Towards a universal ranking system for design parameters’ impact on buildings’ lifecycle energy

Rafaela O Panizza* and Mazdak Nik-Bakht

1 Concordia University, 1455 De Maisonneuve Blvd. W., Montreal, QC H3G 1M8, Canada
* Rafaelapanizza@gmail.com

Abstract. The energy consumption of buildings depends on numerous factors that can be categorized in four major categories: geometry parameters; location; attributes of electric and mechanical systems; and behaviour of users. Most of the existing publications on ‘energy-consumption influencing parameters’ test the sensitivity of energy consumption to these inputs in a single building; not making it possible to correlate different projects. The purpose of this study is to evaluate the impact caused by the model when evaluating parameters. In this paper we have studied a series of nine real-world design projects in cold climate (Québec, Canada) to analyse the behaviour of thirteen design parameters. Among the four major categories mentioned above, our scope is limited to geometry parameters (variation in climate, mechanical systems and occupants is excluded). The parameters include building orientation; window-to-wall ratio; overhang size; insulation; and Solar Heat Gain Coefficient (SHGC) for windows. All parameters are analysed using the Morris method for sensitivity analysis and are ranked based on the simulation results. According to the results, window-to-wall ratio and orientation show lower variation among different models while insulation, overhangs and SHGC appear to be more sensitive. The developed analysis is the starting point to what can be a shortcut for designers to control energy consumptions efficiently in new designs.

1. Introduction

With the growth in popularity of more energy efficient buildings, building energy simulation has become a very important step in the building design process. Energy simulations are normally performed by a simulation software, where the main input is the building model file. This includes the building’s geometry, construction materials, electric and mechanical systems, as well as use and operational schedules. This step is usually performed at the early stage, which is when important decisions can still be taken without major additional costs. When performing the simulations, the four major categories that influence energy consumption in the building include geometry parameters, locational factors, attributes of electric and mechanical systems, and behaviour of the user.

Previous studies have presented a diverse pool of sensitivity analysis in the building energy simulation field. Most only use one single model to evaluate geometry parameters that influence the energy consumption. The objective of such studies was to help in the decision making of that building and/or to help in the efficiency of future designs. Efficiency which would be achieved by the knowledge of parameter impact gained by their single cases. However, studies that analyse only one building limit the possibilities for correlation with other projects and other building types [1-6]. Studies have also mentioned that such analysis are limited to each model [7], but these studies have not shown to what extent different models influence the importance of energy influential parameters.

The purpose of this study is to investigate the possibility of developing a universal ranking for energy influential parameters in the province of Québec, Canada. The remaining of this paper is organized as follows. First, review of the methods previously used to analyse sensitivity of building design parameters. Followed by an overview of the used cases. Next, the methodology used from the selection of parameters and their input ranges to output generation. Then, the steps taken by sensitivity
analysis and the comparison between models. And finally, the summarized findings and their limitations are pointed out, along with the next steps for advancing this study.

2. Literature Review
In the field of building energy modelling (BEM), previous studies have showed a comparison between local and global methods for sensitivity analysis. Local methods have the capability of ranking parameters based on their influence with a low cost of computation [4] [6] [8] [9], however, with a large number of parameters, its analysis becomes very time-intensive [2]. However, global sensitivity analysis methods can provide very advanced results but require a very costly computation effort [5] [7] [10]. The Morris Method, however, is an intermediate method due to its cooperation between quality of results and computational cost [7]. To quantify the comparison between these three types of methods in a BEM-based scenario, Kristensen et al. run all three with the goal to help BEM studies with a valid justification for choosing one method the other [2]. Results of this comparison study quantitatively show that, with a much lower computation cost, the Morris method is able to rank parameters similarly to the more advanced global method [2].

The case by case analysis in the literature also showed that the Morris method was the most appropriate [1] [3]. This method is considered a global sensitivity analysis, but its ability to perform both first-order analysis and, if necessary, second-order at a much lower computational cost than more advanced global methods [7]. That is the main reason why this method is widely used in the BEM field. The Morris method [11] is widely used in this field to rank building parameters based on their impact on energy consumption, from identification of important parameters in sustainable buildings [1] to evaluating geometry’s impact on building’s energy performance [3].

The steps for the Morris method include the identification of question to be answered by the analysis (output variable), followed by the selection of parameters to be included in the analysis, then a probability density function for each input parameter must be assigned. These probability density functions usually vary between uniform, lognormal and normal distributions [1]. The following step is where the sampling happens, in the Morris method, the one-at-a-time (OAT) discrete sampling is the used technique. After a global BEM comes in to create the output variables for all samples. The ranking of the parameters will then be found based on the variation occurred between outputs [1].

3. Methodology
In order to cover a wide range of designs, this paper is taking into consideration 9 building models based on real-world projects located the province of Québec. The models were provided to this research by the industry partner, Akonovia. The idea was to cover a wide range of non-residential buildings with different sizes and uses. The model descriptions of each model can be found in Table 1.

| Model# | Stories | Building Type(s) | HVAC System Available? |
|--------|---------|------------------|------------------------|
| 1      | 2       | Healthcare Clinic| Yes                    |
| 2      | 3       | School           | No                     |
| 3      | 18      | Restaurant, Healthcare Clinic, Office, Residential, Parking | Yes |
| 4      | 8       | Office           | No                     |
| 5 & 6  | 8       | Office           | Yes                    |
| 7 & 8  | 8       | Gymnasium, Dining| Yes                   |
| 9      | 4       | Exercise Center, Healthcare Clinic | No |

Based on the literature reviewed, this paper uses the Morris method for sensitivity analysis. As mentioned, this method identifies and ranks the design parameters that influence energy performance in BEM. The first step was to identify the question to be answered by the study. In this case, the analysis focuses on parameters influencing the building energy performance, so the appropriate output variable is the normalized energy use (energy use intensity kBtu/ft²-yr).

3.1 Parameters Investigated
The set of parameters being investigated in this paper were suggested by our industry partner based on their consulting experiences in the field of building energy analysis. Those parameters cover aspects
such as building orientation; window to wall ratio (W/W); overhangs; wall, roof and window insulation; and solar heat gain coefficient (SHGC) of windows.

For each parameter described above, a uniform distribution was defined by 5 discrete values that were selected based on the appropriate ranges to be tested. These ranges were based on minimum requirements for National Energy Code of Canada for Buildings (NECB 2017), values found in the literature, past reports and (in the case of windows’ parameters) availability in the market. All the discrete values tested for each parameter can be found in Table 2. Due to limitations of the system used for alteration of parameters, the window to wall ratio and overhang parameters are divided based pm the facades north (N), south (S), east (E) and west (W).

All tested parameters are analysed one at a time; since there are no co-dependencies between them. This study, however, does not take into the consideration, the compound effect of co-variation of multiple parameters. Overhang size is applied based on projection factor (overhang depth/window height) however, even though it is dependent on size of the existing windows, a modification on window size does not automatically modify the existing overhangs. The U-value and SHGC on the other hand are applied through the modification of a window type, different window types bring different U-values and SHGC. These two values, however, are not necessarily dependent on one another. In this study, 5 different window types with the same SHGC were used to test variation of U-value, and 5 different window types with the same U-value were used to test variation of SHGC.

| Parameter       | Unit       | Discrete Values |
|-----------------|------------|-----------------|
| Rotation        | °          | 0, 90, 180, 270, 360 |
| W/W             | n/a (Ratio)| 0, 0.1, 0.2, 0.3, 0.4 |
| Overhangs       | n/a (Ratio)| 0, 0.4, 0.8, 1.2, 1.6 |
| Roof R Value    | Ft²hR/Btu | 19.99, 31.57, 43.15, 54.72, 66.3 |
| Wall R Value    | Ft²hR/Btu | 19.99, 25.29, 30.59, 35.89, 41.2 |
| Window U Value  | W/m²K     | 1, 2.493, 3.971, 5.067, 6.878 |
| SHGC            | -          | 0.22, 0.28, 0.33, 0.37, 0.42 |

3.2 Output Generation
In order to investigate the impact of parameters variation on the lifecycle energy consumption of buildings, energy simulations were performed using the EnergyPlus simulation tool, via OpenStudio. The variation of parameters was automated with the help of OpenStudio measures. During this study, simulations of all available models were performed in their original form, as well as with the manipulation of all abovementioned parameters one-at-a-time (OAT).

4. Results and Discussion
Based on the results generated by the sensitivity analysis, both range of variation and ranking of influence data were investigated. The goal of the range of variation analysis is to investigate whether the model (i.e. the project) influences how much variation of each parameter controls energy consumption. The ranking analysis, on the other hand, investigates if the model has any significant impact on the order (rank) of contribution of each parameter to the energy consumption.

4.1 Range of Variation Analysis
To investigate whether the range of variations caused by each parameter was similar throughout different models, the lowest and highest values for each parameter for each model were selected. The differences between those values and the mean for each case were collected to form the “low boundary” and “high boundary” sets respectively. The mean of each set of outputs was considered the baseline value (rather than the values in the original models) because some models had input parameters that were outside the tested ranges. The low and high bands were normalized as a percentage of the mean (to be able to compare them among different projects).

Distribution of low and high boundary percentages for each parameter was investigated more closely and most of them showed a relatively normal distribution behaviour. The portion of values fitting within the mean ± standard deviation (SD) and mean ± 2SD ranges are shown for each parameter in Table 3.
Hence, no major anomalies were identified among the parameters studied and the buildings considered (this was expected, given the comparatively low size of our dataset).

Table 3. Low and high boundary analysis

| Parameter | Low Boundary | High Boundary |
|-----------|--------------|---------------|
| CV        | Ratio Within Mean ± SD | Ratio Within Mean ± 2SD | CV | Ratio Within Mean ± SD | Ratio Within Mean ± 2SD |
| Rotation  | 0.907 | 0.78 | 1 | 0.747 | 0.67 | 1 |
| W/W S     | 0.899 | 0.75 | 1 | 0.886 | 0.75 | 1 |
| W/W N     | 0.577 | 0.78 | 0.89 | 0.605 | 0.78 | 0.89 |
| W/W E     | 0.762 | 0.78 | 0.89 | 0.621 | 0.67 | 1 |
| W/W W     | 0.520 | 0.67 | 1 | 0.537 | 0.78 | 1 |
| Overhang S | 0.931 | 0.56 | 1 | 0.900 | 0.56 | 1 |
| Overhang N | 1.471 | 0.89 | 0.89 | 1.509 | 0.89 | 0.89 |
| Overhang E | 1.113 | 0.78 | 1 | 0.953 | 0.44 | 1 |
| Overhang W | 0.872 | 0.67 | 0.89 | 1.119 | 0.78 | 0.89 |
| Roof R Value | 0.919 | 0.78 | 0.89 | 0.966 | 0.78 | 1 |
| Wall R Value | 0.965 | 0.75 | 1 | 1.062 | 0.75 | 1 |
| Window U Value | 1.765 | 0.89 | 0.89 | 1.770 | 0.89 | 0.89 |
| SHGC      | 1.346 | 0.89 | 0.89 | 1.596 | 0.89 | 0.89 |

To analyse the impact of models on the sensitivity of design parameters, the focus was turned into the variance of the distributions. By calculating the coefficient of variation (CV), it is possible to analyse the size of standard deviation in comparison with the mean of each distribution. All parameters showed comparatively large values for coefficient of variation, which can indicate that different models do have some impact on the sensitivity of parameters.

In the next step we analysed the correlations among parameters’ low and high boundaries in different projects. This was meant to show us those parameters which have similar trends of sensitivity in various models. We evaluated Pearson correlation and formed the correlation matrices for low and high boundaries separately. We filtered out both positive and negative correlations below 60% (as weak or no correlation). The results of both low and high boundary data show strong positive correlation between rotation and window sizes in three facades. The only façade that did not show strong level of correlation with orientation parameter was South. That could be since the peak sunlight in the south façade is at midday, regardless of the season, and during that time the interior lighting use will not vary significantly from one building to another. The results also showed strong positive correlations between window sizes in different façades (North, East and West).

The high bound analysis showed positive correlation among insulation of envelope (wall and windows) and roof, which makes sense since they are all working towards retaining the building’s heat. Lastly, the overhangs South, East and West show strong correlation among each other, which can be because those are the three facades that are in the direction of the sun, the sun moves from Southeast to Southwest in the winter and from Northeast to Northwest through the South in the summer, in both cases reaching their midday peak in the South direction.

When it comes to negative correlations, the lower bound did not show any strong enough correlations to be analysed. However, the high bound shows a negative correlation between overhang and insulation of walls and roofs. This correlation shows that the lack of insulation results in great increase in energy consumption, the addition of overhangs will result in a smaller impact than usual. This happens because the lack of insulation causes a building to retain less heat, and the implementation of overhangs helps in the reduction of costs related to cooling. The building cooling savings will not be as significant given that the building is kept cooler due to lack of insulation.

4.2 Rank Analysis
To look into the impact of model on to the order of influence, a ranking of parameters for each model was generated based on the sensitivity analysis results. These rankings were developed based on the size of the range of variation caused by each parameter in one model. The greatest range represents the
parameter with greater influence on the energy performance. In the used BEM, the SHGC and U-value parameters can only be manipulated by changing the window type (they bring both SHGC and U-value with them). Unfortunately, the Building Component Library (BCL), library available to the EnergyPlus simulation tool, has a limited range of windows with a fixed U-value, causing the SHGC range which could be tested, to be very limited. For that reason, the SHGC parameter was not considered in this section of the analysis.

To better visualize these results, the rankings were divided into 3 major groups of: low, medium and high impact and in each model, the parameters were classified by their respective group. High impact group represents positions 1 through 4; low impact represents 9 through 12, and medium impact group includes the positions in between. A summary of the parameters and their respective groups can be found in Figure 1.

By analysing the distribution of groups for each parameter in the above figure, the first thing that can be seen is that W/W parameters have the greatest overall impact on energy performance, with most of their appearances at the high (and few in the medium) impact group. Following those is the roof insulation, which mostly appears at the top but also shows cases of medium and low impact groups. Building orientation in the medium group, with the highest level of stability among different models. It can be confidently said that the impact of this parameter is least sensitive to the project variation. Varying from medium and low, and high and low are the wall and window insulation (respectively). This wide oscillation observed in the impact caused by the window U-value parameter shows that this parameter is the most sensitive to the model.

Similarly to the previous section, a correlation analysis among the parameters’ rankings was performed. This analysis showed that, in different models, rankings for insulation parameters (for windows, roof and walls) are positively correlated to each other, which makes sense since their united goal is to retain indoor heat in the building. Also, on positive correlations are the overhangs, their three most influential facades (South, East and West faces) are highly correlated to each other, the North façade does not show the same level due to its position towards the sun. On the negative correlation side, the main observed relationship is between overhangs and insulation. This happens due to their simultaneous and opposite impact on indoor temperature.

5. Conclusion
Existing literature has shown that sensitivity analysis is a good way to help in the decision-making process of choosing which parameters to be under more attention when trying to save energy during the lifecycle of a building. Previous studies have identified some sensitive parameters in various contexts of specific buildings, which limits the possibility of reusing those results for other projects. The objective of this research was to test whether developing a universal ranking system for impact of design parameters on the lifecycle energy consumption would be feasible. As an initial step, in this paper we examined to what extend the building model influences the impact of design parameters on the energy consumption while ignoring the impact of climate, occupant behaviour and mechanical systems, since it is already known that these are sensitive parameters.

The acquired building models were used to investigate how much the model influences the percentage change caused by deviating parameters’ values, as well as variation of those parameters’ ranking from one model to another. Even-though the analysis was limited to the number of models
investigated, results of this study have shown that the sensitivity of lifecycle energy consumption to building design parameters would depend on the building and its general specifications, however, due to the limited pool of available models, this study failed to discover which attributes are the cause of these differences in behaviour. Based on the results of this analysis, parameters that mainly influence the indoor temperature tend to have a higher variation throughout different models. In the analysis of parameters’ ranking, it is also clear that the overall ranking is sensitive to the models. However, it was noticeable that the parameters involved in the building temperature also show greater sensitivity to the models, while other parameters such as orientation and, in most cases, window to wall ratio show a less variant behaviour towards their positions compared to others. To better investigate the reasoning behind this aspect, in the future work, heating, ventilation and air conditioning systems (HVAC) will be included in the analysis to analyse the relationship between systems and building parameters.

This study has helped in identifying the next steps towards the development of a universal system. These include the analysis of implementation of mechanical systems to enable the development of buildings classes that have similar behaviour towards the sensitivity of design parameters. In the future, and to realize this goal, it would be essential to include uncertainties caused by occupant behaviour, as well as acquire more models to cover a wider range of building types, which would improve the accuracy of the results.

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References
[1] Heiselberg P, Brohus H, Hesselholt A, Rasmussen, Seinre E and Thomas S 2009 Application of sensitivity analysis in design of sustainable buildings Renewable Energy 34 2030-2036
[2] Kristensen M H and Petersen S 2016 Choosing the appropriate sensitivity analysis method for building energy model-based investigations Energy and Buildings 130 166-176
[3] Hemsath T L and Bandhosseini K A 2015 Sensitivity analysis evaluating basic building geometry’s effect on energy use Renewable Energy 76 526-538
[4] Tavares P F A F and Martins A M O G 2007 Energy efficient building design using sensitivity analysis – A case study Energy and Buildings 39 23-31
[5] Capozzoli A, Mechri H E and Corrado V 2009 Impacts of architectural design choices on building energy performance applications of uncertainty and sensitivity techniques Building Simulation, Glasgow, Scotland
[6] Pushkar S, Becker R and Katz A 2005 A methodology for design of environmentally optional buildings by variable grouping Building and Environment 40 1126-1139
[7] Garcia Sanchez D, Lacarrière B, Musy M and Bourges B 2014 Application of sensitivity analysis in building energy simulations: Combining first- and second-order elementary effects methods Energy and Buildings 68 741-750
[8] Ourghi R, Al-Anzi A and Krarti M 2007 A simplified analysis method to predict the impact of shape on annual energy use for office buildings Energy Conversion Management 48 300-305
[9] Sun Y 2015 Sensitivity analysis of macro-parameters in the system design of net zero energy building Energy and Buildings 86 464-477
[10] Mara T A and Tarantola S 2008 Application of global sensitivity analysis of model output to building thermal simulations Building Simulation 1 290-302
[11] Morris M D 1991 Factorial sampling plans for preliminary computational experiments Technometrics 33 161-174