THE INFLUENCE OF PASSIVE MEASURES ON BUILDING ENERGY DEMANDS FOR SPACE HEATING AND COOLING IN MULTI-UNIT RESIDENTIAL BUILDINGS

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ABSTRACT

This paper explores the development of a methodology to assess the relative impact of passive measures on building system performance. Over the life cycle of a building, its use and occupancy can undergo significant changes when the building is re-purposed. Initial energy modeling assumptions about active systems that respond to occupancy and operating schedules may no longer apply. The most persistent attributes are the passive features of the building such as the building form and solar orientation, the overall effective U-value of the enclosure, fenestration and fixed shading devices, and its thermal mass and airtightness. Parametric simulations of the energy performance of multi-unit residential buildings form the basis of this paper and results are ranked to indicate the relative significance of various passive features to the peak and annual energy demands for space heating and cooling.

INTRODUCTION

It is widely acknowledged that architects and building designers seldom use building performance simulation tools at the early design stage to inform their schematic building designs [1]. Despite the numerous research efforts devoted to advancing early stage design and the significant promise held by the approaches advocated, most architects prefer formulaic versus parametric approaches to building design.

Another trend in building design is the use of rating systems to guide the designer to achieve the maximum rating for the minimum expenditure. This often leads to a situation referred to as 'high cholesterol buildings' where sophisticated HVAC, lighting and control systems compensate for underperforming building envelopes [2].

In view of this reality, and in recognition of the primacy of passive systems in the environmental performance of buildings, this paper is based on the development of a methodology aimed at providing robust default values for passive system parameters for a given building typology in a particular climatic location. The objective is to determine passive attributes, such as overall effective U-value, that are at or near the point of diminishing returns in terms of physical, rather than economic, performance.

METHODOLOGY

The methodology underlying this paper is derived from a larger study aimed at improving the resilience and thermal comfort of new condominium buildings in Ontario and British Columbia. Determining the effectiveness of passive strategies to minimize the demand for space heating and cooling energy is part of a more holistic and comprehensive methodology aimed at developing recommendations for best design practices, as depicted in Figure 1. In this paper, only the Toronto, Canada climate will be considered to demonstrate aspects of the methodology.

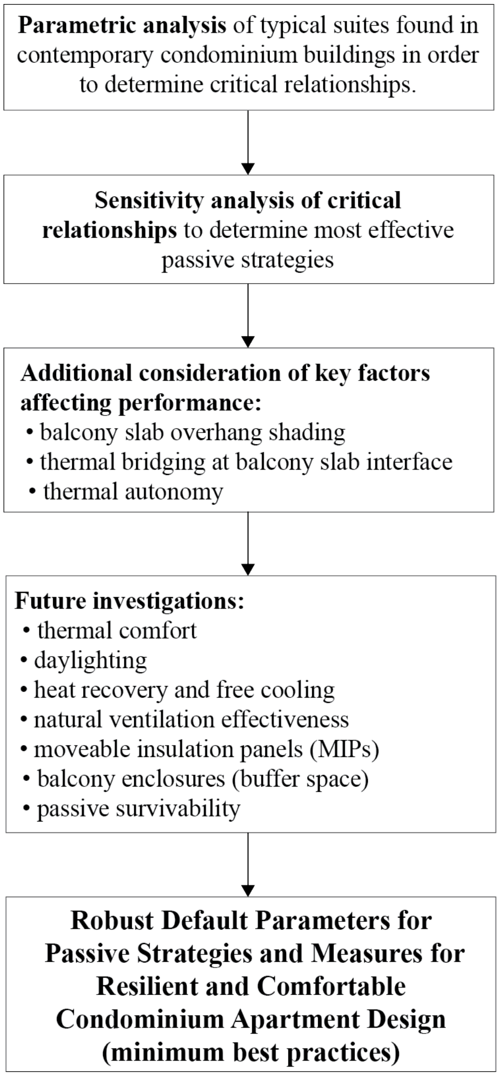

Figure 1. Passive strategies analysis methodology.

SIMULATION

Energy simulations cannot proceed until the physical characteristics of typical condominium buildings have been determined. The economics of land values in urban centres require that most projects are either mid-rise or high-rise buildings. The predominant building type used for the construction of condominium apartment buildings consists of a reinforced concrete frame where the shear walls are used to demise suites adjoining a double-loaded corridor or central core. The majority of suites have single aspect facades except for corner suites that have exterior walls on two sides, and are typically single storey. The provision of cantilevered balconies is optional and most of the buildings employ window-wall glazing systems with high window-to-wall ratios (>80%). According to Urbanation, the average size of a condo in the Greater Toronto Area (GTA) is 70 m^2 (756 ft^2) taking into account bachelor, 1-bedroom, 2-bedroom and 3-bedroon units [3]. This also includes micro-condos which range between 25 to 35 m^2 (270 to 375 ft^2) [4].

Figure 2. Example of mid-rise and high-rise condominium apartment buildings in Toronto, Canada.

EnergyPlus software was used to perform a large number of parametric simulations [5]. Parameters set out in Table 1 were applied to a floor plate comprising all of the suite aspect ratios depicted in Figure 2 in order to conduct the first stage of the analyses. Then additional analyses were performed after critical relationships were identified using the data from the parametric analyses. This paper focuses on space heating and cooling energy performance recognizing that parameters such as daylighting, natural ventilation and occupant comfort and passive survivability will be evaluated as the study proceeds.

Table 1. Parameters and corresponding values used to perform initial set of energy simulations using Toronto, Canada weather data.

Floor Area m^2	30	50	70			
Aspect Ratio	1:2	1:1	2:1			
Window-to-Wall Ratio	40%	60%	80%			
Exterior Walls ($W/m^2.K$)	0.180	0.210	0.247			
Windows	($W/m^2.K$)	1.0	1.5	1.7	2.0	2.5
	SHGC	0.4	0.3	0.35	0.40	0.45
Mechanical Ventilation	15 L/s continuous (24 h avg.)					
Infiltration (ach)	0.06	0.12	0.24			
Orientation	North	South	East	West		
Common Assumptions: Aspect ratio is Width:Depth. Floor to ceiling height is 2.5 m. Suites are located on intermediate floors with no heat transfer across ceiling, floor or adjacent walls. All U-values are effective accounting for thermal bridging. Infiltration rates based on Table 5 in Reference [6]. No heat recovery on ventilation system.						

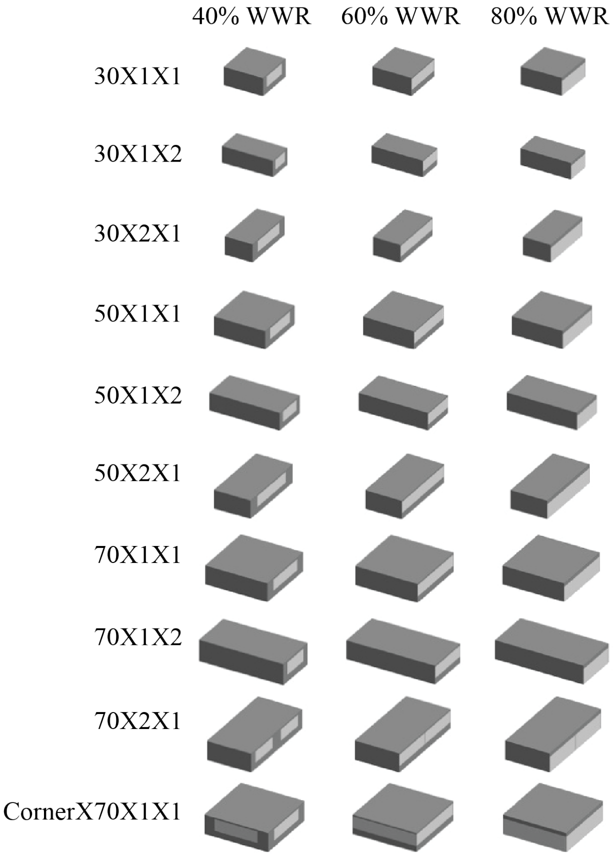

Figure 3. Floor areas, aspect ratios, and window-to-wall ratios used in parametric energy analyses. (Note: Corner units are typically the largest suites.)

An important aspect of the methodology is the selection of parameters and attributes that reasonably reflect the building type to be investigated. The size and aspect ratios of the condominium units (suites) reflect current practices in the Toronto, Canada region. The window-to-wall ratios (WWR) were selected such that acceptable daylighting determined the lower limit (40%) which then ranged up to practically an all glazed facade (80%). Exterior wall U-values begin with the minimum effective thermal resistance for opaque wall assemblies prescribed by applicable codes and standards and range up to an upper value after which sharply diminishing returns in energy conservation are observed. (Note: Performance compliance paths allow trade-offs between envelope and HVAC systems, and effective U-values are seldom enforced in practice.) Window U-values and solar heat gain coefficients reflect technologies that are currently available, again with the least efficient window assembly being prescribed by applicable codes and standards. Mechanical ventilation rates conform to minimum code requirements and for the initial purposes of this paper, were not provided with heat recovery. Heat recovery is not mandatory in Ontario codes and standards and it is also generally not considered a passive energy conservation strategy. Infiltration rates are derived from the literature that examined airtightness and ventilation in contemporary condominium buildings [6]. Solar orientations were simplified to only the four cardinal directions, with the understanding that other orientations could be investigated for a selected subset of interest. A COP of 1.0 for HVAC systems was used in order to estimate demands without the influence of energy conversion efficiencies.

Table 2. Floor areas and gross exterior wall areas corresponding to unit (suite) types.

Unit (Suite) Type	Floor Area (m^2)	Gross Exterior Wall Area (m^2)
30X1X1	26.6	13.7
30X1X2	26.6	9.7
30X2X1	26.6	19.4
50X1X1	45.6	17.7
50X1X2	45.6	12.5
50X2X1	45.6	25.0
70X1X1	63.8	20.9
70X1X2	63.8	14.8
70X2X1	63.8	29.6
CornerX70X1X1	63.8	41.8
Suite heights are assumed to be 2.5 m including thickness of a single 200 mm floor slab (i.e. half thickness for ceiling and half thickness for floor attributed to internal units).		

Table 3. Energy simulation file naming protocol and conventions for unit type labeling.

Filename Parameters					
Location	Air Leakage	WWR %	Wall U-Value	Glazing U-value-SHGC	Balcony
WIN_ TOR_ THB_	Tight_ Avg_ Leaky_	40_ 60_ 80_	W-0.180_ W-0.210_ W-0.247_	G-2.5-0.45 G-2.0-0.40 G-1.7-0.35 G-1.5-0.30 G-1.0-0.40	-NB -BTB -B
Examples: TOR_Tight_40_W-0.180_G-2.5-0.45-NB TOR_Tight_60_W-0.247_G-1.7-0.35-BTB					
WIN - Windsor, TOR - Toronto, THB - Thunder Bay Air leakage as per infiltration rates in Table 1. NB - no balcony BTB - balcony with thermal break B - balcony with thermal bridge					

Unit Type Labeling		
Orientation	Unit Size nominal m^2	Aspect Ratio width x depth
N_ E_ W_ S_ NE_CornerX SE_CornerX SW_CornerX NW_CornerX	30 50 70	X1X1 (1:1) X1X2 (1:2) X2X1 (2:1)
Examples: N_30X1X1 NE_CornerX70X1X1 Note: Only results for simulations running Toronto (TOR) weather data are presented in this paper.		

The parametric simulations are conducted to compare the relative energy demands between the various passive measures and to identify the critical units (worst performing) so that these can undergo more detailed investigation. The rationale guiding the energy performance assessment is two-fold. First, viewed from the inhabitant perspective, the condominium project is only as good as the inhabitant's own suite. Every suite should achieve a minimum level of performance consistent with the environmental regulations and aspirations for the building. This means the worst performing suite(s) must provide acceptable levels of thermal comfort, ventilation, daylighting and energy efficiency. Second, since it is not feasible to customize the enclosure for each suite, the minimum enclosure requirements for the worst performing suite are assumed to be applied uniformly to all opaque assemblies. Components such as windows can, and often should, have different characteristics, and shading devices may also respond uniquely to different solar orientations. Passive systems performance requirements for both the critical suite(s), and the building as a whole must be satisfied.

ANALYSIS

The analysis of the parametric set of energy simulations focused on three aspects of passive measures performance. The first aspect is the analysis of minimum and maximum energy demands across all of the combinations of suite parameters. The second aspect examines the performance improvement of the least energy efficient suite after applying passive measures related to enclosure U-value and window-to-wall ratio. The third aspect compares the difference in energy performance between the least and most efficient passive measures when these are applied to a typical floor of a condominium apartment building.

These aspects of the parametric analysis are also useful in determining the most critical suite(s) for further investigations of air leakage, thermal bridging at cantilevered balcony slabs, shading by balcony overhangs and thermal autonomy.

Table 4. Minimum and maximum peak and annual energy demands and corresponding space heating and cooling site energy use intensity.

	Space Heating Peak Energy Demand & Annual Energy Demand		Space Cooling Peak Energy Demand & Annual Energy Demand		Total Space Heating & Cooling EUI
Toronto (TOR_) Filename/Suite	W	kWh	W	kWh	kWh/m^2
Tight_40_W-0.180_G-1.0-0.40-NB S_30X1X2	584.2	270.3	666.2	326.9	22.2
Leaky_80_W-0.247_G-2.5-0.45-NB NE_CornerX70X1X1	4200.9	4845.5	4017.3	1225.1	96.4
Tight_80_W-0.180_G-1.0-0.40-NB S_70X1X2	699.2	59.8	1104.7	1308.2	21.0
Leaky_80_W-0.247_G-2.5-0.45-BTB NW_CornerX70X1X1	3679.3	5141.3	3588.0	702.9	92.8
Tight_40_W-0.180_G-1.5-0.30-NB N_30X1X2	973.3	764.3	563.9	122.8	33.0
Leaky_80_W-0.247_G-2.5-0.45-NB W_70X2X1	2779.1	3140.4	5431.8	1688.6	75.7
Leaky_40_W-0.247_G-1.5-0.30-BTB S_30X1X1	1280.3	1257.9	700.5	56.7	49.4
Tight_80_W-0.180_G-1.0-0.40-NB SE_CornerX70X1X1	910.5	488.2	4023.3	3110.2	57.2
Tight_40_W-0.180_G-1.0-0.40-BTB S_70X1X2	887.3	471.0	860.8	360.1	12.8
Leaky_80_W-0.247_G-2.5-0.45-NB E_30X2X1	2112.8	2062.1	2707.0	1129.6	122.9
░ Minimum for all runs	▓ Maximum for all runs				

Beginning with the analysis of minimum and maximum space heating energy demands listed in Table 4, it is observed the minimum peak space heating energy demand is 584.2 W, and the maximum peak value is 4,200.9 W. There is more than a 7 times difference that significantly exceeds the difference in exterior enclosure surface areas (9.1 m^2 versus 40.2 m^2) and is attributable to more efficient exterior walls and windows combined with lower infiltration rates.

The annual space heating energy demands range from a minimum of 59.8 kWh, corresponding to a tight and thermally efficient south-facing suite to a maximum of 5,141.3 kWh for a corner suite with north and west exposures - an almost 86 times difference. Passive solar gains and lower infiltration and transmission losses through the enclosure offset most of the space heating energy demands for the south-facing suite. The leaky and thermally inefficient enclosure of the corner suite accounts for the high annual energy demand. It is important to note the S_70X1X2 suite has half the window aperture (ratio of window area to floor area) compared to the NW_CornerX70X1X1 suite. Based on the difference in window area and the difference in overall effective U-value of the two enclosures (0.84 versus 2.05 W/m^2.^{o}C, respectively), the resulting difference in thermal conductance is 11.9 versus 82.5 W/^{o}C, an almost 7 times difference, not accounting for air leakage. This rudimentary analysis indicates that passive solar gains account for most of the difference in annual space heating energy demand, and this is confirmed by the detailed simulation results.

Turning to the analysis of space cooling energy demands, the minimum peak space cooling energy demand is 563.9 W for the N_30X1X2 suite versus 5,431.8 W for the W_70X2X1 suite. Solar orientation and solar heat gain coefficients, along with the difference in gross exterior wall areas and window apertures, account for most of the difference.

For annual space cooling energy demand, the minimum is 56.7 kWh for a S_30X1X1 suite, versus 3,110.2 kWh for a SE_CornerX70X1X1 suite. In this case, the factors most influencing the observed difference are the window area, solar heat gain coefficient, solar orientations and the shading effect of the overhanging balcony slab for the south-facing suite.

The minimum and maximum combined space heating and cooling energy use intensities are 12.8 kWh/m^2 for the S_70X1X2 suite, versus 122.9 kWh/m^2 for the E_30X2X1. Solar orientation, window aperture, overall effective U-value of the enclosure and airtightness account for the observed differences.

The next aspect of the analysis examined the potential performance improvement for a single suite by deploying passive measures for the enclosure. The least energy efficient suite was selected and used as a basis for comparison. Referring to the data in Table 5, going from a leaky and thermally inefficient enclosure to a tight and efficient enclosure, without adjusting the window-to-wall ratio, significantly reduces the space heating peak and annual energy demands by 50.7% and 66.1%, respectively. The peak space cooling energy demand is only slightly reduced by 5.8% and the annual space cooling energy demand actually increases by 36.0%. In the absence of shading devices, a passive strategy to be examined later in the paper, the higher efficiency enclosure retains heat gains thus driving up the demand for space cooling energy.

Table 5. Performance improvement due to passive measures (enclosure U-value and WWR) for the condominium suite having the worst energy performance in Toronto, Canada.

Space Heating Peak Energy Demand & Annual Energy Demand		Space Cooling Peak Energy Demand & Annual Energy Demand		Total EUI
W	kWh	W	kWh	ekWh/m^2
Leaky_80_W-0.247_G-2.5-0.45-NB E_30X2X1				
2112.8	2062.1	2702.0	1129.6	122.9
Tight_80_W-0.180_G-1.0-0.40-NB E_30X2X1				
1040.6	698.1	2549.7	1535.8	86.0
50.7%	66.1%	5.8%	-36.0%	30.0%
Tight_60_W-0.180_G-1.0-0.40-NB E_30X2X1				
994.6	657.8	2189.1	1134.9	69.1
52.9%	68.1%	19.1%	-0.5%	43.8%
Tight_40_W-0.180_G-1.0-0.40-NB E_30X2X1				
989.6	615.5	1718.0	742.6	52.3
53.2%	70.2%	36.5%	34.3%	57.4%
Note: Space cooling analysis for tight enclosures assumes natural ventilation rates equivalent to leaky enclosure infiltration rates.				

On the whole, a higher thermal efficiency enclosure reduces the combined space heating and cooling energy use intensity by 30%. Next this analysis examined the effect of keeping the higher thermal efficiency enclosure and reducing the window-to-wall ratio.

Going from an 80% to 60% WWR reduces space heating energy demands marginally (~2%), but has a significant effect on reducing space cooling loads. This accounts for a 43.8% reduction in the EUI compared to the least energy efficient suite. Likewise, a reduction down to 40% WWR accounts for a further reduction in both peak and annual space cooling energy demands, and a 57.4% reduction in EUI compared to the least energy efficient suite.

At this point in the analysis, it becomes obvious that both the thermal efficiency of the enclosure and the window-to-wall ratio are significant variables influencing the space heating and cooling energy demands of buildings. One question that naturally arises is whether or not enclosure airtightness is also a significant variable.

AIRTIGHTNESS SENSITIVITY ANALYSIS

A sensitivity analysis was conducted to determine if the influence of infiltration was significant. Three levels of infiltration as per Table 1were established by taking air leakage rates measured at 50 Pa in modern condos [6] and correlating these to infiltration rates (n_{50}/25 ach).

Based on the entire set of simulations, going from a leaky to a tight enclosure was found to reduce the site energy use intensity for space heating and cooling anywhere from 17.8% to 39.6% (results not tabled). However, there is a notable difference in how heating and cooling loads are impacted. Annual space heating energy demand is always reduced as airtightness increases, but the cooling load always slightly increases. It is important to realize that the passive cooling delivered by infiltration can be easily substituted by the use of operable windows to provide natural ventilation. For this reason, and to promote occupant comfort and envelope durability, it may be concluded that airtight construction is a vital passive strategy that yields multiple benefits.

In order to avoid unfairly penalizing the impact of airtightness on cooling loads when conducting energy simulations, it is important to include natural ventilation during the cooling season. Inhabitants may open windows when the outdoor temperatures are favourable for passive cooling and keep them closed when active cooling is needed to maintain comfort conditions. Failing to make this accommodation in the energy modeling of airtightness will result in excessive and erroneous cooling loads.

The question of whether or not natural ventilation will provide acceptable indoor air quality and thermal comfort remains to be answered in subsequent phases of the larger study of which this paper is a small part. A related question is whether occupants will operate windows effectively to match energy modeling assumptions.

The next aspect of the analysis involved combining a number of the suites to make up a typical floor in a condominium building. A combination of 4 corner suites and 3 internal suites per solar orientation for a total of 16 suites was analyzed and the results are provided in Table 6.

Table 6. Difference in Energy Performance Between Most and Least Efficient Passive Conservation Measures for a Typical Floor of 16 Suites with a Total Floor Area of 800 m^2.

	Peak Space Heating Energy Demand (W)	Annual Space Heating Energy Demand (kWh)	Peak Space Cooling Energy Demand (W)	Annual Space Cooling Energy Demand (kWh)	Site Heating and Cooling EUI (ekWh/m^2)
Best	16225.2	10287.6	23773.9	11674.8	27.5
Worst	40965.7	41197.7	47442.0	15349.2	70.7
Δ %	60.4%	75.0%	49.9%	23.9%	61.2%

The data reflect the influence of airtightness, enclosure thermal efficiency and window-to-wall ratio only. Shading and natural ventilation effects are not included.

Based on the difference between the most and least efficient set of passive conservation measures for the enclosure, it may be concluded that reductions in space heating and cooling energy demands are highly significant.

Peak and annual space heating energy demands are reduced by 60.4% and 75.0% respectively. Peak space cooling energy demand is reduced by almost one-half, while annual demand is reduced by 23.9%. The net effect is a 61.2% reduction in site space heating and cooling energy use intensity.

An increasingly important consideration in building design is the peak energy demand for electricity due to the limited generating and transmission capacities across many North American electricity grids. Passive measures related to improving the thermal efficiency of the building enclosure can deliver significant reductions in peak electrical energy demands.

Another insight gained from the methodology adopted in the study is that condominium buildings typically use very little additional space heating and cooling energy for common areas and parking garages when compared to the suites comprising the building. This means that simplified approaches to the energy modelling of archetypical buildings can provide invaluable feedback at the early stages of design regarding the relative impact of passive strategies aimed at improving energy efficiency, bypassing more detailed and comprehensive compliance energy modeling that consider all building elements.

This paper now turns to the analysis of other passive measures that influence the space heating and cooling energy demands and/or thermal performance of condominium buildings. The following parameters will be assessed:

- influence of cantilevered balcony overhangs (shading) on heating/cooling;
- influence of thermal bridging at cantilevered balcony slab interface on heating/cooling; and
- thermal autonomy (heating and cooling).

It should be noted that in this paper thermal autonomy is defined as the amount of time the building remains passively between 15 °C and 30 °C without the input of any active systems energy.

ANALYSIS OF SHADING PROVIDED BY CANTILEVERED BALCONY OVERHANG

The results of the simulations are shown in Table 7 where the most thermally efficient enclosure parameters were applied to selected corner and internal units, with and without balconies.

Table 7. Influence of 2 m Deep Balcony Overhangs Serving as Shading Devices on the Energy Performance of Corner and Internal Units Having Different Solar Orientations.

	Peak Space Heating Energy Demand (W)	Annual Space Heating Energy Demand (kWh)	Peak Space Cooling Energy Demand (W)	Annual Space Cooling Energy Demand (kWh)	Site Heating and Cooling EUI (ekWh/m^2)
SE	910.5	488.2	4,023.3	3,110.2	57.2
SE-BTB	1,490.9	961.1	2,777.7	1,324.3	36.3
Δ %	38.9%	49.2%	-44.8%	-134.9%	-57.5%
SW	1,467.2	480.2	3,892.9	2,891.4	53.6
SW-BTB	1,635.8	963.3	3,078.1	1,197.1	34.3
Δ %	10.3%	50.2%	-26.5%	-141.5%	-56.1%
NE	1,964.3	1,424.6	3,817.8	2,259.4	58.5
NE-BTB	2,068.4	1,684.6	2,812.7	1,309.9	47.6
Δ %	5.0%	15.4%	-35.7%	-72.5%	-23.0%
NW	1,612.5	1,420.6	3,744.7	2,048.2	55.1
NW-BTB	2,195.1	1,677.7	3,119.0	1,188.8	45.5
Δ %	26.5%	15.3%	-20.1%	-72.3%	-21.0%
S	958.3	85.6	1,738.3	2,374.2	38.6
S-BTB	1,391.5	402.8	1,820.7	781.0	18.6
Δ %	31.1%	78.7%	4.5%	-204.0%	-107.8%
W	1,271.2	784.5	4,516.4	2,584.8	52.8
W-BTB	1,389.0	1,022.6	3,151.6	1,413.9	38.2
Δ %	8.5%	23.3%	-43.3%	-82.8%	-38.3%

All units have floor areas of 63.8 m^2 and tight enclosures with effective U-values of 0.18 for walls and 1.0 for windows with a SHGC of 0.4. All units have WWR = 0.80. Corner units (i.e., SE, SW, NE, NW) have an aspect ratio of 1:1 and internal units (i.e., S, W) have an aspect ratio of 2:1 (width to depth). Units with thermally broken balcony overhangs are indicated by BTB.

Note that the 2 m deep balconies, assumed to run the width of each suite's exterior facade, have been sized for amenity and functionality, not optimized for passive solar heating and cooling (shading). It may also be noted that other types of exterior shading devices, fixed or adjustable, could be used to obtain the same or similar shading effect as cantilevered balconies.

Based on Toronto weather data, corner units with balcony overhangs demand more space heating energy, but less space cooling energy than corner units with no balcony overhangs. The site energy use intensity is also lower for corner units that have balcony overhangs versus corner units with no balconies.

South-facing internal units with balcony overhangs demand more space heating, but significantly less space cooling energy, and have roughly half the combined space heating and cooling energy use intensity compared to south-facing internal units with no balcony overhangs. A similar relationship is revealed for west-facing internal units as for south-facing units, but significantly less difference is observed due to the balcony overhangs providing less than ideal shading during the cooling season.

A preliminary conclusion is that in all cases, balcony overhangs provide net energy conserving benefits primarily through reductions in cooling energy demands, but the impacts of thermal bridging need to be considered before reaching any final conclusions.

ANALYSIS OF THERMAL BRIDGING AT CANTILEVERED BALCONY SLAB INTERFACE

An extract of the analysis of thermal bridging at cantilevered balconies is summarized in Table 8.

Table 8. Impact on Energy Demands by Thermal Bridging Due to Cantilevered Balconies.

Space Heating Peak Energy Demand & Annual Energy Demand		Space Cooling Peak Energy Demand & Annual Energy Demand		Total EUI
W	kWh	W	kWh	ekWh/m^2
Tight_40_W-0.180_G-1.0-0.40 N_70X2X1				
1735.2	1075.5	1360.2	415.5	23.4
1427.1	1440.6	1434.5	380.5	28.6
21.6%	33.9%	5.5%	-8.4%	22.1%
Tight_60_W-0.180_G-1.0-0.40 N_70X2X1				
1619.8	1298.0	1616.8	511.0	28.4
1797.5	1555.0	1668.8	492.3	32.1
11.0%	19.8%	3.2%	-3.7%	13.2%
Tight_80_W-0.180_G-1.0-0.40 N_70X1X1				
1773.6	1426.3	1939.8	717.2	33.6
1876.3	1562.9	1999.1	709.6	35.6
5.8%	9.6%	3.1%	-1.1%	6.0%
░ No Thermal Break		▨ Thermal Break		□ Δ %

The energy performance of three north-facing suites with effective U-values of 0.18 W/m^2.K for exterior walls and 1.0 W/m^2.K for windows, but three different WWRs, is compared in Table 8. For the case where no thermal break has been provided, it was assumed a thermal bridge with an effective U-value of 3.4 W/m^2.K was introduced along a strip of wall 0.2 m high running the length of the exterior of the suite. North-facing suites were examined because this orientation is least affected by solar gain effects.

The provision of thermal breaks improves overall energy use intensity from 6.0% to 22.1%. A previous study reported that by reducing the heat transfer through balcony slabs, the space heating energy consumption may be reduced by 5–13% and space cooling energy consumption by less than 1% [7]. The larger differences noted in Table 8 than those reported in the literature are due to assessing a very thermally efficient enclosure whereby thermal bridging significantly reduces the overall effective U-value. Hence, the relative percentage impact appears higher than the results reported in the above noted study. It is also interesting to note that smaller the WWR in highly thermal efficient enclosures, the relatively larger impact on energy performance.

Cooling energy demands were found to be higher for balconies with thermal breaks versus those without. The positive cooling effect of thermal bridging is small in absolute terms, but relatively high due to the thermally efficient enclosure. The analysis presented in this paper indicates that a significant proportion of the energy conservation benefits provided by balconies can be compromised by thermal bridging, hence for the Toronto climate, thermal breaks at cantilevered balconies are necessary to preserve thermal integrity.

ANALYSIS OF THERMAL AUTONOMY

Thermal autonomy is a measure of the fraction of time a building can passively maintain comfort conditions without active system energy inputs. Thermal autonomy should not be confused with passive survivability, a measure of how long inhabitants may remain in their dwellings during extreme weather events that knock out their energy supply, thus disabling the operation of most active systems for space heating and cooling. Further research is needed to determine if the minimum and maximum temperatures and the number of hours above or below a particular indoor temperature threshold are indicators of passive survivability. More sophisticated analyses will be conducted later in the study to predict the duration of acceptable indoor temperatures when all space heating or cooling energy are absent, such as during a sustained failure of the electrical grid due to extreme weather events. Results for thermal autonomy are presented in Table 9.

Table 9. Summary of Minimum and Maximum Free Run Temperatures and Hours Above and Below Acceptable Indoor Temperature Thresholds for Selected Suites.

T_i min °C	Hours < 15 °C	T_i max °C	Hours > 30 °C	Passive Fraction
Case #1 S_70X2X1, Tight_80_W-0.180_G-1.0-0.40-BTB Maximum thermal autonomy				
10.5	801.0	36.3	2249.5	65.2%
Case #2 S_70X2X1, Leaky_40_W-0.180_G-1.7-0.35-BTB Lowest max indoor temp + Fewest hours above 30 °C				
-5.3	5008.5	27.9	0.0	42.8%
Case #3 S_70X2X1, Leaky_40_W-0.247_G-1.7-0.35-BTB Most hours below 15 °C				
-5.6	5035.0	27.9	0.0	42.5%
Case #4 N_70X2X1, Leaky_80_W-0.247_G-2.5-0.45-NB Lowest min indoor temp				
-13.1	4728.0	33.7	326.5	42.3%
Case #5 N_70X2X1, Leaky_80_W-0.180_G-1.0-0.40-NB Highest min indoor temp + Fewest hours below 15 °C + Highest max indoor temp + Most hours above 30 °C				
15.3	0.0	55.1	6115.5	30.2%
Case #6 N_70X2X1, Tight_80_W-0.180_G-1.0-0.40-NB Minimum thermal autonomy				
-6.9	3910.0	40.7	2524.0	26.6%
All units have floor areas of 64.8 m^2 and balconies featuring thermal breaks (BTB) are 2.0 wide and run the entire length of the exterior wall of the unit acting as a shading device.				

In this analysis of thermal autonomy acceptable, rather than comfortable, indoor conditions were selected corresponding to a lower threshold of 15 °C and an upper threshold of 30 °C. The data in Table 9 are extracted from a comprehensive analysis of all the combinations and permutations of condo suites for illustrative purposes. The minimum and maximum rankings appearing in the table correspond to a comparison among the six cases, not all of the simulations.

For Case #1, a south-facing suite with a high WWR, thermally efficient enclosure and thermally broken balcony for shading delivers the best thermal autonomy performance on an annual basis with a passive fraction of 65.2%. Case #2, a leaky, south-facing unit with a 40% WWR and glazing with a higher U-value, but lower SHGC than Case #1, exhibits the lowest maximum indoor temperature and the fewest hours above 30 °C with a passive fraction of 42.8%. Assuming appropriate operation, either automatically or by the occupants, adjustable shading devices and natural ventilation could provide the suite in Case #1 with comparable hot weather performance to Case #2 by controlling the solar aperture, while taking advantage of desirable solar gains as per Case #5. In Case #3, the impact of a leaky and less thermally efficient enclosure that is shaded from solar gains may be noted in terms of the number of hours below 15 °C. The thermal efficiency of the enclosure is further reduced in Case #4 where a leaky, north-facing suite exhibits the lowest minimum indoor temperature. Case #5 illustrates how large south-facing WWRs are able to take advantage of solar gains, but in the absence of natural ventilation (air leakage) and shading devices cannot mitigate against overheating. Finally, Case #6 reveals what happens when the best performing Case #1 is re-oriented to face north. This suggests that for skin load dominated buildings such as MURBs in cold climates, different passive strategies are needed corresponding to the solar orientations of the facades.

A conflict was identified between balconies versus no balconies when examining cold weather and hot weather thermal autonomy. Balconies that provide shading enhance hot weather thermal autonomy but block desirable solar gains in winter for south-facing units. This suggests fixed shading devices, such as balconies, should be exchanged for adjustable exterior shading devices. Cold weather thermal autonomy for non-south-facing units is more challenging and an approach combining a shading device with thermal protection, such as exterior insulated shutters, may prove more effective. Such detailed analysis will be explored in subsequent stages of the larger study.

DISCUSSION

In this paper, it is understood that environmental performance includes energy efficiency, indoor air quality, thermal comfort, daylighting and resilience for both the individual subdivision of zones or spaces (suites), and the conglomerated building-as-a-system.

It is important to appreciate that from the perspective of the inhabitants of a condo unit, the energy efficiency, thermal comfort and autonomy of their individual suites are significant factors. From a societal perspective, the peak and annual space heating and cooling energy demands for the entire building are critical considerations. Social policies governing the energy efficiency of buildings should be ideally structured to avoid situations where the fleet averaging of energy performance among constituent suites in a building compromises the performance of a subset of individual suites. People may not only want to live in green buildings, but may also want their individual domiciles to meet socially acceptable environmental performance targets.

Passive systems largely regulate the capacities and types of technologies used for environmental conditioning, and this has implications for architectural and active systems design. Passive systems are also the only strategies that can address issues of thermal comfort and resilience, since active systems are inoperable when they are no longer energized, as occurs when extreme weather events knock out the electricity supply grid. For these reasons, this paper is premised on the idea that passive systems should be privileged in the design of buildings and resolved prior to introducing active systems. It is often overlooked that active systems cannot conserve energy, only more or less efficiently convert energy to serve a purpose. Hence, it is critical to begin building performance modeling with robust default values for passive measures at the early stages of design [8].

At this stage in the study, the influence of overall effective U-values, window-to-wall ratios, and window apertures (window to floor area ratio) is very significant. It should be noted that in conventional building practice, the effective U-values of walls and windows is significantly higher than what was used for the highest performing building envelope components in this study [9], where the guiding rationale was to determine if and at what point diminishing returns were observed. Based on the Toronto climate zone, it appears that an effective U-value of 0.18 W/m^2.K for walls and 1.0 W/m^2.K for windows represent the upper threshold of passive measures for MURBs that have reinforced concrete structures. With the introduction of wood construction for MURBs up to 6 storeys in height within building codes, the influence of reduced thermal bridging and thermal mass will have to be examined.

For reinforced concrete structures, the influence of thermal bridging at balconies is significant, and becomes relatively more critical as the overall effective U-value of the exterior enclosure is reduced. Thermal comfort impacts of balcony thermal bridging remain to be investigated in this study, but at this stage the provision of thermal breaks in cantilevered, reinforced concrete balconies represents a critical passive measure, all comfort benefits aside.

Balconies in new multi-unit residential buildings are very common even though their use and appeal may diminish with increasing building height [10]. Since these serve as fixed shading devices, they may compromise passive solar gains needed for thermal autonomy, even though they improve energy efficiency overall if they incorporate thermal breaks to maintain the thermal efficiency of the enclosure. Subsequent stages of this study will comparatively assess balcony shading versus adjustable shading devices to determine if the latter can achieve both the passive solar gain and shading benefits.

In terms of reconciling energy efficiency and thermal autonomy, corner units are critical because the window aperture (window to floor area ratio) is highest for these units. Dual solar exposures also present design challenges for the accommodation of seasonal and diurnal responses. While it could not be confirmed at this stage in the study, it may prove that solutions across the four corner units that achieve an effective integration of passive measures are extensible to all other unit types. In other words, optimizing the performance of the corner units may generate a suite of measures that can be applied to achieve optimal performance across all of the suites and for the whole building. However, it should be appreciated these measures will likely differ according to solar orientation and climate zone.

Once robust passive measures for the enclosure are achieved, airtightness is essential to preserve the performance gains afforded by the thermal enclosure. Airtightness requirements appear in building codes and standards, but they may not always be enforced, such that significant variations of air leakage rates have been reported by field testing [11]. The control of outdoor air leakage, as well as between suites and common areas of MURBs is also critical to the proper operation of ventilation systems [12]. Even though ventilation and free cooling are associated with active systems, they enhance energy efficiency and a failure to control air leakage will compromise HVAC system performance.

If future stages of the study discover that single aspect facades cannot provide natural ventilation that delivers acceptable indoor quality, then provisions for mechanical ventilation become even more critical to the health and well being of inhabitants.

Thermal autonomy in multi-unit residential buildings for the Toronto climate zone has been studied recently by others, and the results indicated that thermal autonomy was very poor without occupant interaction,

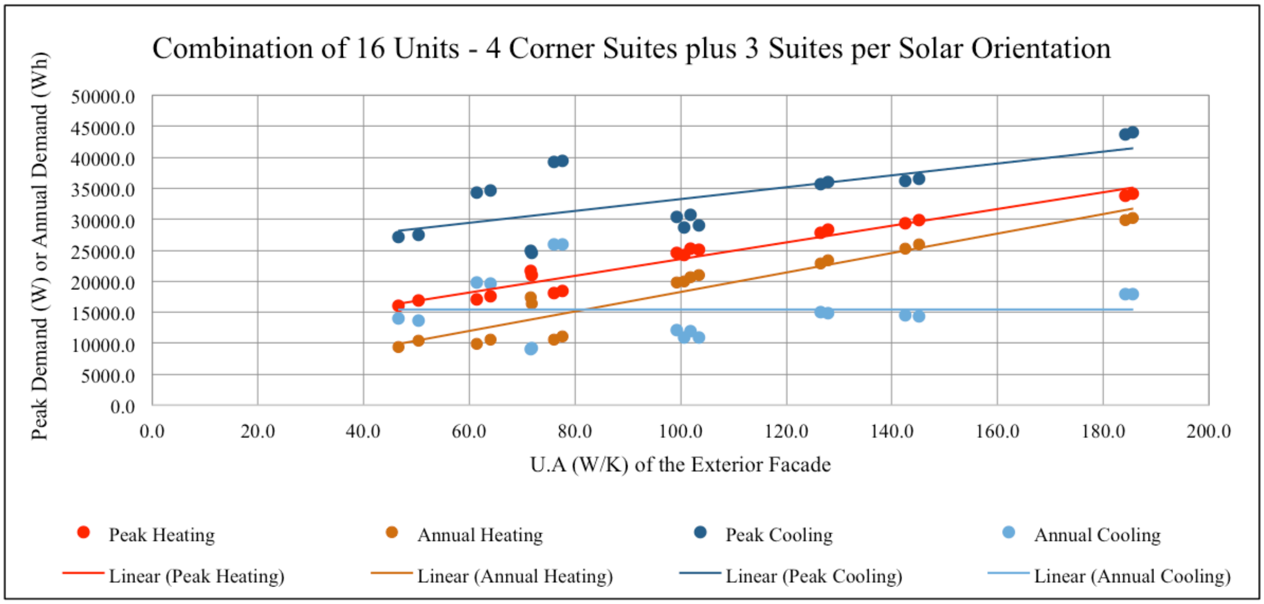

Figure 4. Relationship Between U.A (W/K) of the Exterior Facade and Peak and Annual Space Heating and Cooling Energy Demands for a Typical Floor of Condo Suites.

and the results suggest that adaptive opportunities are at least as important as building envelope design with regards to maintaining comfort in the event of power or system failure [13]. As the study underlying this paper continues, an important set of parameters to examine will be moveable insulation panels (MIPs), that inhabitants can deploy to manage solar gains, daylighting and heat transfer.

A study of moveable insulation panels (MIPs) indicates significant potential for the application of this technology to energy conservation and enhanced daylighting [14]. It is conceivable many of the conflicts between passive heating and cooling arising from cantilevered balconies above windows could be avoided through an appropriate application of MIPs. It is also possible that various retractable balcony enclosures could dampen and minimize negative side effects of fixed shading devices such as balconies. This remains beyond the scope of this paper, but will be investigated later in the study.

Since it is commonly understood by facade designers that solar heat gain coefficients can be manipulated to enhance energy conservation and thermal comfort while affording inhabitants a clear view, the impact of SHGCs was not explicitly analyzed. Relatively high SHGCs were selected in the simulations to privilege solar gains in a Toronto climate that predominantly demands space heating. However, this variable will be considered explicitly in future analyses of this study.

One question this stage of the study attempted to answer was the significance of U.A as an indicator of energy performance for skin load dominated buildings in a cold climate. Figure 4 depicts a plot of the peak and annual energy demands associated with a group of 16 condo suits constituting a typical floor in a MURB. The data strongly suggest that U.A can be used as a significant indicator of all energy demands except annual cooling at the early stages of design without need for more sophisticated analyses.

The research presented in this paper is necessary but insufficient for identifying strategies and measures conducive to achieving environmental performance that delivers energy efficiency, indoor air quality, thermal comfort, daylighting and resilience for both the individual subdivision of zones or spaces (suites), and the conglomerated building-as-a-system. Further study may uncover that the most energy efficient suites violate minimum acceptable levels of natural ventilation, daylighting and resilience. This will require the formulation of suitable strategies to ensure these minimum acceptable levels of environmental performance are not compromised, while recognizing some aspects of performance may no longer prove optimal in themselves. The approach to optimal solutions that will hopefully unfold from this ongoing study is premised on the need to first provide a minimum quality of living environment (comfort, light and air), and then maximizing energy conservation, carbon emission reductions and resilience.

CONCLUSIONS

In terms of the passive systems strategies methodology presented in this paper, the general approach to a particular building typology (i.e., multi-unit residential buildings) is to conduct energy simulations across a range of passive measures, examining parameters primarily related to the thermal efficiency of the enclosure. The simulations should consider both the performance of individual suites and the building as a whole. Once critical units are identified through this parametric assessment, further detailed analyses can be conducted to examine the influence of additional measures such as moveable insulation panels and balcony enclosures. This approach holds promising potential for establishing robust default values for key parameters affecting the performance of buildings.

It is important to appreciate that in this paper, the least thermally efficient enclosure characteristics used in parametric simulations actually represent current best practices. The analyses indicate significant potential for improvement of passive measures related to enclosures in our present codes and standards.

The findings of the early stages of this research study reinforce what has been reported in related studies.

The results of this modelling study indicate that designers seeking to reduce space conditioning loads in multi-unit residential buildings should focus first on building envelope performance parameters. [15]

For the Toronto climate zone and based on the parametric analysis of typical condominium suites in new building projects, the most effective passive strategies to reduce space heating and cooling energy demands for skin-load dominated buildings is a cold climate, in order of effectiveness, are as follows:

1. Overall effective U-value of the enclosure (with minimization/elimination of thermal bridging);
2. Window to wall ratio;
3. Window U-value and solar heat gain coefficient;
4. Window aperture (window to floor area ratio);
5. Airtightness;
6. Shading; and
7. Solar orientation.

These ranked passive measures should be viewed as relatively valid, recognizing they are more qualitative than quantitative in terms of observed building performance. There are many reasons cited in the literature that explain why building energy simulations do not always accurately reflect actual energy consumption [16]. For the purposes of establishing robust default values for passive measures in buildings, it is more practical to be relatively, rather than absolutely, accurate.

The idea of a static enclosure design strategy is challenged by the results of these analyses. Manually and/or automatically invoked measures, for shading and augmenting the thermal efficiency of both opaque and transparent enclosure assemblies, hold the potential to provide inhabitants with more adaptive, efficient, comfortable and resilient dwellings. This holds opportunities and challenges for architectural design in going from static to dynamic facades. It is important to appreciate these new approaches must incorporate serious consideration of the influence of building occupant behaviour on their effectiveness [17].

Before examining sophisticated strategies, basic questions remain to be answered. Is there a consistent correlation between overall enclosure U-value (window-to-wall ratio and window aperture), energy efficiency, comfort and resilience for skin-load dominated buildings? The limited simulations and analyses presented in this paper suggest U-values matter but that different approaches based on facade solar orientation warrant further investigation.

In the context of a low carbon economy, the methodology demonstrated in this paper assumes low energy buildings will become normative within codes and standards. While cost effectiveness cannot be ignored, factors such as carbon pricing may be expected to reward energy efficiency and carbon reductions to a point where technical feasibility will establish minimum performance requirements. Specifically, minimum requirements for the thermal efficiency of building enclosures may be expected to approach levels consistent with what is presently found in leading edge low energy buildings. But designers should be mindful that liveability, not just efficiency, is also an integral aspect of the sustainability agenda.

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