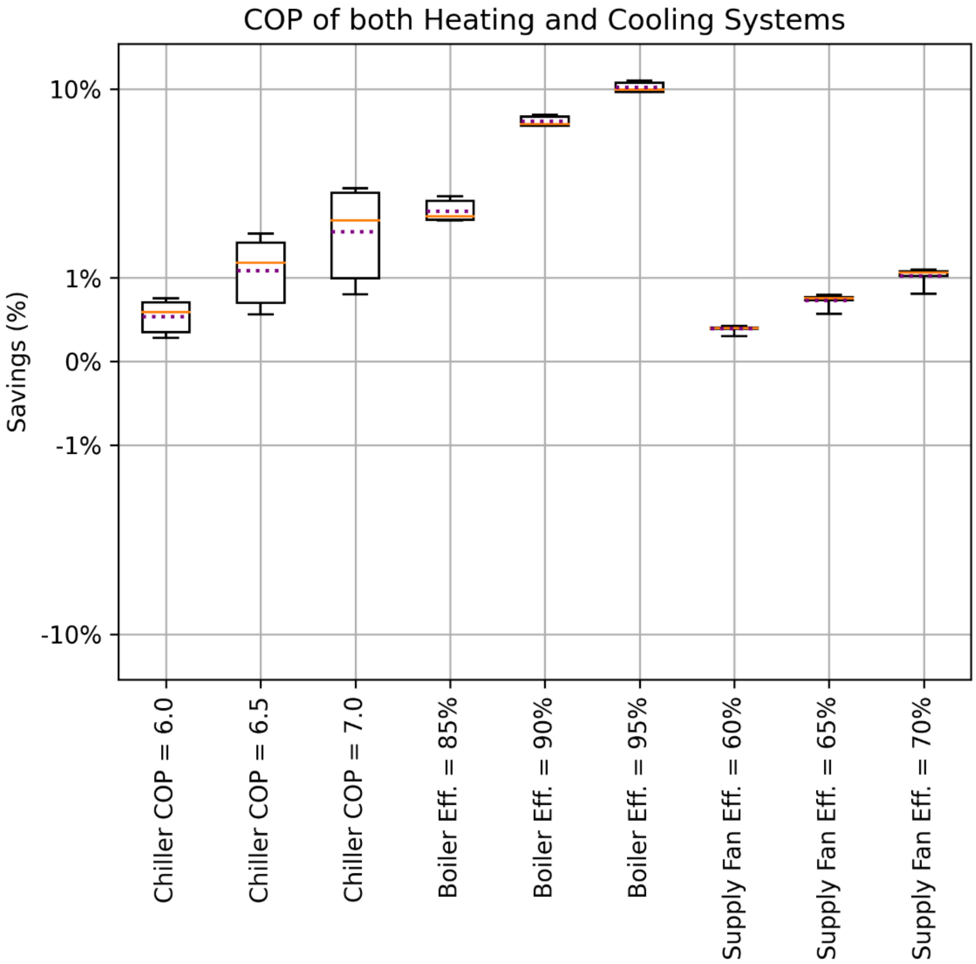


Figure 7.6 - Box plot of the savings in the COP of both Heating and Cooling Systems versus proposed code updates for all climatic zones (positive coefficients relate a decrease in COP).

Table 7.6 - Details of the COP of both Heating and Cooling Systems boxplot

Variable (%)	**Chiller COP 6.0**	**Chiller COP 6.5**	**Chiller COP 7.0**	**Boiler Eff. 85%**	**Boiler Eff. 90%**	**Boiler Eff. 95%**	**Sup Fan Eff 60%**	**Sup Fan Eff 65%**	**Sup Fan Eff 70%**
Minimum	0.3	0.6	0.8	1.7	5.7	9.6	0.3	0.6	0.8
Lower quartile	0.3	0.7	1.0	1.7	5.7	9.6	0.4	0.7	1.0
Median	0.6	1.2	1.7	1.7	5.9	9.9	0.4	0.8	1.1
Mean	0.5	1.1	1.5	1.8	6.1	10.3	0.4	0.7	1.0
Upper quartile	0.7	1.4	2.0	1.9	6.6	11.1	0.4	0.8	1.1
Maximum	0.8	1.5	2.2	2.0	6.7	11.4	0.4	0.8	1.1
Percent relative range	**88.2**	**88.6**	**89.1**	**16.2**	**17.1**	**17.8**	**32.0**	**30.7**	**28.2**

Comparing all 4 groups of proposed changes, the group that presents the highest mean savings in the system COP is the boiler efficiency improvements group with mean savings ranging from 1.8% to 10.1% depending on how substantial the improvement is. The Chiller COP and the supply fan efficiency present a lower impact that is similar in magnitude, ranging from 0.6% to 1.6% and 0.4% to 1.1%, respectively depending on how substantial the improvement is. Improvements to the thermal transmittance of windows can have a positive or negative impact depending on the climate zone. On mean, they present COP savings of 0.0% to 0.2%.

Most variables are considerably impacted by the weather conditions, with varying percent relative ranges. The thermal transmittance of windows is the input variable that is most affected by the weather conditions, with a percent relative range of approximately 1250% to 1350%. The boiler efficiency and the supply fan efficiency are the input variables that are least affected by weather conditions, with a percent relative range of approximately 20% and 30%, respectively.

With regards to improvements in the chiller COP, Zone 4 – Victoria, Zone 5 – Toronto, Zone 6 – Montréal and Zone 7A - Edmonton enjoy the most benefits while Zone 7B – Whitehorse and Zone 8 – Yellowknife enjoy lesser benefits.

With regards to improvements in the boiler efficiency, all climatic zones benefit similarly. The same effect is observed for improvements in the supply fan efficiency.

Improvements in all the suggested input variables bring improvements to the system COP.

A method was proposed in the previous chapters that allowed for the identification of most impactful code's provisions. A series of changes to the minimum efficiency requirements of the identified code's provisions were proposed. These changes were based on readily available technology taken from energy efficiency standards and from recommendations given by institutions that grade energy efficient equipment. Changes to envelope requirements were proposed specifically for each climate zone, while changes to the HVAC equipment were proposed non-specifically for all climate zones.

A simulation was performed to evaluate the impact of the proposals on the EUI, the annual energy cost and the system COP. The simulations were performed in a timely manner, with approximately 30 seconds per eQUEST simulation, plus an extra minute for post processing using MATLAB and Python. Box plots were prepared from the results, illustrating the effect of the climatic zones on the savings.

The results indicate that improvements to the thermal transmittance of windows, chiller COP, boiler efficiency and supply fan efficiency would be effective solutions to reduce the EUI and the annual energy cost of the NECB-2017 baseline building.

Mean savings of ranging from 0.4% to 7.4% can be obtained on the EUI and savings ranging from 0.7% to 3.6% can be obtained on the annual energy cost if improvements on a single category are implemented. If improvements on multiple categories are implemented, it is likely that compound savings of higher magnitudes can be obtained.

Depending on the climatic zone, some savings are higher than others. The savings in the annual energy cost are not only proportional to the number of HDDs but are mainly affected by the energy price in each climatic zone. For improvements in the envelope thermal transmittance, there can be a negative impact to the system COP, even if savings in the EUI and annual energy cost are observed.

The authors recommend that a selection of the proposed measures is implemented in the next code update of NECB. These changes would prove to be among the most effective changes that can be implemented to the different provision categories, using as a metric the EUI and the annual energy cost.

These proposed changes focus mainly on the reducing annual energy use and cost. In this case, advantages in terms of annual energy performance are assumed to be the main criterion for achieving better energy efficient buildings. In future works, the use of embodied energy and life cycle energy and cost relating to these proposed changes could lead to a different set of measures being proposed, with a more holistic view on the impact of these proposals.

CHAPTER 8 : Conclusions and Future Work

A literature review focusing on processes used in updating building energy codes was performed. Three main tools were identified: Building Energy Modelling and Building Performance Simulation (BEM/BPS), Key Performance Indicators (KPI), and Sensitivity Analysis. From the literature review, it was identified that policymakers could benefit from a method that is simple to apply, requires average computational resources and provides an intuitive quantifiable metric to help determine which are the most relevant factors in a code performance.

The proposed method, developed to address the shortcomings identified in the literature review, 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. The method employs three main steps: (i) modelling and simulation; (ii) selection and calculation of KPIs, and (iii) sensitivity analysis and conclusions. For the modelling and simulation step, a case study (reference) building energy model is created using the eQUEST program, developed to be compliant to NECB-2017. The remaining steps are done with the aid of a MATLAB script that collects KPIs from eQUEST's output files and with the aid of a Python script that prepares the boxplots for result visualization.

The sensitivity analysis was generalized to cover all climate zones, by modelling a stock of building models, each model compliant to the energy efficiency requirements of each climate zone. The models also resort to energy prices specific for each climate zone. From this sensitivity analysis, a ranking based on the magnitude of the impact of changes to each input variable was developed. A series of proposals of improvements with climate specific changes was made, incorporating state of the art energy performance for envelope and equipment, taken from standards and certified manufacturers.

Regarding the application of the method in the current 2017 version of NECB, the results indicate that improvements to the thermal transmittance of windows, chiller COP, boiler efficiency and supply fan efficiency would be effective solutions to reduce the EUI and the annual energy cost of the baseline building. Mean savings of up to 7.4% on the EUI and up to 3.6% on the annual energy cost can be obtained by implementing changes in the energy efficiency requirement of a single variable, depending on the measure and the climate zone in which it is implemented. If multiple measures are implemented, the combined effects of both improvements are likely to compound to provide higher savings.

Further updates of NECB-2017 prescriptive requirements should consider prioritizing modifications of design input values based on their impact on these KPIs. Another possible use of the proposed method lies in the allocation of R&D resources in the updating requirements to the building envelope and HVAC equipment based on their impact to selected KPIs. 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 other building types representing a bigger portion of the Canadian building stock. Although the increase of annual building energy efficiency is an important goal, code updates should consider the life cycle cost, energy use and GHG emissions. These additional KPIs would provide policymakers with a holistic view on the impact of code's provisions, allowing the interested parties to make decisions that would improve the energy efficiency and sustainability of Canadian buildings over their lifetime, as opposed to a single year basis. Another focus of future research would be to determine the cost associated with implementing each of the proposed changes. This would provide a measure of how costly achieving additional energy savings are and would improve the financial feasibility of proposing these code updates, considering the investors, and building owners perspectives.

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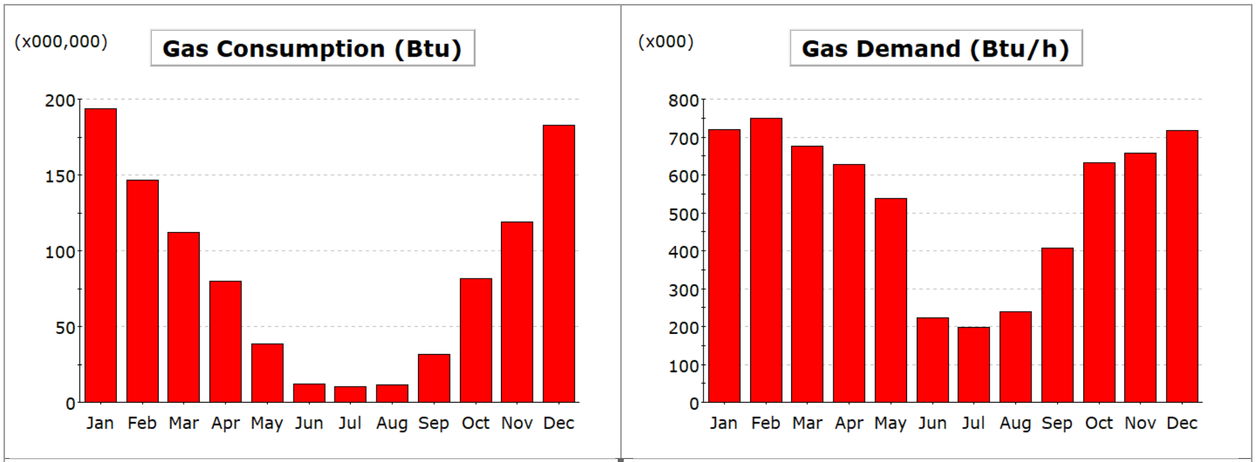
APPENDIX A : Results of the Comparison of Different Heating System Embodiments

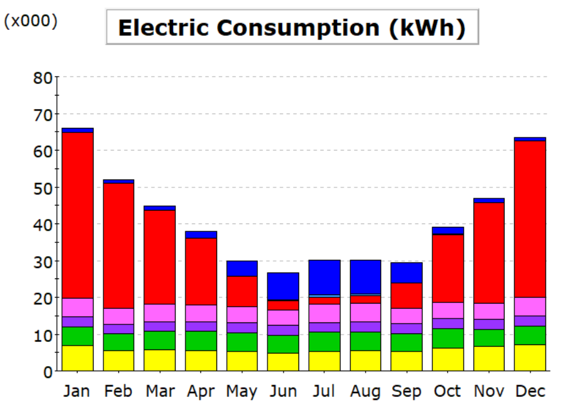
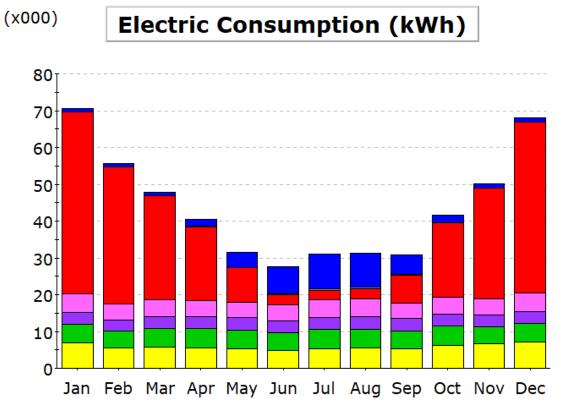
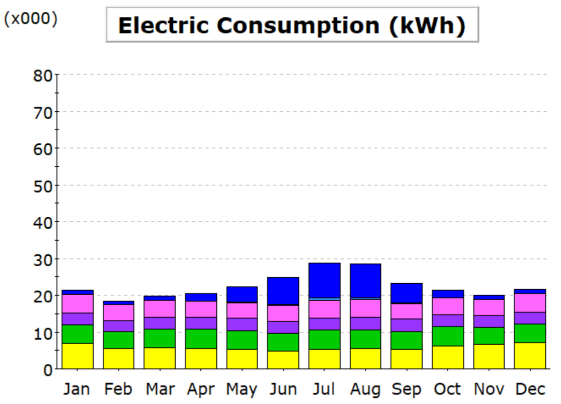
Table A.1 - Monthly Gas consumption and Peak Gas Demand for Embodiment 3



Monthly Gas Consumption MWh (MBtu)						
	Jan	Feb	Mar	Apr	May	Jun
Space Heat	56.8 (194.1)	43.0 (146.8)	32.8 (112.0)	23.4 (80.0)	11.3 (38.5)	3.5 (11.8)
	Jul	Aug	Sep	Oct	Nov	Dec
Space Heat	3.0 (10.3)	3.4 (11.5)	9.3 (31.8)	23.9 (81.5)	34.9 (119.1)	53.5 (182.7)
Total			**298.7 (1,020.3)**			

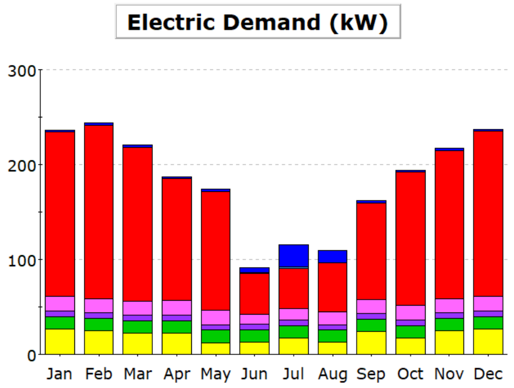
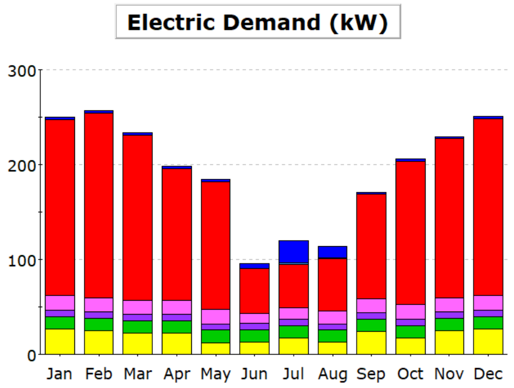
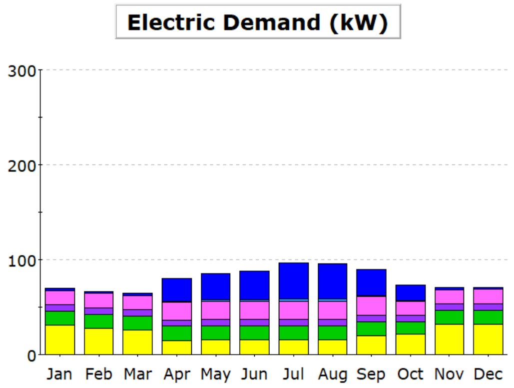
Peak Monthly Gas Demand kW (kBtu/h)						
	Jan	Feb	Mar	Apr	May	Jun
Space Heat	210.7 (719.0)	219.5 (749.0)	198.2 (676.3)	184.0 (627.9)	157.7 (538.2)	65.1 (222.2)
	Jul	Aug	Sep	Oct	Nov	Dec
Space Heat	57.9 (197.5)	70.1 (239.2)	119.4 (407.3)	185.5 (633.1)	193.0 (658.5)	210.5 (718.3)
Max			**219.5 (749.0)**			

Table A.2 - Comparison of Monthly Energy Consumption by Enduse for the three embodiments

	Space Cool	Heat Reject	Space Heat	Vent Fans	Pump Aux	Misc Equip	Area Light	Total	Graph
Embodiment 1 - All Electric Resistance									
Jan	1.1	—	45.2	5.0	2.7	5.1	6.8	65.9	
Feb	1.0	—	34.0	4.3	2.5	4.6	5.6	51.9	
Mar	1.1	—	25.7	4.6	2.7	5.1	5.6	44.8	
Apr	2.0	0.0	18.2	4.5	2.7	5.1	5.6	38.0	
May	4.1	0.1	8.2	4.2	2.7	5.2	5.3	29.8	
Jun	7.3	0.3	2.4	4.3	2.6	4.9	4.8	26.6	
Jul	9.5	0.5	2.0	4.9	2.7	5.2	5.3	30.1	
Aug	9.1	0.5	2.2	5.0	2.8	5.2	5.5	30.1	
Sep	5.3	0.2	6.7	4.2	2.6	4.9	5.4	29.3	
Oct	2.0	0.0	18.4	4.5	2.7	5.2	6.3	39.2	
Nov	1.1	—	27.4	4.4	2.6	4.8	6.6	46.9	
Dec	1.1	—	42.6	5.0	2.7	5.1	7.1	63.6	
Total	44.5	1.7	232.9	55.0	32.2	60.2	69.8	496.2	
Embodiment 2 - Hydronic w/ Electric Boiler									
Jan	1.1	—	49.3	5.0	3.3	5.1	6.8	70.6	
Feb	1.0	—	37.1	4.3	3.0	4.6	5.6	55.6	
Mar	1.1	—	28.1	4.6	3.3	5.1	5.6	47.9	
Apr	2.0	0.0	20.1	4.5	3.3	5.1	5.6	40.5	
May	4.1	0.1	9.3	4.2	3.3	5.2	5.3	31.5	
Jun	7.3	0.3	2.8	4.3	3.2	4.9	4.8	27.6	
Jul	9.5	0.5	2.4	4.9	3.3	5.2	5.3	31.1	
Aug	9.1	0.5	2.7	5.0	3.4	5.2	5.5	31.2	
Sep	5.3	0.2	7.6	4.2	3.2	4.9	5.4	30.8	
Oct	2.0	0.0	20.3	4.5	3.3	5.2	6.3	41.6	
Nov	1.1	—	30.1	4.4	3.2	4.8	6.6	50.1	
Dec	1.1	—	46.5	5.0	3.3	5.1	7.1	68.1	
Total	44.5	1.7	256.2	55.0	39.3	60.2	69.8	526.6	
Embodiment 3 - Hydronic w/ Gas-fired Boiler									
Jan	1.1	—	—	5.0	3.3	5.1	6.8	21.3	
Feb	1.0	—	—	4.3	3.0	4.6	5.6	18.5	
Mar	1.1	—	—	4.6	3.3	5.1	5.6	19.7	
Apr	2.0	0.0	—	4.5	3.3	5.1	5.6	20.4	
May	4.1	0.1	—	4.2	3.3	5.2	5.3	22.2	
Jun	7.3	0.3	—	4.3	3.2	4.9	4.8	24.9	
Jul	9.5	0.5	—	4.9	3.3	5.2	5.3	28.7	
Aug	9.1	0.5	—	5.0	3.4	5.2	5.5	28.5	
Sep	5.3	0.2	—	4.2	3.2	4.9	5.4	23.2	
Oct	2.0	0.0	—	4.5	3.3	5.2	6.3	21.3	
Nov	1.1	—	—	4.4	3.2	4.8	6.6	20.0	
Dec	1.1	—	—	5.0	3.3	5.1	7.1	21.6	
Total	44.5	1.7	—	55.0	39.3	60.2	69.8	270.4	

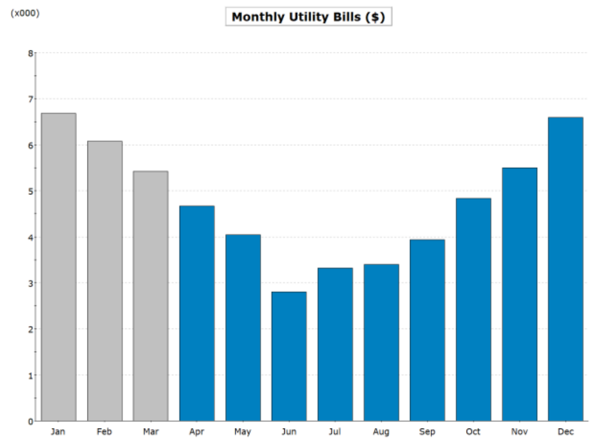
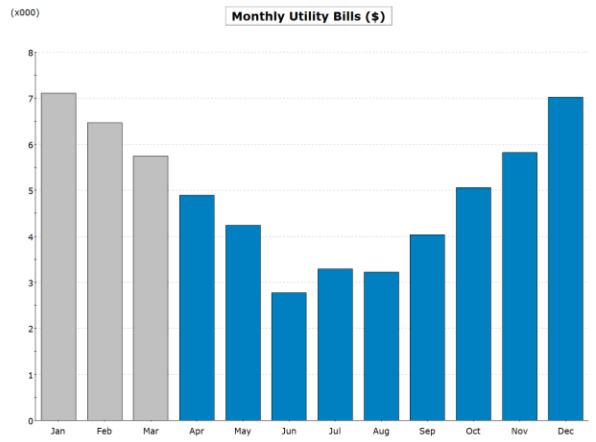
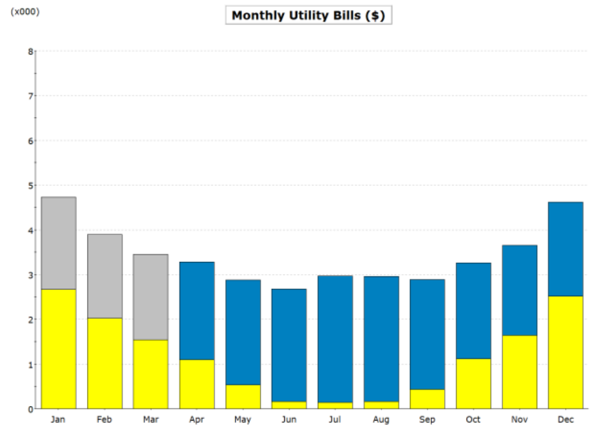
🟨 Area Lighting	⬜ Exterior Usage	🟧 Water Heating	🟦 Refrigeration
🟫 Task Lighting	🟪 Pumps & Aux.	🟥 Ht Pump Supp.	🟦 Heat Rejection
🟩 Misc. Equipment	🟪 Ventilation Fans	🟥 Space Heating	🟦 Space Cooling

Table A.3 - Comparison of Monthly Peak Demand by Enduse for the three embodiments

	Space Cool	Heat Reject	Space Heat	Vent Fans	Pump & Aux	Misc Equip	Area Light	Total	Graph
Embodiment 1 - All Electric Resistance									
Jan	2.2	—	173.3	15.0	6.0	12.9	27.0	236.4	
Feb	2.2	—	183.0	15.0	6.0	12.9	24.8	243.9	
Mar	2.2	—	162.4	15.0	6.0	12.9	22.1	220.7	
Apr	2.2	—	128.6	15.0	6.0	12.9	22.5	187.2	
May	2.2	—	125.1	15.0	6.0	12.9	12.5	173.8	
Jun	5.6	—	43.4	10.6	6.0	12.9	12.8	91.4	
Jul	23.8	1.2	42.4	12.0	6.0	12.9	17.2	115.7	
Aug	12.7	0.3	51.3	13.5	6.0	12.9	12.5	109.3	
Sep	2.2	—	101.6	15.0	6.0	12.9	24.0	161.7	
Oct	2.2	—	140.4	15.0	6.0	12.9	17.6	194.2	
Nov	2.2	—	156.1	15.0	6.0	12.9	24.8	217.1	
Dec	2.2	—	174.2	15.0	6.0	12.9	27.0	237.4	
Max	23.8	1.2	183.0	15.0	6.0	12.9	27.0	243.9	
Embodiment 2 - Hydronic w/ Electric Boiler									
Jan	2.2	—	185.6	15.0	6.8	12.9	27.0	249.6	
Feb	2.2	—	195.1	15.0	6.8	12.9	24.8	256.8	
Mar	2.2	—	174.2	15.0	6.8	12.9	22.1	233.3	
Apr	2.2	—	138.6	15.0	6.8	12.9	22.5	198.1	
May	2.2	—	134.7	15.0	6.8	12.9	12.5	184.2	
Jun	5.6	—	47.0	10.6	6.8	12.9	12.8	95.8	
Jul	23.8	1.2	45.9	12.0	6.8	12.9	17.2	120.0	
Aug	12.7	0.3	55.2	13.5	6.8	12.9	12.5	114.0	
Sep	2.2	—	110.1	15.0	6.8	12.9	24.0	171.1	
Oct	2.2	—	151.2	15.0	6.8	12.9	17.6	205.7	
Nov	2.2	—	167.6	15.0	6.8	12.9	24.8	229.4	
Dec	2.2	—	186.7	15.0	6.8	12.9	27.0	250.6	
Max	23.8	1.2	195.1	15.0	6.8	12.9	27.0	256.8	
Embodiment 3 - Hydronic w/ Gas-fired Boiler									
Jan	2.2	—	—	15.0	6.8	14.8	30.7	69.5	
Feb	2.2	—	—	15.0	6.8	14.8	27.6	66.5	
Mar	2.2	—	—	15.0	6.8	14.8	25.6	64.4	
Apr	23.6	1.1	—	18.6	6.8	14.8	15.0	80.0	
May	28.0	1.6	—	19.2	6.8	14.8	15.1	85.6	
Jun	30.2	2.0	—	19.2	6.8	14.8	15.3	88.2	
Jul	37.3	2.7	—	19.2	6.8	14.8	15.4	96.2	
Aug	36.9	2.5	—	19.2	6.8	14.8	15.2	95.5	
Sep	27.1	1.4	—	19.2	6.8	14.8	20.0	89.4	
Oct	16.1	0.5	—	15.0	6.8	13.0	21.7	73.0	
Nov	2.2	—	—	15.0	6.8	14.8	31.5	70.4	
Dec	2.2	—	—	15.0	6.8	14.8	32.0	70.8	
Max	37.3	2.7	—	19.2	6.8	14.8	32.0	96.2	

🟨 Area Lighting	⬜ Exterior Usage	🟧 Water Heating	🟦 Refrigeration
🟫 Task Lighting	🟪 Pumps & Aux.	🟥 Ht Pump Supp.	🟦 Heat Rejection
🟩 Misc. Equipment	🟪 Ventilation Fans	🟥 Space Heating	🟦 Space Cooling

Table A.4 - Comparison of Monthly Utility Bills for the three embodiments

	2017 HQ Rate M	2018 HQ Rate M	2018 Énergir Business	Total	Graph
Embodiment 1 - All Electric Resistance					
Jan	6,685	—	—	6,685	
Feb	6,076	—	—	6,076	
Mar	5,418	—	—	5,418	
Apr	—	4,666	—	4,666	
May	—	4,048	—	4,048	
Jun	—	2,803	—	2,803	
Jul	—	3,321	—	3,321	
Aug	—	3,403	—	3,403	
Sep	—	3,934	—	3,934	
Oct	—	4,834	—	4,834	
Nov	—	5,499	—	5,499	
Dec	—	6,591	—	6,591	
Total	18,179	39,098	—	57,277	
Embodiment 2 - Hydronic w/ Electric Boiler					
Jan	7,115	—	—	7,115	
Feb	6,468	—	—	6,468	
Mar	5,748	—	—	5,748	
Apr	—	4,896	—	4,896	
May	—	4,243	—	4,243	
Jun	—	2,774	—	2,774	
Jul	—	3,294	—	3,294	
Aug	—	3,220	—	3,220	
Sep	—	4,031	—	4,031	
Oct	—	5,064	—	5,064	
Nov	—	5,823	—	5,823	
Dec	—	7,021	—	7,021	
Total	19,331	40,365	—	59,696	
Embodiment 3 - Hydronic w/ Gas-fired Boiler					
Jan	2,063	—	2,671	4,732	
Feb	1,877	—	2,020	3,897	
Mar	1,913	—	1,541	3,454	
Apr	—	2,178	1,101	3,279	
May	—	2,346	530	2,876	
Jun	—	2,518	163	2,681	
Jul	—	2,824	142	2,966	
Aug	—	2,804	158	2,962	
Sep	—	2,452	437	2,889	
Oct	—	2,139	1,122	3,261	
Nov	—	2,019	1,639	3,658	
Dec	—	2,109	2,515	4,624	
Total	5,853	21,390	14,029	41,282	

🟨 2018 Energir Business
🟦 2018 Hydro-Québec Rate M
⬜ 2017 Hydro-Québec Rate M

APPENDIX B : Batch Directives File Creation Sub-Processes

DEFINE GLOBAL INFORMATION SUB-PROCESS

In this subprocess, the batch version and the batch type properties are defined.

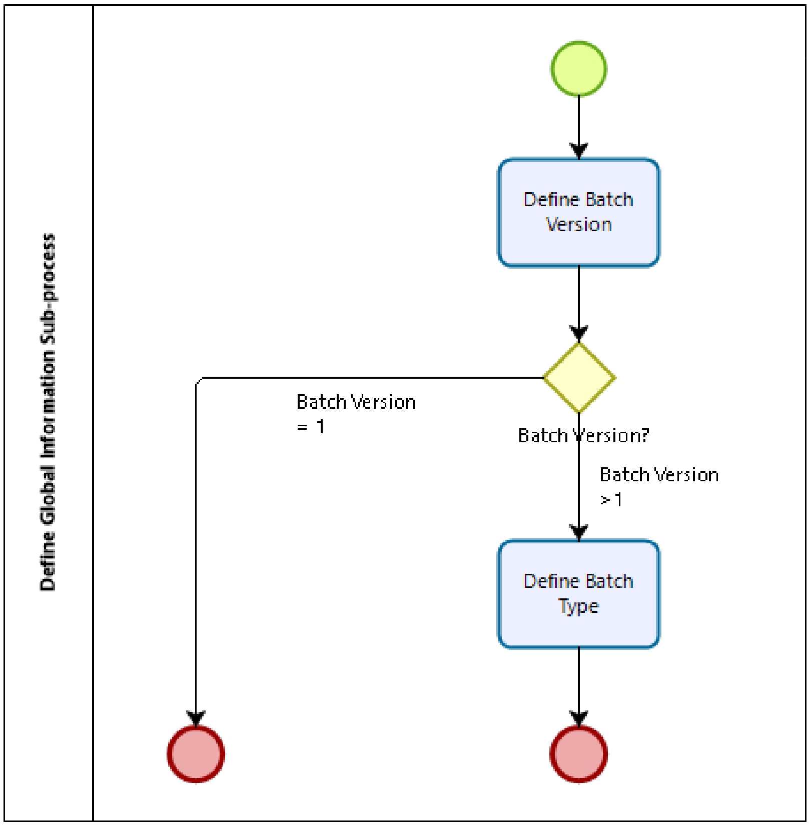


Figure B.1 - Flowchart illustrating the process flow of the Define Global Information Sub-process

Batch Version: Number denoting the version of batch processing mechanism this file written for (for backward compatibility).

Batch Type: Indicates what type of processing is to be performed. Valid options include:

- **Simulation:** Perform one or more DOE-2 simulations, including wizard-generated models & compliance analysis
- **WindowLibrary:** Generate a BDL library of GLASS-TYPE-CODE components from Window4/5 output (added March 2006)
- **EfficiencyMeasures:** Efficiency Measure Runs (Not Yet Implemented)

- **RankedEffMeasures:** Efficiency Measure Runs where each baseline is run with each measure to determine measure ranking.

DEFINE MEASURE ANALYSIS INFO SUB-PROCESS

Four groups of records are specified here, identifying each building type (including configuration and/or HVAC type…), climatic zones, vintages and measures to be analyzed.

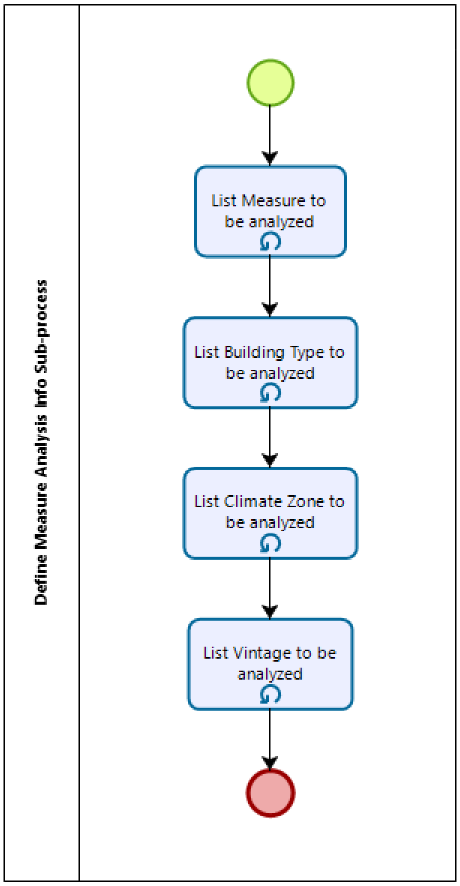


Figure B.2 - Flowchart illustrating the process flow of the Define Measure Analysis Info Sub-process

At least one item of each type must be specified.

The name 'Base' cannot be used to identify any measure, as that is reserved for identifying the baseline configuration.

Measure(s): Baseline run =C139 'Base', no wild cards+C139

Building Type(s): no wild cards

Climatic zone(s): wild card = 'any'

Vintage(s): wild card = 'any'. Valid options include:

- **B:** ASHRAE 90.1-2001
- **C07:** ASHRAE 90.1-2004
- **C11:** Advanced Bldgs Ver 2 kjm 12/9/06 rev "ABG-v2" => "AB-v2"

DEFINE TABLES OF DATA MODIFICATIONS SUB-PROCESS

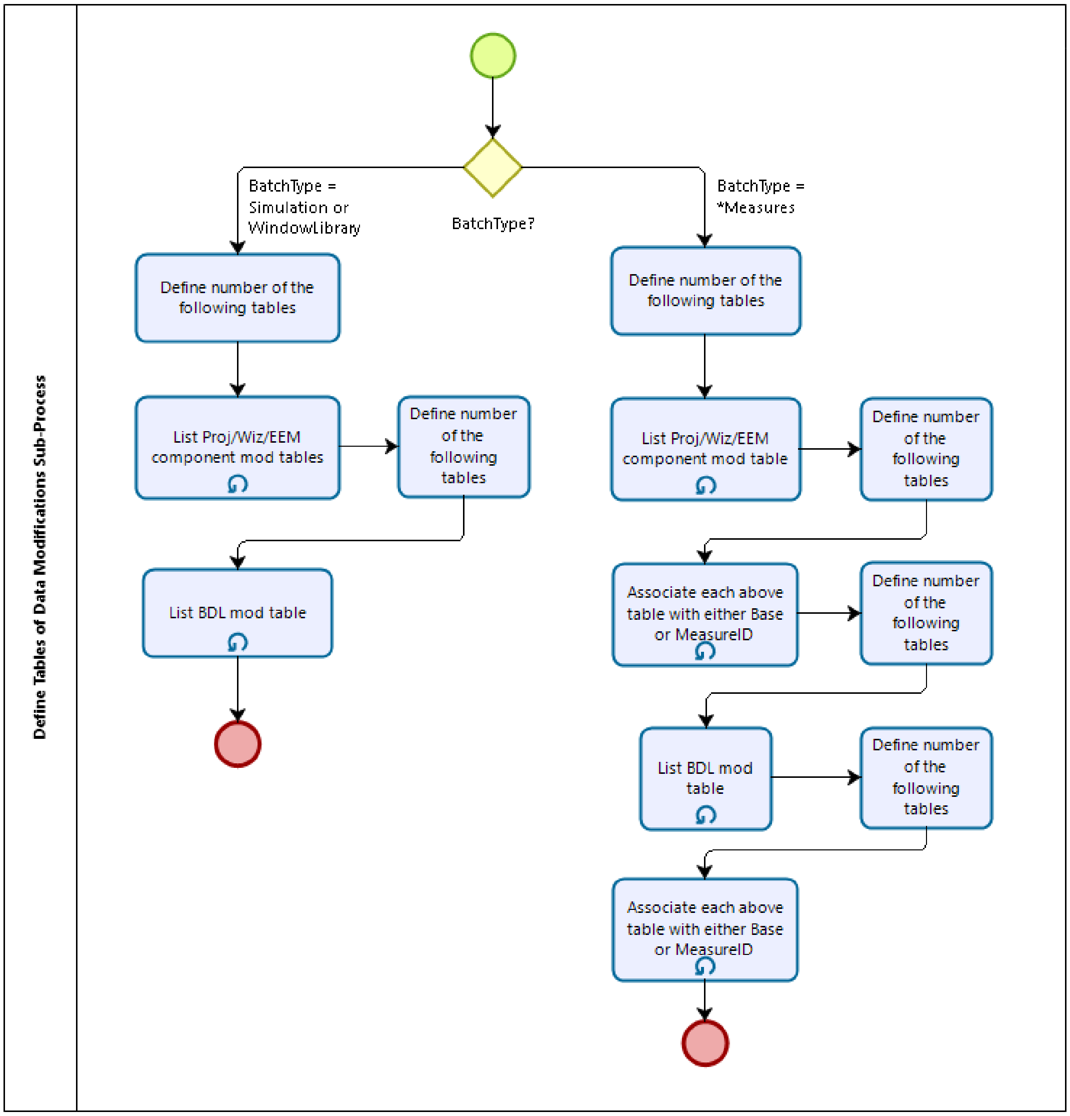


Figure B.3 - Flowchart illustrating the process flow of the Define Tables of Data Modifications Sub-Process

For BatchType = Simulation or WindowLibrary, two records are defined:

- First lists Proj/Wiz/EEM component mod tables, and
- Second lists BDL mod tables

For BatchType = *Measures, four records are defined:

- First lists Proj/Wiz/EEM component mod tables;
- Second associates each above table with either Base or measure ID;
- Third lists BDL mod tables, and
- Fourth associates each BDL mod table with either Base or measure ID

Number of Tables: Number of table names provided in following columns

Table Names: Table names are CSV file names with no path or extension specified (must be located in "batch" directory and have .CSV extension)

DEFINE BATCH PROCESSING ACTIONS SUB-PROCESS

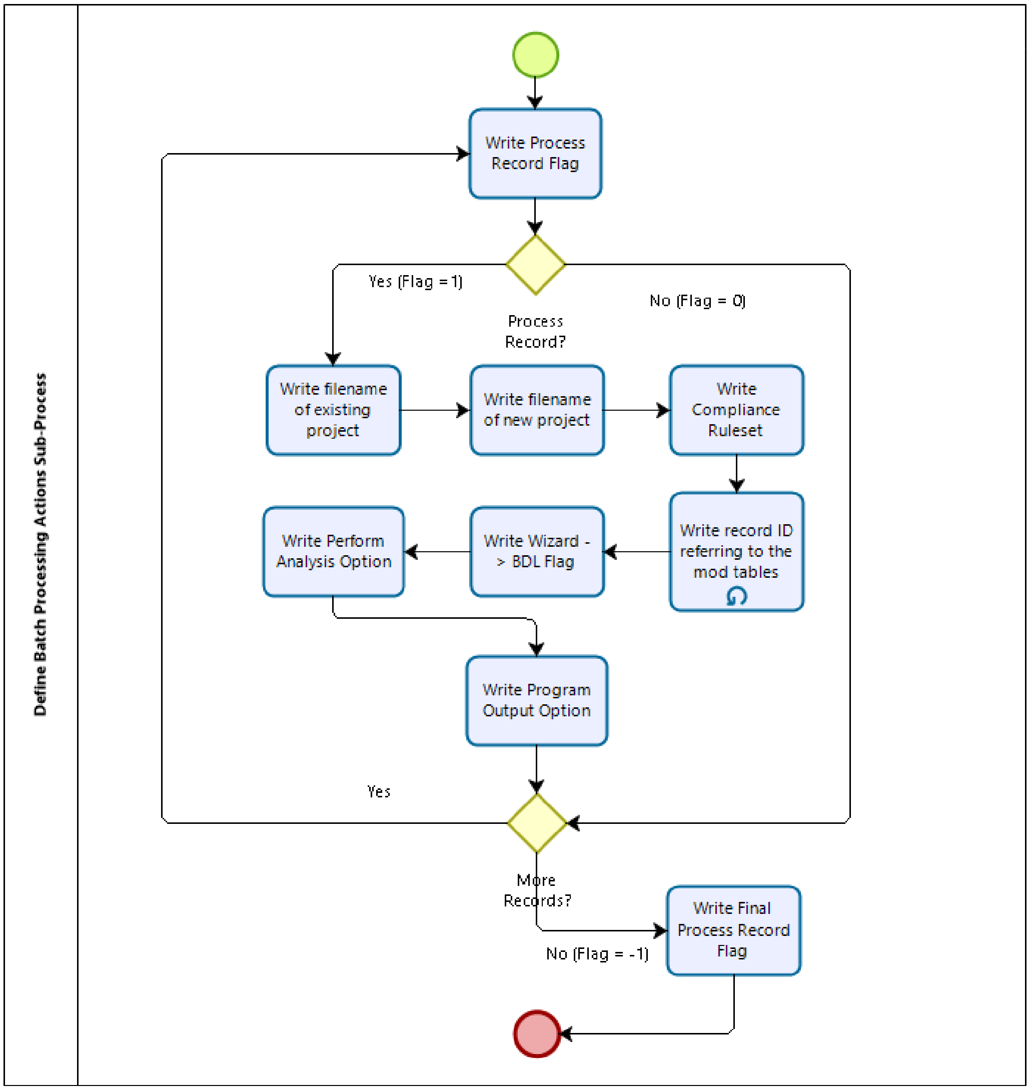


Figure B.4 - Flowchart illustrating the process flow of the Define Batch Processing Actions Sub-Process

Process Record Flag: Indicates what type of processing is to be performed. Valid options include:

- **-1:** End of File
- **0:** Don’t Process Record
- **1:** Process Record

Existing and New Project Filenames: Indicates the syntax of the filename for the projects. Valid options include:

- **new:** Only allowed in existing project or file name column. Don't start by opening project or don't create/save as new project.
- **<project name>:** No occurrences of '\' character. Assumes:
  - File: <project directory>\<project name>\<project name>.PD2
  - Proj: <project name>
- **<partial path>\<project name>:** One or more occurrences of '\' character, not starting with '?:' or '\'. Assumes:
  - File: <project directory>\<partial path>\<project name>.PD2
  - Proj: <project name>
- **<full path>\<project name>:** Starts with '?:' or '\'. Assumes:
  - File: <full path>\<project name>.PD2
  - Proj: <project name>

Compliance Ruleset: Name of compliance ruleset file (must be in '<program>\Compliance' directory and exclude file extension (or 'unchanged')

BDB_* (subsequent tabs) Record ID: Identifies the record numbers contained in the table corresponding to the column label to set BDBase data from. (-1 => Do NOT set data from this table).

Wizard -> BDL Flag: Valid options include:

- **0:** Only translate Wizard data -> BDL inputs if wizard data edited via the previous BDB_* table data
- **1:** Convert the Wizard data -> BDL inputs regardless of whether or not the wizard data was edited

Perform Analysis: Valid options include:

- **no;**
- **Simulate;**
- **SimWizard;**
- **SimEEMs, and**
- **Compliance.**

Program Output: Can be a combination of the following output identifiers:

- **CumCSV;**
- **T24CSV;**
- **RankMsr_Min:** (Only valid for Batch Type = RankedEffMeasures) CumCSV output with addition of columns indicating ranking of each measure performed. Only baseline and the final combined measure run will be output.
- **RankMsr_Mid:** (Only valid for Batch Type = RankedEffMeasures) CumCSV output with addition of columns indicating ranking of each measure performed. Records written for each baseline and each measure to be added to baseline in rank order.
- **RankMsr_Max**: (Only valid for Batch Type = RankedEffMeasures) CumCSV output with addition of columns indicating ranking of each measure performed. Records written for each and every run performed throughout the iterative analysis.

APPENDIX C : Tables of Data Modifications Creation Sub-Processes

DEFINE BATCH MODS COLUMN KEYS SUB-PROCESS

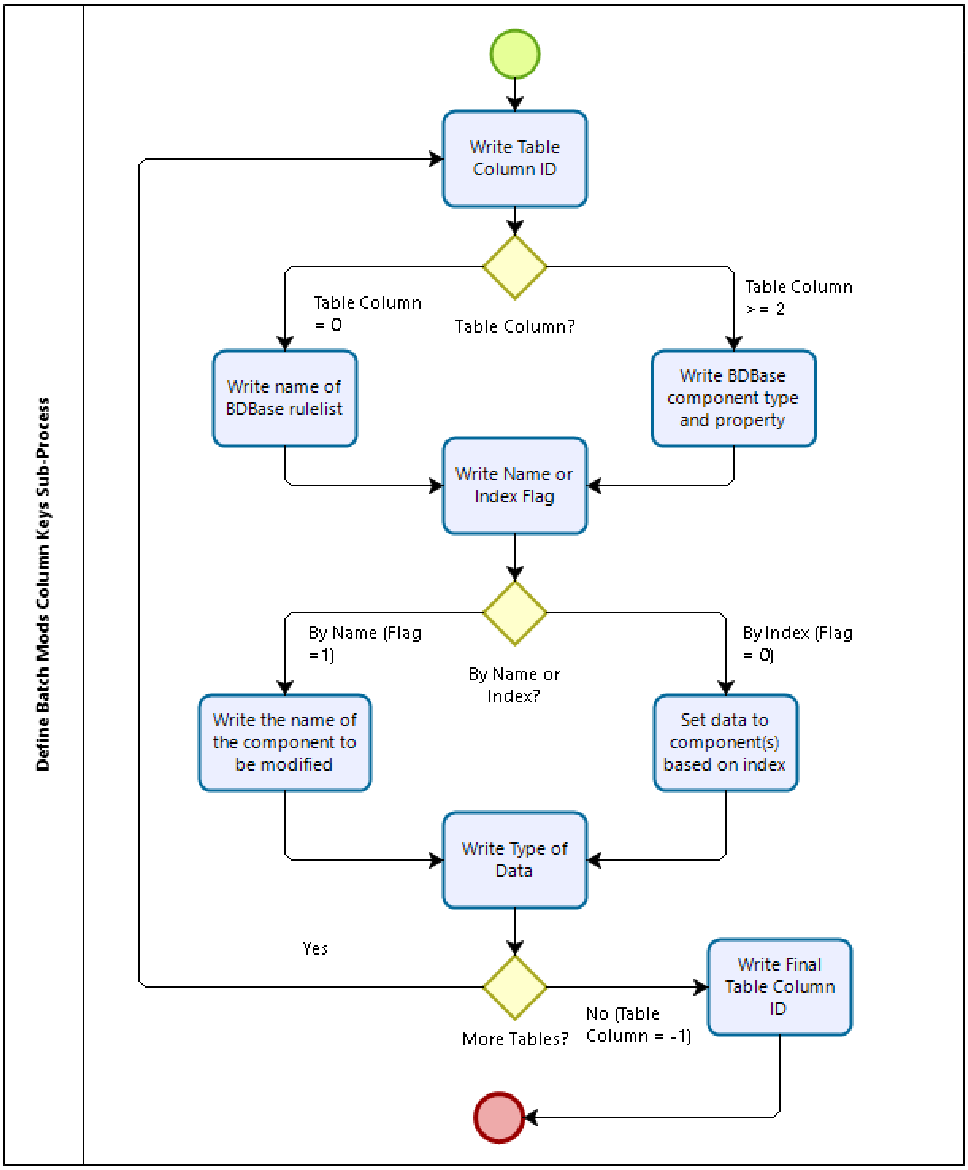


Figure C.1 - Flowchart illustrating the process flow of the Define Batch Mods Column Keys Sub-Process

Table Column: Valid options include:

- **>= 2:** Column of Data Table (below) that this record describes
- **0:** Indicates that a wizard rulelist is to be evaluated

- **-1:** End of Column Key Table

Obs.: (Column numbers MUST be entered in order, 2-N)

Wiz Rulelist: Name of BDBase rulelist to evaluate after setting prior columns of data and before setting following columns.

Comp:Prop([#]): BDBase component type ':' property '[' OPTIONAL 1-based array index ']'

By Name or Index: Valid options include:

- **0:** Set data to components based on the 1-based index of that components existence
- **1:** Component's Name used to identify which component to apply the change to

Component Name: Valid options include:

- **-1**: Set data to ALL components of the type specified
- **>= 1**: Set data to the single component for which the index references

Index: Valid options include:

- **string:** The name of the component to be modified

Type of Data: Valid options include:

- **Integer:** Data in this column are integers (any numeric or symbol BDBase data)
- **Float:** Data in this column are floating point numbers
- **String:** Data in this column are character strings (symbol or string BDBase data)

DEFINE BATCH MODS DATA SUB-PROCESS

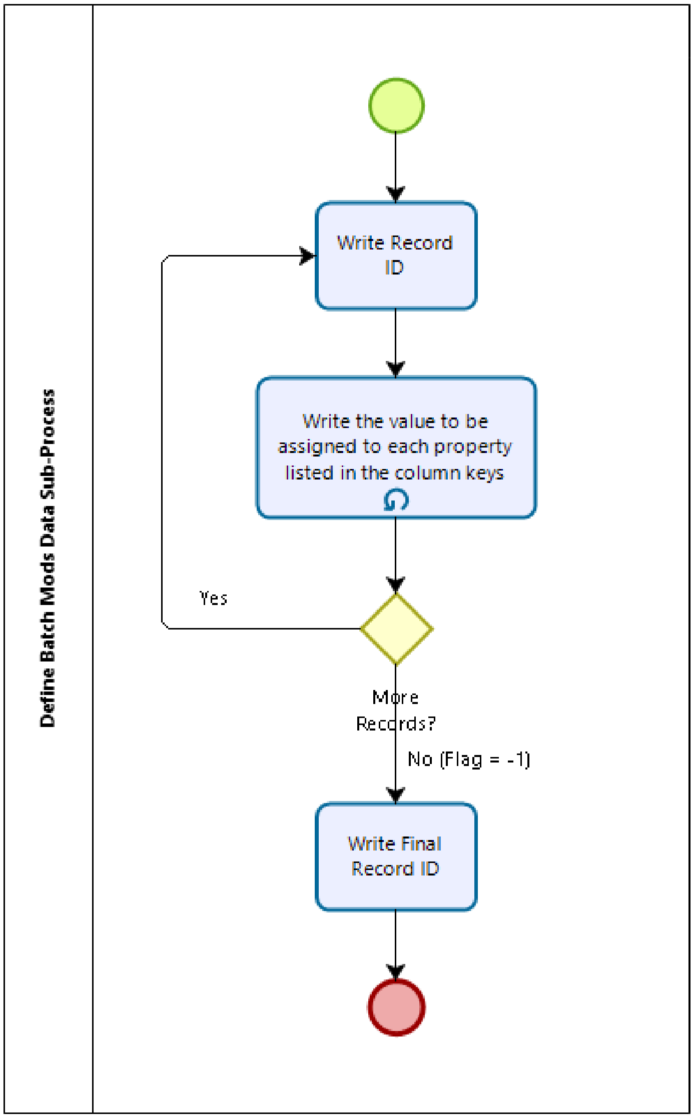


Figure C.2 - Flowchart illustrating the process flow of the Define Batch Mods Data Sub-Process

Record ID: Valid options include:

- **>= 1:** ID of record - maps to column E (for .pd2 files) or column F (for .inp files) of the TestBatchMaster sheet
- **-1:** End of File

Property: Valid options include:

- **Integer:** Data in this column are integers (any numeric or symbol BDL data)
- **Float:** Data in this column are floating point numbers
- **String:** Data in this column are character strings (symbol or string BDL data)
- **Symbol:** Data in this column is a TYPE symbol

APPENDIX D : Data Extraction and Compilation MATLAB Code

```
%%% BEGIN Cleaning previous variables %%%

clc          %clears Command Window
clear        %remove items from workspace
close all    %closes all open figures

%%% END Cleaning previous variables %%%
%%% BEGIN Grabbing all .SIM filenames in the folder %%%

SIMfiles = dir ('*.SIM');

f = waitbar(0,'Fetching .SIM files');
pause(.5)

for i = 1:length(SIMfiles)
    SIMfilenames{i}=SIMfiles(i).name;
    waitbar(i/length(SIMfiles),f,sprintf('Fetching
%2.0f',i/length(SIMfiles)*100));
end

close(f)

%%% END Grabbing all .SIM filenames in the folder %%%
%%% BEGIN Converting all .SIM files to .txt files %%%

f = waitbar(0,'Converting .SIM files to .txt files');
pause(.5)

for i=1:length(SIMfilenames)
    txtfilenames{i} = strrep(SIMfilenames{i},'.SIM','.txt');
    copyfile(SIMfilenames{i},txtfilenames{i},'f');
    waitbar(i/length(SIMfiles),f,sprintf('Converting
%2.0f',i/length(SIMfiles)*100));
end

close(f)

%%% END Converting all .SIM files to .txt files %%%
%%% BEGIN Reading .txt files into tables %%%

f = waitbar(0,'Reading files into tables');
pause(.5)

impopts = detectImportOptions(txtfilenames{1});

for i=1:length(SIMfilenames)
    SIMtable{i} = readtable(txtfilenames{i}, impopts);
    waitbar(i/length(SIMfiles),f,sprintf('Reading
%2.0f',i/length(SIMfiles)*100));
```

```
end

close(f)

%%% END Reading .txt files into tables %%%
%%% BEGIN Removing ATTN report %%%

f = waitbar(0,'Deleting ATTN report');
pause(.5)

for i=1:length(SIMfilenames)
    rowb = find(strcmp(SIMtable{1,i}.Var2, 'ATTN'))-2;
    rowe = find(strcmp(SIMtable{1,i}.Var2, 'SV-A'))-3;
    SIMtable{1,i}([rowb:rowe],:) = [];
    waitbar(i/length(SIMfiles),f,sprintf('Deleting
%2.0f',i/length(SIMfiles)*100));
end

close(f)

%%% END Removing ATTN report %%%
%%% BEGIN Collecting Information %%%

RunName = SIMfilenames';

for i=1:length(SIMfilenames)
   FloorAreaIP(i) = SIMtable{1,i}.Var3(20583);            %FloorArea from
SV-A Report
   MaxOcc(i) = SIMtable{1,i}.Var4(20583);                 %Maximum
Occupants from SV-A Report

   TotalWallAreaIP(i) = SIMtable{1,i}.Var8(14909);        %Gross Wall Area
(Walls + Windows), no roof from LV-D Report
   TotalWindowAreaIP(i) = SIMtable{1,i}.Var6(14909);      %Window Area
from LV-D Report
   TotalRoofAreaIP(i) = SIMtable{1,i}.Var7(14908);        %Roof Area from
LV-D Report

   EnergyUseIP(i) = SIMtable{1,i}.Var4(22706);            %Energy Use from
BEPS Report
   EUIIP(i) = SIMtable{1,i}.Var6(22706);                  %Energy Use
Intensity from BEPS Report
   AboveCooling(i) = SIMtable{1,i}.Var9(22710);           %Hours any zone
above cooling throttling range from BEPS Report
   BelowHeating(i) = SIMtable{1,i}.Var9(22711);           %Hours any zone
below heating throttling range from BEPS Report

   PeakElectricDemand(i) = SIMtable{1,i}.Var15(22421);    %Peak Electric
Demand from PS-E Report
   PeakLightsDemand(i) = SIMtable{1,i}.Var3(22421);       %Peak Electric
Lighting Demand from PS-E Report
   PeakEquipsDemand(i) = SIMtable{1,i}.Var5(22421);       %Peak Electric
Equipment Demand from PS-E Report
```

```
   AnnualCost(i) = SIMtable{1,i}.Var1(23431);               %Annual Energy
Cost from ES-D Report

   PeakSystemCoolLoadIP(i) = SIMtable{1,i}.Var2(20726);     %Peak System
Cooling Load from SS-A Report
   PeakSystemHeatLoadIP(i) = SIMtable{1,i}.Var3(20726);     %Peak System
Heating Load from SS-A Report

   PeakHVACCoolLoadIP(i) = SIMtable{1,i}.Var2(20654);       %Peak HVAC
Cooling Load from SS-D Report
   PeakHVACHeatLoadIP(i) = SIMtable{1,i}.Var3(20654);       %Peak HVAC
Heating Load from SS-D Report

   AnnCircCoolLoadIP(i) = SIMtable{1,i}.Var4(22324);        %Annual HVAC
Cooling Load from PS-D Report
   PeakCircCoolLoadIP(i) = SIMtable{1,i}.Var4(22325);       %Peak HVAC
Cooling Load from PS-D Report
   AnnCircHeatLoadIP(i) = SIMtable{1,i}.Var4(22328);        %Annual HVAC
Heating Load from PS-D Report
   PeakCircHeatLoadIP(i) = SIMtable{1,i}.Var4(22329);       %Peak HVAC
Heating Load from PS-D Report
   AnnCircHeatRejLoadIP(i) = SIMtable{1,i}.Var4(22332);     %Annual HVAC
Heat Rejection Load from PS-D Report
   PeakCircHeatRejLoadIP(i) = SIMtable{1,i}.Var4(22333);    %Peak HVAC Heat
Rejection Load from PS-D Report

   AnnBldgCoolLoadIP(i) = SIMtable{1,i}.Var2(16996);        %Annual Building
Cooling Load from LS-D Report
   AnnBldgHeatLoadIP(i) = SIMtable{1,i}.Var3(16996);        %Annual Building
Heating Load from LS-D Report

   CHWLoopCapIP(i) = SIMtable{1,i}.Var2(22189);             %Chilled Water
Loop Capacity from PV-A Report
   HWLoopCapIP(i) = SIMtable{1,i}.Var1(22191);              %Hot Water Loop
Capacity from PV-A Report
   CWLoopCapIP(i) = SIMtable{1,i}.Var2(22193);              %Condenser Water
Loop Capacity from PV-A Report

   AnnFanConHeat(i) = SIMtable{1,i}.Var2(20702);            %Annual Fan
Electric Energy During Heating from SS-M Report
   AnnFanConCool(i) = SIMtable{1,i}.Var3(20702);            %Annual Fan
Electric Energy During Cooling from SS-M Report
   AnnFanConHeatCool(i) = SIMtable{1,i}.Var4(20702);        %Annual Fan
Electric Energy During Heating-Cooling from SS-M Report
   AnnFanConFloat(i) = SIMtable{1,i}.Var5(20702);           %Annual Fan
Electric Energy During Floating from SS-M Report

   AnnBlr1HeatLoadIP(i) = SIMtable{1,i}.Var2(22288);        %Annual Boiler
Heating Load from PS-C Report
   AnnBlr1FuelUseIP(i) = SIMtable{1,i}.Var4(22288);         %Annual Boiler
Fuel Use from PS-C Report
   AnnBlr2HeatLoadIP(i) = SIMtable{1,i}.Var2(22292);        %Annual Boiler
Heating Load from PS-C Report
   AnnBlr2FuelUseIP(i) = SIMtable{1,i}.Var4(22292);         %Annual Boiler
Fuel Use from PS-C Report
```

```
   AnnChlCoolLoadIP(i) = SIMtable{1,i}.Var2(22296);        %Annual Chiller
Cooling Load from PS-C Report
   AnnChlElecUse(i) = SIMtable{1,i}.Var4(22296);           %Annual Chiller
Electricity Use from PS-C Report

   AnnCTHeatRejLoadIP(i) = SIMtable{1,i}.Var2(22300);      %Annual Cooling
Tower Heat Rejection Load from PS-C Report
   AnnCTElecUse(i) = SIMtable{1,i}.Var3(22300);            %Annual Cooling
Tower Electricity Use from PS-C Report

   AnnCHWPumpElecUse(i) = SIMtable{1,i}.Var2(22304);       %Annual CHW Pump
Electricity Use from PS-C Report
   AnnHWPumpElecUse(i) = SIMtable{1,i}.Var2(22308);        %Annual HW Pump
Electricity Use from PS-C Report
   AnnCWPumpElecUse(i) = SIMtable{1,i}.Var2(22312);        %Annual CW Pump
Electricity Use from PS-C Report

   DesignCHWPumpFloIP(i) = SIMtable{1,i}.Var4(22199);      %Design CHW Pump
Flow from PV-A Report
   %DesignCHWPumpHeadIP(i) = table{1,i}.Var5(22199);    %Design CHW Pump
Head from PV-A Report
   DesignCHWPumpPwr(i) = SIMtable{1,i}.Var8(22199);        %Design CHW Pump
Power from PV-A Report

   DesignHWPumpFloIP(i) = SIMtable{1,i}.Var4(22202);       %Design HW Pump
Flow from PV-A Report
   %DesignHWPumpHeadIP(i) = table{1,i}.Var5(22202);     %Design HW Pump
Head from PV-A Report
   DesignHWPumpPwr(i) = SIMtable{1,i}.Var8(22202);         %Design HW Pump
Power from PV-A Report

   DesignCWPumpFloIP(i) = SIMtable{1,i}.Var4(22205);       %Design CW Pump
Flow from PV-A Report
   %DesignCWPumpHeadIP(i) = table{1,i}.Var5(22205);     %Design CW Pump
Head from PV-A Report
   DesignCWPumpPwr(i) = SIMtable{1,i}.Var8(22205);         %Design CW Pump
Power from PV-A Report

   DesignFanFloIP(i) = SIMtable{1,i}.Var2(20587);          %Design Fan Flow
from SV-A Report
   DesignSupplyFanPwr(i) = SIMtable{1,i}.Var4(20587);      %Design Supply
Fan Power from SV-A Report
   DesignReturnFanPwr(i) = SIMtable{1,i}.Var4(20588);      %Design Return
Fan Power from SV-A Report

   AnnEnergyCost(i) = SIMtable{1,i}.Var1(23431);           %Annual Total
Charge from ES-D Report

   AnnAvgCoolTmpIP(i) = SIMtable{1,i}.Var3(20888);         %Annual Cooling
Average Space Temperature from SS-K Report
   AnnAvgHeatTmpIP(i) = SIMtable{1,i}.Var4(20888);         %Annual Heating
Average Space Temperature from SS-K Report
end
```

```
%%% END Collecting Information %%%
%%% BEGIN Converting from cell to double and transposing for posterior
exporting %%%

MaxOcc = celltodouble(MaxOcc);

FloorAreaIP = celltodouble(FloorAreaIP);
TotalWallAreaIP = celltodouble(TotalWallAreaIP);
TotalWindowAreaIP = celltodouble(TotalWindowAreaIP);
TotalRoofAreaIP = celltodouble(TotalRoofAreaIP);

EnergyUseIP = celltodouble(EnergyUseIP);
EUIIP = celltodouble(EUIIP);

PeakElectricDemand = celltodouble(PeakElectricDemand);
PeakLightsDemand = celltodouble(PeakLightsDemand);
PeakEquipsDemand = celltodouble(PeakEquipsDemand);

AnnualCost = celltodouble(AnnualCost);
AboveCooling = celltodouble(AboveCooling);
BelowHeating = celltodouble(BelowHeating);

PeakSystemCoolLoadIP = celltodouble(PeakSystemCoolLoadIP);
PeakSystemHeatLoadIP = celltodouble(PeakSystemHeatLoadIP);
PeakHVACCoolLoadIP = celltodouble(PeakHVACCoolLoadIP);
PeakHVACHeatLoadIP = celltodouble(PeakHVACHeatLoadIP);
PeakCircHeatLoadIP = celltodouble(PeakCircHeatLoadIP);
PeakCircCoolLoadIP = celltodouble(PeakCircCoolLoadIP);
PeakCircHeatRejLoadIP = celltodouble(PeakCircHeatRejLoadIP);

AnnBldgCoolLoadIP = celltodouble(AnnBldgCoolLoadIP);
AnnBldgHeatLoadIP = celltodouble(AnnBldgHeatLoadIP);

CHWLoopCapIP = celltodouble(CHWLoopCapIP);
HWLoopCapIP = celltodouble(HWLoopCapIP);
CWLoopCapIP = celltodouble(CWLoopCapIP);

AnnFanConHeat = celltodouble(AnnFanConHeat);
AnnFanConCool = celltodouble(AnnFanConCool);
AnnFanConHeatCool = celltodouble(AnnFanConHeatCool);
AnnFanConFloat = celltodouble(AnnFanConFloat);

AnnBlr1HeatLoadIP = celltodouble(AnnBlr1HeatLoadIP);
AnnBlr1FuelUseIP = celltodouble(AnnBlr1FuelUseIP);
AnnBlr2HeatLoadIP = celltodouble(AnnBlr2HeatLoadIP);
AnnBlr2FuelUseIP = celltodouble(AnnBlr2FuelUseIP);

AnnChlCoolLoadIP = celltodouble(AnnChlCoolLoadIP);
AnnChlElecUse = celltodouble(AnnChlElecUse);

AnnCTHeatRejLoadIP = celltodouble(AnnCTHeatRejLoadIP);
AnnCTElecUse = celltodouble(AnnCTElecUse);
```

```
AnnCHWPumpElecUse = celltodouble(AnnCHWPumpElecUse);
AnnHWPumpElecUse = celltodouble(AnnHWPumpElecUse);
AnnCWPumpElecUse = celltodouble(AnnCWPumpElecUse);

AnnCircCoolLoadIP = celltodouble(AnnCircCoolLoadIP);
AnnCircHeatLoadIP = celltodouble(AnnCircHeatLoadIP);
AnnCircHeatRejLoadIP = celltodouble(AnnCircHeatRejLoadIP);

DesignCHWPumpFloIP = celltodouble(DesignCHWPumpFloIP);
DesignCHWPumpPwr = celltodouble(DesignCHWPumpPwr);

DesignHWPumpFloIP = celltodouble(DesignHWPumpFloIP);
DesignHWPumpPwr = celltodouble(DesignHWPumpPwr);

DesignCWPumpFloIP = celltodouble(DesignCWPumpFloIP);
DesignCWPumpPwr = celltodouble(DesignCWPumpPwr);

DesignFanFloIP = celltodouble(DesignFanFloIP);
DesignSupplyFanPwr = celltodouble(DesignSupplyFanPwr);
DesignReturnFanPwr = celltodouble(DesignReturnFanPwr);

AnnEnergyCost = celltodouble(AnnEnergyCost);

AnnAvgCoolTmpIP = celltodouble(AnnAvgCoolTmpIP);
AnnAvgHeatTmpIP = celltodouble(AnnAvgHeatTmpIP);

%%% END  Converting from cell to double %%%
%%% BEGIN Calculating Derived Check Figures and KPIs %%%

OccupancyIP = FloorAreaIP./MaxOcc;
FDWR = TotalWindowAreaIP./TotalWallAreaIP;
PeakElectricDemandIPPFA = PeakElectricDemand./FloorAreaIP;
AnnualCostIPPFA = AnnualCost./FloorAreaIP;

PeakLightsDemandIPPFA = PeakLightsDemand./FloorAreaIP;
PeakEquipsDemandIPPFA = PeakEquipsDemand./FloorAreaIP;

PeakSystemCoolLoadIPPFA = PeakSystemCoolLoadIP./FloorAreaIP;
PeakSystemHeatLoadIPPFA = PeakSystemHeatLoadIP./FloorAreaIP;

PeakHVACCoolLoadIPPFA = PeakHVACCoolLoadIP./FloorAreaIP;
PeakHVACHeatLoadIPPFA = PeakHVACHeatLoadIP./FloorAreaIP;

PeakCircHeatLoadIPPFA = PeakCircHeatLoadIP./FloorAreaIP;
PeakCircCoolLoadIPPFA = PeakCircCoolLoadIP./FloorAreaIP;
%PeakCircHeatRejLoadIPPFA = PeakCircHeatRejLoadIP./FloorAreaIP; No physical meaning

CHWLoopCapIPPFA = CHWLoopCapIP./FloorAreaIP;
HWLoopCapIPPFA = HWLoopCapIP./FloorAreaIP;
%CWLoopCapIPPFA = CWLoopCapIP./FloorAreaIP; No physical meaning
```

```
AnnHVACConHeatIP = AnnFanConHeat*0.003412141 + AnnBlr1FuelUseIP +
AnnBlr2FuelUseIP + AnnHWPumpElecUse*0.003412141;
AnnSPRHeat = AnnCircHeatLoadIP./AnnHVACConHeatIP;

AnnHVACConCoolIP = AnnFanConCool*0.003412141 + AnnChlElecUse*0.003412141 +
AnnCHWPumpElecUse*0.003412141 + AnnCWPumpElecUse*0.003412141 +
AnnCTElecUse*0.003412141;
AnnSPRCool = AnnCircCoolLoadIP./AnnHVACConCoolIP;

AnnHVACConBothIP = ((AnnFanConHeat+AnnFanConCool-
AnnFanConHeatCool+AnnFanConFloat)*0.003412141) + AnnChlElecUse*0.003412141
+ AnnCHWPumpElecUse*0.003412141 + AnnCWPumpElecUse*0.003412141 +
AnnCTElecUse*0.003412141 + AnnBlr1FuelUseIP + AnnBlr2FuelUseIP +
AnnHWPumpElecUse*0.003412141;
AnnCircBothLoadIP = abs(AnnCircCoolLoadIP)+abs(AnnCircHeatLoadIP);
AnnSPRBoth = AnnCircBothLoadIP./AnnHVACConBothIP;

CostPerAnnEnergyIP = AnnEnergyCost./EnergyUseIP;

AnnChlCOP = AnnChlCoolLoadIP./(AnnChlElecUse*0.003412141);

AnnBlr12HeatLoadIP = AnnBlr1HeatLoadIP + AnnBlr2HeatLoadIP;
AnnBlr12FuelUseIP = AnnBlr1FuelUseIP + AnnBlr2FuelUseIP;
AnnBlrEff = -AnnBlr12HeatLoadIP./AnnBlr12FuelUseIP;

AnnCTPerformance = (AnnCTElecUse*0.003412141)./AnnCTHeatRejLoadIP;

CHWPumpPwrDemand = (DesignCHWPumpPwr*3.412141)./CHWLoopCapIP;
HWPumpPwrDemand = (DesignHWPumpPwr*3.412141)./HWLoopCapIP;
CWPumpPwrDemand = (DesignCWPumpPwr*3.412141)./CWLoopCapIP;

DesignFanFloIPPFA = DesignFanFloIP./FloorAreaIP;

CombinedFanPwrDemandIP =
(DesignSupplyFanPwr+DesignReturnFanPwr)*1000./DesignFanFloIP;

TotalBldgLoadsperTotalHVACCon =
(AnnBldgCoolLoadIP+abs(AnnBldgHeatLoadIP))./AnnHVACConBothIP;

%%% END Calculating Derived Check Figures and KPIs %%%
%%% BEGIN Converting from Imperial to International %%%

FloorAreaSI = FloorAreaIP*10.764;   %ft² to m²
OccupancySI = OccupancyIP*10.764;   %ft²/p to m²/p

TotalWallAreaSI = TotalWallAreaIP*10.764;   %ft² to m²
TotalWindowAreaSI = TotalWindowAreaIP*10.764;   %ft² to m²
TotalRoofAreaSI = TotalRoofAreaIP*10.764;   %ft² to m²

EnergyUseSI = EnergyUseIP/3.4121;   %MBtu to MWh
EUISI = EUIIP*(0.0010550559/10.764);    %kBtu/ft² to GJ/m²

PeakElectricDemandSIPFA = PeakElectricDemandIPPFA/10.764;   %W/ft² to W/m²
```

```
AnnualCostSIPFA = AnnualCostIPPFA/10.764;   %$/ft² to $/m²

PeakLightsDemandSIPFA = PeakLightsDemandIPPFA/10.764;   %W/ft² to W/m²
PeakEquipsDemandSIPFA = PeakEquipsDemandIPPFA/10.764;   %W/ft² to W/m²

PeakSystemCoolLoadSI = PeakSystemCoolLoadIP*0.29307;    %kBtu/hr to kW
PeakSystemHeatLoadSI = PeakSystemHeatLoadIP*0.29307;    %kBtu/hr to kW

PeakHVACCoolLoadSI = PeakHVACCoolLoadIP*0.29307;    %kBtu/hr to kW
PeakHVACHeatLoadSI = PeakHVACHeatLoadIP*0.29307;    %kBtu/hr to kW

AnnCircCoolLoadSI = AnnCircCoolLoadIP*0.29307;    %MBtu to MWh
PeakCircCoolLoadSI = PeakCircCoolLoadIP*0.29307;    %kBtu/hr to kW
AnnCircHeatLoadSI = AnnCircHeatLoadIP*0.29307;    %MBtu to MWh
PeakCircHeatLoadSI = PeakCircHeatLoadIP*0.29307;    %kBtu/hr to kW
AnnCircHeatRejLoadSI = AnnCircHeatRejLoadIP*0.29307;    %MBtu to MWh
PeakCircHeatRejLoadSI = PeakCircHeatRejLoadIP*0.29307;    %kBtu/hr to kW

PeakSystemCoolLoadSIPFA = PeakSystemCoolLoadIPPFA*(0.29307/10.764);
%kBtu/hr-ft² to kW/m²
PeakSystemHeatLoadSIPFA = PeakSystemHeatLoadIPPFA*(0.29307/10.764);
%kBtu/hr-ft² to kW/m²

PeakHVACCoolLoadSIPFA = PeakHVACCoolLoadIPPFA*(0.29307/10.764);
%kBtu/hr-ft² to kW/m²
PeakHVACHeatLoadSIPFA = PeakHVACHeatLoadIPPFA*(0.29307/10.764);
%kBtu/hr-ft² to kW/m²

PeakCircHeatLoadSIPFA = PeakCircHeatLoadIPPFA*(0.29307/10.764);
%kBtu/hr-ft² to kW/m²
PeakCircCoolLoadSIPFA = PeakCircCoolLoadIPPFA*(0.29307/10.764);
%kBtu/hr-ft² to kW/m²

CHWLoopCapSI = CHWLoopCapIP*0.29307;    %kBtu/hr to kW;
HWLoopCapSI = HWLoopCapIP*0.29307;    %kBtu/hr to kW;
CWLoopCapSI = CWLoopCapIP*0.29307;    %kBtu/hr to kW;

CHWLoopCapSIPFA = CHWLoopCapIPPFA*(0.29307/10.764);    %kBtu/hr-ft² to
kW/m²
HWLoopCapSIPFA = HWLoopCapIPPFA*(0.29307/10.764);    %kBtu/hr-ft² to kW/m²

AnnHVACConHeatSI = AnnHVACConHeatIP*0.29307;    %MBtu to MWh
AnnHVACConCoolSI = AnnHVACConCoolIP*0.29307;    %MBtu to MWh
AnnHVACConBothSI = AnnHVACConBothIP*0.29307;    %MBtu to MWh

AnnCircBothLoadSI = AnnCircBothLoadIP*0.29307;    %MBtu to MWh

CostPerAnnEnergySI = CostPerAnnEnergyIP/293.07;     %$/MBTU to $/kWh

AnnFanConHeatIP = AnnFanConHeat*0.0034121;      %kWh to MBtu
AnnFanConCoolIP = AnnFanConCool*0.0034121;      %kWh to MBtu
AnnFanConHeatCoolIP = AnnFanConHeatCool*0.0034121;      %kWh to MBtu
AnnFanConFloatIP = AnnFanConFloat*0.0034121;    %kWh to MBtu
```

```
AnnBlr1HeatLoadSI = AnnBlr1HeatLoadIP*0.29307;    %MBtu to MWh
AnnBlr1FuelUseSI = AnnBlr1FuelUseIP*0.29307;    %MBtu to MWh
AnnBlr2HeatLoadSI = AnnBlr2HeatLoadIP*0.29307;    %MBtu to MWh
AnnBlr2FuelUseSI = AnnBlr2FuelUseIP*0.29307;    %MBtu to MWh

AnnBlr12HeatLoadSI = AnnBlr12HeatLoadIP*0.29307;    %MBtu to MWh
AnnBlr12FuelUseSI = AnnBlr12FuelUseIP*0.29307;    %MBtu to MWh

AnnChlCoolLoadSI = AnnChlCoolLoadIP*0.29307;    %MBtu to MWh
AnnChlElecUseIP = AnnChlElecUse*0.0034121;    %kWh to MBtu

AnnCTHeatRejLoadSI = AnnCTHeatRejLoadIP*0.29307;    %MBtu to MWh
AnnCTElecUseIP = AnnCTElecUse*0.0034121;    %kWh to MBtu

AnnCHWPumpElecUseIP = AnnCHWPumpElecUse*0.0034121;    %kWh to MBtu
AnnHWPumpElecUseIP = AnnHWPumpElecUse*0.0034121;    %kWh to MBtu
AnnCWPumpElecUseIP = AnnCWPumpElecUse*0.0034121;    %kWh to MBtu

DesignCHWPumpFloSI = DesignCHWPumpFloIP*0.06309;    %gpm to L/s
DesignHWPumpFloSI = DesignHWPumpFloIP*0.06309;    %gpm to L/s
DesignCWPumpFloSI = DesignCWPumpFloIP*0.06309;    %gpm to L/s
DesignFanFloSI = DesignFanFloIP*0.47195;    %cfm to L/s

DesignFanFloSIPFA = DesignFanFloIPPFA*(0.47195/10.764);  %cfm/ft² to L/s-m²

CombinedFanPwrDemandSI = CombinedFanPwrDemandIP*(1/10.764);  %W/ft² to W/m²

AnnAvgCoolTmpSI = (AnnAvgCoolTmpIP-32)*5/9;
AnnAvgHeatTmpSI = (AnnAvgHeatTmpIP-32)*5/9;

%%% END Converting from Imperial to International %%%
%%% BEGIN Inputs for Sensitivity Analysis %%%

tbl_WallUvalIP=[
0.044
0.044
0.044
0.044
0.044
0.044
0.044
0.044
0.044
0.044
0.044
0.044
0.044
0.044
0.044
0.044
0.044
0.044
0.044
```

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0.044
0.044
0.044
0.044
0.044
0.044
0.044
0.044
0.044
0.044
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0.044
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0.044
0.044
0.044
0.044
0.044
0.044
0.044
0.044
0.044
0.044
0.044
0.035
0.040
0.048
0.053];

tbl_RoofUvalIP=[
0.0278
0.0278
0.0278
0.0278
0.0278
0.0278
0.0278
0.0278
```

```
0.0278
0.0278
0.0278
0.0278
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0.0278
0.0278
0.0278
0.0278
0.0278
0.0278
0.0278
0.0278
0.0278
0.028
0.009
0.018
0.035
0.044
0.0278
0.0278
0.0278
0.0278
```

```
0.0278];

tbl_FenestrationUvalIP=[
0.330
0.330
0.330
0.330
0.330
0.330
0.330
0.330
0.330
0.330
0.330
0.330
0.330
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0.330
0.330
0.330
0.330
0.330
0.330
0.330
0.330
0.330
0.330
0.330
0.330
0.264
0.299
```

```
0.370
0.405
0.330
0.330
0.330
0.330
0.330
0.330
0.330
0.330
0.330
0.330];

tbl_ChillerEIR=[
0.180
0.180
0.180
0.180
0.180
0.180
0.180
0.180
0.180
0.180
0.180
0.180
0.180
0.180
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0.180
0.180
0.180
0.180
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0.180
0.180
0.180
0.180
0.222
0.200
0.167
0.154
0.180
0.180
0.180
0.180
0.180
0.180
0.180
0.180
0.180
0.180
0.180
0.180
0.180
0.180
0.180];

tbl_BlrHIR=[
1.205
1.205
1.205
1.205
1.205
1.205
1.205
1.205
1.205
1.205
1.205
1.205
1.205
1.205
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1.205
1.205
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1.205
1.205
1.205
1.205
1.205
1.205
1.205
1.205
1.205
1.205
1.333
1.250
1.176
1.111
1.205
1.205
1.205
1.205
1.205
1.205
1.205
1.205
1.205
1.205
1.205
1.205
1.205
1.205
1.205
1.205
1.205
1.205
1.205
1.205];

tbl_CTEIR=[
0.013
0.013
0.013
0.013
0.013
0.013
0.013
0.013
0.013
0.013
0.013
0.013
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0.013
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0.013
0.013
0.013
0.009
0.011
0.015
0.017
0.013
0.013
0.013
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0.013
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0.013
0.013
0.013
0.013
0.013
0.013
0.013
0.013
0.013
0.013
0.013];

tbl_CHWPumpEff=[
0.674
0.674
0.674
0.674
0.674
0.674
0.674
0.674
0.674
```

```
0.674
0.674
0.674
0.674
0.674
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0.674
0.674
0.674
0.674
0.674
0.674
0.674
0.674
0.674
0.674
0.674
0.674
0.674
0.550
0.600
0.700
0.750
0.674
0.674
0.674
0.674
0.674
0.674
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0.674
0.674
0.674
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0.674
0.674
0.674
0.674
0.674
0.674
0.674
0.674
0.674
0.674];
```

```
tbl_HWPumpEff=[
0.658
0.658
0.658
0.658
0.658
0.658
0.658
0.658
0.658
0.658
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0.658
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0.658
0.658
0.658
0.658
0.658
0.658
0.658
0.550
0.600
0.700
0.750
0.658
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0.658
0.658
0.658
0.658
0.658
0.658
0.658
0.658
0.658
0.658
0.658];

tbl_CWPumpEff=[
0.695
0.695
0.695
0.695
0.695
0.695
0.695
0.695
0.695
0.695
0.695
0.695
0.695
0.695
0.695
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0.695
0.695
0.695
0.695
0.695
0.550
0.600
0.700
0.750
0.695
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0.695
0.695
0.695
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0.695
0.695
0.695
0.695];

tbl_SupFanEff=[
0.550
0.550
0.550
0.550
0.550
0.550
0.550
0.550
0.550
0.550
0.550
0.550
0.550
0.550
0.550
0.550
0.450
0.500
0.600
0.650
0.550
0.550
0.550
0.550
0.550
0.550
0.550
0.550
0.550
0.550
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0.550
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0.550
0.550
0.550
0.550
0.550
0.550
0.550
0.550
0.550
0.550
0.550
0.550
0.550];

tbl_RetFanEff=[
0.300
0.300
0.300
0.300
0.300
0.300
0.300
0.300
0.300
0.300
0.300
0.200
0.250
0.350
0.400
0.300
0.300
0.300
0.300
0.300
0.300
```

```
0.300
0.300
0.300
0.300
0.300
0.300
0.300
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0.300
0.300
0.300
0.300
0.300
0.300
0.300
0.300
0.300
0.300
0.300];

tbl_HeatSPIP=[
71.600
71.600
71.600
71.600
71.600
71.600
68.000
69.800
73.400
75.200
```

```
71.600
71.600
71.600
71.600
71.600
71.600
71.600
71.600
71.600
71.600
71.600
71.600
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71.600
71.600
71.600
71.600
71.600
71.600
71.600
71.600
71.600
71.600
71.600
71.600
71.600];
```

```
tbl_CoolSPIP=[
75.200
71.600
73.400
77.000
78.800
75.200
75.200
75.200
75.200
75.200
75.200
75.200
75.200
75.200
75.200
75.200
75.200
75.200
75.200
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75.200
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75.200
75.200
75.200
75.200
75.200
75.200
```

```
75.200
75.200
75.200
75.200
75.200
75.200
75.200
75.200
75.200
75.200];

InputsIP =
table(tbl_WallUvalIP,tbl_RoofUvalIP,tbl_FenestrationUvalIP,tbl_ChillerEIR,t
bl_BlrHIR,tbl_CTEIR,tbl_CHWPumpEff,tbl_HWPumpEff,tbl_CWPumpEff,tbl_SupFanEf
f,tbl_RetFanEff,tbl_HeatSPIP,tbl_CoolSPIP);

for i=1:(size(InputsIP,1)/5-1)
    rowdel(i) = i*5+1;
end

InputsIP(rowdel,:) = [];

%%% END Inputs for Sensitivity Analysis %%%
%%% BEGIN Converting Inputs from IP to SI %%%

InputsSI = InputsIP;

InputsSI{:,1} = InputsSI{:,1}*5.67826334112335;
InputsSI{:,2} = InputsSI{:,2}*5.67826334112335;
InputsSI{:,3} = InputsSI{:,3}*5.67826334112335;
InputsSI{:,4} = 1./InputsSI{:,4};
InputsSI{:,5} = 1./InputsSI{:,5};
InputsSI{:,6} = 1./InputsSI{:,6};
InputsSI{:,12} = (InputsSI{:,12}-32)*5/9;
InputsSI{:,13} = (InputsSI{:,13}-32)*5/9;

InputsSI.Properties.VariableNames =
{'tbl_WallUvalSI','tbl_RoofUvalSI','tbl_FenestrationUvalSI','tbl_ChillerCOP
','tbl_BlrEff','tbl_CTPerf','tbl_CHWPumpEff','tbl_HWPumpEff','tbl_CWPumpEff
','tbl_SupFanEff','tbl_RetFanEff','tbl_HeatSPSI','tbl_CoolSPSI'};

%%% END Converting Inputs from IP to SI %%%
%%% BEGIN Performing local sensitivity analysis %%%

InputsMatrixSI = table2array(InputsSI);

%%% END Performing local sensitivity analysis for absolute variation %%%
%%% BEGIN Creating vectors with relative changes in KPIs %%%

R_EUISI = EUISI./EUISI(1)-1;
R_PEDSI = PeakElectricDemandSIPFA./PeakElectricDemandSIPFA(1)-1;
R_AECSI = AnnualCostSIPFA./AnnualCostSIPFA(1)-1;
R_CPESI = CostPerAnnEnergySI./CostPerAnnEnergySI(1)-1;
```

```
R_PCCSI = PeakCircCoolLoadSIPFA./PeakCircCoolLoadSIPFA(1)-1;
R_PCHSI = PeakCircHeatLoadSIPFA./PeakCircHeatLoadSIPFA(1)-1;

R_SPRHE = AnnSPRHeat./AnnSPRHeat(1)-1;
R_SPRCO = AnnSPRCool./AnnSPRCool(1)-1;
R_SPRBO = AnnSPRBoth./AnnSPRBoth(1)-1;

R_CHCOP = AnnChlCOP./AnnChlCOP(1)-1;
R_BLREF = AnnBlrEff./AnnBlrEff(1)-1;
R_CTEFF = AnnCTPerformance./AnnCTPerformance(1)-1;

R_CHWPD = CHWPumpPwrDemand./CHWPumpPwrDemand(1)-1;
R_HWPPD = HWPumpPwrDemand./HWPumpPwrDemand(1)-1;
R_CWPPD = CWPumpPwrDemand./CWPumpPwrDemand(1)-1;

R_SAFSI = DesignFanFloSIPFA./DesignFanFloSIPFA(1)-1;
R_CPDSI = CombinedFanPwrDemandSI./CombinedFanPwrDemandSI(1)-1;

R_BLPHC = TotalBldgLoadsperTotalHVACCon./TotalBldgLoadsperTotalHVACCon(1)-
1;

%%% END Creating vectors with relative changes in KPIs %%%
%%% BEGIN Performing local sensitivity analysis for relative variation %%%

InputsRelMatrix = InputsMatrixSI;

for i = 1:size(InputsRelMatrix,2)
    InputsRelMatrix(:,i) = InputsRelMatrix(:,i)./InputsRelMatrix(1,i)-1;
end

RIMTransposed = transpose(InputsRelMatrix);
RIMMult1 = mtimes(RIMTransposed,InputsRelMatrix);
RIMInv = inv(RIMMult1);
RIMMult2 = mtimes(RIMInv,RIMTransposed);

RCSA_EUISI = mtimes(RIMMult2,R_EUISI);
RCSA_PEDSI = mtimes(RIMMult2,R_PEDSI);
RCSA_AECSI = mtimes(RIMMult2,R_AECSI);
RCSA_CPESI = mtimes(RIMMult2,R_CPESI);

RCSA_PCCSI = mtimes(RIMMult2,R_PCCSI);
RCSA_PCHSI = mtimes(RIMMult2,R_PCHSI);

RCSA_SPRHE = mtimes(RIMMult2,R_SPRHE);
RCSA_SPRCO = mtimes(RIMMult2,R_SPRCO);
RCSA_SPRBO = mtimes(RIMMult2,R_SPRBO);

RCSA_CHCOP = mtimes(RIMMult2,R_CHCOP);
RCSA_BLREF = mtimes(RIMMult2,R_BLREF);
RCSA_CTEFF = mtimes(RIMMult2,R_CTEFF);

RCSA_CHWPD = mtimes(RIMMult2,R_CHWPD);
RCSA_HWPPD = mtimes(RIMMult2,R_HWPPD);
```

```matlab
RCSA_CWPPD = mtimes(RIMMult2,R_CWPPD);

RCSA_SAFSI = mtimes(RIMMult2,R_SAFSI);
RCSA_CPDSI = mtimes(RIMMult2,R_CPDSI);

RCSA_BLPHC = mtimes(RIMMult2,R_BLPHC);

%%% END Inputs for Sensitivity Analysis %%%
%%% Absolute variation %%%

InputsAbsMatrix = InputsMatrixSI;

for i = 1:size(InputsAbsMatrix,2)
    InputsAbsMatrix(:,i) = InputsAbsMatrix(:,i) - InputsAbsMatrix(1,i);
end

AIMTransposed = transpose(InputsAbsMatrix);
AIMMult1 = mtimes(AIMTransposed,InputsAbsMatrix);
AIMInv = inv(AIMMult1);
AIMMult2 = mtimes(AIMInv,AIMTransposed);

ACSA_EUISI = mtimes(AIMMult2,R_EUISI);
ACSA_PEDSI = mtimes(AIMMult2,R_PEDSI);
ACSA_AECSI = mtimes(AIMMult2,R_AECSI);
ACSA_CPESI = mtimes(AIMMult2,R_CPESI);

ACSA_PCCSI = mtimes(AIMMult2,R_PCCSI);
ACSA_PCHSI = mtimes(AIMMult2,R_PCHSI);

ACSA_SPRHE = mtimes(AIMMult2,R_SPRHE);
ACSA_SPRCO = mtimes(AIMMult2,R_SPRCO);
ACSA_SPRBO = mtimes(AIMMult2,R_SPRBO);

ACSA_CHCOP = mtimes(AIMMult2,R_CHCOP);
ACSA_BLREF = mtimes(AIMMult2,R_BLREF);
ACSA_CTEFF = mtimes(AIMMult2,R_CTEFF);

ACSA_CHWPD = mtimes(AIMMult2,R_CHWPD);
ACSA_HWPPD = mtimes(AIMMult2,R_HWPPD);
ACSA_CWPPD = mtimes(AIMMult2,R_CWPPD);

ACSA_SAFSI = mtimes(AIMMult2,R_SAFSI);
ACSA_CPDSI = mtimes(AIMMult2,R_CPDSI);

ACSA_BLPHC = mtimes(AIMMult2,R_BLPHC);

%%% BEGIN Plotting Graphs %%%

names = InputsSI.Properties.VariableNames';

names = {'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'};

%%% BAR CHARTS KPI VS ALL INPUTS

i=1;

figure(i)
bar(RCSA_EUISI(1:11)*100)
set(gca,'xticklabel',names)
title('Energy Use Intensity per floor area')
ylabel('SC (%)')
xtickangle(90)
print('-f1', '-dpng',strcat(pwd,'\Images\','1EUIPFA_SC','.png'))
i=i+1;

figure(i)
bar(RCSA_PEDSI(1:11)*100)
set(gca,'xticklabel',names)
title('Peak Electrical Demand per floor area')
ylabel('SC (%)')
xtickangle(90)
print('-f2', '-dpng',strcat(pwd,'\Images\','2PEDPFA_SC','.png'))
i=i+1;

figure(i)
bar(RCSA_CPESI(1:11)*100)
set(gca,'xticklabel',names)
title('Energy Cost per Energy Consumption')
ylabel('SC (%)')
xtickangle(90)
print('-f3', '-dpng',strcat(pwd,'\Images\','3ACAEC_SC','.png'))
i=i+1;

figure(i)
bar(RCSA_AECSI(1:11)*100)
set(gca,'xticklabel',names)
title('Energy Cost per floor area')
ylabel('SC (%)')
xtickangle(90)
print('-f4', '-dpng',strcat(pwd,'\Images\','4AECPFA_SC','.png'))
i=i+1;

%%%

figure(i)
```

```
bar(RCSA_PCCSI(1:11)*100)
set(gca,'xticklabel',names)
title('Peak Circulation Cooling Load PFA')
ylabel('SC (%)')
xtickangle(90)
print('-f5', '-dpng',strcat(pwd,'\Images\','5PCCPFA_SC','.png'))
i=i+1;

figure(i)
bar(RCSA_PCHSI(1:11)*100)
set(gca,'xticklabel',names)
title('Peak Circulation Heating Load PFA')
ylabel('SC (%)')
xtickangle(90)
print('-f6', '-dpng',strcat(pwd,'\Images\','6PCHPFA_SC','.png'))
i=i+1;

%%%

figure(i)
bar(RCSA_BLPHC(1:11)*100)
set(gca,'xticklabel',names)
title('Total Building Heating and Cooling Loads per Total HVAC Energy Consumption')
ylabel('SC (%)')
xtickangle(90)
print('-f7', '-dpng',strcat(pwd,'\Images\','31BLPHC_SC','.png'))
i=i+1;

figure(i)
bar(RCSA_SPRHE(1:11)*100)
set(gca,'xticklabel',names)
title('System Performance Ratio for Heating')
ylabel('SC (%)')
xtickangle(90)
print('-f7', '-dpng',strcat(pwd,'\Images\','7SPRH_SC','.png'))
i=i+1;

figure(i)
bar(RCSA_SPRCO(1:11)*100)
set(gca,'xticklabel',names)
title('System Performance Ratio for Cooling')
ylabel('SC (%)')
xtickangle(90)
print('-f8', '-dpng',strcat(pwd,'\Images\','8SPRC_SC','.png'))
i=i+1;

figure(i)
bar(RCSA_SPRBO(1:11)*100)
set(gca,'xticklabel',names)
title('System Performance Ratio for Both Heating and Cooling')
ylabel('SC (%)')
xtickangle(90)
print('-f9', '-dpng',strcat(pwd,'\Images\','9SPRHC_SC','.png'))
i=i+1;
```

```
%%%

figure(i)
bar(RCSA_CHCOP(1:11)*100)
set(gca,'xticklabel',names)
title('Annual Average Chiller COP')
ylabel('SC (%)')
xtickangle(90)
print('-f10', '-dpng',strcat(pwd,'\Images\','10CHCOP_SC','.png'))
i=i+1;

figure(i)
bar(RCSA_BLREF(1:11)*100)
set(gca,'xticklabel',names)
title('Annual Average Boiler Efficiency')
ylabel('SC (%)')
xtickangle(90)
print('-f11', '-dpng',strcat(pwd,'\Images\','11BLEFF_SC','.png'))
i=i+1;

figure(i)
bar(RCSA_CTEFF(1:11)*100)
set(gca,'xticklabel',names)
title('Annual Average Cooling Tower Efficiency')
ylabel('SC (%)')
xtickangle(90)
print('-f12', '-dpng',strcat(pwd,'\Images\','12CTEFF_SC','.png'))
i=i+1;

%%%

figure(i)
bar(RCSA_CHWPD(1:11)*100)
set(gca,'xticklabel',names)
title('CHW Pump Power Demand')
ylabel('SC (%)')
xtickangle(90)
print('-f13', '-dpng',strcat(pwd,'\Images\','13CHWPD_SC','.png'))
i=i+1;

figure(i)
bar(RCSA_HWPPD(1:11)*100)
set(gca,'xticklabel',names)
title('HW Pump Power Demand')
ylabel('SC (%)')
xtickangle(90)
print('-f14', '-dpng',strcat(pwd,'\Images\','14HWPD_SC','.png'))
i=i+1;

figure(i)
bar(RCSA_CWPPD(1:11)*100)
set(gca,'xticklabel',names)
title('CW Pump Power Demand')
```

```
ylabel('SC (%)')
xtickangle(90)
print('-f15', '-dpng',strcat(pwd,'\Images\','15CWPD_SC','.png'))
i=i+1;

%%%

figure(i)
bar(RCSA_SAFSI(1:11)*100)
set(gca,'xticklabel',names)
title('Fan Design Supply Airflow PFA')
ylabel('SC (%)')
xtickangle(90)
print('-f16', '-dpng',strcat(pwd,'\Images\','16FNFLO_SC','.png'))
i=i+1;

figure(i)
bar(RCSA_CPDSI(1:11)*100)
set(gca,'xticklabel',names)
title('Combined Fan Power Demand over Flow')
ylabel('SC (%)')
xtickangle(90)
print('-f17', '-dpng',strcat(pwd,'\Images\','17PDFLO_SC','.png'))
i=i+1;

%%% LINE PLOTS KPI VS SINGLE INPUT

figure(i)
plot(InputsRelMatrix([50:51 1 52:53],1)*100,R_EUISI([50:51 1
52:53],1)*100,'-o')
xlim([min(min(InputsRelMatrix(:,1:11)))*100
max(max(InputsRelMatrix(:,1:11)))*100])
ylim([min(R_EUISI(10:53))*100 max(R_EUISI(10:53))*100])
title('EUI = f(Wall U-val)')
xlabel('Change in Input (%)')
ylabel('Change in KPI (%)')
grid on
print('-f18', '-dpng',strcat(pwd,'\Images\','18EUI_WALL','.png'))
i=i+1;

figure(i)
plot(InputsRelMatrix([46:47 1 48:49],2)*100,R_EUISI([46:47 1
48:49],1)*100,'-o')
xlim([min(min(InputsRelMatrix(:,1:11)))*100
max(max(InputsRelMatrix(:,1:11)))*100])
ylim([min(R_EUISI(10:53))*100 max(R_EUISI(10:53))*100])
title('EUI = f(Roof U-val)')
xlabel('Change in Input (%)')
ylabel('Change in KPI (%)')
grid on
print('-f19', '-dpng',strcat(pwd,'\Images\','19EUI_ROOF','.png'))
i=i+1;

figure(i)
```

```
plot(InputsRelMatrix([42:43 1 44:45],3)*100,R_EUISI([42:43 1
44:45],1)*100,'-o')
xlim([min(min(InputsRelMatrix(:,1:11)))*100
max(max(InputsRelMatrix(:,1:11)))*100])
ylim([min(R_EUISI(10:53))*100 max(R_EUISI(10:53))*100])
title('EUI = f(Windows U-val)')
xlabel('Change in Input (%)')
ylabel('Change in KPI (%)')
grid on
print('-f20', '-dpng',strcat(pwd,'\Images\','20EUI_WDW','.png'))
i=i+1;

figure(i)
plot(InputsRelMatrix([38:39 1 40:41],4)*100,R_EUISI([38:39 1
40:41],1)*100,'-o')
xlim([min(min(InputsRelMatrix(:,1:11)))*100
max(max(InputsRelMatrix(:,1:11)))*100])
ylim([min(R_EUISI(10:53))*100 max(R_EUISI(10:53))*100])
title('EUI = f(Chiller COP)')
xlabel('Change in Input (%)')
ylabel('Change in KPI (%)')
grid on
print('-f21', '-dpng',strcat(pwd,'\Images\','21EUI_CHCOP','.png'))
i=i+1;

figure(i)
plot(InputsRelMatrix([34:35 1 36:37],5)*100,R_EUISI([34:35 1
36:37],1)*100,'-o')
xlim([min(min(InputsRelMatrix(:,1:11)))*100
max(max(InputsRelMatrix(:,1:11)))*100])
ylim([min(R_EUISI(10:53))*100 max(R_EUISI(10:53))*100])
title('EUI = f(Boiler Eff.)')
xlabel('Change in Input (%)')
ylabel('Change in KPI (%)')
grid on
print('-f22', '-dpng',strcat(pwd,'\Images\','22EUI_BLEFF','.png'))
i=i+1;

figure(i)
plot(InputsRelMatrix([30:31 1 32:33],6)*100,R_EUISI([30:31 1
32:33],1)*100,'-o')
xlim([min(min(InputsRelMatrix(:,1:11)))*100
max(max(InputsRelMatrix(:,1:11)))*100])
ylim([min(R_EUISI(10:53))*100 max(R_EUISI(10:53))*100])
title('EUI = f(CT Perf.)')
xlabel('Change in Input (%)')
ylabel('Change in KPI (%)')
grid on
print('-f23', '-dpng',strcat(pwd,'\Images\','23EUI_CTEFF','.png'))
i=i+1;
```

```
figure(i)
plot(InputsRelMatrix([26:27 1 28:29],7)*100,R_EUISI([26:27 1
28:29],1)*100,'-o')
xlim([min(min(InputsRelMatrix(:,1:11)))*100
max(max(InputsRelMatrix(:,1:11)))*100])
ylim([min(R_EUISI(10:53))*100 max(R_EUISI(10:53))*100])
title('EUI = f(CHW Pump Eff.)')
xlabel('Change in Input (%)')
ylabel('Change in KPI (%)')
grid on
print('-f24', '-dpng',strcat(pwd,'\Images\','24EUI_CHWEFF','.png'))
i=i+1;

figure(i)
plot(InputsRelMatrix([22:23 1 24:25],8)*100,R_EUISI([22:23 1
24:25],1)*100,'-o')
xlim([min(min(InputsRelMatrix(:,1:11)))*100
max(max(InputsRelMatrix(:,1:11)))*100])
ylim([min(R_EUISI(10:53))*100 max(R_EUISI(10:53))*100])
title('EUI = f(HW Pump Eff.)')
xlabel('Change in Input (%)')
ylabel('Change in KPI (%)')
grid on
print('-f25', '-dpng',strcat(pwd,'\Images\','25EUI_HWEFF','.png'))
i=i+1;

figure(i)
plot(InputsRelMatrix([18:19 1 20:21],9)*100,R_EUISI([18:19 1
20:21],1)*100,'-o')
xlim([min(min(InputsRelMatrix(:,1:11)))*100
max(max(InputsRelMatrix(:,1:11)))*100])
ylim([min(R_EUISI(10:53))*100 max(R_EUISI(10:53))*100])
title('EUI = f(CW Pump Eff.)')
xlabel('Change in Input (%)')
ylabel('Change in KPI (%)')
grid on
print('-f26', '-dpng',strcat(pwd,'\Images\','26EUI_CWEFF','.png'))
i=i+1;

figure(i)
plot(InputsRelMatrix([14:15 1 16:17],10)*100,R_EUISI([14:15 1
16:17],1)*100,'-o')
xlim([min(min(InputsRelMatrix(:,1:11)))*100
max(max(InputsRelMatrix(:,1:11)))*100])
ylim([min(R_EUISI(10:53))*100 max(R_EUISI(10:53))*100])
title('EUI = f(Supply Fan Eff.)')
xlabel('Change in Input (%)')
ylabel('Change in KPI (%)')
grid on
print('-f27', '-dpng',strcat(pwd,'\Images\','27EUI_SFANEFF','.png'))
i=i+1;

figure(i)
plot(InputsRelMatrix([10:11 1 12:13],11)*100,R_EUISI([10:11 1
12:13],1)*100,'-o')
```

```
xlim([min(min(InputsRelMatrix(:,1:11)))*100
max(max(InputsRelMatrix(:,1:11)))*100])
ylim([min(R_EUISI(10:53))*100 max(R_EUISI(10:53))*100])
title('EUI = f(Return Fan Eff.)')
xlabel('Change in Input (%)')
ylabel('Change in KPI (%)')
grid on
print('-f28', '-dpng',strcat(pwd,'\Images\','28EUI_RFANEFF','.png'))
i=i+1;

figure(i)
plot(InputsSI{[6:7 1 8:9],12}-InputsSI{1,12},R_EUISI([6:7 1 8:9],1)*100,'-
o')
ylim([min(R_EUISI(1:9))*100 max(R_EUISI(1:9))*100])
title('EUI = f(Heating SP)')
xlabel('Change in Input (°C)')
ylabel('Change in KPI (%)')
grid on
print('-f29', '-dpng',strcat(pwd,'\Images\','29EUI_HEATSP','.png'))
i=i+1;

figure(i)
plot(InputsSI{[2:3 1 4:5],13}-InputsSI{1,13},R_EUISI([2:3 1 4:5],1)*100,'-
o')
ylim([min(R_EUISI(1:9))*100 max(R_EUISI(1:9))*100])
title('EUI = f(Cooling SP)')
xlabel('Change in Input (°C)')
ylabel('Change in KPI (%)')
grid on
print('-f30', '-dpng',strcat(pwd,'\Images\','30EUI_COOLSP','.png'))
i=i+1;

%%% END Plotting Graphs %%%

function a = celltodouble(b)

if isequal(class(b),'double') == 0
    a = str2double(b)';
else
    a = b';
end

end

% to find reports use find(strcmp(table{1,1}.Var2, 'SS-A'))
```

APPENDIX E : Key Performance Indicators for Energy Performance

The following tables are a collection of Key Performance Indicators

Table E.1 -Whole Building Check Figures & KPIs

Variable	Unit
Whole Building Check Figures & KPIs	
Total Floor Area	m² (ft²)
Maximum Occupants	person (person)
Occupancy	m²/person (ft²/person)
Total Gross Wall Area	m² (ft²)
Total Window Area	m² (ft²)
FDWR	%
Total Roof Area	m² (ft²)
Energy Use	$MWh_{ele,gas}$ ($MBtu_{ele,gas}$)
Energy Use Intensity	$MWh_{ele,gas}/m^2$ ($kBtu_{ele,gas}/ft^2$)
Peak Electric Demand	kW_{ele}
Peak Electric Demand per floor area	W_{ele}/m^2 (W/ft²)
Annual Energy Cost	$
Annual Energy Cost per floor area	$/m² ($/ft²)
Energy Price	$\$/kWh_{ele,gas}$ ($\$/kBtu_{ele,gas}$)
Lighting Peak Electric Demand	kW_{ele}
Lighting Peak Electric Demand per floor area	W_{ele}/m^2 (W/ft²)
Miscellaneous Equipment Peak Electric Demand	kW_{ele}
Miscellaneous Equipment Peak Electric Demand per floor area	W_{ele}/m^2 (W/ft²)

Table E.2 - Heating and Cooling Check Figures & KPIs

Variable	Unit
Heating and Cooling Check Figures & KPIs	
Peak System Cooling Load	kW_{th} (kBtu/hr)
Peak System Cooling Load per floor area	kW_{th}/m^2 (kBtu/hr-ft²)
Peak System Heating Load	kW_{th} (kBtu/hr)
Peak System Heating Load per floor area	kW_{th}/m^2 (kBtu/hr-ft²)
Peak Building HVAC Cooling Load	kW_{th} (kBtu/hr)
Peak Building HVAC Cooling Load per floor area	kW_{th}/m^2 (kBtu/hr-ft²)
Peak Building HVAC Heating Load	kW_{th} (kBtu/hr)
Peak Building HVAC Heating Load per floor area	kW_{th}/m^2 (kBtu/hr-ft²)
Peak Circulation Loop Cooling Load (Chiller Load)	kW_{th} (kBtu/hr)
Peak Circulation Loop Cooling Load per floor area	kW_{th}/m^2 (kBtu/hr-ft²)
Peak Circulation Loop Heating Load (Boiler Load)	kW_{th} (kBtu/hr)
Peak Circulation Loop Heating Load per floor area	kW_{th}/m^2 (kBtu/hr-ft²)
Peak Circulation Loop Heat Rejection Load (CT Load)	kW_{th} (kBtu/hr)
Chilled Water Loop Capacity	kW_{th} (TR)
Cooling Capacity per floor area	m^2/kW_{th} (ft²/TR)
Hot Water Loop Capacity	kW_{th} (kBtu/hr)
Heating Capacity per floor area	m^2/kW_{th} (ft²/kBtu)
Condenser Water Loop Capacity	kW_{th} (kBtu/hr)

Table E.3 - HVAC System Check Figures & KPIs

Variable	Unit
HVAC System Check Figures & KPIs	
Annual HVAC System Thermal Load (Heating)	MWh_{th} ($MBtu_{th}$)
Annual HVAC System Energy Consumption (Heating)	MWh_{ele} ($Mbtu_{ele}$)
System Performance Ratio (Heating)	$W_{th}/W_{ele,gas}$ (Btu/Btu)
Annual HVAC System Thermal Load (Cooling)	MWh_{th} ($MBtu_{th}$)
Annual HVAC System Energy Consumption (Cooling)	MWh_{ele} ($Mbtu_{ele}$)
System Performance Ratio (Cooling)	W_{th}/W_{ele} (Btu/Btu)
Annual HVAC System Thermal Load (Both)	MWh_{th} ($MBtu_{th}$)
Annual HVAC System Energy Consumption (Both)	$MWh_{ele,gas}$ ($Mbtu_{ele,gas}$)
System Performance Ratio (Both)	$W_{th}/W_{ele,gas}$ (Btu/Btu)
Total System Performance Ratio	$kWh_{th}/\$$ ($kBtu_{th}/\$$)

Table E.4 - Chiller Check Figures & KPIs

Variable	Unit
Chiller Check Figures & KPIs	
Annual Chiller Thermal Load	MWh_{th} ($MBtu_{th}$)
Annual Chiller Energy Consumption	MWh_{ele} ($Mbtu_{ele}$)
Chiller COP (Yearly Average)	W_{th}/W_{ele} (Btu/Btu)

Table E.5 - Boiler Check Figures & KPIs

Variable	Unit
Boiler Check Figures & KPIs	
Annual Boiler Thermal Load	MWh_{th} ($MBtu_{th}$)
Annual Boiler Energy Consumption	MWh_{gas} ($Mbtu_{gas}$)
Boiler Efficiency (Yearly Average)	W_{th}/W_{gas} (Btu/Btu)

Table E.6 - Cooling Tower Check Figures & KPIs

Variable	Unit
Cooling Tower Check Figures & KPIs	
Annual Cooling Tower Thermal Load	MWh_{th} ($MBtu_{th}$)
Annual Cooling Tower Energy Consumption	MWh_{ele} ($Mbtu_{ele}$)
Cooling Tower Performance (Yearly Average)	W_{ele}/W_{th} (Btu/Btu)

Table E.7 - Pumping Check Figures & KPIs

Variable	Unit
Pumping Check Figures & KPIs	
Annual CHW Loop Pump Energy Consumption	MWh_{ele} ($MBtu_{ele}$)
CHW Loop Pump Power	kW_{ele} (HP)
CHW Loop Pump Design Flow	L/s (gpm)
Annual HW Loop Pump Energy Consumption	MWh_{ele} ($MBtu_{ele}$)
HW Loop Pump Power	kW_{ele} (HP)
HW Loop Pump Design Flow	L/s (gpm)
Annual CW Loop Pump Energy Consumption	MWh_{ele} ($MBtu_{ele}$)
CW Loop Pump Power	kW_{ele} (HP)
CW Loop Pump Design Flow	L/s (gpm)
Heating Pumping Power Demand	W_{ele}/kW_{th} (Btu/Btu)
Heat Rejection Pumping Power Demand	W_{ele}/kW_{th} (Btu/Btu)
Cooling Pumping Power Demand	W_{ele}/kW_{th} (Btu/Btu)

Table E.8 - Air Distribution Check Figures & KPIs

Variable	Unit
Air Distribution Check Figures & KPIs	
Annual Fan Energy Consumption	MWh_{ele} ($MBtu_{ele}$)
Supply Fan Power Demand	kW_{ele} (HP)
Return Fan Power Demand	kW_{ele} (HP)
Fan Airflow Capacity	L/s (cfm)
Supply Airflow per floor area	L/s-m² (cfm/ft²)
Combined supply and return fan power demand (Design Conditions)	W_{ele}/L-s (10^{-3} HP/cfm)