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SHAPING HIGH-RISE TOWERS TO MEET BC ENERGY STEP CODE

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ABSTRACT

Large commercial developments regularly require multi-phase build-outs. Each phase needs to comply with the energy code at the time of permit application which, in British Columbia (BC), can mean different stages of the BC Energy Step Code. These standards are performance-based codes that could be met by thousands of design solutions. In order to identify suitable and desirable design options, we developed and applied a parametric simulation and data sensitivity analysis workflow to explore a vast number of potential choices for a project. Based on this analysis, it is recommended that the design considers the interactions of floor plate, glazing ratio, shade depth at an early stage to produce in a more cohesive design and give weighted attention to different parameters to receive effective results.

INTRODUCTION

The orchestration of building space is the art of the collaborative design process. Historically, it was not uncommon to design a tower's shape based on non-energy requirements only – such as views, apartment size, aesthetics and more – and then calculate the level of required envelope performance and mechanical systems performance. Instead, in this study, we focus on how these performance levels are impacted by the floor plate form and layout, the orientation, the window-to-wall ratio (WWR), and other attributes. In order to reduce the annual energy use with more confidence, we use large-scale data analysis to support informed decision making.

It is a critical cycle because successful load reduction enables the use of high-efficiency and low capacity HVAC systems, which generally allows for a lifetime of low-energy use. Some key recommendations derived from the study are summarized to inform the design.

In traditional preliminary building energy modelling procedures, a focus has been on massing orientation and simple zoning method, which separates building into core and perimeter according to ASHRAE 90.1 Appendix G (American Society of Heating 2011). This is unlikely to cue architects to perform robust and elegant design actions. Also, research has shown that this method could not represent a high accuracy and resolution for energy simulation (Dogan, Saratsis, and Reinhart 2015). However, as the parametric model tools and simulation engines improve, a significant potential is the ability to compare energy performance between different building shape design.

This calls for us to change our workflow in archtecural design from a performance-anaylsis workflow to performance-informed. It requires, among other measures, fundamental thinking of the role of performance simulation to make this change happen. On the other hand, as Canada embarks on a trajectory to significantly reduce the energy consumption of its building stock, there is a greater need to investigate building shape design, which is least understood, especially regarding affordable energy consumption strategies.

The project studied in this paper is viewed as a workflow for parametric demonstration of various performative outcomes according to building space exploration, including exterior shape and interior layout, for the preliminary design phase. It contains sufficient architectural information for energy zoning and enables various iterations with the facilitation of computer-based parametric simulations. Performance can be tracked as designs iterations are initially developed, and then analytically investigated, helping to draw out more comfortable and more sustainable buildings with low energy demand.

BUILDING ENERGY CODE AND PERFORMANCE ANALYSIS

Step Code Requirements in City of Burnaby

As listed in Table 1, the BC Energy Step Code (Step Code), enacted in 2017, is comprised of a series of specific measurable energy targets, and groups them into "steps" that are increasing levels of energy performance. By progressively adopting one or more steps, a local government can increase the building performance requirements of its community (Governments 2019). Different stages of Step Code have incremental requirements for building Thermal Energy Demand Intensity (TEDI) and Total Energy Use Intensity (TEUI) independently.

The studied project is located in Burnaby, BC, where the BC Energy Step Code applies (Services et al. 2018). The City of Burnaby adpopted Step 1 in November 2018 and Step 2(if project is combined with low-carbon energy system and GHG limits) and 3(if project is NOT combined with low-carbon energy system and GHG limits) in July 2019. As this project has extensive phases for development for several residential towers in the coming decades, it will be using Step 2 for Phase 1 and Step 3 for Phase 2 to 4. Presumably, the city will adopt even higher steps during the multi-phase development of this project. It is necessary to discuss how to meet these requirements at different stages through different strategies at the beginning of this project.

Table 1 Step Code requirement for residential tower in City of Burnaby

STEP	TEDI, KWH/ (M^2 ·YEAR)	TEUI, KWH/ (M^2 ·YEAR)	ADOPTION TIME
1	Energy modeling and air tightness testing		November 2018
2	45	130	July 2019
3	30	120	July 2019
4	15	100	Future

Parametric Energy Simulation

In recent years, great advances have been made in parametric simulations for whole-building energy analysis. They are now routinely used in the building design process for new construction. They have been helpful in guiding the architect in the early stages of design to optimize geometric aspects.

For example, Wang optimized facade design in terms of building materials, window size and orientations by using EnergyPlus based parametric simulations(Wang, Liping, Julie Gwilliam 2009). Anton analyzed building shapes in terms of solar radiation, solar access in a complex urban environment and daylight for skylight design by using parametric modelling in EnergyPlus, Radiance, Daysim, and OpenStudio. (Anton, Ionut 2015). Li investiaged the energy impact of varying the building's window-to-wall ratio by using EnergyPlus and MEESG. (Li, Ziwei, Borong Lin, Shuai Lv 2013). Kim studied ciomplex kinetic facades with parametric BIM-based energy simulations. (Kim, Hyoungsub, Mohammad Rahmani Asl 2015). Qingsong optimized window areas in different orientations with the aim of minimzing energy consumption while maximizing daylight illuminance for an office building in Beijing, China with Ladybug. (Qingsong, Ma 2016).

Parametric simulations have also been used to analyze energy efficiency measures (EEMs). For example, Attia used EnergyPlus based parametric simulations to optimize passive (e.g. orientation, geometric features, envelope properties) and active (e.g. HVAC, ventilation, photovoltaic, solar thermal) building elements, to support decisions for early-stage design of zero-energy buildings (Attia, Shady, Elisabeth Gratia, Andre De Herde 2012). Parker used the OpenStudio Parametric Analysis tool to analyize EEMS and to suggest a workflow with the tool. (Parker, Andrew, Kyle Benne, Larry Brackney, Elaine Hale, Dan Macumber, Marjorie Schott 2014). Al-ajmi performed a parametric sensitivity analysis of EEMs relating to building envelope, window type, size and direction, infiltration, and ventilation using TRNSYS-PREBID. (Al-ajmi, Farraj, Mohammad T.A. Alkhamis 2017).

In this reviewed research, there is readily improved interoperability between the parametric model tools and simulation engines. It enables the significant ability to compare energy performance between different building forms and other properties to demonstrate and inform decision making. But there remains a research gap, in building layout scale, of how to integrate computational design platforms into the design process to generate a more diverse and unique population of building geometric and thermal attributes. This could provide the architect with design options with a greater balance between performative outcomes of a computational model and design independence.

SIMULATION METHODOLOGY

Workflow Setup

Regarding the changing Step Code compliance at different phases of the project, this paper deploys parametric simulation and data sensitivity analysis to explore a multi-objective design process that researches a vast number of potential design solutions. It is anticipated that the large-scale data analysis could help to inform decisions on how to reduce the annual energy end uses with more confidence and deeper insight. The workflow is divided into four steps (Figure. 1).

The first step is to attain geometry information. The target is to translate a model from a 3D modelling software, such as Revit or IESVE, to a simple space volume into Rhino. The acceptable import file types for Rhino include DWG, SKP, GBXML etc. Next, in Rhino, zone volume, window, and shade are set up based on the design with geometry check. In this study, the building geometries are set up in Rhino/Grasshopper (Robert McNeel & Associates. 2018).

The second step is to input model parameters. Geometry information obtained from Rhino/Grasshopper is directly inputted into the Ladybug tool (Roudsari 2015). Weather data, loads, schedules, and other parameters are inputed as well. The building performance model is then sent to the simulation engine to prepare various simulations, including weather analysis, energy simulation, daylight simulation, and CFD simulation. In this study, models are simulated using the EnergyPlus (Janssen, Chen, and Basol 2011).

Thirdly, the main computer manually or automatically distributes the patch files to other computers to undertake parallel simulation simultaneously. There are readily some tools to deploy, such as Colibri (Core.thorntontomasetti.com, 2019). The last step is visualization and analysis. All simulated results are recorded in the form of a data.csv file and a series of images. The data can be uploaded to the parallel coordinate platform. The parallel coordinate analysis provides us with the opportunity to visually analyze the large data set generated by parametric simulations and interact with the result. Design solutions can be identified under certain constraints through filtering such as Energy Step Code performance targets. Furthermore, the data can be imported to JMP to undertake the analytical analysis. This could navigate decision-makers to put more attention to the parameter(s) that matters more for the TEDI, cooling demand, or TEUI.

Model Inputs & Assumptions

According to the design requirement for the example high-rise project, the simulated floor plate area is 702 m^2 with different shape complexity and floor layouts, including square, complex square, rectangle with inside core and rectangle with outside core (Figure 2 and 3). These four shapes are commonly used in the high-rise residential building design in BC.

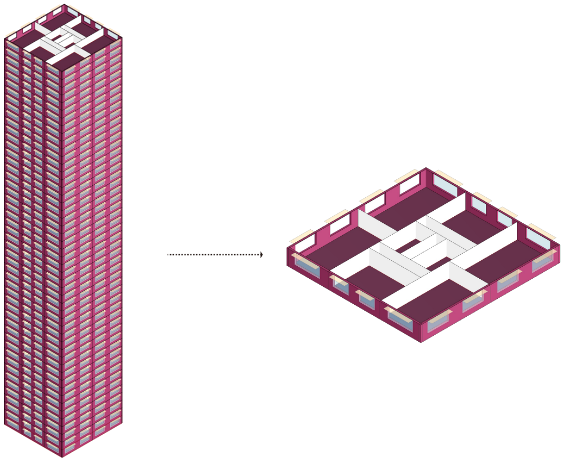


Figure 2 Extract a typical residential floor plate

There are two comparative questions set up through these four shapes. The first question is the influence of different floor footprints through comparing square, complex square and rectangle with central core floor types. The second question investigates the impact of different floor layout, such as moving the stair/elevator core from inside to outside, through comparing rectangle

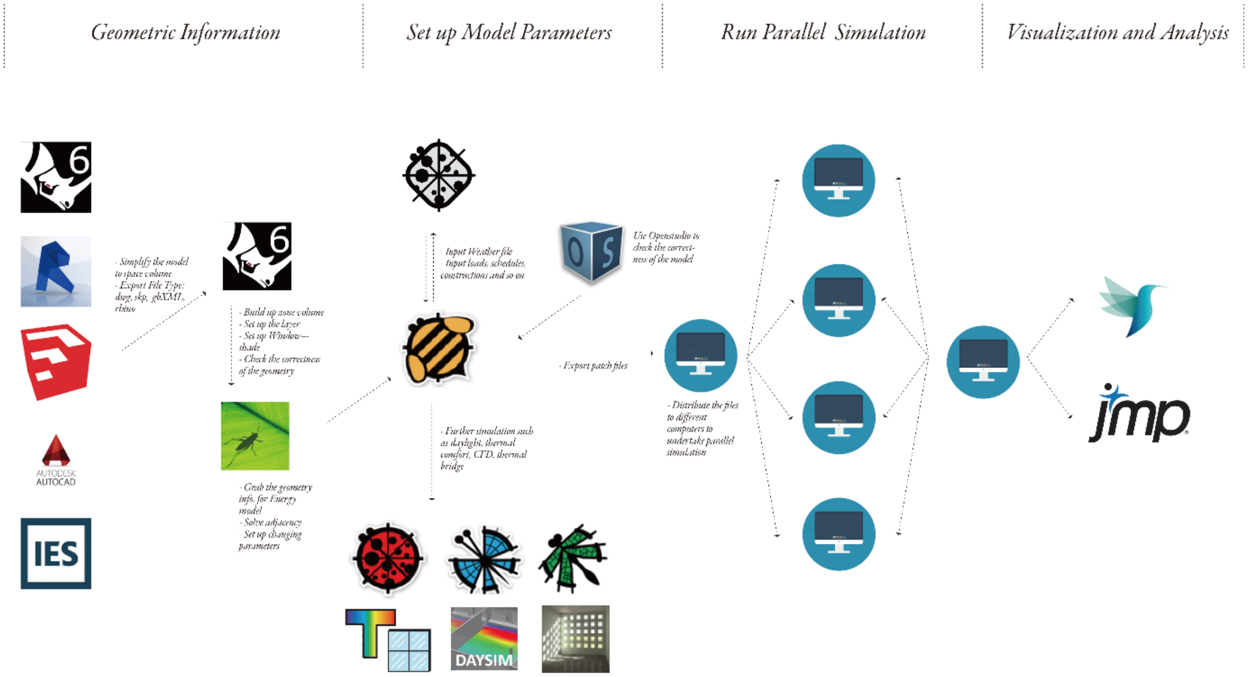
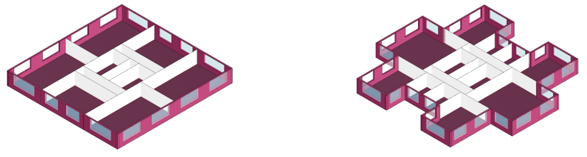
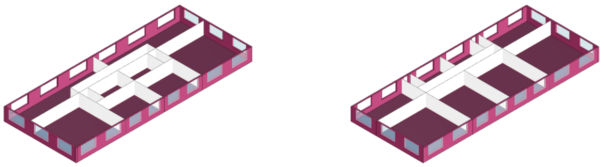


Figure 1 Parallel Simulation Workflow

with central core and rectangle with outside core floor types. Each floor type has the same area of stair and elevator shaft and a slightly different residential area due to the changing corridor area. The elevator shaft has no cooling/heating. The basic building orientation is facing to the south. Other inputs consist of orientation, overall window-to-wall ratio (WWR), horizontal shade depth (metres), wall R-value (^{o}K·ft^{2}/Btuh) and window U-value (Btuh/ ^{o}K·ft^{2}). Detailed variables are presented in Table 2.



Square *Complex square*



Rectangle with inside core *Rectangle with outside core*

Figure 3 Floor layout Inputs, including square, complex square, rectangle with inside core and rectangle with outside core (from left to right and top to bottom)

Table 2 Summary of variables(except floor layout Inputs)

INPUTS	1	2	3	4	5
Orientation, degree	0	30	60	90	
Overall WWR, %	30	40	50		
Horizontal Shade Depth, m	0	0.4	0.8	1.2	1.6
Wall R-value, ^{o}K·ft^{2}/Btuh	10	15	20	40	60
Window U value, Btuh/ ^{o}K·ft^{2}	0.14	0.20	0.32	0.45	

In this study, the model does not include HVAC systems but uses “ideal air loads”. Heating recovery ventilation is set as 65%, which is a common practice in the current market. Outdoor air “economizer mode” is turned off, meaning that the potential for “free” cooling through increased outside air rates when temperatures allow, is not considered in this study. The study evaluates a high-rise design, so roof and floor thermal performance have a negligible impact on overall energy needs, though they still are important for other reasons (i.e. comfort, durability). Other simulation settings, such as heating /cooling schedule, setpoints, equipment/lighting loads and occupancy schedules, comply with the City of Vancouver modelling guidelines version 2.0 (City of Vanouver 2018) as required by the BC Building Code.

Simulation Outputs

The simulation output includes three categories: 1) TEDI, which represents the total annual heating energy demand for space conditioning and conditioning of ventilation air; 2) Cooling Demand Intensity, which is the cooling energy needed in the space, under the scenario that outdoor air economizer and natural ventilation is turned off; and 3) TEUI, which is the sum of all heating energy, cooling energy, lighting, equipment energy and domestic hot water. The energy for domestic hot water is calculated to be 26.6 kWh/m^{2}/year without applying any reduction strategy as per Vancouver Energy Modelling Guideline.

DISCUSSION AND RESULT ANALYSIS

After running a parametric energy study with 5760 simulation cases, the huge amount of results data is presented in a parallel coordinates graph. Using this graph, an optimal floor plan type that meets the energy code targets can be found. In the second step, numeral variables are then evaluated in statistical tools to undertake sensitivity analysis through JMP tool(Anon, 2019).

Parametric Design Analysis

Firstly, the number of results complying with different steps of Step Code are laid out in Table 3 for each floor plate type respectively. It shows that Step 2 of the Step Code can be met by most floor plan type, WWR, shade depth and other envelope construction choices, with an overall passing rate at 96.5%. It demonstrates that if the design follows most of the prescriptive design and construction choices Table 2, there is no worry of breaching the code. Among all the floor types, the rectangle shape with outside core and square floor type ranks the highest while rectangle shape with central core ranks the lowest.

Secondly, for Step 3, the target is TEUI Maximum = 120 kWh/ (m^{2} ·year), TEDI Maximum = 30 kWh/ (m^{2} ·year). Out of the 5760 results, 4615 cases could meet the requirement at a percentage of 80.1% (see Table 3). However, the passing rates for different floor plate types have a significant difference. The individual passing rate for square shape, complex square shape, rectangle shape with stair core inside and rectangle shape with stair core outside is 94.0%, 78.5%, 50.5% and 97.6% respectively. For rectangle shape with stair core outside, except when higher window U-value combined combine with no shade resulting in large cooling demand, most choices can meet Step 3 (Figure 4). Whereas, Step 3 eliminates the lower insulation options from the complex square shape and the rectangle shape with the central core (Figure 5).

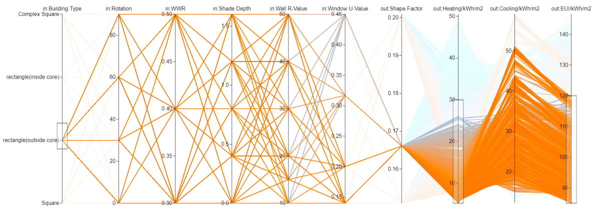


Figure 4 Step 2 for rectangle shape with outside core

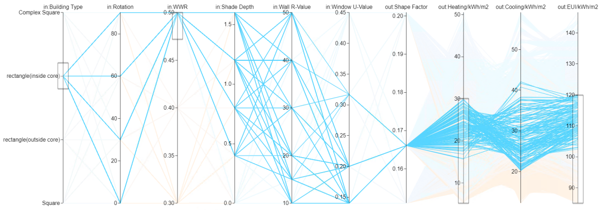


Figure 5 Step 2 for rectangle shape with central core

Thirdly, Step 4 sets the target for residential buildings at TEUI Maximum = 100 kWh/ (m^2 ·year), TEDI Maximum = 15 kWh/ (m^2 ·year), which is a very stringent goal and with its TEDI requirement being equivalent to the Passive House (PHI 2018) requirement. Out of the 5760 results, 1325 cases could meet the requirement at a percentage of 23.0% (Table 3). Step 4 favours a more compact floor type within the square shape or the more strategic floor layout with the core on outside of the building. The separate passing rate for square shape, complex square shape, rectangle shape with stair core inside and rectangle shape with stair core outside is 27.9%, 19.1%, 0.1% and 44.9% respectively. This means that, for the rectangle shape with central core, there are only two cases fulfill the Step 4 requirement. This happens only when the rotation is at 90 degrees, WWR is at 30%, shade depth is at 0.4 meters, wall R-value is at 50 and window U-value is at 0.14. Another case is when the rotation is at 60 degrees, WWR is at 40%, shade depth at 1.6 meters, wall R-value at 50 and window U-value at 0.14. These two cases expect a significant higher building envelope thermal performance, which could result in higher cost and construction requirements (Figure 6).

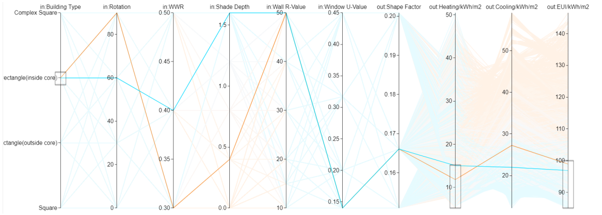


Figure 6 Step 4 for rectangle shape with the central core

From the parametric energy study, results are mapped out that floor types significantly impact energy performance. The articulated square floor plan has more envelope area for the same floor area of living space (shape factor). This results in poor energy performance due to the increased heat transfer area. If the floor shapes are well-designed however, comparing the articulated square and the rectangle, we find that a higher shape factor does not necessarily result in less optimal energy

Table 3 Feasible Options for Step Code Steps

STEP	OVERALL PASSING RATE	FLOOR TYPE	FEASIBLE CASES	SEPARATE PASSING RATE
2	96.5%	Square Shape	1437	99.7%
		Complex Square Shape	1363	94.7%
		Rectangle Shape (inside core)	1321	91.7%
		Rectangle Shape (outside core)	1440	100%
3	80.1%	Square Shape	1353	94.0%
		Complex Square Shape	1130	78.5%
		Rectangle Shape (inside core)	727	50.5%
		Rectangle Shape (outside core)	1405	97.6%
4	23.0%	Square Shape	402	27.9%
		Complex Square Shape	275	19.1%
		Rectangle Shape (inside core)	2	0.1%
		Rectangle Shape (outside core)	646	44.9%

performance. The impact of different floor layouts can be understood by comparing the rectangular shape with a central core option between another option where the core is on the orth side of the building. The rectangular floor plan with the core in the center can only meet Step 4 requirements with two variations of very high requirements in all other parameters. Conversely, the rectangular floor plan with the core on the north façadecan meet Step 4 with the largest range of options. This is largely due to the fact that the stair core has a lower heating setpoint, and its thickness has a high thermal mass, while not limiting passive solar heating on the south façade.

The analysis shows that the design cooperation of floor plate type, WWR, shade depth should be considered at an early stage to result in a more cohesive design. As the study demonstrates, the higher requirement of energy code does not necessarily exclude high WWR or low wall R-value options. In some cases, less insulted walls (R-10) could still be used with an appropriate choice of floor plate type and other considerations.

Multivariate Sensitivity Analysis

In the second step, the statistical method is applied to explore how relevant and significant the variables relate to each other. Since the floor type is not a numerical parameter, it is not analyzed at this part.

In this study, the JMP program is deployed to undertake the statistical study regarding two metrics. The first metric is correlation, which is a statistical factor of assessing a possible two-way linear association between two continuous variables. The second is line of fit, which finds the line that fits the points to minimize the residual sum of squares. Here the one-degree line is used due to the limit of time and scope. For example, Figure 7 plot out the line of fit and correlation between inputs and TEDI.

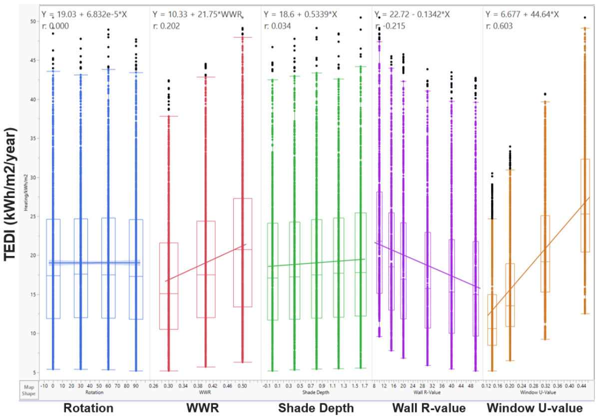


Figure 7 Sensitive Analysis for TEDI

The results from the sensitivity analysis are summarized in Table 4. Firstly, the table presents that, in order to effectively decrease TEDI, more attention shall be put to

Table 4 Sensitive Analysis on TEDI, cooling and TEUI

TARGET	VARIABLES	CORRELATION	LINE OF FIT
TEDI	Window U-value	0.603	6.677 + 44.64 * Window U-Value
	Wall R-value	-0.215	22.72 – 0.1342 * Wall R-Value
	WWR	0.202	10.33 + 21.75 * WWR
	Shade Depth	0.034	18.6 + 0.5339* Shade Depths
	Rotation	0	19.03 + 6.832e-5* Rotation
Cooling	Shade Depth	-0.729	36.86 – 11.09 * Shade Depth
	WWR	-0.215	5.979 + 55.03* WWR
	Window U-value	-0.242	32.85 – 17.57* Window U-value
	Rotation	0.051	27.4 + 0.01311 * Rotation
	Wall R-value	0	28 – 0.000299* Wall R-value
TEUI	WWR	0.559	76.21 + 76.78*WWR
	Shade Depth	-0.533	115.4 – 10.56 * Shade Ddepth
	Window U-value	0.286	99.43 + 27.07 * Window U-value
	Wall R-value	-0.169	110.6 – 0.1345* Wall R-value
	Rotation	0.039	106.3 + 0.01318* Rotation

decrease window U-value and WWR whereas it is not cost-effective to add the wall R-value if it is already high. Furthermore, shade depth does not have a significant negative impact on TEDI. This finding is a interesting as shade is always considered to largely impact sunlight during winter. However, in winter for this location, the cloud cover is always high due to the long rainy period, which mitigates the effect that shade will block out solar energy in winter.

Secondly, if we want to decrease cooling, the designer needs to increase the shade depth or decrease the WWR to get a significant decrease on cooling intensity rather than increasing the wall R-value or changing the window U-value.

Thirdly, with the aim of reducing TEUI, the designer could try to increase the depth of the shade, decrease the WWR and window U-value to get a more effective influence on TEUI rather than increase the wall R-value.

Fourthly, the building orientation does not have a big influence on energy performance, at least, in this case. This is possibly because the WWR is homogenous in each façade and the floor shape is almost symmetrical in this study. In principle, the orientation of the building shall influence the solar radiation on the building façade which willinfluence the resulting performance. Due to the time limitation, the changing orientation with different WWR in different facades of the building is not analyzed in this study but could be further researched.

This part shows that to effectively decrease the TEDI, a decrease in window U-value and WWR is much more effective than adding insulation to the wall when the R-value is already relatively high. This contributes to reducing the EUI.

CONCLUSION

As local municipalities are beginning to adopt increasingly stringent energy performance targets, it will be contingent on designers to identify building forms that can satisfy indoor environmental quality requirements as passively as possible. Also, analyzing the giant database generated by building parametric simulation tools is critical to finding a cost-effective design approach. This study explores the use of computational tools for design of projects complying to the BC Step Code. It evaluates whether the integration of optimization algorithms and building performance simulation tools in the architectural design process can realize markedly affordable low-energy building designs in comparison to their typical use in the engineering design process. Besides, more inputs and outputs could be added as the design develops into detail, such as mechanical system parameters and costs.

However, here are limitation to this study as it cannot focus on every changing parameter. For example, the shade could possibly create thermal bridges for building envelope, which will result in a degraded wall R-value. The R-value input used in this study is the effective R-value, which takes the thermal bridge impact into account. This model also only represents the main space types of a residential building, but some space types such as the lobby, swimming pool and mechanical rooms are not modelled here. These space types may affect the results, but the principles explored in this study are still valid as these additional space types only occupy a small amount of area in the whole building. Lastly, this study does not intend to be a definitive report to describe the BC Step Code compliance through 5760 cases. Rather, regulation officers, developers, citizens and design consultants should sit together to use this study to perform a preliminary analysis of the possible design choices.

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