BUILDING ENVELOPE ENERGY OPTIMIZATION FOR MULTI-UNIT RESIDENTIAL BUILDINGS

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ABSTRACT

This paper investigates the impact of building envelope design on the energy performance of multi-unit residential buildings (MURBs). Using calibrated energy models by RDH Building Engineering Ltd. (2012) as a guide, a base reference model for multistory residential building envelopes is developed, and subsequently altered, to create an array of near-optimal energy performance design options. An exhaustive parametric study, employing parallel computing, simulates all possible design combinations for eight design parameters. Working from the database of results, correlations are made between energy performance and the configuration of envelope components. For this study on Vancouver MURBs, simulations are used to explore the effects of various envelope designs on heating, cooling, and solar generated energy at the suite level. In addition, analysis is conducted to delineate trends and identify variable interrelatedness that influence the energy consumption and generation potential associated with the building envelope.

By aggregating individually simulated suites together, the energy performance of a floor of a building is examined. Results show that by optimizing building envelope parameters, combined heating and cooling loads can be reduced by up to 81%, and net energy consumption reduced by up to 49%, compared to the base case.

INTRODUCTION

Residential buildings in Canada consume about 17% of primary energy (Energy and Mines Ministers' Conference 2012). The compact geometry of MURBs plays an important role in their energy performance, generally requiring up to 50% less heating per square meter compared to a single-family 2-storey house (Hachem et al. 2014).

Building envelope decisions are made during the early stages of the design process, and play an important role in the energy performance of buildings (Hemsath 2013). Designers should use their experience, together with performance feedback, to find near-optimal solutions for high performance building designs (O'Brien et al. 2009). Assuming that there will continue to be diversity in the visual, functional and structural aspects of multi-unit residential buildings, it is unlikely that a single optimized envelope design will be universally adopted. It is therefore essential to have efficient and effective support tools for

designers to find near-optimal solutions that balance the various requirements for their specific projects (Wang et al. 2005). It is important, when evaluating near-optimal solutions, to understand the sensitivity and interrelatedness of input variables with respect to desired outcomes.

Parametric studies are conducted using various methods, including sequential search, genetic algorithms, and exhaustive search methods. In a review of computational optimization methods, Evins (2013) found that sequential search and genetic algorithms were the most popular techniques for optimizing energy, cost, and comfort for sustainable building design. The sequential search method optimizes each parameter individually while holding the other parameters constant. The effectiveness of this method is influenced by the order that parameters are optimized, and does not take into account the interrelatedness of variables. Genetic algorithms find globally optimized solutions, based on a defined cost function, but do not provide flexibility to find near-optimal solutions. Samuelson et al. (2016) found that the exhaustive search method was more computationally intensive than other methods, but provided the most flexibility for analysis. It is argued in this paper that for the purposes of responding to the iterative, flexible nature of the design process to find near-optimal solutions, it is more important to have results for all possible outcomes of a defined design space than it is to effectively find single optimized scenarios.

Building designers are often challenged to integrate energy performance into more traditional architectural requirements for aesthetic, function, and structure (Wingate 2012). Previous studies have identified a variety of building envelope parameters that affect building energy performance. Christensen et al. (2006) identifies geometric design parameters such as thermal resistance for walls/roof/floor, building orientation, infiltration rates, thermal mass, window size/type, and photovoltaic (PV) potential. RDH Building Engineering Ltd (2012) identified architectural input parameters associated with energy performance, including wall RSI, window size/type, and infiltration rates. Others have identified a combination of geometric and architectural variables as high-importance parameters including building orientation and shape, window size/type, wall/roof RSI, and passive solar shading controls (Attia et al., 2012).

The objective of this paper is to investigate the impact of building envelope design decisions on the energy performance of MURBs. An exhaustive parametric study is conducted to delineate a population of design options, based on building envelope parameters that affect energy consumption and renewable energy generation potential. An optimized scenario is presented, along with analysis of near-optimal solutions that provide insight into designing high energy performance buildings.

METHODOLOGY AND SIMULATIONS

The methodology in this paper is subdivided into four sections. First, a description of the base case is provided, followed by details of the simulations and parametric study. Then, the definition of the lowest net energy (LNE) scenario is provided, followed by a discussion about near-optimal solutions.

Base Case

Figure 1 shows the geometry for eight suite types, each with an area of 90m^2, making up a single floor plate at mid-level height in a MURB. The corner suites (SW, SE, NW, NE) have double the exterior surface area compared to the single faced suites (N, S, E, W), with a corresponding doubled window area. The central

area, labelled 'C', represents the mechanical and corridor space of the building, and is not included in the simulations for the sake of simplicity.

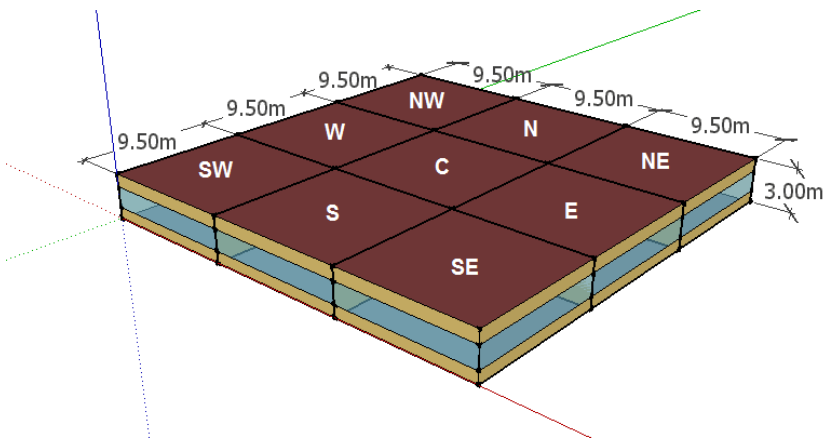

Figure 1: Geometry of the eight unique suite types of the base case, and common area 'C'.

The base case is built to represent typical MURB construction in the Vancouver area. This base case provides the reference against which the optimized cases are compared to quantify improvements in the design. Table 1 shows the simulation input parameters that are used in the study, along with the source for each value. Infiltration rates are defined with units of air changes per hour (ACH) for the average suite.

Table 1: Base case parameter values.

Parameter	**Value**	**Units**	**Source**
Plug Load	5.6	W/m^2	RDH, 2012
Suite Lighting Load	6.5	W/m^2	NRCAN, 2011
Infiltration Rate	0.572	ACH (5Pa)	RDH, 2012
Ventilation Rate	0.35	ACH (5Pa)	ASHRAE, 2003
Cooling Setpoint	24	°C	NRCAN, 2011
Heating Setpoint	18-22	°C	NRCAN, 2011
People Load	1.9	Persons per suite	CMHC, 2013
Suite Area	90	m^2	RDH, 2012
Thermal Mass	10cm concrete slab with carpet		Athienitis, 1997
Window to Wall Ratio	40	%	NRCAN, 2011
Overall Wall RSI	3.6	m^2K/W	NRCAN, 2011
Overall Window U-value	2.2	W/m^2K	NRCAN, 2011
Window SHGC	0.41	dimensionless	Carmody and Haglund, 2012
Storey Height	3	m	Modified from RDH, 2012
Occupancy Schedule		fractional	NRCAN, 2011
Suite Lighting Schedule		fractional	NRCAN, 2011
Plug Load Schedule		fractional	NRCAN, 2011
Weather Data	Vancouver	.epw file	U.S. Department of Energy, 2016
PV System Efficiency	12	percent	Hachem et al., 2013
Heat Recovery Efficiency	65	percent	NRCAN, 2011

Energy Type	electric		
Heat Pump Efficiency	4.0	average COP	NRCAN, 2002
Domestic Hot Water Efficiency	2.62	KWh/occupant/day	Sartori et al., 2010

Parametric Study

An exhaustive parametric study is conducted to investigate every combination of eight input variables related to the building envelope design for MURBs. Discrete variations are provided for each parameter, representing the range of possible design variations related to energy performance. The results from the simulations are collected into a database for analysis. The following sections go into greater detail about the simulation engine, parametric study, definition of design parameters, response variables, and optimization strategy that is used in the analysis.

Simulations and Parametric Workflow

EnergyPlus™ v8.5 is selected to evaluate the annual energy performance of building envelope designs, using the Vancouver weather file (U.S. DOE 2015). EnergyPlus™ parameter value substitutions for the parametric study are conducted following the methodology of jEPlus software (Zhang 2012). This software allows the user to define variables in the EnergyPlus™ input file, which are then subsequently substituted with alternative values to be simulated individually. In this study, an input data file is created for each unique combination of parameters, simulations are completed, and annual results aggregated into a database.

Suites within the building are simulated individually, assuming that the exterior wall interacts with the outdoors, and interior walls/ceiling/floor are adiabatic. This assumption is meant to represent the energy performance of a floor mid-height in the building, where all interior zones are maintained at the same thermostat settings.

Studied Input Parameters

The discrete parameter substitutions that are made to the base case scenario are listed in Table 2. Parameters include wall RSI, thermal mass represented by a concrete slab, infiltration rate, horizontal shading overhangs, vertical window fins, window U-value and solar heat gain coefficient (SHGC), window to wall ratio (WWR), and façade orientation. A sufficient number of parameter variations are included to define trends, while staying within the computational limitations of the study.

Table 2: Envelope parameters and values considered in this research. (* indicates base case values)

Parameters	**Units**	**Values**							
Wall RSI	m^2K/W	1.76	3.6*	6.2	8.8				

Thermal Mass		10cm slab with carpet *	10cm slab	20cm slab					
Infiltration Rate (4 Pa)	ACH	0.03	0.09	0.27	0.57*				
Overhang: Window Ratio	%	0*	33	66	100				
Fin: Window Ratio	%	0*	16	50	100				
Window U-value/SHGC	W/m2 K	0.77 / 0.41	1.08 / 0.18	1.14 / 0.41	2.2* / 0.41*	3.57 / 0.26	3.63 / 0.38		
Window:Wall Ratio	%	20	40*	60	80				
Façade Orientation		SW	S	SE	W	E	NW	N	NE

The range of wall RSI values is chosen to provide one option below the NECB 2011 prescriptive value, and an upper limit based on the analysis by RDH (2012). Thermal mass values are chosen to investigate the effects of doubling the typical concrete slab thickness (Athienitis 1997), and adding a layer of carpet. The range of infiltration rates is chosen with the Passivhaus requirement of 0.03 ACH (5Pa) (Passivhaus Institut, 2015) as the lower limit, and the typical MURB infiltration rate of 0.572 (RDH, 2012). Infiltration rates are defined for the average suite, and do not take into account the varying external surface area of the corner and single-faced suites. The range of horizontal shading overhang depths, measured as the perpendicular distance from the wall, is chosen from 0m (no shading) to 100% of the window height, based on analysis by Rajput et al. (2014). To facilitate the variable substitution method used in the parametric study, the window is subdivided into six sections, each 1.6 m in width, with two bordering vertical fins for each section. The range of vertical fin depths, measured as the perpendicular distance from the wall, is chosen from 0m (no shading) to 100% of the width of each window section. All combinations of overhang and fin depths are included in the study, including the complete removal of each. Four WWR values are selected to provide enough sampling points to adequately define a trend.

The window U-value/SHGC values shown in Table 2 are associated with the window assemblies shown in Table 3. The NECB 2011 minimum window is the prescribed U-value under NECB 2011 (NRCAN 2011) for Vancouver with SHGC and visible transmittance (VT) based on the triple, low-e, high SHGC, argon filled window.

Table 3: Window assemblies used for the base case and parametric study (*-Carmody and Haglund 2012)

Assembly	**Frame**	**U-Value**	**SHGC**	**VT**
Double, low-e, high SHGC, argon filled*	Aluminum	3.63	0.38	0.61
Double, low-e, low-SHGC, argon filled*	Aluminum	3.57	0.26	0.49
NECB 2011 minimum U-value window (NRCAN 2011)		2.2	0.41	0.50
Triple, low-e, high SHGC, argon filled*	Improved non-metal	1.14	0.41	0.5
Triple, low-e, low SHGC, argon filled*	Improved non-metal	1.08	0.18	0.37

Quadruple, low-e, high, SHGC, krypton filled*	Improved Non-metal	0.77	0.41	0.36

Response Variables

The main response variables are heating and cooling loads, heating and cooling energy, electrical loads, and PV energy generation. Heating and cooling loads account for heat transfer mechanisms through the building envelope, solar heat transfer, and internal heat gain sources (e.g. people, lights and appliances). These heating and cooling loads are converted into energy variables with the assumption that mechanical heating and cooling are supplied by a heat pump with coefficient of performance (COP) equal to four. PV generation is measured by assuming the best case scenario that 100% of the opaque wall and shading overhang surfaces are covered with solar cells capable of converting sunlight into electrical energy.

The simulation results for each design are used to evaluate the energy consumption and energy generation outcomes of the combined parameters. It is important to note that heat gain or loss can be either beneficial or costly depending on the interior temperature relative to the desired thermostat range. For example, solar heat gain is beneficial to offset mechanical heating during colder months, but contributes to overheating of the suite during the summer. Similarly, heat gain from internal loads (occupants, lighting, and equipment) is either a benefit or a cost depending on the interior temperature scenario.

Net energy is calculated for each suite based on the heating energy, cooling energy, electrical equipment, water heating energy, and PV generation using this formula:

$$Net\ Energy = Heating + Cooling + Lighting + Equipment + Water\ Heating - PV$$

Electrical loads are associated with lighting and suite electrical equipment, excluding the heat pump. Lighting power density, electrical equipment, and domestic hot water heating requirements are unchanged from the base case. Energy requirements for common areas (i.e.: corridor heating and lighting) and centralized services (i.e.: elevators, lobby) and the rooftop solar energy generation for the building are not included in the calculation.

Optimization Strategy - Extreme Scenario

In this paper, an extreme scenario is selected from the parametric study results to illustrate the lowest possible net energy consumption based on the available inputs and assumptions. Since the parametric study is conducted at the suite level, there are eight extreme scenarios representing the building envelope design of the eight suite types (N, S, E, W, NW, NE, SW, SE). Although it is not utilized in this paper, a variation on the LNE consumption is also possible where the design parameters for the eight suites are forced to be the same. The extreme scenario achieves the objective of minimizing net energy consumption, but is likely not truly optimal in a general sense (e.g. cost vs. benefit) due to, in some cases, diminishing returns for parameter improvements.

Near-Optimal Solutions

It is important to find a diversity of near-optimal solutions that allows flexibility in design. Geometric parameters, such as WWR and added façade elements (e.g. fins, overhangs) are likely to be altered from the optimal configuration to respond to design considerations not associated with energy performance. Adverse impacts of geometric constraints can be compensated for by selecting complementary parameters, such as the thermal resistance of windows and walls, and thermal mass to find a near-optimal solution.

An important aspect of identifying near-optimal solutions is to allow for an asymmetric envelope design for the building. Exploiting the advantages of each façade with tailored parameters can contribute to higher energy performance for the entire building, since it removes the need to find a compromise that is adequate for all orientations.

In this paper, analysis is conducted to show the diversity of envelope options that are available when targeting near-optimal energy performance designs.

RESULTS

The following discussion of results uses the LNE extreme case in the parametric study as the starting point to examine various near-optimal solutions. The extreme case identifies the combination of input parameters that result in the best possible energy consumption and renewable energy generation outcomes for the parametric study. By altering the extreme case, near-optimal solutions are highlighted that offer design flexibility without sacrificing energy performance to a significant degree. Input parameters that are analyzed include WWR, overhang and fin depth, wall RSI, window type, and infiltration rate.

The study parameters that make up the LNE case are shown in Table 4. Values for wall RSI and overhang depth are consistently set to the highest levels available in the scope of this parametric study, while values for infiltration, fin depth, and window size are minimized. Quadruple pane windows are selected for the N, SW, S, SE suites, and the remaining suites have triple pane windows with a slightly lower U-value and significantly lower SHGC compared to the quadruple pane windows.

Table 4 Parameters for LNE scenario (*- asymmetric results)

Parameter	**Units**	**SW, SE, S, N Suite**	**E, W Suites**	**NW, NE, Suites**
Wall RSI	RSI	8.8	8.8	8.8
Thermal Mass*		20cm Slab	20cm Slab	10cm Slab
Infiltration (5 Pa)	ACH	0.03	0.03	0.03
Fin:Window Ratio	%	0%	0%	0%
Overhang:Window Ratio	%	100%	100%	100%
Window U-value*	W/m^2K	0.77	1.08	1.08
Window SHGC*		0.41	0.18	0.18
WWR	%	20%	20%	20%

Figure 2 shows the heating and cooling energy, PV generation, and electrical loads associated with the base case and LNE case for an eight suite floor plate made up of one of each of the suite types. Heating and

cooling energy for the LNE case are reduced, relative to the base case, by 82% and 79% respectively. PV generation is increased by 52%, due to the increased opaque wall area and overhang surfaces equipped with solar cells. Electrical loads are assumed to be the same in all simulations.

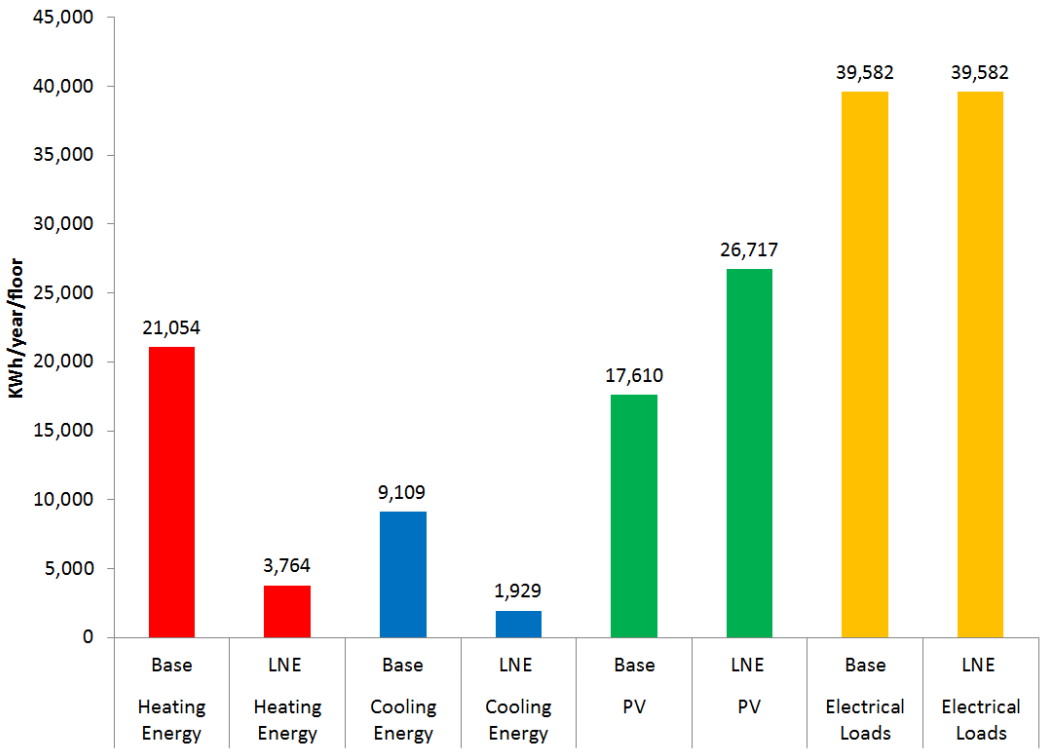

Figure 2: Heating and cooling energy, PV generation, and electrical loads for base case and LNE case.

Sensitivity and Interrelatedness of Variables

The LNE case shown in the previous section might not be practically adopted due to the influence of requirements not associated with energy consumption and energy generation. It is therefore important to understand the impact on the energy performance of varying the input variables from the extreme case. The following analysis starts from the extreme case and shows the impact on heating and cooling loads, and PV generation of varying selected geometry and quality input parameters for each of the eight suite types. Geometry parameters include window size, and overhang and fin depth. Quality parameters include wall RSI, thermal mass, infiltration rate, and window type. It is worthwhile noting that in this study, only geometry parameters have an effect on PV generation, whereas both geometry and quality parameters affect the heating and cooling loads. The impacts of temperature on the solar cell efficiency are not included in this study.

Geometry Parameters

Figure 3 shows the changes that are observed in the heating and cooling loads and PV generation when WWR is increased from the value of 20% found in the LNE case. As the window size increases, there is a consistent trend of increasing heating and cooling loads and decreasing PV generation for each of the eight

suites, with the exception of the S suite heating load which shows a minor decrease. The trends on the corner suites (SW, SE, NW, NE) are steeper than the single façade suites (S, W, E, N) due to the compounding effect of the doubled exterior surface. The overall thermal resistance of the exterior facades is reduced as window size increases, since the glazed areas of the facades have a relatively lower thermal resistance than the opaque areas. It is interesting to note that the heating load trend for the SW, S, SE suites are nearly flat, indicating that the benefit of increased passive solar heating has offset the impact of larger conductive heat losses. PV generation decreases with increasing window size, since there is less opaque area available for the installation of solar cells. Net energy consumption is increased by 57% for the average suite when WWR is increased from 20% to 80%.

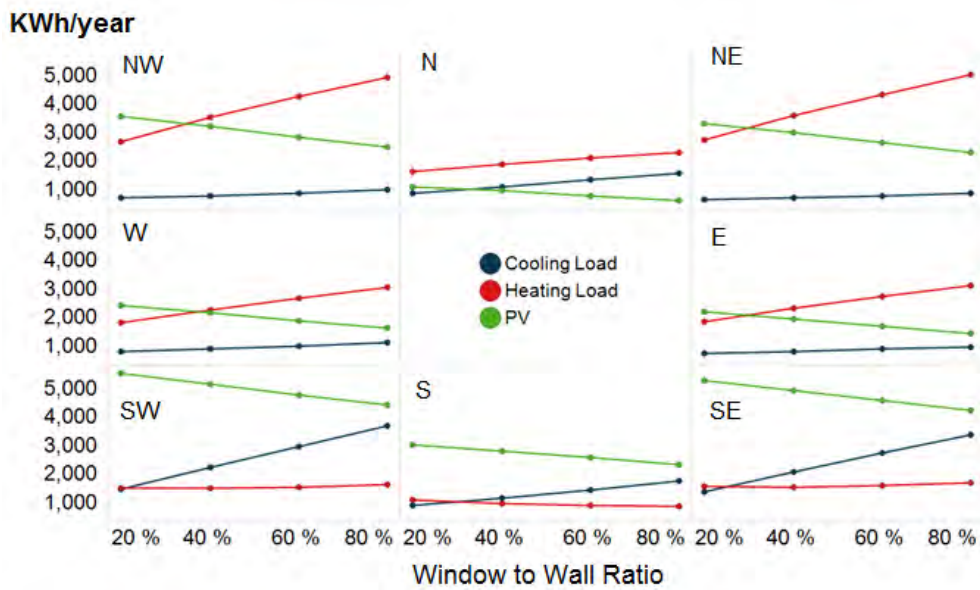

Figure 3: Heating and cooling load and PV generation for varying WWR for each suite

The effect of changing shading overhang depth relative to the window height on the heating and cooling load and PV generation is shown in Figure 4. Overhangs have a significant effect on cooling loads for the suites with a south facing window, as they reduce the unwanted passive solar energy entering the suites during the summer months when the angle of the sun is higher. There is also a moderate increase in heating load with increasing overhang depth due to the reduction in beneficial passive solar energy that is blocked. Since the additional surface area provided by overhangs is utilized for PV energy generation, there is a positive correlation between overhang depth and PV generation, especially for suites with a southern facing facade. The benefit of collecting solar power from the overhang surfaces outweighs the losses in PV generation on the facades due to shading effects. Overall, the incorporation of shading overhangs has a positive effect on energy performance. When the shading overhangs are removed from the LNE scenario, cooling loads increase by 69%, heating loads decrease by 14%, and net energy consumption increases by 22% for the average suite.

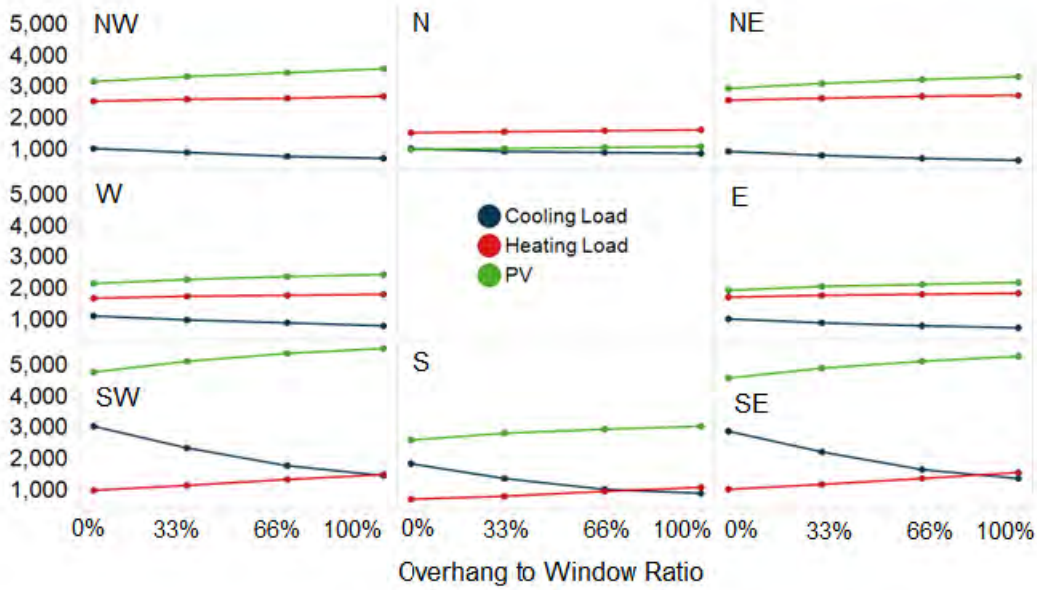

Figure 4: Heating and cooling load and PV generation for varying overhang to window ratios for each suite

Variations in fin depth are investigated in Figure 5. It is noted that energy performance is less sensitive to the depth of fins than it is to the other geometry parameters for the LNE case, shown by the relatively shallow slope on the trends. For each of the suites, heating load increases and cooling load decreases due to the reduction of passive solar energy, blocked by the shading fins. The combination of small windows, long horizontal overhangs, and low SHGC for the E, W suites, combine to reduce the relative impact of fin design for the LNE scenario. PV generation is marginally affected, as the fins cast shadows across the opaque wall areas during part of the day. The addition of maximum depth fins adds 9% to the net energy consumption for the average suite, compared to the LNE case.

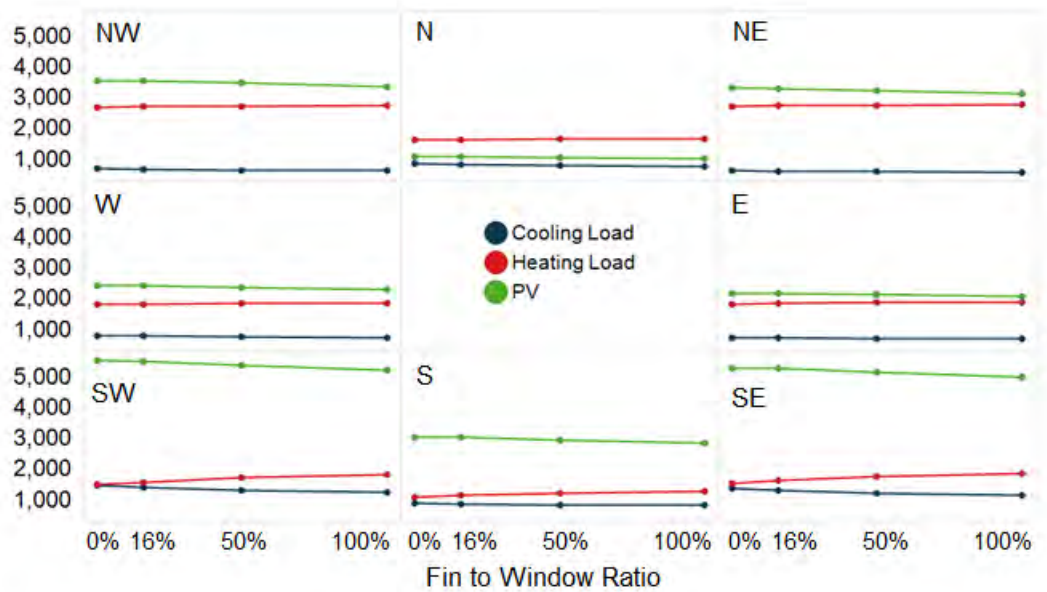

Figure 5: Heating and cooling load and PV generation for varying fin to window ratios for each suite

In addition to their individual impacts, the geometric parameters also have interrelated effects on the energy performance as shown in Figure 6. For each graph, all parameters are held at the LNE scenario except for the two that are being investigated. For example, the left graph shows the impact on the average net energy consumption for the eight suite types when the WWR and overhang depth is allowed to vary from the LNE case. Darker colours on the heat map show a relative improvement in energy performance, and the asterisk marks the LNE case.

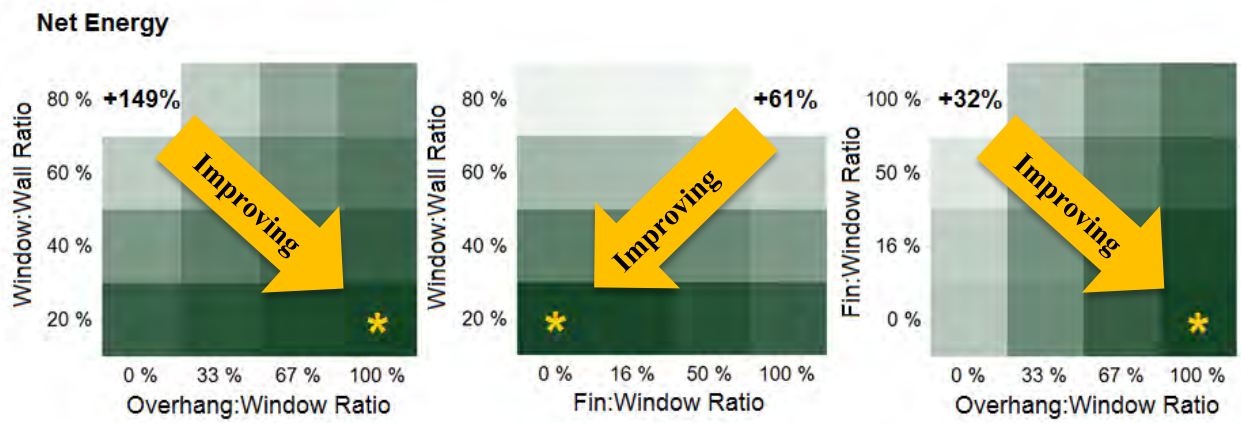

Figure 6: Interrelated effects of geometry variables on net energy consumption for the average of the eight suite types

The left graph of Figure 6 shows that, for the average of the eight suites, energy performance improves as WWR decreases and overhang depth increases for near-optimal scenarios. The highest performing scenarios are associated with a WWR=20%, illustrating that the size of glazed areas is more important to consider than the overhang depth. It is also noted that increasing overhang depth is beneficial regardless of the window size, but has a greatest effect on larger windows. Adjusting the parameters to their lowest performance level, with WWR=80% and no shading overhangs, increases the net energy consumption by 149% compared to the LNE case.

The centre graph of Figure 6 illustrates that the interrelated impacts of varying the WWR versus changes in shading fin depth. In this comparison, the window size is clearly dominant over the depth of fins when considering the net energy consumption. Minimizing the depth of fins is associated with a very moderate improvement in performance, regardless of window size. When the WWR is set to 80% and fin to window ratio is set to 100%, net energy consumption is 61% higher than the LNE case.

The right graph of Figure 6 shows a moderate improvement in performance, for the average suite, when fins are decreased in depth. However, the trend is negligible when compared to the benefits of increasing the overhang depth. The net energy is increased by 32% when overhangs are removed and fins set to their maximum depth, compared to the LNE case.

Overall, the conclusion that can be reached is that higher performing designs tend to have relatively smaller window size, with a shading overhang depth equal to the height of the window. Shading fins have a minimal effect for this scenario, and can therefore be included or removed without significant concern about affecting net energy consumption levels.

Quality Parameters

The following discussion shows the relative variation in energy performance observed when selected quality parameters are varied from the LNE case shown in Table 4. Quality parameters in the study include wall RSI, thermal mass, infiltration rate, and window type. Changes in the quality parameters do not affect the PV generation in this study, since they do not change the amount of solar energy reaching the opaque wall or overhang areas. They do, however, have a significant effect on heating and cooling loads, and therefore net energy consumption, as shown in Figure 7.

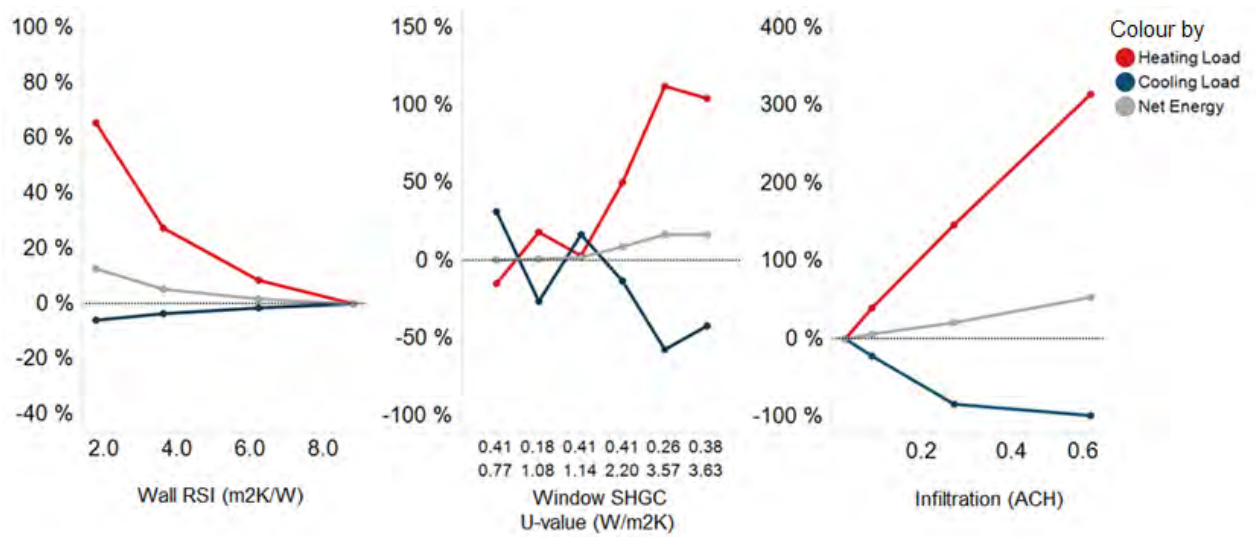

Figure 7: Percentage change in heating and cooling load and net energy due to variations in quality parameters

The left graph in Figure 7 shows the percentage change in the heating and cooling loads and net energy consumption when the wall RSI is reduced from the LNE case. As the wall RSI is reduced, there is a marginal improvement in cooling loads, and an increase of 65% in heating loads at the minimum value. Suite temperatures drop more quickly with lower wall RSI values, resulting in a minor improvement to cooling loads, for Vancouver's mild climate which seldom exceeds 24°C. It is noted that of the three quality parameters in Figure 7, changes in the wall RSI have the lowest impact on energy performance, at 13% higher than the LNE scenario for an RSI value of 1.76.

The centre graph of Figure 7 shows the relationship between energy consumption and changing window type. In this analysis, both the U-value and SHGC have a significant, interrelated effect on performance. As U-value decreases, heating loads decrease due to higher thermal resistance, and cooling loads increase due to a reduction of beneficial heat loss through the window assemblies when suite temperatures are at the cooling setpoint. As SHGC values increase, heating loads are offset by beneficial solar heat gain, and cooling loads increase due to the additional periods of unwanted solar heat gain. The resulting changes to net energy consumption are greatest, at 17% above the LNE scenario, for the triple pane windows with U-values/SHGC 3.57/0.26. Since U-value and SHGC are tied together to represent commercially available window construction options, it is not practical to investigate each one separately.

As shown in the right graph of Figure 7, the infiltration rate has the largest effect on heating and cooling loads, and therefore net energy consumption. Although there is a benefit to the cooling effect of infiltration

when suite temperatures are at the cooling setpoint and outdoor temperatures are cooler, there is a very strong correlation between increasing infiltration rates and heating loads during colder months. When the two effects are combined, the net energy consumption can be seen to increase by 53% at the high end of infiltration rate values.

DISCUSSION

MURB designers must balance many factors, including aesthetic, function, structure, and energy performance. It is unlikely that the optimal envelope parameters to achieve high energy performance will be adhered to by building designers in the majority of cases. It is therefore critical to have an evidence based approach to finding near-optimal solutions to optimize the energy performance of the design, while allowing flexibility. Using the simulation results of an exhaustive parametric study, an understanding of the variable sensitivities and interrelatedness can be established to support design decisions during the early stages.

In this study, building envelope design parameters are divided into two categories; geometry and quality. Parameters from both categories are likely to be varied to achieve overall design goals. In order for the designer to maintain a high level of energy performance, while balancing numerous competing requirements, the relative energy impacts of design decisions must be evaluated. For example, if a WWR of 80 percent is established as a design requirement, changes to the remaining input parameters may be required to maintain a standard of energy performance. In the analysis provided, it is shown that reducing window size and improving infiltration rate have the highest impact on net energy consumption. Alternately, increasingly higher levels of wall RSI and shading fins are shown to have a relatively smaller impact on performance. Based on the analysis of sensitivity and interrelatedness of the input variables, it is observed that energy performance cannot be achieved by optimizing a single aspect of the building envelope. Rather, it is the optimal combination of input parameters that lead to high performing outcomes.

Greater flexibility in design decisions are afforded by allowing for asymmetric solutions. This parametric study, conducted at the suite level, shows that the LNE scenario is made up of varying parameters depending on the orientation and geometry of the suite. The amount of passive solar and PV energy that is available to the suite is highly asymmetric, with southern aspects capturing the greatest amount. With the exception of the window SHGC, impacts due to changes in the quality parameters are not significantly affected by the orientation of the external façade. Geometry parameters, on the other hand, are highly affected by the orientation, as illustrated by the variations in passive solar energy captured by the eight suite types in the LNE case. In order for energy consumption and renewable energy generation capabilities to be optimized, asymmetric designs can be proposed to maximize the impact of each decision about geometry and quality. Even if the geometric elements of the building must remain consistent for aesthetic, functional, or structural reasons, a more balanced energy performance between suites can be achieved by implementing asymmetry of quality parameters.

It is noted, when observing the parameters for the LNE case, that some of the parameters are subject to diminishing returns. For example, although shading overhangs are included in the LNE scenario for the N suite, the benefits of including solar shading are very minor, and would not justify the expense of construction to include them. Also, the decision to invest in quadruple pane windows would not be

supported by the small improvement in net energy consumption observed compared to triple pane windows (CMHC, 2015). Evaluating near-optimal solutions provides a method to identify, and eliminate parameter selections that are subject to diminishing returns.

Further study into the effects of window blinds is needed to investigate their effectiveness at reducing energy consumption. Thermal mass and shading fins are found to have minor impacts on energy performance for the LNE case in this study. Further study into these parameters is required to investigate alternative modeling strategies.

The observations in this study are limited to MURBS in the Vancouver area. Although some observations are likely to be consistent across the country, the parametric simulations will need to be re-calculated with a new weather file for each region for accurate results.

CONCLUSION

A parametric study of eight building envelope design parameters is conducted to assemble a database of energy performance options for MURBs in Vancouver, BC. Simulation results show that combined heating and cooling loads can be reduced by up to 81% compared to the base case. Assuming that opaque façade areas and shading overhangs are used to generate electricity using PV, optimization of the building envelope parameters can result in as much as a 49% reduction in net energy consumption compared to the base case. If PV capability is removed from the base case, net energy consumption of the optimized case is reduced by up to 68% relative to the base case.

The sensitivity of changing individual input parameters, relative to the net energy consumption, is investigated for a selection of geometry and quality parameters in the parametric study. Geometry parameters analyzed include WWR, and shading overhang/fin depth, and quality parameters analyzed include wall RSI, window type, and infiltration rate. Results show that net energy consumption is most sensitive to changes in the WWR and infiltration rate. The lowest impact variable changes are associated with increased wall RSI (above the base case value), and shading fin depth.

Variable interrelatedness is discussed for geometric parameters, highlighting that for variations to the LNE case, increasing shading overhangs and reducing shading fins is beneficial, regardless of the WWR. Reducing WWR decreases net energy consumption regardless of whether shading overhangs or fins are included in the design.

Building envelope design is influenced by numerous requirements and many are not related to energy performance. Finding near-optimal energy performance solutions provides an evidence-based approach to balancing the consideration for aesthetic, functional, structural, and energy performance related parameters for MURB envelope design.

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