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POLICY AND PERFORMANCE EVALUATION OF CLADDING SYSTEMS WITH LARGE WINDOW AREAS IN TALL RESIDENTIAL BUILDINGS

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Abstract: As governing bodies attempt to reach ambitious GHG goals, urban development is being increasingly regulated to improve energy efficiency and ensure long-term sustainability of the built infrastructure. With the growing popularity of tall buildings in dense urban centres and the demands for net-zero energy buildings, the Window-to-Wall Ratio (WWR) of these buildings is seen as a low-hanging fruit to help reduce energy loads, leading to stricter prescriptive WWR regulations. In this paper, a critical review of the WWR regulations for tall residential buildings in the city of Toronto, with one of the highest urban development rates in North America, is presented, which included the examination of 283 tall towers. Instead of relying solely on WWR, this research introduces the effective WWR (EWWR) as an additional occupant-focused measure of the window area of tall buildings, which considers the occupant's living experience in tall towers. Finally, alternative passive solutions are presented, which can provide a balance between energy performance and livability in tall towers without reducing the WWR.

1 INTRODUCTION

A dramatic increase in the demand and construction of tall buildings in Toronto has resulted in the city producing the highest per capita number of residential towers in North America (Emporis 2014). Multi-unit residential buildings (MURBs) constitute 55% of all dwelling units in Toronto (Touchie, et al. 2013). Most new tall residential buildings are constructed with window wall or curtain wall cladding systems with high window-to-wall ratios (WWR). These systems are used for many reasons including livability, market demand, increased daylight, affordability, and constructability. However, there are concerns about the energy efficiency of highly glazed enclosures. MURBs accounted for more than 17% of the total annual greenhouse gas (GHG) emissions associated with natural gas and electricity consumption in Toronto in 2004 (ICF International 2007). With climate change becoming an important issue for all levels of government in Canada, new and existing buildings have emerged as important targets for reducing GHG emissions. Lowering GHG emissions is synonymous with improved energy efficiency. Municipalities and property developers are therefore encouraged to improve building standards to reduce GHG emissions and ensure high energy-efficiency for buildings during and after their development (Yip and Richman 2015).

The City of Toronto and the Government of Ontario have both committed to becoming world leaders in the fight against climate change, with GHG emissions set for an 80% reduction of their 1990 levels by the year 2050 (Government of Ontario 2015; City of Toronto 2007). These efforts include improving building efficiency standards and providing financial incentives for developers to build more energy efficient buildings. For example, ASHRAE Standard 90.1, an energy standard for all buildings other than low-rise residential, is referenced in Ontario's SB-10 standard and has been adopted in some parts of the United States. Most states, however, use the 2009 or more recent versions of the International Energy Conservation Code (IECC 2009). Every three years or so, these codes become stricter with the goal of continuously improving the energy efficiency of buildings. The convergence toward zero-energy or energy-positive building design is foreseeable in the future for energy codes (Yip and Richman 2015).

Compliance with energy codes is usually achieved in one of three ways: prescriptive, performance, or trade-off. To achieve prescriptive compliance, specific requirements detailed in the code must be met by the design. Performance compliance is demonstrated using a computer-based energy model of the building that shows that the anticipated energy performance is better than or equal to the standard prescriptive building. The trade-off option requires the weighted average heat loss rate of the building envelope to be less than or equal to the prescriptive target rate but allows some components to be non-compliant to the prescriptive code as long as other components exceed the prescriptive code. ASHRAE 90.1 prescribes a maximum 40% WWR for large buildings, including high-rise commercial and residential towers (ASHRAE 2007). Performance-based and trade-off regulations allow a higher WWR if energy-saving methods are used to balance the increased WWR, such as improved HVAC systems, lighting systems, boilers, and reduced thermal bridging. If the prescriptive limit continues to decrease, however, these trade-offs will be neither sufficient nor economically feasible to comply with the future codes, and reducing the WWR will be necessary to meet the performance-based regulations. It can also be difficult to significantly exceed the 40% limit on vision glazing with the newer codes to meet the required wall R-value using glazing systems and insulated spandrel panels commonly available today (Marceau, et al. 2014). The IECC has moved its prescriptive WWR limit to 30%, and there have been attempts in ASHRAE 90.1 and the standard for green buildings, ASHRAE 189.1, to reduce the WWR limit to 30% (ASHRAE 2013).

While improving energy efficiency is critical for our future, applying commercial codes to residential buildings may not be appropriate. Most research that recommends an optimal WWR for energy efficiency does not provide an urban development perspective regarding residential tall buildings, and it is not difficult to see how this happened. Before 2000, 90% of existing buildings in the City of Toronto over 150m in height were commercial buildings. In recent years, however, 90% of newly constructed towers over 150m are residential (CTBUH 2015). This substantial change in building use and occupancy type needs to be reflected in building and energy codes. In high-rise residential towers, occupants desire balconies, operable windows, a connection to the outdoors, and as much natural light as possible while minimizing the initial cost to the homeowner. Commercial building occupants, on the other hand, require no balconies or operable windows, prefer moderate natural light, and demand low operating costs.

This paper provides a critical review of the international regulations, codes, and standards affecting WWR in residential and commercial buildings. The effective WWR is then presented as an alternative occupant-focused measure of window area for tall residential buildings. Finally, several alternative passive solutions are summarized that would increase the energy efficiency of glass cladding for tall residential buildings without compromising the functionality of these units as sustainable high-density living space alternatives.

2 WINDOW-TO-WALL RATIO

The window-to-wall ratio, fenestration ratio, and glazing ratio are synonyms. They are typically expressed as a percentage and represent a building's total visible glazing area divided by its total exterior envelope area. The visible glazing area may be defined differently in each code as to whether they include or exclude window frames, skylights, and exterior doors. Similarly, the total exterior envelope area might include the roof, solid doors, or below grade walls and slab, depending on the code. In a punched-window cladding assembly, the WWR measurement is more intuitive as the openings are usually distinct from the cladding. In modern glazing systems commonly used in tall buildings, such as curtain walls and window-walls, the WWR can be deceptive to approximate by visual inspection. Insulated spandrel panels, not always discernable from the outside, may be present, providing most of the thermal resistance in the building enclosure. Counted as wall and not window area, spandrel panels may be clad with opaque glass or shadow boxes, which have glazing visible on the outside with an opaque wall on the inside.

The WWR is considered one of the most important variables that directly affects energy performance in buildings (Straube 2012). The window area impacts a building's heating, cooling, and lighting requirements. Relatively large glazing areas can help reduce the lighting load of buildings with increased daylight. Solar gain through windows can also reduce the heating load in the winter; but that same heat gain in the summer is one of the main causes of increased cooling loads. More importantly, glazing assemblies typically have significantly worse thermal resistance compared to typical opaque wall assemblies. The objective of placing a limit on window areas is therefore to reduce the heating load in winter and the cooling load in summer.

WWR restrictions did not always exist. In the wake of the oil crisis in the 1970s, focus was put on the energy efficiency of buildings and the first energy codes were implemented. In the last 30 years, structural use of glass and implementation of new technologies, such as insulated glazing units (IGUs) and low-e coatings helped improve glazing performance and allowed window areas to increase. However, as shown in **Error! Reference source not found.**, energy codes have regularly moved to decrease the allowable fenestration area in efforts to improve efficiency. ASHRAE 90.1 first introduced a prescriptive WWR limit of 50% in 1989

(ASHRAE 1989). In the first IECC in 2000, a 50% WWR was also prescribed (ICC 2000). WWRs were reduced to 40% by IECC and ASHRAE in 2003 and 2007, respectively (ASHRAE 2007).

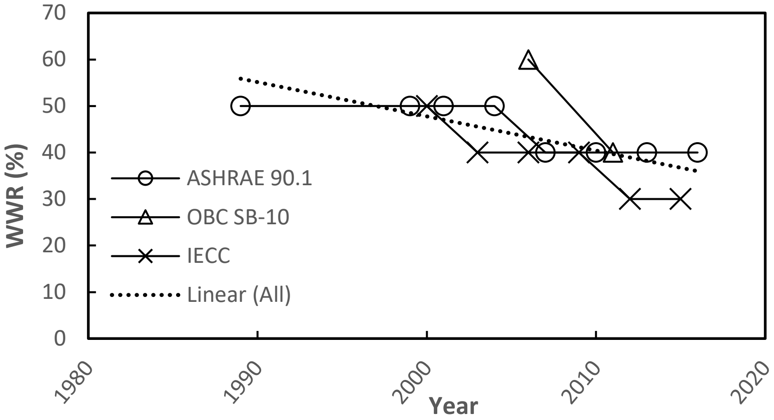

Figure 1: WWR Restriction in Codes over time

In Ontario, supplementary standard SB-10 was introduced to the Building Code Act in 2006 and allowed a maximum of 60%, but prescribed higher performing windows than those used in the 40% option. In 2011, the prescriptive SB-10 reduced WWR to 40% (MMA 2011). ASHRAE 90.1 and 189.1 attempted to reduce their ratios to 30% in 2010 and 2014, respectively (ASHRAE 2007), but both proposals were ultimately rejected because of strong industry opposition (Velikov 2013; Glass Magazine 2014). The IECC 2009 has a prescriptive 30% WWR for most North American climate zones, but 40% is allowed when some specific daylighting measures are incorporated into the design (ICC 2011). It is important to note again, that the WWR can exceed the prescriptive restrictions with a performance or trade-off compliance path.

Numerous studies have attempted to find the optimal WWR for energy performance. How the WWR affects the performance depends on many factors such as the climate zone, window orientation, building orientation, and shading. In cold climates, such as Canada, a WWR of 25-35% has been suggested with consideration of energy efficiency and daylight optimization (Johnson, et al. 1984; Carmody, et al. 2004). Unfortunately, none of these studies are based specifically on high-rise residential towers and do not capture the unit-level requirements for a high-density residential occupancy. These studies, however, are encouraging energy codes to continue to reduce the allowable window area for high-rise residential units as well as commercial buildings.

Windows on a residential unit provide the occupants with a connection to the outdoors. With the mounting affordability issues in dense urban centres, there is a strong need for family-friendly high-density living spaces. Window size and views continue to be an important selling point for condominium units (Bennet 2015). In an occupant survey of 20 condominium units, 90% of participants with large windows wanted to keep their existing window proportions. When asked why they would not want smaller windows, participants mentioned concerns about the effects of reduced daylight, reduced view, sense of space, air flow, and the undesirable aspects of small windows (Bennet 2015). In one field study (Dogrusoy and Tureyen 2007), the occupants' visual satisfaction was achieved when the WWR was between 44% and 100%. In another, a window area of 50-80% was preferred (Ludlow 1976). Still, another found that a WWR of between 50-60% was most desirable (Ochoa, et al. 2012). Quantifying the aesthetic importance of window size and how it affects the occupant experience in MURB units is much more difficult than quantifying the energy loss of window sizes. Therefore, finding the optimal window size for MURB units needs to consider both the energy efficiency as well as occupant experience, and is outside the scope of this article. However, a balance between energy performance and occupant experience should be a primary objective in MURB design.

As Governments attempt to achieve their GHG emission goals, building codes will be major targets for reductions. There have already been attempts to reduce the allowable WWR to 30% or lower to have a more efficient prescriptive baseline. While a 30% limit would certainly improve the energy efficiency of MURB units, the livability of these units and occupants' perspective is not being considered in these WWR reductions. Instead, other alternatives can be considered to achieve the energy goals with moderately sized window areas, which are summarized later in this paper.

3 PRESCRIPTIVE VS PERFORMANCE BASED COMPLIANCE

Building energy codes have been decreasing the allowable fenestration area over the last 30 years (**Error! Reference source not found.**), but restrictions have not been effective in decreasing the WWR of tall buildings. **Error! Reference source not found.** shows tall MURBs of 20+ storeys constructed in Toronto over the past 40 years. Insulated spandrel panels can sometimes look like visible glazing from the exterior, so unit floorplans and photos of the buildings were used together to estimate the WWR. **Error! Reference source not found.** demonstrates how the WWRs have trended upward despite stricter codes. This trend is also evident in Vancouver (RDH Building Engineering 2012).

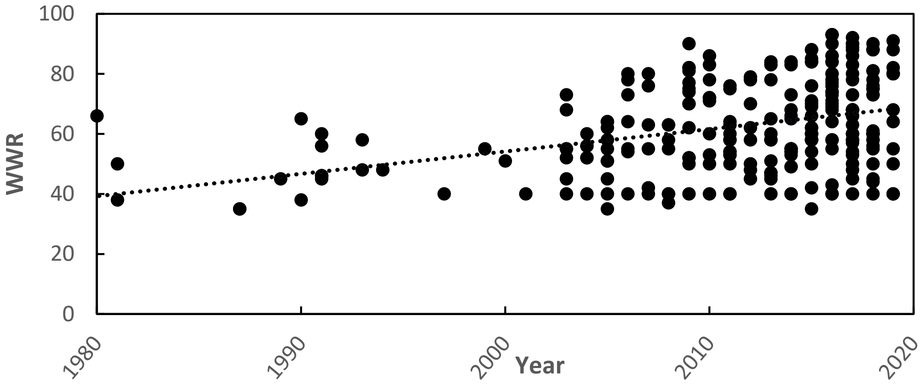

Figure 2: WWR of Tall residential buildings in Toronto

The average WWR of the 283 towers investigated in this research was 62.5%, with 88.5% of the buildings exceeding 40% WWR. The data also showed that over 93% of the buildings constructed since 2011 when SB-10 introduced the 40% prescriptive maximum, had WWRs of over 40%. The significance is that almost all new tall MURBs in Toronto are using the performance compliance path instead of the prescriptive path in order to allow larger fenestration areas, and therefore rely on whole building energy modeling or trade-off methods. It is also worth noting that none of these tall buildings had WWRs of 30% or less.

The purpose of a prescriptive code is to provide a strong and meaningful benchmark that encourages stakeholders to improve. Therefore, these codes are often made stricter with time. Prescriptive codes provide a formula for compliance but often do not allow much design flexibility, so most codes also have a performance-based compliance option which allows more flexibility. The performance option for energy allows designers to disregard many aspects of the prescriptive code if an energy model meets the same energy baseline as if it were the prescriptive building. This way, the governing bodies can achieve their policy goals while allowing innovation and creativity. To exceed the prescribed WWR, designers must create two energy models. The first model, called the reference or baseline model, represents the building as defined in the prescriptive requirements. The second model represents the desired design, which must have equal or better energy efficiency than the baseline. This process is iterative and very labour intensive.

To meet the code, the energy modeling balances less energy efficient glazing, i.e. larger WWRs, with improvements to other components in the building, such as better mechanical systems. In this case, active (requiring energy to operate) systems are used to accommodate under-performing passive systems. In terms of resilience, the loss of electricity for an extended time could have devastating effects, as the thermally weak enclosure would not keep occupants comfortable against the cold or the heat for very long. Ideally, the building design and energy modeling focus should be on ways to meet the baseline requirements through passive systems, with active systems used only as transient components that supplement the passive systems of a building (Kesik 2015). Codes should move away from allowing exchanges between poor enclosures and strong active systems, and focus on strong thermal resistance of the building envelope. Moreover, this can be achieved with moderate and large sized windows, as discussed later in this paper.

Performance-based compliance also relies on the assumption that energy modeling is an accurate representation of actual energy use. Energy models should accurately predict the performance of a proposed design at any stage of that design. Unfortunately, significant discrepancies between simulated results and actual measured consumption have been found (Frankel and Turner 2008). In a study of 121 buildings, the ratio between measured and simulated energy consumption ranged between 0.25 and 2.5 (Raftery, et al. 2011). The level of model detail and thus accuracy in the energy modeling process can also be at odds with tight schedules and design timelines (Richman, et al. 2014). If performance compliance becomes the norm, then significant improvements are needed in building energy simulation tools. The accuracy of predictions depends on occupant behaviour, building systems operation, the quality of construction, quality of materials, and the completeness and constructability of design (OAA 2016).

The current prescriptive path's maximum WWR is not being followed by most developers and designers in Toronto. If the allowable window area continues to be reduced, the energy baseline would improve but even fewer designs would follow the prescriptive code for new buildings. Policy makers, rightfully, are concerned with energy conservation goals. An alternative could be to have a maximum whole-building effective thermal transmittance value (U-value) that would allow flexibility in design, keep a standard in efficiency, and not restrict the WWR (Urban Green Council 2014). With a target U-value from the beginning of the process, architects and developers will be encouraged to consider the WWR, the quality of fenestration units, and other passive solutions for high-performing enclosures from an early design stage.

4 WWR IN LOW-RISE VS HIGH-RISE RESIDENTIAL BUILDINGS

The regulatory agencies have not been able to keep pace with the rapid shift from using high-rise buildings solely for commercial purposes to the recent urban development demands for high-rise residential buildings in dense urban centres. In Ontario, two supplementary standards were introduced in the Building Code to improve energy efficiency: SB-12 for low-rise (4 or fewer storeys) residential buildings, and SB-10 for all other buildings including both high-rise commercial and residential buildings, without making specific distinctions between the two. SB-10 has a prescriptive maximum of 40% WWR (MMA 2011). As the primary energy code for low-rise residential units, SB-12 has a prescriptive maximum WWR of 17% but can go as high as 22% if windows with better U-values are used (MMA 2016). However, the rules for calculating the WWR in the low rise and high rise codes differ significantly.

In SB-12, the 17-22% WWR in low-rise detached single-family homes is calculated based on the building's entire vertical enclosure area as demonstrated in Figure 3. With windows spread over 4 walls, light can enter the living space from all directions. The WWR is calculated as:

$$[1] \qquad \mathrm{WWR}_{\text{SB-12(Single)}} = \frac{\text{Glazing area of building (1 living unit)}}{\text{Area of vertical perimeter of building}} * 100\%$$

When calculating the enclosure area for attached low-rise units such as townhomes, SB-12 A-2.1.1.1 clauses (7) (8) and (10) explain:

> "For attached homes, the above grade portions of the walls that are common to other conditioned units are also included in the wall area" (MMA 2016)

The equation to calculate the WWR in this case is:

$$[2] \qquad \mathrm{WWR}_{\text{SB-12(Attached)}} = \frac{\text{Glazing area of living unit}}{\text{Area of vertical perimeter of living unit}} * 100\%$$

As shown in Figure 3: Simplified low-rise house Figure 4, the interior common walls are included in the calculation for the WWR. Because interior common walls cannot have windows, the total window area can be placed in the two exterior walls, allowing significant light to enter the living space from two directions.

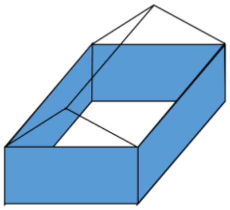

Figure 3: Simplified low-rise house

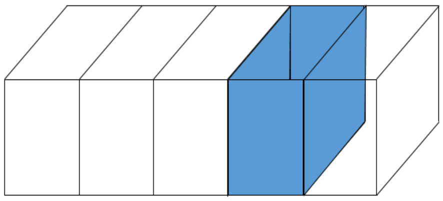

Figure 4: Simplified low-rise attached townhome

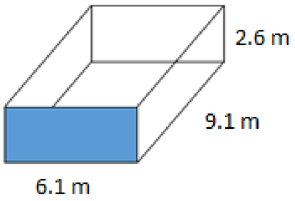

Figure 5: Simplified MURB unit

High rise living units are assessed differently. To demonstrate, a simplified 55.7 m2 (600 ft^2) high-rise MURB unit is shown in Figure . It has two interior walls common to the adjacent suites, one common wall adjoining the hallway and one exterior wall (shaded). The three interior walls are windowless and natural light enters the suite from one direction only. Each interior wall, floor, and ceiling is perfectly insulated since the temperature on both sides is approximately the same.

Under SB-10, the WWR is calculated on a whole-building versus living-unit basis, so the interior walls are not included in the WWR calculation. The equation is:

$$[3] \qquad WWR_{SB\text{-}10} = \frac{\text{Glazing area of whole building}}{\text{Area of vertical perimeter of whole building}} * 100\%$$

This is inconsistent with the WWR calculation using SB-12 as it does not consider the number of units in the building and the individual living unit's access to light. Also, the code for high-rise buildings, originally developed for large open floor commercial buildings, imposes a significantly stricter WWR limit than its low-rise counterpart. In fact, if SB-12(attached) is used, 100% windows on the exterior wall represents a 20% WWR for the unit in Figure . As previously mentioned, a 20% WWR is allowable in the prescriptive code for low-rise living units as calculated under SB-12.

5 EFFECTIVE WINDOW-TO-WALL RATIO (EWWR)

To address this inconsistency in the codes, the Effective Window-to-Wall Ratio (EWWR) is herein introduced. It defines the window-to-wall ratio of a MURB unit taking into consideration the confines of the living space from the perspective of the occupant. Like SB-12, the EWWR considers all perimeter walls of a living unit. The EWWR calculation is:

$$[4] \qquad EWWR = WWR_{SB\text{-}12(Attached)} = \frac{\text{Glazing area of living unit}}{\text{Area of vertical perimeter of living unit}} * 100\%$$

The EWWR of the simplified unit with the corresponding whole-building WWRs are described in Table 1 and demonstrated in Figure 5.

Table 1: Simplified Side Unit WWR (%) * denotes units shown in Figure 6

WWR (SB-10) [3]	100	90	80*	70	60*	50	40*	30	20*
Effective WWR (SB-12) [4]	20	18	16	14	12	10	8	6	4

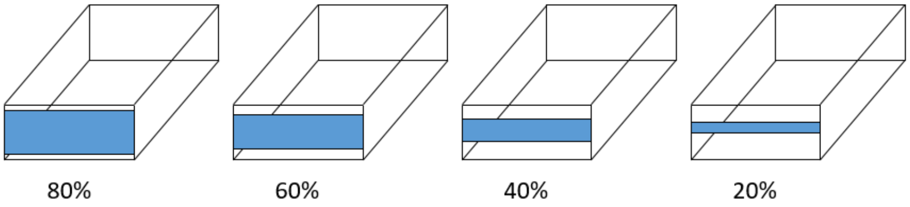

Figure 5: WWR representations for the simplified unit

If this simplified unit was designed to meet the SB-10 prescriptive 40% WWR requirement, it would effectively be an 8% EWWR for a side unit and a 20% EWWR for a corner unit. This example shows that, from the occupant's perspective, the WWR of their living unit is likely much smaller than the building's WWR. If efforts to reduce the prescriptive code to 20% or 30% WWR were successful, side units might only have a 4-6% EWWR, as shown in Table 1. To validate the simplified calculations, the WWR and EWWR were calculated for 8 recently built MURB buildings in Toronto for which architectural drawings were obtained. The results are shown in Table .

Table 2: Case study EWWR (%)

Building	Year Constructed	SB-10 WWR	Avg. EWWR side units	Avg. EWWR corner units
1	2017	58	13	32
2	2017	53	11	22

3	2017	66	15	27
4	2017	68	16	22
5	2017	60	13	22
6	2014	83	20	34
7	2014	54	18	31
8	2012	78	20	36
AVG	--	65	16	30

Although the WWRs of the eight buildings were all above the SB-10 prescriptive limit of 40%, the calculated EWWR [4] of the side units were between 11% and 20%. The average EWWR for the corner units in these buildings was 30%, while the average building WWR, calculated as per SB-10 [3], was 65% and well above the prescriptive limits of 40%.

Currently, high-rise residential buildings follow the same energy codes as commercial buildings, while their occupancy, functionality, and even their construction are very different. Commercial buildings are typically constructed with large open space on each floor and tenants are responsible for putting up walls and partitions to meet their operational needs. These spaces are renovated and reconfigured regularly. Current trends of open office spaces and openings or glazed interior partitions allow natural light to permeate throughout the floor from all windows. These spaces rarely have operable windows or balconies and occupants typically spend forty hours per week in their workplace. A residential tower, however, is divided into living units from the very beginning. Common walls between units are solid, permanent, and rarely modified during the building's functional life. Occupants can spend little or all their time in their homes. Balconies provide limited access to the outdoors, but it is not the same as stepping directly onto lawn or other landscaping as from a low-rise home.

Based on the above differences between the residential and commercial towers, and from a policy perspective, it is recommended that different codes and regulations be applied to WWR for these towers. Owners of both commercial and residential buildings share a common goal of reducing energy loads, but practical differences exist between the two. A new code for MURBs could have a unit-based approach. Compartmentalization requirements could be detailed, which would not be applicable to most commercial buildings. A minimum requirement for the efficiency of the unit could be considered. Considerations for the EWWR, unit orientation, shading, and size of units could be made. From a user perspective, the area of windows affects the living experience of the occupant. As the common wall between units in townhomes is included in their WWR calculation, similar consideration should be made for high-rise units.

When choosing high-density living, occupants are selecting an option that contributes to the reduction of greenhouse emissions (Mohareb and Mohareb 2014). Living in a thriving urban area means that the residents are more likely to use public transit, bicycles, or walk to their destinations rather than use personal vehicles (Smith 1984). This has secondary benefits on health and well-being. In addition, occupants are likely choosing a smaller footprint for their home than other low-rise options. When considering small MURB units such as a studio or 1-bedroom unit, having large window areas can give the illusion that the living space extends beyond the walls. This "borrowed space" also adds a valuable connection to the outdoors. From a sustainable urban development perspective, living in a MURB should be encouraged, and making units more livable with consideration for occupant visual comfort could sway young families and professionals to choose this living option. In addition to being more appealing, natural sunlight can have many advantages to human well-being such as increased productivity, improved livability, and stress reduction (Wang and Boubekri 2011; Singh, et al. 2010, and Edwards and Torcellini 2002).

6 PASSIVE SOLUTIONS FOR HIGH-PERFORMING BUILDING ENVELOPES

Space heating and total energy consumption in high-rise residential buildings appear to have increased over the past 30 years despite improvements in energy efficiency (Finch, 2010). For sustainable and resilient building infrastructure, passive solutions must be part of the strategy for improving the energy efficiency of buildings. Active systems can greatly enhance high-performing buildings, but the code minimum may be ineffective if it relies on complex mechanical/electrical systems for compliance. Several passive measures can improve the performance of building envelopes without reducing the WWR.

Better IGUs and alternatives are important options for improving the overall R-values of the building enclosure. The overall R-values of the building envelope for high-rise MURBs have improved very little over the past 40 years (Finch, 2010). If the trend of higher WWR continues, high-performing glazing and frame units will be necessary. Emerging technologies are providing thermally efficient windows as well as visually comfortable enclosures. Triple pane windows, Vacuum Insulated Panels, Aerogel panels, electrochromic windows and Photovoltaic glazing are all examples of IGU technologies that can significantly improve the performance of the enclosure, which in turn will help with both the heating and cooling loads. These technologies are all currently being used in the market by constructors building high-performance buildings. As costs are reduced, they will become more common and contribute toward our energy goals while satisfying occupant demands for natural light and a connection to the outdoors.

Reducing thermal bridging and strengthening the building airtightness are other important passive measures that should be targeted. Thermal bridging occurs when heat flows at a higher rate through one part of an assembly than another, allowing heat to bypass insulated areas. It can greatly affect the thermal performance of assemblies. The most effective solution to most thermal bridging is an exterior layer of continuous insulation (Straube 2012). It is standard practice in North America to account for the thermal bridging within the building enclosure and calculate the effective U-value of the assembly. However, thermal bridging at architectural and structural details, such as interfaces between assemblies is often ignored or oversimplified (Marceau, et al. 2014). Simple changes to the assembly design to reduce thermal bridging may be more effective at reducing energy use than simply adding more insulation. Airtight buildings require less conditioning of the interior air for heating/cooling by the active mechanical systems. Tight building envelope construction has received more attention in the past 25 years than some other aspects discussed in this paper, but improvements can still be made.

Reducing energy consumption and GHG emissions is an important goal for sustainable urban development around the world. Architects, engineers, and developers should work together to resolve energy issues while maintaining a reasonable level of occupant satisfaction to keep high-density living viable and enticing. The continuous reduction of allowable window area in prescriptive codes can be avoided if smart design that allows the reduction of the window area while maintaining occupant satisfaction is achieved. There are many reported examples of glazing installed in inappropriate areas, such as directly beside the toilet, refrigerator, other appliances, or furniture where opaque insulated panels would have been more appropriate than floor-to-ceiling glass. It has also become commonplace to have glazing behind cylindrical concrete columns. Architects, developers, interior designers, and engineers should work together early in the design stage to avoid such situations and maximize where opaque panels can be effectively used.

Another easy way to reduce the WWR would be to install the clear glazing on top of 0.5-1 metre insulated spandrel panels, as demonstrated in Figure 7. The section of insulated paneling above the floor does not significantly detract from the views and improves the thermal efficiency of the wall.

Figure 6: View from a condominium in Toronto with & without simple windowsill that can be insulated

Moderately sized windows, solar shading, and operable windows can greatly reduce an occupant’s dependency on mechanical heating and cooling systems (Bennet 2015). A balance between energy efficiency and unit livability may be achieved by keeping the average EWWR within the SB-12 guidelines of 17-22%, depending on the quality of the glazing units.

7 CONCLUSION

With the mounting affordability problems in dense urban centres, the vertical urban development in the form of high-rise residential buildings has been growing in popularity. Unlike their commercial counterparts, residential towers provide a living space for families, and as such need to meet occupant requirements, such as sufficient access to daylight and a connection to the outdoors. High-rise residential towers have been under extreme pressure to examine their contributions toward the government's aim to reduce GHG emissions. These pressures have focused on reducing WWR without considering the impact that it has on the occupants' access to natural light. Unlike other methods of increasing the energy efficiency of building envelopes such as increasing insulation, reducing thermal bridging, or raising the standard for airtightness, reducing the allowable area of glass in buildings can have negative effects on occupant experience, comfort, and health. WWR restrictions also make an assumption of poor glazing performance, while new technologies are quickly developing high-performance glazing systems that may perform better than typical opaque sections. From a small MURB unit occupant's perspective, the window area is their only connection to the outdoors. The EWWR introduced in this research illustrates how glazing areas in high-rise MURBs are already equivalent to or less than prescribed limits for low-rise homes.

Based on the findings of this research, the existing prescriptive code is not currently being followed by a majority of tall residential buildings in Toronto, which means that most buildings have been designed using the performance-based alternative that involves energy modelling. Therefore, further reduction in the allowable WWR will be unsustainable and other passive solutions need to be considered to improve the energy efficiency of building envelopes for tall residential towers. A balance between energy performance and occupant satisfaction is achievable. A minimum overall U-value for enclosures could be one method for enforcing energy efficiency without restricting window area. Smart design can find a compromise between living demands of occupants and strong energy performance.

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