Performance and Policy Analysis of Cladding Systems with Large Window Areas in Tall Residential Buildings

by

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A thesis submitted in conformity with the requirements for the degree of Master of Applied Science
Department of Civil Engineering
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Abstract

Highly-glazed modular systems such as the curtain wall and window wall have been the most popular cladding systems for modern tall buildings in North America. There exists little in academic literature about the window wall, prompting a detailed analysis of the system in comparison with the curtain wall. The systems were analyzed and compared for building science and construction management parameters. Further, energy codes around the world have been restricting window-to-wall ratios (WWR) in an attempt to help reduce the energy loads of building envelopes. As ambitious goals are trying to be reached, there are concerns that maximum WWRs will be lowered to levels that might harm human comfort and liveability of multi-unit residential building (MURB) units. A different way to calculate glazing area from an occupant’s perspective is introduced. A maximum effective U-value for the enclosure attained using innovative passive solutions may be a more effective method for ensuring efficient building envelopes. More accurate energy modeling, energy reporting and benchmarking and occupant education are also discussed as methods for improving building performance.
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# Table of Contents

Acknowledgments ........................................................................................................................... iii

Table of Contents ............................................................................................................................... iv

List of Tables ....................................................................................................................................... vi

List of Figures ...................................................................................................................................... vii

Chapter 1 Introduction ....................................................................................................................... 1

1.1 Background .................................................................................................................................. 2

1.2 Objectives .................................................................................................................................... 4

1.3 Scope .......................................................................................................................................... 5

1.4 Methodology ................................................................................................................................. 6

1.5 Industry Partners ......................................................................................................................... 9

1.6 Organization of Thesis ................................................................................................................. 9

Chapter 2 WINDOW WALL AND CURTAIN WALL: AN OBJECTIVE REVIEW ............................ 11

2 Window Wall and Curtain Wall: An Objective Review ............................................................... 11

2.1 Abstract ....................................................................................................................................... 11

2.2 Introduction ................................................................................................................................. 12

2.3 The Curtain Wall ......................................................................................................................... 14

2.4 The Window Wall ......................................................................................................................... 15

2.5 Comparison ................................................................................................................................. 17

2.5.1 Thermal Performance ............................................................................................................. 17

2.5.2 Water Penetration & Air Leakage ......................................................................................... 19

2.5.3 Condensation .......................................................................................................................... 21

2.5.4 Installation ............................................................................................................................... 22

2.5.5 Cost and Maintenance ............................................................................................................ 24

2.6 Improvements ............................................................................................................................... 26

2.7 Conclusion .................................................................................................................................. 27
List of Tables

Table 1: Summary of Building Height Classifications and Applicable Energy Standard ............. 6
Table 2: R-Values of Typical Sections (Morrison Hershfield, 2016) ........................................ 18
Table 3: Glazing System Assembly Costs (Morrison Hershfield, 2014) ..................................... 24
Table 4 Simplified Side Unit WWR (%) .................................................................................. 36
Table 5 Simplified Corner unit WWR (%) .................................................................................. 37
Table 6 Case study EWWR (%) ............................................................................................... 38
List of Figures

Figure 1: Evolution of the Glass Façade – left, Hallidie Building (1918), right, One World Trade Centre (2013) .................................................................................................................................................................................. 13

Figure 2: Simplified Window Wall and Curtain Wall ........................................................................................................................................................................... 16

Figure 3: Thermal Gradients of Window Wall and Curtain Wall (Morrison Hershfield, 2016) .. 19

Figure 4 WWR Restriction in Codes over time ......................................................................................................................................................................................... 32

Figure 5 Simplified low-rise house .............................................................................................................................................................................................. 34

Figure 6 Simplified low-rise attached townhome ............................................................................................................................................................................. 35

Figure 7 Simplified MURB unit ................................................................................................................................................................................................. 36

Figure 8 WWR representations for the simplified unit ............................................................................................................................................................... 37

Figure 9 WWR of Tall residential buildings in Toronto ......................................................................................................................................................... 40

Figure 10 View from a condominium in Toronto with & without simple windowsill that can be insulated ...................................................................................................................................................................................... 47

Figure 11 Configurations of 40% area on a square ................................................................................................................................................................. 48

Figure 12 Energy Code Improvements vs Actual Energy Use (U.S. Energy Information Administration, 2016) & (Duggin, 2017) ....................................................................................................................................................................................... 52
Chapter 1
Introduction

Tall Buildings are being constructed at high rates in Canada and around the world. Since 2000, over 950 buildings measuring 200m or taller were completed worldwide, while only 260 existed beforehand (CTBUH, 2017). To counter excessive urban sprawl, many of these tall buildings are multi-unit residential buildings (MURBs). Before 2000, 90% of existing buildings over 150m in Toronto were commercial buildings; in recent years, 90% of newly constructed towers over 150m are residential property (CTBUH, 2015). The increasing urbanization and high-density urban areas help provide affordable living, facilitate efficient supply of services, and can help in efforts to reduce greenhouse gas (GHG) emissions. Further, as there is high demand for space and little available land, building vertically is the logical solution. As engineering breakthroughs in structural, wind and earthquake resistance were discovered and construction methods improved, high-rise buildings not only became an important component of sustainable urban growth, but also became a symbol for prosperity, success, and technical achievement.

New challenges regarding the construction of tall buildings are being faced in the Canadian construction industry. The Residential Construction Council of Ontario (RESCON) is the industry partner of the Building Tall Research Centre at the University of Toronto and identified many topics of interest to the industry that should be investigated. The increasing height of buildings introduces challenges in logistics, productivity, and operability. Technical aspects such as the structural engineering and the stack effect are also complicated as the height of buildings increase. Newly constructed tall buildings also most commonly use modern highly-glazed modular cladding assemblies as opposed to more traditional cladding such as masonry, concrete, or stone. The focus of this research is on glazed cladding systems such as the window wall and curtain wall, and the legislation that regulates them. These systems are being challenged by many organizations and researchers due to their energy performance and life-cycle in the Canadian climate.

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. 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 incentives for developers to build more efficiently and effectively. Net zero-energy or energy-positive building design is a foreseeable goal in future energy codes.

Easy-to-construct modular cladding systems are key elements of thousands of residences and will continue to be for many decades. Their operational properties such as thermal efficiency, air tightness, water tightness, condensation control, life cycle costs, and resilience should be optimized to ensure high-performing building envelopes. Construction methods, commissioning, and maintenance of these systems should also be improved to ensure reliable high-performance systems, avoid early failure and be cost effective. From the occupant perspective, these systems must provide comfortable and visually pleasing high-rise units to motivate occupants to choose high-rise living as their lifestyle. Similar to other technologies, many innovations related to cladding systems are still being developed to ensure that these goals are achieved. As the window wall and curtain wall continue to be improved, they will shape the skylines of modern cities as green and reliable choices.

1.1 Background

One of the initial research themes identified by RESCON was improving the energy performance and maintainability of modular cladding assemblies and window-wall systems. Members of RESCON, who develop, construct, and manage many high-rise residential buildings in Ontario raised concerns with perceived shortcomings of highly-glazed cladding of tall buildings. One large concern is the energy performance of these cladding systems. Other concerns exist regarding the lifespan, reliability, and resilience of highly-glazed cladding. Building scientists have written that the current window-wall systems are “thermally inefficient and questionably durable”, thus requiring further research and development (Kesik, 2011). In a feature piece by the Canadian Broadcasting Company, some industry experts referred to buildings in Toronto with window walls as “throw-away buildings” that would face many problems within 15-25 years of being constructed, such as insulation failures, water leaks, skyrocketing energy and maintenance costs and declining resale potential (CBC News, 2011). Industry experts have long challenged this characterization as one-sided and not representative of most tall residential buildings. This discussion helped motivate my research to find problematic issues with the window wall, provide
potential solutions and contribute a fair and balanced analysis of the high-glazed cladding systems in tall residential buildings.

Early in the research phase, it became apparent that there was little written in academic literature about the window wall. Other than patents describing the inventions, very few articles described the performance of the systems or how they compare to the curtain wall. The window wall and curtain wall (extensively defined in Chapter 2) are quite similar to the layman and the terminology can even be confusing. The window wall has been considered by some as a type of curtain wall (Frey, 2013) and perhaps even more blurring is that when the curtain wall technology was first being developed, it was referred to as a window wall (Yeomans, 2001). Before being able to identify problems and potential solutions that face the window wall, definitions and an objective comparison of the two main cladding systems are provided.

Later in the literature review, the window-to-wall ratio (WWR) stood out as one of the most important building properties regarding energy consumption and code compliance. Buildings with high WWRs in almost all case studies were buildings with window wall or curtain wall cladding systems. Most building energy codes today have a prescriptive maximum WWR to help reduce cooling loads in the summer and heating loads in the winter. This is based on the principle that the windows are less thermally efficient than opaque sections that are typically well insulated. Yet in cities like Toronto and Vancouver, most new tall residential buildings are constructed with larger glazing ratios than prescribed in the code. A performance compliance path that involves energy modeling is available and allows larger window areas if the prescriptive energy baseline is achieved. However, there are concerns about the accuracy of whole-building energy modeling. Regardless, there have been attempts to further decrease the allowable window area to reduce building energy loads.

While reducing building energy consumption is important, questions arise whether the continuous reduction of the allowable window areas might affect occupant visual comfort and ultimately the liveability of high-rise residential units. Livability is dependent on the tolerance of the occupants and varies with seasons, weather, mechanical system effectiveness, occupant behaviour, building orientation, etc. Green building objectives must include and embrace human health issues along with the environmental effects. As Canadians spend most of their time indoors, daylight and visual comfort are provisions that should not be sacrificed for increased thermal efficiency. There are
many examples of short-sighted solutions for reducing greenhouse gas emissions and being environmentally friendly that had unforeseen adverse secondary effects. As biofuels were being promoted as a green fuel, there was a massive demand for raw materials, which reduced the availability of corn grown for food and made food security in the developing world more difficult to achieve (Pauli, 2010). Similarly, while the development of biodegradable soaps that use fatty acids from palm trees appeared progressive, it triggered massive stripping of rainforests to grow more palms, thereby destroying the habitat of many animals including the orangutan (Pauli, 2010). These seemingly benign ‘advances’ somehow backfired because the secondary impacts were not considered.

The reduction or, in the extreme, elimination of glazing in buildings will reduce the heating and cooling energy demand of those buildings. However, there is more at stake, including occupant visual comfort, access to natural light, and free access to fresh air. High-rise residential buildings in Ontario follow the same codes and standards as commercial buildings even though they have very different uses and contexts than commercial buildings. As policy-makers continue (rightfully so) to improve the standard for energy efficiency in buildings, it may be important to consider the context of an occupant in a high-rise residence separately from a commercial building workplace.

1.2 Objectives

The overall purpose of this research project is to help improve the performance of building envelopes for tall residential buildings, while considering constructability, cost and the occupant’s perspective and visual comfort.

The main objectives are to:

1. Objectively compare two glazed cladding systems, namely curtain wall and window wall, from a construction and occupant perspective.

2. Objectively assess the codes and regulations related to window-to-wall ratio on how they are applied, compliance trends, and future opportunities.
3. Recommend changes to codes, regulations, and best practices to bridge the gap between design trends, occupant needs and technology.

The research resulted in two papers: *Window Wall and Curtain Wall: An Objective Review*, a conference paper published at the CSCE2017 in Vancouver, BC, and *Evaluation of Window to Wall Ratio restrictions for Tall Residential Buildings in Toronto* which was submitted to the Canadian Journal of Civil Engineering on June 19th 2017.

### 1.3 Scope

Glazed cladding systems in newly constructed high-rise residential buildings in Ontario are the focus of this research. The two specific cladding systems used in new tall buildings in Ontario are the window wall and curtain wall. As previously mentioned, these systems can often be confused for each other but a clear and distinct definition of both systems is offered in Chapter 2. When speaking about curtain walls and window walls, both refer to the common vocabulary used in Canada to describe glass cladding systems. Many different types of curtain wall systems exist, including stick built, unitized, panel, cable nets, point supported, store fronts, glass fin walls and double wall assemblies. For the purposes of the comparison between the curtain wall and window wall in Chapter 2, the unitized system is used for simplicity and its resemblance to the window wall as pre-constructed modular systems.

High-rise buildings in the context of this study refer to buildings over 12 storeys. The Ontario supplementary standard SB-10, which is referred to extensively in Chapter 3, is the energy standard for all commercial and residential buildings above 4 storeys. The City of Toronto defines low-rise buildings as 4 storeys or below, mid-rise buildings as 5 to 11 storeys, and high-rise buildings are 12 storeys and taller (City of Toronto, 2017). Emporis standards label high-rise buildings between 35m and 100m tall or 12-39 floors as high-rise buildings (ESN 18727), while 100m+ buildings are labeled as skyscrapers (ESN 24419) (Emporis, 2017). These are summarized in Table 1. The analysis captured in Figure 9 of Chapter 3 defined tall buildings as structures with more than 20 storeys, for the sake of limiting the number of data points.
Table 1: Summary of Building Height Classifications and Applicable Energy Standard

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<tr>
<td>Low-rise</td>
<td>≤ 4 storeys</td>
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<td>SB-12: For residential buildings ≤ 4 storeys</td>
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<tr>
<td>Mid-rise</td>
<td>5-11 storeys</td>
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<td>SB-10: For commercial and residential buildings ≥4 storeys</td>
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<tr>
<td>High-rise</td>
<td>≥12 storeys</td>
<td>35-100m or 12-39 storeys</td>
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<td>Skyscraper</td>
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<td>≥100m</td>
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The definition of Window-to-Wall Ratios (WWR) and the way in which they are calculated are taken from North American codes and standards such as ASHRAE 90.1 and Ontario’s SB-10 supplemental standard of the building code. Sometimes called the fenestration ratio or glazing ratio, it may be calculated differently around the world depending on its definition.

The context of this research is the cold-humid climates of the Great Lakes basin. Toronto experiences cold winters and hot summers so design strategies will be different compared to colder areas of Canada or hot humid climates such as Florida or coastal Texas. Some problems and solutions discussed may be applicable to all climates, however results and recommendations are based on the Toronto context.

This research examines and discusses policy, but does not outline or recommend direct policy change. Recommendations and conclusions from this research are suggestions for consideration when drafting future codes and standards.

1.4 Methodology

To achieve the research objectives, three sources of data were used, namely, peer-reviewed academic and regulatory literature, drawings and images for 252 tall residential buildings in Toronto from which WWR were extracted, and interviews with experts. Analysis and comparisons are based on the literature and on calculations based on data collected by the author. Most analysis in this research was qualitative.
To accomplish the first research objective, a literature review and interviews with experts provided key information. Topics covered include the basics of building science and cladding systems, thermal conductivity of windows, and energy loads in buildings. As the topic of research narrowed toward the window wall and curtain wall, it became clear that there was very little in the literature that referred to the window wall as described in Canadian construction. Some patents exist, however almost no peer-reviewed research articles discussed performance or how the window wall compared to other cladding types. Articles referring to the curtain wall were plenty, and the performance and improvements to the system are well documented. Some blog posts on the internet described the difference between the two glazed cladding systems, however there was a need for reliable, non-biased sources. To get in-depth information about the window wall, industry experts, architects, professors, and manufacturers were interviewed. We were also able to tour a window wall factory, as well as a building under construction that was getting window walls installed to further understand the system and its benefits and weaknesses. Regarding the performance evaluation of both systems, the curtain wall’s performance was well documented while only a few studies completed by industry looked at the window wall.

The second research objective required a detailed study of codes and standards to understand the WWR restrictions in North America. The ASHRAE 90.1, IECC, and OBC SB-10 and SB-12 (current and previous versions) were reviewed to examine how the codes regulate maximum allowable window areas. Since a building’s WWR is not commonly available through public databases, data collection was also necessary. RESCON members generously provided 8 full building plans and window schedules for newly constructed high-rise residential towers in Toronto. The WWR of a building, as referenced in the OBC’s SB-10 is calculated as:

$$WWR = \frac{\text{Vertical glazing area of building}}{\text{Area of vertical perimeter of building}} \times 100\%$$

With exact dimensions on the window schedule and building elevation drawings, the WWR was calculated. For the first building, this calculation involved detailing each floor and each orientation or elevation (North, East, South, West). The concrete slab thickness was included in the vertical area of the building. Being very time intensive, another method was attempted: to calculate one typical floor’s WWR in each orientation, instead of the entire building since all floors were similar. This estimate had a very similar WWR result. Using the whole building method, the WWR was
calculated to be 52%, while the single floor WWR was 54%. A margin of error is to be expected when calculating only one floor. When calculating the whole building WWR, the top floor may not have windows due to being a mechanical room, while the first floor may have an open concept lobby with 100% WWR. For the purposes of this research and this data, the approximation was acceptable as long as the rest of the elevation was reasonably similar to the floor on which the WWR was calculated. The remaining 7 buildings’ WWR were calculated using the one-floor method and are shown in Table 5.

To better represent the occupant’s access to natural light in a high-rise residence, an alternative to the WWR is introduced in Chapter 3. The Effective Window-to-Wall Ratio (EWWR) requires careful evaluation of the floor plans of the building units. It is calculated as:

\[
EWWR = \frac{\text{Glazing area of living unit}}{\text{Area of vertical perimeter of living unit}} \times 100\%
\]

The EWWR calculates the window area ratio of a single residential unit. The common interior walls are included as part of the vertical perimeter of the living unit. The dimensions of the interior walls of each unit were taken from the floor plans and the EWWR of each unit on a typical floor of each building was calculated. The average EWWR for side units and corner units on one typical floor are found in Table 5.

Later in the analysis, we estimated the WWR of all tall residential buildings in Toronto. For this, 252 MURBs above 20 storeys were selected. While the detailed floor plans and window schedules were not accessible for all buildings, real estate floor plans were available online. Most floor plans show where there is visible glazing, which is used to calculate the horizontal portion of the windows while the exterior photos can give an estimation of the vertical measurement of the windows. Paired with photos of the exterior of the building also available online, the unit floor plans gave enough information to estimate the WWR of the building. For most buildings, it can be clearly seen which portions are spandrel panels and which are windows. However, cases where the definition between spandrel panes and windows was ambiguous, conservative judgement was used i.e. the areas were considered windows.

Recommended changes to the codes, regulations and best practices to bridge the gap between design trends, occupant needs, and technology were found through literature review and interviews.
with industry experts. No experiments or tests were done in this study to validate the recommendations given in Chapter 3.

1.5 Industry Partners

The Residential Construction Council of Ontario (RESCON) is the industry partner of this research. RESCON is a construction association that represents the majority of the large residential builders and developers in Ontario. RESCON members are responsible for the construction of over 80% of all new units in the Greater Toronto Area (GTA) over the last 30 years. The focus of the association among other things is promoting innovation in the Ontario construction industry and removing barriers for the implementation of these innovations. RESCON also plays a critical role in the areas related to the buildings code, technical issues and innovations in construction practices and methods.

As RESCON identified cladding systems as a key issue worth investigating, they helped support and guide this research. We met with RESCON members several times to discuss the path the research was taking and to ask questions to their industry experts. RESCON members generously offered building plans to many of their properties and projects for analysis. We were also able to conduct a site visit of a project under construction, which greatly helped in understanding how the cladding systems were installed. Members also got us in contact with the Canadian Window Wall Association (CWWA) which helped organize a factory tour of a window wall manufacturer. The CWWA also helped answer important questions and give valuable information about the window wall.

1.6 Organization of Thesis

The organization of this thesis document is described in this section. In Chapter 2, a conference paper titled *Window Wall and Curtain Wall: An Objective Review* is presented. The paper was published in the CSCE Annual Conference 2017 in Vancouver. The theme of the conference was Leadership in Sustainable Infrastructure, which was appropriate for this paper which discussed the difference between two of the most used cladding systems in tall building construction. The
performance of the two systems are compared for thermal performance, water and air leakage, condensation, constructability, maintenance, and cost. Improvements for both systems are also detailed.

In Chapter 3, *Evaluation of Window to Wall Ratio restrictions for Tall Residential Buildings in Toronto* is presented. The journal paper was submitted to the Canadian Journal of Civil Engineering in June 2017. It evaluates past and current WWR restrictions in Ontario and its effects on the energy load as well as occupant visual comfort. A new method for calculating the relative window area of tall residential buildings from an occupant’s perspective is introduced. Further, methods for improving the thermal performance of building envelopes through passive measures without changing window areas are explained.

In Chapter 4, further analysis related to the research topic that could not be included in the two previous chapters are discussed. Energy modeling, energy reporting and benchmarking, and occupant education are the main topics explored.

In closing, the study findings and recommendations are summarized in Chapter 5. Contributions to academia are highlighted. This section also presents the bigger picture regarding the research topic. Limitations of the research are presented and other ideas for further study are suggested.
Chapter 2
WINDOW WALL AND CURTAIN WALL: AN OBJECTIVE REVIEW

The entirety of Chapter 2 is an article presented at CSCE 2017: Vancouver entitled Window Wall and Curtain Wall: An Objective Review.


2   Window Wall and Curtain Wall: An Objective Review

2.1 Abstract

The enclosure designs for modern tall buildings in Canada often incorporate highly glazed cladding systems such as the window wall and the curtain wall. Simply put, the main difference between the systems is that the window wall structurally sits between the suspended reinforced concrete slabs while the curtain wall is hung off the slab edges by anchors. However, there are many more intricacies that differentiate the systems. The aesthetically slick and more expensive curtain wall is most often used in commercial buildings, while the highly customizable and constructible window wall is mostly used in residential construction. Further, curtain walls are designed to be self-supporting structures and must be installed from the outside via crane or rig while window walls are supported by the existing structure and can be installed from inside. In this paper, a comprehensive comparison of the two systems is presented. Thermal performance, water penetration, air leakage and moisture control are used as the metrics for each system’s overall performance. A comparison is also made for the two systems’ constructability, cost, and maintainability. Recommendations are outlined for the best use of each system, and improvements to their standard builds are defined. Overall, the window wall and curtain wall are very similar systems that can both be improved significantly from their typical designs. Both systems have their strengths, and can prove to be useful alternatives to each other with careful design.
2.2 Introduction

Over the last 150 years, many important innovations have led the evolution of tall buildings. Technological advances such as elevators, tower and “kangaroo” cranes, air conditioning, and design methods for earthquake and wind forces have allowed buildings to reach taller and taller (Massarella, 2008). Most important, however, was the change in materials so that the building envelope no longer served as one of the main structural elements of the building. Moving away from stone and bricks as structural elements, the introduction of steel and concrete enabled buildings to reach higher and allowed them to have non-structural façades. Prominent early adaptors of this method like the Fuller Flat Iron building (1902) and the Empire State Building (1931) in New York were able to build tall with steel frames and stone façades. Tall buildings were reserved for commercial use at the time, but high-rise residential buildings soon followed. Early iterations of the façades used stone and brick, and later cast in place concrete and pre-cast concrete panels were used. Glass façades were famously introduced on a large scale with The Crystal Palace (1851) in London for the Great Exhibition, however, it is argued that the modern glass façade as we know it, also known as the glass and metal curtain wall, first appeared with the Hallidie Building in San Francisco in 1918 (Yeomans, 2001). As the technology developed, and window glass became a more accessible material, the curtain wall grew to be a favourite of modern architects and wealthy companies who wanted to design and construct state of the art buildings. While the aesthetic was the main driver in its popularity, glass curtain walls also provided great daylighting, visual connection to the outdoors, and could promote a transparent corporate culture. Further, glass is an extremely durable material and acts as the buildings rain screen, air barrier and vapour barrier. The glass building is now a defining feature of modern city skylines. Some of the most prominent buildings in the world have all-glass facades, such as the Burj Khalifa (2009) in Dubai and the One World Trade Centre (2013) in New York City.
Figure 1: Evolution of the Glass Façade – left, Hallidie Building (1918), right, One World Trade Centre (2013)

Today, there are two main types of glass cladding systems: the window wall and the curtain wall. They are quite similar and the terminology can even be confusing. The window wall has been considered by some as a type of curtain wall (Frey, 2013) and perhaps even more blurring is that when the curtain wall technology was first being developed, it was referred to as a window wall (Yeomans, 2001). There is very little written in academia about the window wall, perhaps because it is lumped into articles that discuss curtain walls. In the Canadian construction industry, there is a clear difference between the systems. Simply put, the difference between the systems is that the window wall structurally sits between the slabs and the curtain wall is hung off the slabs (CMHC, 2004). However, there are many more intricacies that make these systems different.

First of all, the curtain wall is aesthetically slick, modern and desirable for many architects. It is used primarily for commercial buildings, and some unique residential projects. Curtain walls are structurally engineered and typically installed from the outside using a crane or a rig, which make them more expensive than their competitor and more rigorous to install. The window wall is generally less expensive and is installed from the building interior, but in early versions provided a break at every floor which detracted from its sleek continuity. They are almost exclusively used in residential buildings since they provide a practical and cost effective method to install highly glazed cladding, while still allowing balconies and operable windows. With modern window wall systems, it is possible to closely mimic the sleek aesthetic look of a curtain wall (United States Patent No. 0113891, 2015).
Commercial buildings have a variety of uses and are therefore constructed differently than residential buildings. For example, in residential construction there are usually many more enclosure penetrations needed for mechanical penetrations; here, a highly customizable window wall becomes very favorable. These penetrations are not as prevalent in commercial buildings which usually have centralized mechanical ventilation that services the entire building using vertical duct runs. Another difference that affects the façade is that commercial buildings do not typically have operable windows and balconies on every floor, thereby allowing the continuous cladding system found in curtain walls.

The two cladding systems are used in different situations, but a thorough performance comparison has yet to be made. This review paper offers an objective comparison of the two systems and recommends their best use and possible improvements. Caveat: the authors recognize details regarding both systems vary depending on location, manufacturer, and design. This paper’s conclusions may not be applicable to all cladding systems.

2.3 The Curtain Wall

A curtain wall is an external, non-bearing wall that separates the exterior and interior environments (Carmody, 2004). The term “curtain wall” actually defines a broad spectrum of different wall types, but the everyday reference to the curtain wall refers to the glass and metal curtain wall (CMHC, 2004). Unlike windows placed into a wall also known as punched windows, curtain walls can comprise the entire outer skin of the building. They consist of vision glazing as well as opaque spandrel panels. Vision glazing simply means that the glass is transparent or translucent. A spandrel panel is an opaque, thermally insulated unit in the curtain wall. The exterior finish on the spandrel panel may be glass, forming a continuous exterior envelope made completely of glass and framing materials. Aluminium is used almost exclusively as the frame material in curtain walls. Some steel is used as well but it is often clad on the exterior with aluminium or stainless steel caps (Carmody, 2004).

There are two main types of curtain wall: stick and unitized. In the stick system, the curtain wall is installed piece by piece in the field. The framing components are one or two storey vertical mullions and horizontal rails equal in length to the glazing or opaque panels. Used primarily in low to mid-rise buildings, they are labour intensive and require a specialized crew to install it (CMHC, 2004). Most stick systems are standard, off-the-shelf products and therefore have
relatively low material cost. An advantage of the stick system is the low expense of shipping and handling due to the ability to efficiently package and transport the separate components. In the unitized system, which is more common in high-rise buildings, large panels are preassembled in a factory and are shipped for installation on site. The unitized panels are faster to install and have better quality control at the joint seals because they are assembled in the controlled environment of the factory as opposed to onsite assembly (CMHC, 2004). Other types of curtain wall include cable net systems, point-supported glazing and glass fin walls (Frey, 2013).

The curtain wall is attached to the building with anchors that hold the dead and lateral loads of the wall. The anchors are either cast in place or drilled into the slab edge. If embedded in the concrete slab, the anchors must be installed long before the curtain wall is installed, and end up in the critical path of the construction (CMHC, 2004).

The curtain wall also has different methods for connecting the glazing to the frame. The basic method for designing the connection is to use pressure plates. The glass is held in place by a metal pressure plate on the outside which is attached to the metal framing members on the interior. Synthetic rubber profiles can also be used to hold glazing units in place. As a means of minimizing the exterior portion of the frame for aesthetic reasons, structural sealant glazing was developed. Silicone adhesives permit the glass to structurally adhere directly to the interior frame. The silicone carries some of the weight of the glass itself and transfers wind pressure to the frame. All that appears on the outside are the glazing panes with narrow, sealed joints in between.

### 2.4 The Window Wall

Sometimes referred to as a type of curtain wall, the window wall is an aluminium framed unitized cladding system used primarily on mid and high-rise residential construction. The distinctive feature of the window wall is that it spans between the floor slabs. At the base of the system on each floor, the window wall units are laterally fastened to an aluminium angle, which, in turn, is fastened to the floor slab. The floor slab directly supports the vertical load of the unit. The top of the unit is fastened with aluminium straps on the underside of the slab overhead. The window wall panels are typically installed from the building interior which improves logistics, simplifies installation and costs (YKK-AP, 2017).
Typically, the majority of the panels in a window wall system are vision glazing, however, at various locations such as shear wall and column covers, opaque panels are installed. The system is prefabricated in a factory and installed on site similarly to the unitized curtain wall system. The window wall requires substantially less infrastructure to facilitate installation. Since the curtain wall completely bypasses the slab edge, fire stopping and extra finishing are typically required, as opposed to the window wall. Early versions of the window wall left an exposed slab edge that caused problems which lead to innovations. Second generation window walls have a slab band cover spanning the depth of the slab that can be installed independently of the window wall system or as an extension of the window wall frame (Hoffman, 2001). Modern window wall systems can have the slab cover be part of the unitized panel as shown in Figure 2.

![Figure 2: Simplified Window Wall and Curtain Wall](image)

Unlike the unitized curtain wall, which typically relies on rubber gaskets to provide air seals, water resistive barrier, and rain screen, early versions of the window wall relied heavily on sealant (Hoffman, 2001). Sealant, typically silicone, is applied at the interior face junction of the mullions to provide an air tight and water resistive barrier. Therefore, the performance of the window system is heavily reliant on the quality of site workmanship. More modern window walls can use a combination of plant installed seals as well as site applied material. Often, as sealant application occurs near the end of the project, there is pressure to both install quickly, and to install in
inclement weather, such as when it is too damp or too cold. The building envelope engineer must be willing to step in and prevent installation in conditions that may negatively affect the long-term performance of the cladding.

Window walls are very customizable and can easily incorporate operable windows, balcony doors, and other desired penetrations compared to the curtain wall. The window wall also compartmentalizes the units better than a curtain wall would since there is no gap between the slab edge and the cladding. Compartmentalization has become desired to reduce the stack effect and improve energy efficiency (RDH Building Engineering Ltd, 2013). Since window walls are installed between floors unlike the continuous curtain wall, sound, smoke and odour transmission between floors is reduced, which is desirable for multi-unit residential buildings.

2.5 Comparison

When comparing the two systems, a focus is placed on the unitized curtain wall, since it is the most similar to the window wall. The metrics of thermal resistance, water, air and moisture control and cost are used to compare the systems. It is important to note that window-to-wall ratio (WWR) and insulating glazing unit (IGU) selection will have significant impacts on all metrics, but their impacts would be the same in both systems so they are not significant to this comparison.

2.5.1 Thermal Performance

Glazing systems have three significant heat flow paths: through the frames, through the edge-of-glass region and through the center-of-glass region (Straube, 2012). The IGU performance is the same for the window wall and curtain wall systems. What will change is the framing and the way the cladding connects to the structure. Typical framing is aluminum, which is more conductive than glass and creates a thermal bridge. Thermal bridges are localized areas of high heat flow through walls and other building envelope assemblies. Thermal bridging is caused by highly conductive elements that penetrate the thermal insulation. These paths allow heat flow to bypass the insulating layer and reduce the effectiveness of the insulation. Heat flow through thermal bridges can be significant and disproportionate to the overall enclosure area, which can cause a seemingly well-insulated building to underperform (Finch, 2014). Windows are targeted as obvious thermal bridges because of their relatively low thermal performance especially compared to surrounding walls, but exposed concrete slab edges and protruding balconies have nearly as
much influence (Finch, 2014). Thermal barriers and/or breaks are needed to avoid major heat loss (Carmody, 2004). A thermal break is a non-conductive material that interrupts a conductive heat flow path.

There are 3 types of thermal transmittances: clear wall, linear, and point. Clear wall transmittance is the heat flow through uniformly distributed components, such as through a typical wall section. Linear transmittance is the heat flow through details that are linear such as slab edges, corners, and transitions between assemblies. Point transmittance is the heat flow caused by thermal bridges that occur at single infrequent locations. Typical curtain walls have point connections with the aluminium or steel anchors, which do not introduce nearly the same degree of thermal bridging as window walls that have linear connections at the top and bottom of each floor (Morrison Hershfield, 2016). Window walls with balconies or without slab edge covers also expose a critical thermal bridge through the concrete slab. Thermal bridges caused by uninsulated concrete slab edges and balconies can reduce the effective R-value of full height wall assemblies by over 60% (Finch, 2014).

### Table 2: R-Values of Typical Sections (Morrison Hershfield, 2016)

<table>
<thead>
<tr>
<th>R-Values for Typical Sections</th>
<th>Window Wall</th>
<th>Curtain Wall</th>
</tr>
</thead>
<tbody>
<tr>
<td>Clear Wall (1.1.1 &amp; 3.1.1)</td>
<td>3.2</td>
<td>3.8</td>
</tr>
<tr>
<td>Slab Intersection (1.2.1 &amp; 3.2.1)</td>
<td>2.8</td>
<td>3.7</td>
</tr>
<tr>
<td>Improved Spandrel Bypass (1.2.2)</td>
<td>4.2</td>
<td>N/A</td>
</tr>
</tbody>
</table>

According to thermal modeling done in the Building Envelope Thermal Bridging Guide 1.1 (Morrison Hershfield, 2016), the curtain wall has overall better performance than the window wall (Table 1). Both at the clear wall and the slab intersection, the curtain wall has a better R-value than the window wall. However, with an improved spandrel bypass with interior spray foam insulation, the window wall can exceed the R-value of a typical curtain wall (Morrison Hershfield, 2016). If the window wall design combines improved spandrel bypass and thermal breaks in the balcony slabs to ensure a continuous thermal barrier, relatively strong thermal performance can be achieved.
2.5.2 Water Penetration & Air Leakage

Water penetration is one of the most persistent problems in all wall types. Five forces are responsible for the migration of water through an exterior wall system: gravity, kinetic energy, air pressure difference, surface tension, and capillary action (Vigener, 2016). Unlike other wall types like masonry and stone that have the capacity to absorb water, most materials in curtain walls and window walls are impervious to moisture. This is one of the big advantages of glass cladding as it greatly reduces the risk of water penetration. However, this puts much more importance on the joints and seals.

There are three main design concepts for controlling water penetration: exterior face seal, internal drainage, and pressure equalized rain screen (PER). The exterior face seal was commonly used throughout the 1960s and relies on the integrity of the exterior sealant and gaskets to control water penetration. However, there were many problems as water still found a way to enter. Despite continuous industry improvement of sealant materials, excessive water leakage persisted due to poor workmanship and stress fatigue caused by wall joint movement (Ting, 2012). Designers started to assume that water will enter and provided a drainage path. The internal drainage system provides backup drainage to the exterior and was used through the 1960s and 70s in Canada and is still common in the USA. A downside of this system is that the intentional openings in the air barrier can lead to condensation (CMHC, 2004), especially in cold climates. The PER is the most common and contemporary design in Canada and has an intentional delineation of cavities.

Early window wall and curtain wall systems were commonly face-sealed systems and therefore susceptible to water infiltration (Hoffman, 2001). Chronic water infiltration problems were due
primarily to deficiencies in the primary exterior seal, among other problems. In response, the pressure equalized rainscreen was adapted. The key to preventing water infiltration is redundancy within the system so there are many drainage paths for the water to take.

As curtain walls do not have exposed slab edges, the key factor for air and water tightness is the interface between the IGUs and the mullions and rails, which uses rubber gaskets to provide an air seal and water barrier. If the window wall has an exposed slab edge or penetrating balcony slab, there are extra interfaces that must be sealed. Even with flush slab edge covers, window walls have more interfaces, which increase the risk of water and air leakage (Ting, 2012). To ratify these leakage paths, a water drainage surface within the slab edge cover should be designed (Ting, 2012). Both systems have problems with connections between the system and other interfaces such as brick veneers, concrete panels and even window wall to curtain wall connections (Hoffman, 2001).

Water penetration and air leakage in curtain walls and window walls are closely interlinked (CMHC, 2004). Limiting air leakage through the building envelope is significant for controlling energy efficiency, moisture problems, noise transfer, smoke propagation, indoor air quality, and durability (Becker, 2010). Air leaks in a building envelope are also prone to water penetration. In the face sealed and rainscreen concepts, an impermeable plane is theoretically able to also provide an air barrier. In the case of curtain walls and window walls, most components are composed of airtight materials which are joined using contact or sliding joints, which therefore restrict the air flow to the contact areas. The air barrier system consists of the glass, frames, and gaskets and sealants that connect and join components together and at the interfaces to other assemblies (RDH Building Engineering Ltd, 2013). Window walls and curtain walls are tested to meet the requirements outlined in CSA A440, NFRC or ASTM standards. Therefore, the components tend to be very airtight (RDH Building Engineering Ltd, 2013). The largest variables in the airtightness are the quality of workmanship, design flaws or deformations caused by loads (thermal, gravitational and wind) (Becker, 2010).

Overall, since the curtain wall has fewer exposed parts and simpler connections to the structure, it has an inherent advantage over the window wall in terms of water penetration and air leakage. Further, operable windows and balcony doors are extra variables that are rarely present in curtain walls that would significantly raise the risk of leaks. However, if properly designed and installed, the window wall can outperform a typical curtain wall. In tall residential and commercial
buildings, wind driven rain and strong winds will be major concerns and technically-sound design of either curtain wall or window wall is needed to achieve good performance.

2.5.3 Condensation

After water penetration, condensation is the most often reported performance issue (CMHC, 2004). The control of condensation is closely related to the thermal performance of the glazing system. Thermal bridging increases the chance of surface condensation in a fenestration system (Yan, 2014). Effective thermal breaks that retard heat flow from the warm interior to the cold exterior, or vice-versa, will help prevent condensation problems. Design for condensation resistance is effectively a process of minimizing the frequency and extent of condensation formation. It is not practical to expect that no condensation will ever occur as there will always be some extreme condition under which it can form. Instead, guidelines provide an allowable level of condensation under specific indoor and outdoor temperatures and indoor relative humidity at which the level is to be evaluated.

In both the curtain wall and window wall systems, the larger risk of condensation is within the spandrel panels. The typical construction of the spandrels uses a single exterior plate such as aluminum or single pane opaque glass with insulation behind it (Ting, 2012). In this case, the surface temperature on the back side of the exterior skin can be very low in the winter, presenting potential problems. Moisture on the interior of the spandrel panels can lead to the deterioration of the wet insulation, corrosion of steel parts, and in extreme cases, mold. These problems can be avoided with the careful detailing of insulation and air/vapor barriers (Vigener, 2016). Most systems include condensation drainage, which collects and drain water away from the spandrel to the exterior.

Curtain walls may have condensation problems with shadow boxes. A shadow box creates the appearance of depth in a spandrel panel by incorporating transparent glass a few inches away from the opaque layer. They are used to provide a more uniform appearance to the curtain wall. Detailing to allow venting of the space to prevent excessive heat build-up and thermally isolating the cavity from the interior can prevent condensation problems in the shadow boxes (Vigener, 2016).

Current window wall systems now add a cover to the exposed edges of the concrete slabs to make it aesthetically smoother, protect the concrete edge from environmental damages and prevent
thermal bridging. However, in cold climates, there is a high potential for condensation in these cavities (Ting, 2012). The curtain wall does not have this problem as there is a separation between the slab edge and the spandrel cover. The condensation can be controlled with the help of an improved design known as air loop system. In the air loop system, the slab edge cover cavity is vented, allowing pressure equalization and easy drainage to the outside (Ting, 2012). If the slab cover is well designed, the window wall can achieve similar performance to the curtain wall in this respect. Note that certain provisions to improve the thermal performance like insulating the mullions or filling the window frame with expansion foam can lead to condensation in cold climates (McCowan, 2016).

Both the window wall and curtain wall have potential condensation problems that should be considered in their design. The window wall has the disadvantage of having a slab edge cover, but the air loop system can prevent damaging condensation problems.

2.5.4 Installation

Even a well-designed glazing system can be easily degraded by poor installation methods. Unitized curtain walls and window walls are both highly engineered and factory built with close tolerances. However, the placement of these precisely manufactured assemblies on a structure that was built to much greater dimensional tolerances can lead to issues with the overall façade, such as air and water leakage as well as unanticipated repairs.

Window walls are manually installed from the interior. An aluminum angle is fastened to the floor slab, and the prefabricated window wall panels are then fastened to the angle. The top of the unit is fastened with aluminum straps directly to the underside of the overhead slab. The most common installation errors are discontinuities in the sealant installation at the joints in the system and the perimeter where the window wall interfaces with the slabs and walls. Since window walls are installed from the interior, shear walls and columns can present problems if their location interferes with the window wall. One solution is to leave a gap between the slab edge and the column or shear wall to allow access, but this reduces useable space on the interior.

Curtain walls are typically installed from the outside, and the panels are lifted into place by a crane or a hoisting rig. If the anchors are not cast directly into the slab, field installation begins with the layout and installation of anchors on the slab edges. The panels are then fastened to the anchors.
The curtain wall contractor will rely on the offset lines and elevation benchmarks set by the general contractor. Any error in setting these lines will impact the installation of the wall. All such marks should be set well in advance of the curtain wall installation to allow cross-checking and preparation by the curtain wall contractor.

For both systems, wind is a limiting factor during installation as the panels are heavy and have a large surface area that can be affected by wind and be difficult to place. Extreme cold and extreme heat are also problematic because these systems are designed to close tolerances, and the weather can impact both the worker and the materials being handled. As some window walls are sealed with caulking, installation during extreme temperatures can cause the caulking to take longer to cure (YKK-AP, 2017). The quality of installation can be affected by poor workmanship due to rushed installation, working in inclement weather, having multiple or untrained trades involved, and having complicated design details.

Installation issues are not always attributable to the façade/cladding installation. Variations in the tolerances of the building frame elements can be a significant quality issue when installing window walls and curtain walls. It is not uncommon to find floor slabs 50 mm above or below the specified elevation, slab edges out of alignment or columns out of plumb in existing buildings (CMHC, 2004). Curtain walls have an advantage for adapting to these variations than window walls since they are installed outside of the building and attach to the building at point anchors only. However, if the concrete slab edge is too far in or out from design position, the curtain wall installation can be affected if the position of the slab edge exceeds the adjustment tolerances of the anchor (CMHC, 2004). Alignment issues with the slabs and walls into which the window wall assemblies fit can be much more troublesome. Gaps, constrictions, and unlevel surfaces can make installation very challenging for all parts of the window wall system, including using the flush slab edge cover.

Exterior construction hoists are common to most multi-storey construction projects. The hoists and their supporting towers stay in place for a significant portion of the construction schedule, often for several months after the window wall or curtain wall is installed. As such, the cladding system cannot be installed in those areas. When the interior elevators are operational, the exterior hoists can be removed and the cladding is completed. The challenge is that as the units are designed to fit together at the mullions and the last unit cannot be fit to its neighbour as intended. The wall area must be specially detailed to allow installation after the rest of the wall is complete. Extra care
must be taken to ensure that the air barrier is maintained. Depending on the time lapse between the first and final installations, the newly installed material may not initially match the already completed areas due to the weathering of the installed material. This is an issue for both systems.

Lab mock-ups are carried out for both systems so that constructability can be verified before the systems are manufactured (Lemieux, 2016). Field mock-ups should also be constructed on site to ensure that workers know how the systems are to be assembled, demonstrate that the system fits within the specified construction tolerances and enable testing of the system for water infiltration. Even though detailed 3D models can be made, they do not allow the trades an opportunity to practice the installation (Pietroforte, 2012).

2.5.5 Cost and Maintenance

Window walls are typically less expensive than curtain walls as shown by the cost estimates in Table 2 (Morrison Hershfield, 2014). Costs here include installation, material, and labour related to the assembly.

<table>
<thead>
<tr>
<th>Assembly Category</th>
<th>Detailed Description</th>
<th>Cost ($/ft²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Window Wall (§1.2.1)</td>
<td>Double glazed with insulated slab bypass</td>
<td>53.7</td>
</tr>
<tr>
<td>Unitized Curtain Wall (§3.2.1)</td>
<td>Double glazed with insulated metal backpan</td>
<td>104.9</td>
</tr>
<tr>
<td>Window Wall (§1.2.2)</td>
<td>Double glazed with insulated slab bypass and interior foam insulation</td>
<td>54.6</td>
</tr>
</tbody>
</table>

Construction costs vary widely in practice, but Table 2 gives an order of magnitude of the differences. A typical unitized curtain wall costs about double the costs of a typical window wall. Reasons for the lower cost of the window wall include fewer major hoisting equipment needed during installation, simpler components for manufacturing, and the lack of a requirement for it to be structurally engineered to be self-supported. Also noticeable is the relatively low increase in price for the addition of the interior foam insulation, which significantly increases its thermal resistance (Table 1).
Both curtain walls and window walls require maintenance to maximize their service life. Perimeter sealants, when properly designed and installed, have a typical service life of 10 to 15 years (Vigener, 2016). It is very important to keep the exterior seals in good condition. Exposed glazing seals and gaskets require inspection and maintenance to minimize water penetration, limit exposure of frame seals, and protect insulating glass seals from wetting (Vigener, 2016). Preformed tape and dry gasket are the most common form of the exterior seal on most modern curtain walls. In window walls, sealant is used but newer systems are converting to dry gaskets. Tapes and gaskets have a number of advantages over sealant but one notable disadvantage is the tendency for tapes and gaskets to shrink (CMHC, 2004). The application of sealant at the shrunken joint is the most cost-effective maintenance of these seals. For wall systems that use exposed exterior sealants, it is advisable to plan on localized inspection and maintenance to the sealants on a three to five-year cycle. Such maintenance work can be conducted in conjunction with regular cleaning of the wall.

In window walls, IGUs are installed from the interior with removable plastic stops and are therefore relatively easy to remove and replace and do not need an expensive exterior swing stage, as is needed to access the curtain wall. Replacement of curtain wall IGUs can also be more intrusive to tenants, as replacing larger panels can affect multiple floors; a compartmentalized window wall IGU replacements only affect one unit. However, maintenance for opaque panels in the window wall has access issues after installation. The exterior metal panels and metal back-pans are fastened with mechanical fasteners which are concealed within the mullions upon unit installation. Another limitation of window wall design is that the units are installed shingle fashion, with the mullions locked together through the entire height of the building. This makes the removal of a single or multiple units a very destructive process.

The design of both curtain walls and window walls should allow for easier replacement of defective components. The service life of even the most durable systems may be shorter than that of adjacent cladding such as stone or brick masonry veneer. Therefore, the design of the curtain wall and window wall interface with perimeter construction should permit removal and replacement without removing adjacent wall components.
2.6 Improvements

The thermal performance of both the curtain wall and window wall systems can be improved. Using high-quality IGUs such as low-e triple glazed units are one of the best ways to ensure better performance in both systems. Reducing window-to-wall ratio is also a proven way to improve thermal performance (Straube, 2012). New technologies such as electrochromic windows, vacuum insulated windows and integrated photovoltaics can potentially all help with thermal performance (Carmody, 2004).

The most important factor that will lead to a successful enclosure is proper installation. Both systems can be expertly designed but if imperfectly installed, will not perform as designed. There must also be careful detailing. Holes in the cladding system, too much sealant that blocks drainage paths, and improper compression of the gaskets should all be avoided. Commissioning and regular cladding inspection can greatly improve the performance of these systems.

To improve thermal performance, thermal bridging cannot be ignored. Insulated slab edge covers are essential for reducing a key thermal bridge pathway with window wall units. Balconies should be avoided, but if necessary, thermal breaks in the balcony slab should be installed to reduce the energy losses and improve comfort for the occupant. Filling the window wall frames with low-expansion foam will maximize the thermal resistance of the frames (Straube, 2012). Aluminium frames are also very conductive, so frames with less conductive materials such as fiberglass or wood can help reduce thermal bridging. More attention needs to be spent on interface details. The interface connections between window walls, curtain walls, and other cladding types are not only thermally weak spots but present problems with water and air leakage as well.

When considering air tightness, the drawings of the construction details should be checked carefully including a virtual simulation of the sequence of construction activities to detect all 3D air paths that may develop due to the various dry joints (Vigener, 2016). Sealing these paths should be done carefully and with supervision. The façade design should start with the assumption that the external glazing seals, perimeter sealant joints, and sills will leak. The resulting water should be collected and drained to the exterior. Drainage holes should not be blocked when sealing. The drainage system should handle condensation as well as rain. In window walls, condensation at the insulated slab edge cover can be an issue, especially in colder climates. The condensation can be controlled with the help of an improved design known as the air loop system (Ting, 2012). The
joint cavities will be well vented and pressure equalized and the infiltrated water is drained to the outside.

In curtain walls with pressure plate glazing, the glass and infill panels are installed from the exterior, typically against dry gaskets. The outer layer of gaskets is installed and the gaskets are compressed against the glass by the torque applied to fasteners securing a continuous pressure plate. The plate is later typically covered with a snap-on mullion cover. This system provides reasonable performance but is susceptible to leaks at corners or joints in dry gaskets. Four-sided gaskets can be fabricated at additional cost for improved performance (Vigener, 2016).

2.7 Conclusion

The two main glass cladding systems in Canada are the window wall and curtain wall. The defining difference between the systems is that the window wall structurally sits between the slabs and the curtain wall is hung off the slab edges. The window wall is used in residential construction as it allows a cost efficient way to compartmentalize the units, and allow units with operable windows and balconies. Typical curtain walls have an overall better performance than the typical window wall, but many improvements in new window wall designs allow it to outperform a typical curtain wall while still being less expensive. Curtain walls are more expensive, take longer to install and require specialized crew and equipment to install. Window walls can also take away some useable floor space and can be aesthetically less appealing, which can cause commercial constructors to prefer the curtain wall. Both systems’ performance relies heavily on appropriate design and installation. Many of the window wall’s perceived faults are attributed to its older iterations, such as the lack of slab covers. With the new technological advances, the window wall can be a good alternative to the more expensive curtain wall.
Chapter 3
EVALUATION OF WINDOW TO WALL RATIO RESTRICTIONS FOR TALL BUILDINGS IN TORONTO

The entirety of Chapter 3 is a technical paper submitted on June 19th 2017 for peer-review.


3 Evaluation of Window to Wall Ratio restrictions for Tall Residential Buildings in Toronto

3.1 Abstract

As governing bodies attempt to reach ambitious GHG goals, energy codes are being modified to improve energy efficiency. The Window-to-Wall Ratio (WWR) in tall residential buildings is seen as a “low-hanging fruit” to help reduce energy loads, leading to stricter prescriptive WWR regulations and codes. It is foreseeable that the allowable WWR will continue to decline as net-zero energy buildings become a universal target. In this paper, the Effective WWR (EWWR) is introduced as an occupant-focused measure of the window area of tall buildings, which considers the occupant’s living experience in tall towers. The WWRs of 283 buildings were examined, which revealed that over 92% of tall buildings constructed in Toronto since 2011 do not meet the existing prescriptive limits, making further reduction to the existing limits potentially ineffective. Finally, alternative passive solutions are presented, which can provide a balance between energy performance and visual comfort without reducing the WWR.

3.2 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). Before 2000, 90% of existing buildings in the city over 150m were commercial buildings; in recent years, however, 90% of newly constructed towers over 150m are residential (CTBUH, 2015). Multi-unit residential buildings (MURBs) constitute 55% of all dwelling units in Toronto (Touchie, Binkley, & Pressnail, 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 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 (Cuddihy, Kennedy, & Byer, 2005). Municipalities and property developers are therefore encouraged to improve building standards to ensure strong efforts are in place to reduce GHG emissions and ensure high energy-efficiency for buildings during and after their development (Yip & 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 it 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 & Richman, 2015).

Compliance with energy codes is usually achieved one of three ways: prescriptive, performance, or trade-off (Hoffman & Torok, 2013). To achieve prescriptive compliance, specific requirements detailed in the code must be met by the design. For windows, this includes U-values, which measure thermal transmittance, where lower values are better. For walls and other performance metrics, effective R-value is typically used, which measures thermal resistance and is the inverse of the U-value. In this case, higher R-values are better. Performance compliance is completed with a computer-based energy model of the entire building that demonstrates that the energy performance is better than or equal to the standard prescriptive building. The trade-off option
allows designs with a heat loss rate less than or equal to the prescriptive target rate (Hoffman & Torok, 2013).

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, Hehar, & Hoffman, 2014).

In 2010, the City of Toronto implemented the Toronto Green Standard (TGS), which requires a higher efficiency standard for new construction and a second higher voluntary standard with financial incentives. The TGS mandates a 15% energy efficiency improvement over the Ontario Building Code, while the voluntary standard is 25% better than the current code (City of Toronto, 2015). 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).

The effort to reduce the energy loads of buildings through the continuous reduction of window area may have unanticipated outcomes. Most academic research that recommends an optimal WWR for energy efficiency does not discuss the potential negative secondary effects of reduced daylighting, such as visual comfort or psychological health and wellbeing of occupants. This is particularly impactful on MURB dwellers because they typically have access to only one outside wall.

Oddly, the same energy code is used for residential and commercial tall buildings; however, they are constructed differently and have distinct functional requirements. In high-rise residential construction, occupants desire balconies, operable windows, as much natural light as possible, and low initial costs. Commercial building occupants, on the other hand, want fewer distractions (no
balconies or operable windows), moderate natural light, and low operating costs. These are just a few of the differences that affect construction and functionality.

3.3 Objectives

In this paper, we examine the WWR regulations, codes, and standards, how they differ between residential and commercial construction, and the effect of those differences. A more meaningful and consistent measure of the window area for residential units in tall buildings is introduced. Finally, we review current passive solutions to increase the thermal performance of the building envelope and maintain reasonable visual comfort levels without the need for further reductions in the WWR.

3.4 Restricting the Window-to-Wall Ratio

The window-to-wall ratio, fenestration ratio, and glazing ratio are synonyms. They are typically expressed as a percent 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 with the bare eye. 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 visible glazing 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 electric 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. Further, glazing assemblies typically have significantly worse thermal resistance compared to typical opaque wall assemblies, which makes them cold during the winter. 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, extra focus was put on the energy efficiency of buildings and the first energy codes were implemented (Dong, Kennedy, & Pressnail, 2005). In the last 30 years, new technologies, such as insulated glazing units (IGUs) and low-e coatings, helped improve glazing system performance and allowed windows areas to increase. However, codes were moving in the opposite direction as shown in Figure 4. ASHRAE 90.1 first introduced a prescriptive WWR maximum limit of 50% in 1989 (ASHRAE, 1989). In the first IECC in 2000, a 50% WWR was also prescribed (International Code Council, 2000). In the IECC 2003 and AHSRAE 90.1-2007, it was reduced to 40% (ASHRAE, 2007). In Ontario, supplementary standard SB-10 was introduced to the Building Code Act in 2006 and allowed a maximum of 60%, but prescribed better performing windows based on the WWR. In the 2011 update to SB-10, the prescriptive WWR was reduced to 40% (MMA, 2011). ASHRAE 90.1 and 189.1 attempted to reduce their ratios to 30% in 2010 and 2014, respectively (ASHRAE, 2007). 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 (International Code Council, 2011). Here again, the WWR can exceed the prescriptive restrictions with a performance or trade-off compliance path.

![Figure 4 WWR Restriction in Codes over time](image-url)
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, Bodart & De Herde, 2001, Love et al, 2008, Poirazis et al, 2008, ASHRAE 2009 p.15.51, Ross, 2009, Lee, 2010). Unfortunately, none of these studies were based specifically on high-rise residential towers and they considered the WWR of the entire building, instead of considering each unit of a high-rise MURB as a living space. Further, the studies did not account for occupant visual satisfaction and the psychological health connection to the outdoors.

The WWR is sometimes called the “path of least resistance” for better-performing buildings, but such statements often downplay the secondary effects of reduced glazing area. Significant health benefits are related to access to daylight and outdoor views. Daylighting is the most-energy efficient way to deliver the natural light required for human well-being (Veitch, 2012). A view of outdoors also contributes to well-being, particularly if it is a natural or attractive view (Veitch, 2012). At the other extreme, uncontrolled daylight can cause visual discomfort.

Visual comfort indicators are not as easily quantified as thermal performance indicators. An attractive view can be quite subjective but 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 & 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, Aries, van Loenen, & Hensen, 2012). It is recognized that window sizes below 50% would use less energy but they also have unacceptable levels of visual comfort and illuminance performance (Ochoa, Aries, van Loenen, & Hensen, 2012). A balance between energy performance and visual comfort should therefore be the primary objective.
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. However, it is not justifiable to continue reducing the allowable fenestration area when there are alternative ways to achieve the energy goals with moderately sized windows.

Two supplementary standards were introduced in the Ontario 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 high-rise commercial and residential. SB-10 has a prescriptive maximum of 40% WWR (MMA, 2011). 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 two codes differ significantly.

In low-rise detached single-family homes in SB-12, the 17-22% WWR is calculated based on the building’s entire vertical enclosure area as demonstrated by the shading in Figure 5. With windows located over 4 walls, light can enter the living space from all directions. The WWR is calculated as:

\[
WWR_{SB-12(Single)} = \frac{\text{Glazing area of building (1 living unit)}}{\text{Area of vertical perimeter of building}} \times 100\%
\]

![Figure 5 Simplified low-rise house](image)

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

\[
WWR_{SB-12(Attached)} = \frac{Glazing \ area \ of \ living \ unit}{Area \ of \ vertical \ perimeter \ of \ living \ unit} \times 100\%
\]

As shown in Figure 6, 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 6 Simplified low-rise attached townhome](image)

A simplified 55.7 m2 (600 ft2) high-rise MURB unit is shown in Figure 7. 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:

\[
WWR_{SB-10} = \frac{Glazing \ area \ of \ whole \ building}{Area \ of \ vertical \ perimeter \ of \ whole \ building} \times 100\%
\]

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.
If SB-12(attached) is used, 100% windows on the exterior wall represents a 20% WWR for the unit in Figure 7. As previously mentioned, a 20% WWR is allowable in the prescriptive code for a low-rise residential building (single living unit) as calculated under SB-12.

![Sample 55.7 m² MURB unit](image)

**Figure 7 Simplified MURB unit**

3.5 Effective Window-to-Wall Ratio (EWWR)

To address this inconsistency in the codes, the Effective Window-to-Wall Ratio (EWWR) is proposed. It defines the window-to-wall ratio of a MURB unit within 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:

\[
EWWR = \frac{\text{Glazing area of living unit}}{\text{Area of vertical perimeter of living unit}} \times 100\%
\]

The EWWR of the simplified unit with the corresponding whole-building WWRs are described in **Error! Reference source not found.** and demonstrated in Figure 8.

<table>
<thead>
<tr>
<th>WWR</th>
<th>100</th>
<th>90</th>
<th>80*</th>
<th>70</th>
<th>60*</th>
<th>50</th>
<th>40*</th>
<th>30</th>
<th>20*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Effective WWR</td>
<td>20</td>
<td>18</td>
<td>16</td>
<td>14</td>
<td>12</td>
<td>10</td>
<td>8</td>
<td>6</td>
<td>4</td>
</tr>
</tbody>
</table>

* Denotes units shown in Figure 8
If this simplified unit was designed to meet the SB-10 prescriptive 40% WWR requirement, the unit would have 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.

The EWWR of a corner unit with the same dimensions can be found in Table 5. In this example, a 100% WWR denotes the extreme case where the two exterior walls compromising the corner of the unit (or 50% of the entire unit walls) are vision glass panels.

<table>
<thead>
<tr>
<th>WWR</th>
<th>100</th>
<th>90</th>
<th>80</th>
<th>70</th>
<th>60</th>
<th>50</th>
<th>40</th>
<th>30</th>
<th>20</th>
</tr>
</thead>
<tbody>
<tr>
<td>Effective WWR</td>
<td>50</td>
<td>45</td>
<td>40</td>
<td>35</td>
<td>30</td>
<td>25</td>
<td>20</td>
<td>15</td>
<td>10</td>
</tr>
</tbody>
</table>

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 3.

Although the WWRs of the eight analysed buildings were above the SB-10 prescriptive limit of 40%, the EWWR of the side units were between 11% and 20%; units completed in 2017 have SB-10 WWR under 70% therefore EWWRs below the SB-12 limit of 17%. Why are the common walls of the adjoining units included for the WWR for attached homes and townhomes under SB-12, but are not for high-rise residential units?
### Table 6 Case study EWWR (%)

<table>
<thead>
<tr>
<th>Building</th>
<th>Year Constructed</th>
<th>SB-10 WWR</th>
<th>Avg. EWWR side units</th>
<th>Avg. EWWR corner units</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2017</td>
<td>58</td>
<td>13</td>
<td>32</td>
</tr>
<tr>
<td>2</td>
<td>2017</td>
<td>53</td>
<td>11</td>
<td>22</td>
</tr>
<tr>
<td>3</td>
<td>2017</td>
<td>66</td>
<td>15</td>
<td>27</td>
</tr>
<tr>
<td>4</td>
<td>2017</td>
<td>68</td>
<td>16</td>
<td>22</td>
</tr>
<tr>
<td>5</td>
<td>2017</td>
<td>60</td>
<td>13</td>
<td>22</td>
</tr>
<tr>
<td>6</td>
<td>2014</td>
<td>83</td>
<td>20</td>
<td>34</td>
</tr>
<tr>
<td>7</td>
<td>2014</td>
<td>54</td>
<td>18</td>
<td>31</td>
</tr>
<tr>
<td>8</td>
<td>2012</td>
<td>78</td>
<td>20</td>
<td>36</td>
</tr>
<tr>
<td>AVG</td>
<td>--</td>
<td>65</td>
<td>16</td>
<td>30</td>
</tr>
</tbody>
</table>

Currently, high-rise residential buildings follow the same energy codes as commercial buildings, but the functionality of these buildings is very different. Commercial buildings are typically constructed as open space 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. These spaces rarely have operable windows or balconies. 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 permanent and rarely modified during the building’s functional life. Occupants can spend little or all of their time in their homes. Balconies can provided 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.

Something that could be considered is a slightly different code or regulation for tall MURBs. Owners of both commercial buildings and residential buildings share a common goal of reducing energy loads, but 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 visual comfort of the
home, and can prevent sentiments of claustrophobia. As low-rise residential attached buildings such as townhomes get to consider the common wall between the units as part of their WWR, some considerations should be made for the total window area that an occupant in a MURB unit would receive in their home. A suggestion could be to ensure that the EWWR stays close to the window area allowed in low-rise residential buildings (17-22%).

If codes continue to reduce the allowable window area, occupant visual comfort may be a secondary casualty. Reducing the allowable WWR is a short-sighted reaction to an issue that can be addressed through the appropriate use of glazing and innovation.

When choosing high-density living, occupants are selecting an option that contributes to the reduction of greenhouse emissions (Mohareb & 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 units, having large window areas can give the illusion that the living space extends beyond the small space. This “borrowed space” also adds a valuable connection to the outdoors. From a sustainability 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 sustainable 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).

3.6 Prescriptive vs. Performance Based Compliance

Building energy codes have been decreasing the allowable fenestration area over the last 30 years (Figure 4), but restrictions have not been effective in decreasing the WWR of tall buildings. Figure 9 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 calculate the estimated WWR. Figure 9 demonstrates how the WWRs have trended upward despite stricter codes. This trend is
also evident in Vancouver (RDH Building Engineering, 2012).

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 so they can have larger fenestration areas, and therefore rely on whole building energy modeling. 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 pushes 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. 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. It 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 (Kesik, 2015). 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 without eliminating 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. Some buildings used more energy than permitted by the code (Frankel & Turner, 2008). In a study of 121 buildings, the ratio between measured and simulated energy consumption ranged between 0.25 and 2.5 (Raftery, Keane, & O'Donnell, 2011). LEED-certified buildings are not immune. Designed at a higher standard than required by most building codes and confirmed with mandated energy modeling, 28-35% of LEED buildings used more energy than their conventional non-LEED counterparts (Newsham, Mancini, & Birt, 2009).

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, Zirnhelt, & Fix, 2014). If performance compliance becomes the norm, then significant improvements are needed in building energy
simulation tools. The accuracy of energy performance 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 compliance path’s maximum WWR is not being followed by most developers and designers in Toronto. If the allowable window area continues to reduce, the energy baseline might 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 U-value that would allow flexibility in design, keep a standard in efficiency, and not restrict the WWR (Urban Green Council, 2014). New designs and technologies could also be introduced as a means to achieve compliance. With a target U-value from the very 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.

3.7 Passive Solutions for High-Performing Enclosures

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, 2016). 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. Therefore, a discussion of passive measures to improve the performance of building envelopes without reducing the WWR follows.

3.7.1 Better IGUs and alternatives

The overall R-values of the building envelope for high-rise MURBs have improved very little over the past 40 years (Finch, 2016). If the trend of higher WWR continues, then high-performing glazing and frame units will be necessary to achieve energy efficiency. Emerging technologies are improving windows continuously, providing a thermally efficient as well as visually comfortable enclosure.

**Triple pane windows.** As the name suggests, triple pane windows have three panes of glass separated by two spacers. A triple pane window with low-e coating and filled with noble gas can
deliver a U-value 50% lower than double glazing (ASHRAE, 2005) and provide improvements in sound transmission performance but allow less light transmittance and are heavier and more expensive than traditional double-glazed windows. Using plastic film instead of glass as middle panes provides similar thermal benefits with very little weight gain.

**Vacuum insulated glass.** Like a thermos, a vacuum is the most thermally efficient fill between glass panes; if the vacuum pressure is low enough, conductive and convective heat exchange is eliminated, thereby increasing the R-value. A vacuum insulated glass window usually also has a low-e coating to reduce radiative heat transfer.

**Aerogel:** Aerogel is a material that is 99% air by volume, has very high thermal resistivity, and in some cases, high transparency. Common aerogel can have RSI 0.69 (m2K/W)/cm compared to commonly used plastic foams like XPS (RSI 0.35 (m2K/W)/cm), EPS (RSI 0.28 (m2K/W)/cm), PIC (RSI 0.45 (m2K/W)/cm), and PU (RSI 0.42 (m2K/W)/cm) (Kosny, Fallahi, & Shukla, 2013). Therefore, in situations where the thickness of the envelope matters, aerogel can be a very good alternative to common insulative materials. It is also lightweight, nontoxic and water repellent. Unfortunately, it is new and very expensive because of the relatively low production volumes currently being achieved. Aerogel can be used in spandrel panels as well as between panes of glass. The aerogel window is translucent and can provide extra daylight while still being extremely insulating.

**Photovoltaic (PV) glazing.** PV glazing, where solar cells are laminated inside clear glazing, can provide shading as well as electricity generation. The area of the solar cells is directly correlated to the total heat gain (Fung & H., 2008). Compared to clear glass, PV glazing can reduce heat gain by over 50% and add electricity generation (Chow, Li, & Lin, 2010). Drawbacks of the technology include cost, output efficiency, and life expectancy (Chow, Li, & Lin, 2010).

**Smart windows.** Smart windows can vary their tint using chromogenic technologies to change the material properties in response to external stimuli (Chow, Li, & Lin, 2010). Photochromic windows change in response to light intensity. They can be used to enhance daylighting as they can allow enough light through for lighting purposes but diminish excess sunlight that causes glare and extra load on the cooling system. Thermochromic windows change their transparency depending on the temperature. Electrochromic windows can change their transparency using very low voltage power and are the most promising technology in this field. The electrochromic glazing
can switch between clear and fully coloured states and can even have intermediate states between the two extremes. The Solar Heat Gain Coefficient (SHGC), which is a fraction of solar radiation admitted through a window, both directly transmitted and absorbed and then released inward, can range from 0.1 to 0.5 (Chow, Li, & Lin, 2010). Concerns with the electrochromic window include long switching times, uncertain reliability, and high costs.

These IGU technologies can significantly improve the performance of the enclosure, which in turn will help with both the heating and cooling loads, especially when combined. For example, a novel vacuum PV insulated glass unit had a U-value of 0.8, generated 74W of power, and improved indoor thermal comfort (Zhang et al., 2017). 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 providing natural light, views, and high quality living.

3.7.2 Thermal Bridging

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, Hehar, & Hoffman, 2014). The procedures outlined in the ASHRAE Handbooks and the two-dimensional steady-state heat transfer software that are currently being used by designers to predict heat loss and determine the effective U-value of the enclosure are either silent, oversimplify, or allow partial or full exemptions for complex three-dimensional architectural details for the intersections between assemblies (Morrison Hershfield, 2016). The reasons for these simplifications may be the belief that these details do not have a significant impact on the overall enclosure performance are threefold (Marceau, Hehar, & Hoffman, 2014). First, they compromise a small area compared to the total enclosure area. Second, it would take too much effort to quantify all the thermal bridges that have complicated 3D heat flow paths. Finally, there is a lack of comprehensive thermal transmittance data for standard details. However, highly conductive materials that bypass thermal insulation can have a significant
effect on the performance. Simple changes to the assembly design to reduce thermal bridging may be more effective at reducing the energy use than simply adding more insulation. Introducing thermal breaks in the frames will reduce the effects of thermal bridging, as do alternative framing materials such as fiberglass. Accounting for these details is now more straightforward as the ASHRAE Report 1365 outlines procedures for quantifying the impact of common details.

In North America, balconies are typically an extension of the concrete floor slab with no thermal break, thereby creating a strong thermal bridge along its contact length with the building envelope. The cantilever length of the balcony does not significantly affect energy loss, but smaller balconies are not used as frequently as larger ones (Brown, 2015). Balcony thermal breaks can reduce annual space heating energy consumption by 5-11% (Ge, McClung, & Zhang, 2013) and increase occupant comfort especially in the winter.

### 3.7.3 Improving Air Tightness and Air flow control

Another key factor that affects the energy load of a building is its airtightness. The more airtight a building, the less the active mechanical systems will need to condition the interior air for heating/cooling. 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. Common cladding systems for tall residential buildings in Canada such as the window wall and curtain wall, are relatively airtight, but improvements can be made to installation methods and connections with other cladding systems. The airtightness of a modern MURB should be between 0.25 and 1 (L/s)/m2 at 50 Pa, and larger air leakage rates would likely indicate a deficiency in the air barrier (RDH Building Engineering, 2012).

Operable windows and balcony doors, especially in high-rise buildings, can significantly affect building and living unit energy performance. Openings in the building envelope drive stack effect airflow, which can have operational, energy, noise, comfort, and serviceability impacts on the building. It is recommended that in-suite space heating and ventilation systems where occupants control and pay for their energy consumption can reduce stack effect, and improve occupant behaviour and comfort (RDH Building Engineering, 2012).

Another way to reduce stack effect is compartmentalization of the living unit. Compartmentalization involves creating an airtight barrier between the unit and adjacent units, the
corridor, and the outdoors (RDH Building Engineering, 2013). In doing so, the driving forces for air movement through the building enclosure are much smaller (RDH Building Engineering, 2013). Energy efficient in-suite ventilation systems such as heat recovery ventilators (HRV) and energy recovery ventilators (ERV) must be implemented with this system for it to be fully effective.

3.8 Smart Design: A compromise

The author acknowledges that reducing energy consumption and GHG emissions is an important goal for society and achieving acceptable visual comfort levels does not require extremely large window areas. Architects, engineers, and developers should work together to discover ways to resolve energy and comfort issues while maintaining great views and natural daylight. While the continuous reduction of allowable window area in prescriptive codes should be avoided, smart design that allows the reduction of the window area while maintaining acceptable visual comfort levels is recommended. More glass doesn’t necessarily mean better views. There have been many reported examples of glazing being installed in inappropriate areas, such as directly beside the toilet, refrigerator, and 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 areas and optimize where opaque panels can be installed.

Another easy way to reduce the WWR would be to install the clear glazing 0.5-1 metre above the floor with insulated spandrel panels beneath the window, as demonstrated in Figure 10. The section of insulated paneling above the floor does not significantly detract from the views and improves energy conservation.
Moderately sized windows, solar shading, and operable windows can greatly reduce dependency on mechanical heating and cooling systems (Bennet, 2015), and there are few significant positive daylight or energy impacts when the WWR is greater than 60% (Straube, 2012). Large windows can also lead to thermal discomfort, glare, and privacy issues. In New York, without regard to the window orientation or time of day, blinds cover 59% of windows on average in residential high-rises (Urban Green Council, 2013).

A balance between energy efficiency and visual comfort may be achieved by suggesting the EWWR of units be considered in design and perhaps kept within the allowable low-rise residential levels of 17-22%, depending on the quality of the glazing units. The SB-10 status quo in Ontario of 40% WWR is achievable and may be an appropriate balance between energy efficiency and visual comfort. As seen in Figure 11, 40% can still represent a large amount of the area depending on the configuration; reducing the prescriptive allowable area to make buildings more efficient can be avoided. Efficiency through better details, better IGUs, better accounting for thermal bridging and airtightness should all be considered instead of methods that impede occupant’s visual comfort and negatively impact their living space.
3.9 Conclusion

As building energy codes become more stringent, there is concern that the prescriptive maximum WWR will continue to decrease. Unlike other methods of increasing the energy efficiency of building envelopes such as increasing the minimum levels of insulation, reducing thermal bridging, or raising the standard for airtightness, a reduction in the allowable glazing area can potentially have secondary consequences. 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 which involves energy modelling. As builders continue to prefer larger window sizes than permitted in the prescriptive path, further reduction to the allowable WWR will lead to even less buildings following the prescriptive code. The current performance compliance paths can allow problematic trade-offs and actual building performance is not considered.

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.

A balance between energy performance and visual comfort is achievable. Passive solutions should be considered to improve the energy efficiency of building envelopes for tall residential towers. 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 great views, appropriate daylight, and strong energy performance.
Chapter 4
Further Research

Chapter 4 contains research that did not fit into the two papers in Chapter 2 and 3.

4 Further Research

Many aspects were studied related to highly-glazed cladding systems and improving the energy performance of building envelopes that were not included in the previous two chapters. They include:

1. The accuracy of energy modeling is becoming more important as it is the system being used for code compliance in Ontario. Therefore, as part of this research, an investigation into energy modeling is completed. Second, an evaluation into the new energy benchmarking requirements is completed.
2. As Toronto is implementing mandatory reporting for large MURBs by 2020, the benefits and risks are discussed.
3. Finally, occupant education is explored as an extremely important tool for reducing energy use and motivating more green construction.

4.1 Energy Modeling

Performance-based compliance relies on the assumption that energy modeling is an accurate representation of actual energy use. Energy models should be able to accurately predict the performance of a proposed design at an early design stage. Unfortunately, there are significant discrepancies between simulation results and actual measured consumption. In a study of 121 buildings, ratio between measured and simulated consumption ranged between 0.25 and 2.5 (Raftery, Keane, & O'Donnell, 2011). Another study investigated LEED-certified buildings, which are voluntarily designed at a higher standard than most building codes and rely on energy modeling, and found that 28-35% of LEED building used more energy than their conventional non-LEED counterparts (Newsham, Mancini, & Birt, 2009). Other studies have showed that many of the buildings used more energy than permitted by the code baseline (Frankel & Turner, 2008). If prescriptive requirements can be avoided with the performance compliance path, significant improvements are required in whole building energy simulation.
Energy systems are extremely complex and therefore their simulations must be as well. Factors that affect the energy use of a building are the climate, building envelope, building energy and services systems, indoor design criteria, building operation and maintenance, and occupant behavior (Yan, et al., 2015). Simulation capabilities for climate are well established, however modifications for climate change and increasing extreme weather events should be accounted for. The simulations for the building envelope, energy and service systems, and operation have also been improving. However, occupant behaviour is a major contributing factor to building performance that remains very difficult to accurately model. Especially in residential buildings, occupant behaviour is extremely variable and can include interactions with operable windows, lights, blinds, thermostats, and plug-in appliances, which can significantly affect the energy use. Conventionally, occupants are represented in simulations with static schedules, which is a simplification that does not properly model the complexity of the influence of occupants on the indoor environment (Yan, et al., 2015).

Not all energy modeling software on the market is equivalent. There are many systems approved by the various codes; some are detailed and complex while others are simple and more appropriate for early design decisions. Some software is more comprehensive and will simulate the entire building such as *eQuest* or *EnergyPlus*, while others focus on a specific aspect of a building’s interaction with the environment such as *WUFI* or *TRNSYS*. Overly complex software may be difficult to use, and the sheer number of inputs and parameters involved in whole building energy simulations may discourage their use. In an early design stage, many assumptions are made, and if the assumptions are false, the energy model will be false.

In the United States, energy codes have become more restrictive since the 1980s but energy use in buildings has not been improving. According to the 2012 Commercial Buildings Energy Consumption Survey done by the U.S. Energy Information Administration, commercial buildings constructed more recently have not shown improvements in regard to energy use intensity (EUI) (kBTU/ft²) despite ASHRAE 90.1 and IECC improving their codes (U.S. Energy Information Administration, 2016). Figure 6 shows how energy codes ASHRAE 90.1, MEC, and IECC have become more restrictive since the mid 1980s (Duggin, 2017). However, especially in recent years, but the energy use intensity of commercial buildings in the United States has remained relatively stagnant over the same period. The relative energy use index of the commercial building energy
codes compared to the first 1975 code is presented on the left axis and the EUI of commercial buildings in the United States is presented on the right axis.

**Figure 12 Energy Code Improvements vs Actual Energy Use (U.S. Energy Information Administration, 2016) & (Duggin, 2017)**

In more local terms, MURBs constructed between the 1960s and 1990s in Toronto did not significantly improve their EUI (Touchie, Binkley, & Pressnail, 2013). Similar results exist in Vancouver (Finch, Ricketts, & Knowles, 2010), where energy use in MURBs has slowly increased in the last 40 years. One of the important reasons is that the overall effective R-values of high-rise MURB enclosures have improved very little over the last 40 years (Finch, 2016).

Considering the EUI of MURBs has remained stagnant or increased while the relative energy baseline mandated by codes has continuously improved, and that a large majority of tall MURBs are using energy models for performance-based compliance, it can be concluded that there are significant faults in the process. There are many possible errors in the way that the models are implemented that may explain the discrepancy between the simulations and the actual data. One of the causes is that various components of new buildings such as controls, economizers, lighting...
and daylighting systems, or envelope air sealing often do not perform as well as intended (Frankel, 2010). When modeling the building performance, these systems are assumed to work as designed which leads to underestimation of the actual energy use. It is possible that the energy models are under-representing how much the window area affects the energy use, or over-representing how much the active mechanical systems make up for the energy loss in the envelope. Significant improvements to models can be made in modeling thermal bridging and air leakage especially at interface intersections. A comprehensive industry report showed that current modeling methods greatly underestimate the effects of thermal bridging, which can lead to design errors that lead to the energy use plateau (Morrison Hershfield, 2016). The solution for many of the problems is to calibrate the energy codes to actual building performance. The effects of the stack effect, which drives occupants in upper and lower floors to behave differently and counterproductively is also not addressed in most energy modeling software.

As the EUI remains stagnant, the WWR will continue to be a target for energy improvements and proponents who want larger window areas should advocate for more accurate energy modeling so that the window area is not always blamed for poor energy performance. It should be clear that the accuracy of energy performance predictions is dependent on occupant behaviour, operation, the quality of construction, materials, and the completeness and constructability of design (OAA, 2016). Builders should somehow be accountable for actual performance with the support of a comprehensive commissioning process. Significant improvement is required if whole building energy simulation is what is being used as the tool for code compliance.

4.2 Energy Reporting and Benchmarking

Energy reporting and benchmarking is an important step towards improving the energy performance and reducing greenhouse gas emissions from buildings. Energy benchmarking is a process where the energy use and performance of different buildings with similar characteristics are tracked and compared. In order to manage or reduce building energy use, it should first be able to be measured. When comparing to other similar buildings, owners of poorly performing buildings can be encouraged to improve according to the benchmarking results.
Energy reporting and benchmarking also has many other benefits. It can help governments achieve climate and energy goals by more effectively managing energy efficiency policies and programs. Different regulatory approaches can be monitored for their effectiveness; energy awareness and literacy among building owners, managers, and consumers will improve; and recognition can be given to owners of high-performing buildings (CaGBC, 2016). Currently, voluntary programs such as LEED give recognition to buildings that were designed and constructed for high performance, but very little importance is put in the operation phase. Energy reporting and benchmarking can ensure buildings are performing once operational. Benchmarking of more than 35,000 buildings between 2008 and 2011 found that energy savings improved by 7% over the period (Environmental Protection Agency, 2012).

The Ontario government has approved legislation for Energy and Water Reporting and Benchmarking for large buildings, which will apply to high-rise residential buildings. By the July 1st, 2020, all MURBs that are 50,000 square feet or larger will report all of their energy and water use to the government (Ontario Ministry of Energy, 2017). This can also help improve energy modeling, as the actual energy use can easily be compared to the modeled data and calibrated. Energy benchmarking data can also provide a foundation from which performance-based regulations can be developed. Comparing the energy use of buildings with similar characteristics will help identify buildings that consume more and find the aspects of the building that hinder their energy efficiency. Targets can then be developed that identify an acceptable level of building performance. For example, MURBs of similar size, orientation, and shape can be compared to see how cladding systems such as window walls compare to other systems. As more data are available for analysis, better strategies can be developed to improve energy performance in buildings.

Some areas of concerns exist about energy reporting and benchmarking. Reputational damage is a large concern if poor performance is recorded. There are different approaches to address the issue, such as not making the first year available to the public, allowing an opportunity to improve the building’s efficiency before the reports are made public. Another approach could be to only disclose the information to the government and the general public could see aggregate data. Privacy concerns also exist about information that will reveal patterns in energy use that would not want to be disclosed. Suite-level energy data is never disclosed under existing energy reporting and benchmarking programs, only whole building data. The time, effort, and cost required to comply are also concerns. However, in a collective effort to improve our energy efficiency, energy
reporting and benchmarking is an important step towards being informed and being able to act towards more sustainable communities.

### 4.3 Occupant Education

One of the most important factors that can improve the energy performance of buildings is occupant education. The average person’s knowledge of building science is minimal, and therefore can lead to more energy use. Tenants who have less knowledge or who are uniformed about residential energy consumption have shown to consume more energy than tenants who were more informed (Guerin, 2000). Understanding how a building works is not taught in Canadian high schools and therefore an effort must be put into educating the general public by proponents who wish to improve the performance of buildings. Most energy metrics are complex and difficult to understand for most non-engineers which limits the conversation for deep energy reduction. However, other industries have successfully educated the public about complicated issues through smart marketing. The average consumer today knows to ask about how many gigabytes of storage there is in a smartphone or computer, or how many pixels there are in a flatscreen TV (Kesik, 2011). Educational campaigns could inform consumers about the insulation value of their walls and windows. If more people knew the amount of money they could save on their energy bills through better performing walls and windows, surely more people would invest in these high-performing products.

With meaningful indicators, it may be possible to provide building information in a manner that is understandable by all stakeholders. (Kesik, 2015) suggests labelling buildings similarly to food products with nutritional labeling. A single indicator could be the Energy Use Intensity (EUI) for buildings (ekWh/m2) with an average cost of conditioning per square meter. Some other indicators such as the WWR, the overall thermal U-value, amount of daylight, and the natural ventilation of a building envelope could also be made available to all, and even provide comparisons to the industry average. With this type of labeling, occupants would be able to understand if the building envelope is below average or if it is a strong performer.

Many factors that affect occupant behaviour such as age, socio-economic status and other demographics can significantly impact an occupant’s energy use. Occupants’ environmental
attitudes can also influence their energy use. In a study, it was found that MURB occupants in Toronto who were more environmentally-conscious used less energy than their counterparts (Mohazabieh, 2014). Occupant behaviour is hard to predict, but the fact that the more energy consumption-aware occupants consume less energy, indicates enough motivation for occupant education campaigns.

4.4 Limitations of Research

Limitations for this research project are described in this section. The focus of the study was on high-rise residential buildings in Toronto. Methods of construction, systems and materials may differ for commercial buildings, for low-rise residential and internationally. The window wall refers to the modular aluminium cladding system used in Canada which is anchored between the slabs as opposed to beyond the slab edge. It may be referred as another system internationally. While the research does discuss Ontario policies, the SB-10 code uses an international standard (ASHRAE) as a reference therefore conclusions from Chapter 3 may apply to policies or codes that reference ASHRAE 90.1. High-rise residential buildings are considered in the same category as commercial buildings in ASHRAE 90.1 and SB-10, and may not be in other codes or standards. The sample size for calculating the WWR trend in Toronto was large and included all 283 residential buildings in Toronto that were 20 storeys or taller. Included in this sample are buildings either under construction or buildings approved which will be completed before 2020. There exist many MURBs between 4 and 19 storeys that were omitted from Figure 9, and it is possible that many of these buildings had WWRs of 40% or lower and used the prescriptive method. Energy data was extremely limited for the buildings targeted in this study, and therefore we were unable to correlate energy data with the WWRs calculated. The WWRs were approximately calculated and should not be taken to be exact. There exists a lack of data considering the WWRs of buildings. The City of Toronto does not keep record of the WWR of buildings after they have been approved.
Chapter 5
Conclusion

The enclosure designs for modern tall buildings in Canada often incorporate highly glazed cladding systems such as the window wall and the curtain wall. The systems are well suited for high-rise construction as they can be installed efficiently and cost-effectively. In addition, the systems can provide large areas of glass for increased daylight, views, and a visual expansion of space in small living units. As energy efficiency standards continue to improve, building envelopes with window wall or curtain wall systems will need to as well.

In this study, the difference between the window wall and curtain wall systems was established, and the objective comparison of their performance is an important contribution to literature. Overall, the method in which the curtain wall is attached to the structure gives it slightly better thermal, air leakage and water leakage performance than the window wall. However, many of the window wall’s problems and perceived faults are from early iterations of the technology. Modern window wall systems can achieve similar or better performance than a typical curtain wall especially when considering constructability, maintenance, and cost as performance indicators. Window walls also are better suited for residential construction as they easily allow for operable windows, balcony access, and noise/sound compartmentalization. Even well designed balconies with thermal breaks can provide access to outdoor air and shading from the summer sun to lower floors. If well designed and installed, window walls can be a good alternative to the curtain wall, even for commercial use.

From a small MURB unit occupant’s perspective, the window area is their only connection to the outdoors as all interior walls are windowless. As building energy codes become more stringent, there are concerns that the prescriptive maximum WWR will continue to decrease and negatively affect occupant comfort and health. Other methods such as increasing the minimum levels of insulation, reducing thermal bridging, or raising the standard for airtightness can improve the energy performance of building envelopes without reducing the area of glass. The EWWR introduced in this research also 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. 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 visual comfort 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 great views, appropriate daylight, and strong energy performance. Other methods for improving energy performance include more accurate energy modeling, energy benchmarking and occupant education.

There are many opportunities to expand on this research in the future. First, much of the referenced performance comparison of the two cladding systems was completed with computer modeling software, which may have oversimplified some complicated components of the systems. Completing field tests experiments on the two systems for thermal performance, air leakage and water penetration would be of great value and offer tangible results. More analysis should be completed from the findings that most tall buildings in Toronto are not following the prescriptive code. The implications of almost all new tall buildings relying on energy modeling for code compliance should be explored and analysed. Further, analysis should be completed on the question of what is a more important factor in thermal losses: the WWR or thermal bridging. The effects of thermal bridging have often been underestimated and the effect of the WWR is greatly diminished when using high-performing windows. As IGU technologies keep improving, there may be a shift in which building property leads to more energy loss. As whole-building energy modeling is becoming the standard for compliance, more research should be completed on ensuring the allowable software can accurately predict energy use. As energy reporting and benchmarking becomes mandatory for many buildings in Ontario, research should be completed on its effects. Finally, occupant education about how MURB units work, including the effects of windows on energy, comfort and their bills can be greatly improved. The best methods for teaching occupants about the importance of their building envelope should be established.

The contributions of this research help reach this goal by defining and comparing the two important highly-glazed cladding systems, offering a new perspective on how maximum window areas are calculated for high-rise units, and offering promising methods for improving the building envelope without reducing the window area. Highly-glazed cladding systems are now part of our collective
infrastructure and with careful and innovative design, proper installation, and regular maintenance these systems can continue to be part of our future sustainable communities.
References


http://www1.toronto.ca/City%20Of%20Toronto/Environment%20and%20Energy/Programs%20for%20Residents/Files/pdf/C/clean_air_action_plan.pdf


https://www1.toronto.ca/wps/portal/contentonly?vgnextoid=f2337c3cd546c510VgnVCM10000071d60f89RCRD


http://www.oaa.on.ca/professional+resources/practice+tips+&+regulatory+notices/practice+tips/36.1


https://www.ontario.ca/laws/regulation/120332


RDH Building Engineering Ltd. (2013). *Air Leakage Control in Multi-Unit Residential Buildings*. Vancouver: CMHC.


