A Quantitative Comparison of Adaptive Reuse Strategies of Residential Towers in Northern Climates

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Abstract. Tall concrete structures with cantilevered balconies have prevailed as the main type of multi-family housing construction in Canada since the 1950s. Within aging residential structures, balcony degradation is a prominent contributor to overall performance. This includes high levels of structural failures, low energy performance, and inefficient use. Some common strategies for improvements to balconies in residential towers include structural reconstruction, thermal insulation, enclosure of balconies, and reconstruction of guards. While these strategies can greatly improve existing conditions of residential towers, there is opportunity for anticipating the future needs of dense urban environments through adaptive reuse of residential balconies. This project analyses balcony adaptive reuse strategies focusing on structural and environmental refurbishment as well as spatial conversion in terms of various performance metrics. The goals of this project are to investigate methods for analysing existing buildings for their potential adaptive reuse at the scale of the balcony and optimize decision making through developing an index for adaptability.

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1. Introduction

Concrete cantilevered balconies in Canada first emerged during the economic and population boom of the mid 20th-century. This boom gave rise to a large number of high-rise housing neighbourhoods across the country, with significant concentrations in Southern Ontario. From the 1950's, the balcony became a common feature of the residential tower in the City of Toronto. The next wave of concrete multi-family construction followed in the form of high-rise condominium ownership in the 1970's and lasted for 10 years (Rosen, Walks, 2015). From the 1960's to the late 1970's, there was an increase in the popularity in the use of balconies in residential buildings. The use of balconies was minimized in the 1980's and 1990's with most towers being built in this era having 0% to 20% of their facades covered with balconies. The balcony proliferation patterns of the 1970's, with high numbers of towers possessing 40% to 100% of balcony coverage and minimal buildings with no balconies at all, have been ongoing from the late 1990s onwards. The next wave of popularity was brought on by Toronto's on-going condo boom (Figure 1). During this time, cantilevered balconies gained more momentum in tall buildings, and played an important role in the housing market (Figure 1).

More than 22,000 residential units were built within the City of Toronto in 2018, and this is expected to increase yearly to about 30,000 in 2020 (Dingman, 2018). Out of these, 60-80% of balconies are expected to be cantilevered. This marks Toronto as the largest condominium, and cantilevered balcony market, in North America (Lehrer, Keil & Kipfer, 2010). The future development of the residential tower is assured and supported by a 30% population increase expected by 2050 in the Greater Toronto Area (Hoornweg, Pope, 2014), the ongoing popularity of apartment unit ownership, and the provincial plan for future development (Lehrer, Keil & Kipfer, 2010) (Rosen, Walks, 2015).Currently, with shrinking unit sizes and despite the rising expense of cantilevered balcony construction, the balcony continues to remain an attractive feature of dense urban living. Through the last several decades, many changes have affected the form, context and use of concrete residential towers. From the 1950s onwards, planning and cultural changes have varied the form and context of the concrete residential towers from towers-in-the-park, dominant in the 20th century, to contemporary urban point towers and tower-podiums. (Rosen, Walks, 2015).

1970s: 40% Balconies

1970s: 60% Balconies

1970s: 80% Balconies

1970s: 100% Balconies

Percentage of Balcony Coverage in Residential Towers Built in the 1970s.

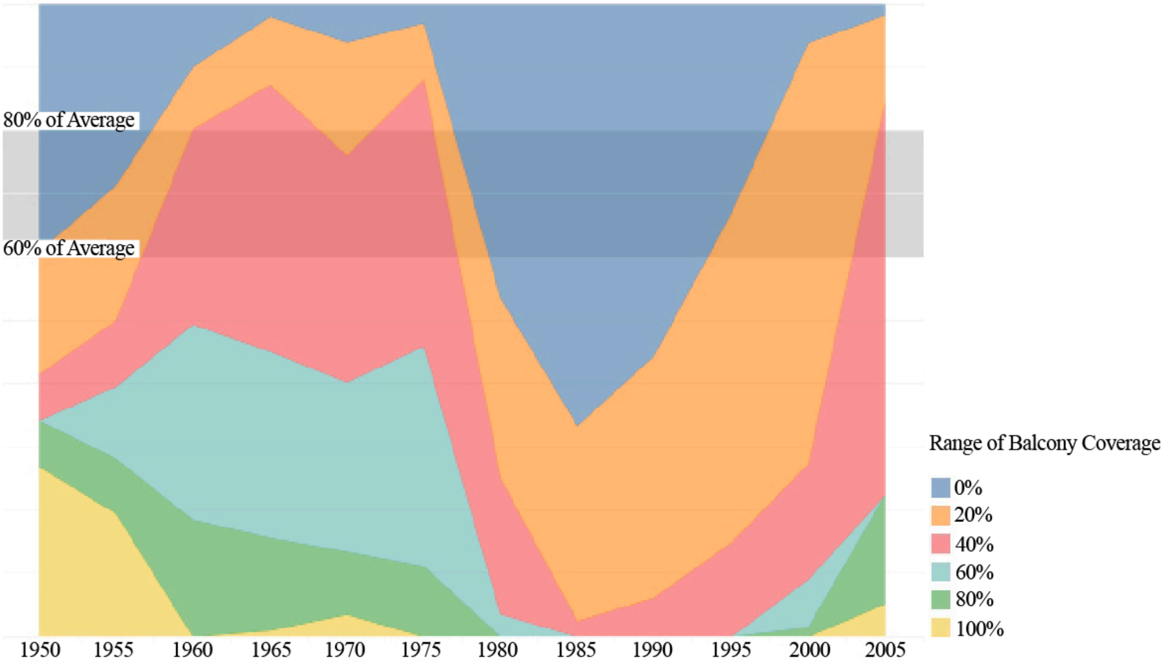


Figure 1: Percentage of Balcony Coverages in Residential Towers built from the 1950s to the 21st Century Across the Greater Toronto Area. (ACO Toronto 2016).

Currently, most of 20th century high-rise concrete towers have reached the end of their first lifecycle in terms of structural integrity, environmental performance, and contextual relevance. Meanwhile, limited improvements have been made in terms of structural integrity and environmental performance of balconies in residential towers. Multi-family towers are typically rigid in structure and therefore limited in use, making them prone to obsolescence (Kesik, 2009). Building obsolescence is directly related to shortcoming of designing prescribed housing arrangements and their limited life cycles, causing about 60% of all building demolitions in North America (Ross et al., 2016) (Chen, D. A., Klotz & Ross, 2016). Therefore, the obsolescence and redundancy of existing dated residential building stock is identified as a critical issue for sustainable development (Manewa et al., 2016). Meanwhile, balcony degradation is a prominent factor in aging multi-family housing including high levels of structural failures, low energy performance, and inefficient use (Kesik, 2009).

Structural failures for weather exposed concrete of balconies include concrete spalling, cracking and rust of reinforcements. The exposure of both sides of the concrete to the weather, and the stagnation of water on balconies result in balconies deteriorating more quickly as compared to vertical surfaces of buildings. Environmental performance issues in 20th century housing are also common due to aging envelope systems and lack of insulation (Kesik, 2009). While similar designs and construction methods have prevailed in concrete construction of the cantilevered balcony over the decades, it is anticipated that recent and new construction will face similar problems and shortcomings in the future. Therefore, it is important to consider adaptive reuse strategies that address the limitations of current and common balcony systems as an alternative to demolition, a tool for revitalizing aged multi-family housing, reducing energy consumption and improving life cycle of existing building stock.

Strategies for Adaptive Reuse

Strategies currently in practice for improving conditions of existing balconies are closely tied to improving the overall conditions of residential towers (Leblanc, 2012). Immediate and common strategies for improvements include structural and aesthetic remediation of balconies. More intrusive strategies involve addressing thermal issues. Thermally insulating the building envelope and permanently enclosing balconies are proven to increase environmental performance and minimize occupant health risks from the reduction of thermal bridging at the balcony (Hensel, 2013) (Tower Renewal Partnership, 2017). Strategies extracted from case study analysis can be divided in to the two categories of refurbishment and spatial conversion. Primarily, environmental and structural refurbishment strategies that aim at improving the current condition of residential towers highlighted in this research include: 1) Restructuring of the balcony slab and guards, 2) Extension of glazing, 3) Re-cladding, 4) Enclosing balconies and 5) Insulating balconies. Secondary strategies, categorized as spatially restructuring, have also been highlighted that aim at improving urban relevance, spatial use, and occupant comfort aside from addressing environmental and structural issues. These strategies include: 1) Addition, 2) In-setting, 3) Layering and 4) Extension of balconies.

2. Objectives and Methodology

There are multiple guidelines and models developed for evaluating a building for its adaptive reuse potential (Conejos, Langston & Smith, 2015). Currently, no formal and structured process exists for evaluating, quantifying, and comparing benefits of altered adaptive reuse designs for residential balconies (Gosling et al., 2013). The objective of this research is to develop a methodology for improving decision making in adaptive reuse of residential balconies. Focusing on adaptive reuse of balconies in multi-family residential buildings, a comparison model is developed based on simulation and analysis of multiple adaptive reuse strategies.

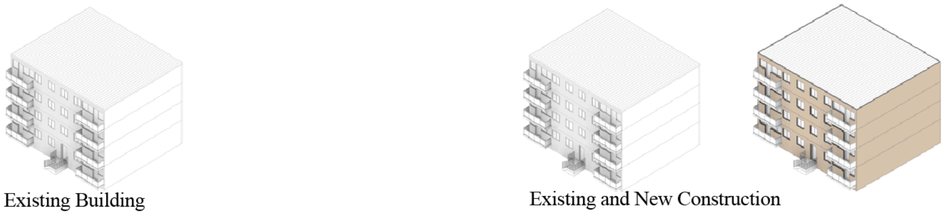
Ten balcony adaptive reuse strategies are identified from case study analysis. Each strategy is analysed regarding environmental, life cycle and cost benefits metrics in comparison to the existing building base case. A BIM platform is used to study relationships of strategies by simultaneous analysis of multiple criteria (Peters, 2018). The results are categorized in an index score system for adaptability, in order to create a basis for understanding the implications of adaptive reuse strategies. 6D BIM models of each strategy is developed in Revit®, including detailed information regarding construction phase, cost and life cycle phasing. Models include information of existing conditions and alterations as part of the adaptive reuse strategy for accurate analysis. Various simulation software is used to measure the following parameters: 1) Energy use, 2) Thermal comfort, 3) Daylighting, 4) Natural Ventilation, 5) Systems performance, 6) Life cycle analysis, 7) Cost and 8) Constructability. This paper focuses on highlighting results from life cycle analysis simulation and calculations.

Structural and Environmental Refurbishment

Restructuring is an immediate and common strategy for improvements to the general condition of residential towers is through the remediation of the balcony structure and railings of balconies. This strategy is one of the least intrusive and is most common across the City of Toronto. Re-glazing involves the replacement of windows or increasing the amount of glazing is a strategy to improve environmental performance of the envelope, increase daylighting and ventilation. Re-cladding involves the restructuring the building envelope to increase the environmental performance and to eliminate tenant health hazards primarily include thermally insulating the envelope in order to improve building performance and the elimination of thermal bridging in the balconies. This strategy is common as complimentary to other strategies, including re-glazing and enclosing. Enclosing the balcony is a strategy to protect the balcony from the environment while not thermally mediating the balcony space as part of the interior. Enclosing of the balcony is often a stand-alone strategy aimed at improving the spatial qualities of the balcony by providing more weather-protected living space, while at the same time beginning to mediate the interior space through a layered approach. Lastly, insulating balconies and creating a unified enclosure over the building façade can increase thermal performance and occupant comfort and the reduction of mold and health hazards (Kesik, 2009). Thermally over-cladding the envelope and permanently enclosing balconies as a solution, will strengthen the thermal boundary of the building creates a rigid boundary. This approach contributes to a mainstream and traditional environmental division (Figure 2).

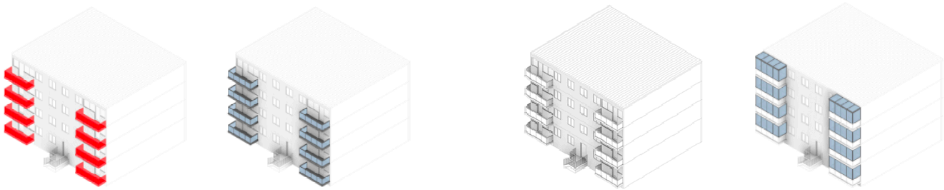
Spatial Conversion

The following strategies are aimed at larger scale conversions of balconies and the building envelope. These strategies address spatial concerns of residential towers including densification and rearrangement, as examples. Addition of balconies typically requires additional structural support, and reconstruction of the building envelope to include openings. Interior modifications are also common as the relation between the interior and exterior changes. While addition of balconies is common as part of more complex adaptive reuse of towers that involves various strategies, relocation of balconies can be a resultant strategy from extension or interior modifications of the building. In-setting of the balcony, while not common due to financial justification, considers the development of balconies from already existing interior spaces. Layering of the balcony is often made possible through extension of the balcony and the introduction of different layers to the building envelope to create mediating spaces, such as winter gardens, and as a strategy to better control the environment. Outward extension involves a complete spatial and structural reconfiguration of the balcony and is a result of densification requirements and often a reconfiguration of interior spaces to add more units, as examples (Figure 3).



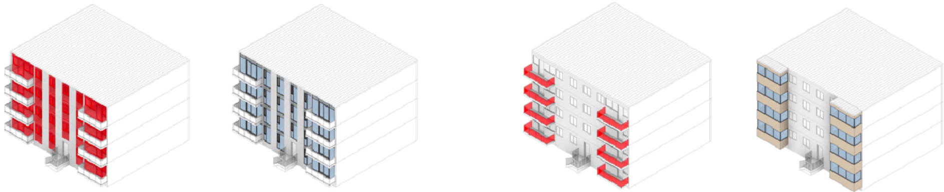
Existing Building
Base Case

Existing and New Construction
Recladding



Demolition and New Construction
Reconstruction

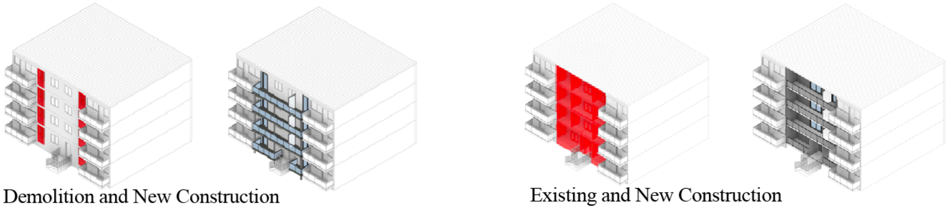
Existing and New Construction
Enclosing



Demolition and New Construction
Extending Glazing

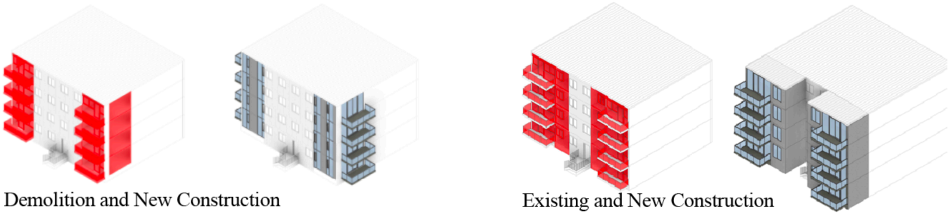
Demolition and New Construction
Insulating

Figure 2: 6D BIM Models of Structural and Environmental Refurbishment Strategies



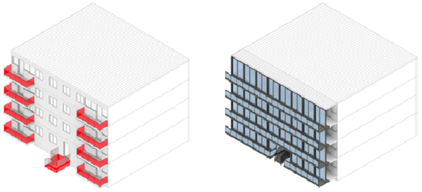
Demolition and New Construction
Adding

Existing and New Construction
Recladding



Demolition and New Construction
Reconstruction

Existing and New Construction
Enclosing



Demolition and New Construction
Extending Glazing

Figure 3: 6D BIM Models of Spatial Conversion Strategies

BIM Integration with Simulation

The integration of BIM and Building Performance Simulation (BPS) tools can facilitate the development of holistically efficient and sustainable structures through the simultaneous analysis of multiple parameters (Krygiel, 2008) (Chen, S., 2018). BIM and BPS processes are being increasingly integrated to analyze and predict various performance measures while communicating through images and analyzed data (Attia et al., 2012). Simulations evaluate and analyze various performance metrics with an objective to advance understanding regarding the various factors influencing design strategies and facilitate optimized decision-making (Attia et al., 2012) (Peters, 2018). The integration of simulation tools with BIM in this manner is proven to be beneficial from preliminary stages of a design process (Chen, 2018).

BIM integration with BPS has been made possible through easy exchange between BIM software and simulation tools. As an example, Autodesk Revit® includes built-in BPS software and multiple plugins from Autodesk and other developers that provide extended simulation capabilities. Insight, Autodesk Revit®'s built-in environmental simulation tool uses integrated EnergyPlus® engines to simulate a building's energy cost range, lighting analysis, solar analysis and insolation ranges. Autodesk Revit® also hosts other simulation plugins including Autodesk CFD® for ventilation and air flow simulation, and Robot Structure Analysis®, for structural performance, as examples. Independent software, such as Sefaira® for energy, daylighting and systems simulation, also have BIM plugins that allow a seamless flow of data between their tools and BIM models. In this process, the plugins easily communicate geometric and contextual data to simulation engines, and analysis results are either transferred back and visualized in the BIM software (Chen, 2018) , or are housed and organized as iterations on the cloud, in the case of Sefaira®.

Application of simulations in BIM includes the abilities to find relationships, map similarities and differences, and be able to organize results efficiently by correlating geometry and performance. These relationships can be studied by simultaneous analysis of multiple criteria including energy, thermal comfort, daylighting, direct sunlight and shadow, ventilation, and acoustics as examples (Peters, 2018). There have been increasing efforts in improving the integration, interoperability and communication of simulation tools. A tool for McNeel's Rhino® Grasshopper is being developed by Burrohapold as a 'Smart Building Analyzer' that can simulate and analyze energy use, thermal comfort, daylighting, acoustics, security, fire safety and circulation simultaneously. Through simulation and visualization, and working at a multidisciplinary boundary, a comprehensive tool like this can create a precedent for improved accessibility and integration of simulation tools in all stages of a project (Peters, 2018).

The future of simulation is rooted in development of comprehensive tools that aside from measuring energy and carbon, can also begin to predict occupant centric measures including productivity, health, wellbeing and happiness. The applicability of simulations in the design process is encouraged by the move away from static two-dimensional drawings to the integrated use of accurate and live building information models for design and documentation. Since simulation is optimized with multi-disciplinary knowledge and improvements in collaboration, BIM is therefore a great starting point for its proliferation. New and integrated tools, and immersive simulation and visualization capabilities, with ability to customize codes allows the participation of users in the development and customization of tools within BIM (Azhar, Brown, 2009)(Sinha et al., 2013) (Peters, 2018).

3. Results and Analysis

BIM can be used to conduct accurate Life Cycle Analysis (LCA) and can assist in better understanding life cycle of projects in design, construction, maintenance, and operation stages of a building (Park, Kim & Cho, 2017). Performing a comprehensive LCA can be challenging due to the effort required to gather and input necessary data, the volume of information required to process a correct evaluation, and the management of changes over the various phases of a project (Finnveden et al., 2009). There are many LCA tools for BIM that are effective in overcoming these challenges and are validated for accuracy, including GaBi® and Tally® amongst others (Wu, Issa, 2015). Tally® is an integrated tool within Autodesk Revit®, and through an interface for matching existing BIM data with LCA databases in Tally®, allows for an integrated calculation of LCA that can be updated in real-time to geometry and material changes.

The main metrics for LCA are analyzed in this study and include Global Warming Potential (GWP) and Primary Energy Demand (PED). GWP measures greenhouse emissions including carbon dioxide and methane. Increases in greenhouse emissions increase the radiation emitted by the earth leading to increased temperatures negatively affecting ecosystems, health and resources. PED measures the total amount of energy extracted for use, and measures energy resource use excluding environmental impacts. The various life cycle stages considered in Tally® calculations include product, maintenance and replacement, end of life and potential of reuse after life of building, including energy recovery and material recycling, referred to as Module D (Cays, 2017) (De Wolf, Pomponi & Moncaster, 2017). Lastly, information regarding operational energy is input manually for calculation by Tally®. Required operational energy data includes energy use intensity (kWh/m2/year) and total electricity demand (kWh). The energy use information for each strategy is gathered through Sefaira® energy analysis. The effects of GWP for product, construction, use, end-of-life and Module D are represented for each strategy compared to GWP for OE (Operational Energy) in Figure 4. GWP and PED are calculated for various life cycle stages of the base building and adaptive reuse strategies, ranging from raw building materials to final disposal. The sums for the estimated 60-year life of the building are combined in Figure 5.

The results for life cycle analysis of the base case strategy and the ten adaptive reuse strategies can be summarized as follows. The base case is estimated to have a total global warming potential of 3,213,745 kgCO2eq and a primary energy demand of 65,322,390 MJ. Adaptive reuse strategies of re-glazing, re-cladding, insulating, and in-setting show reductions in GWP and PED as compared to the base case over the life cycle of the building. While adding and in-setting demonstrate 16% and 17% improvements in GWP respectively, the effect of insulating is 10%. Enclosing, relocating, layering and extending show a negative effect on life cycle impacts. Layering has the highest negative GWP and PED impact at 3%.

As described earlier, life cycle analysis is only one dimension of the adaptability index being developed. The results of the comprehensive analysis index for enclosing and layering strategies are compiled and summarized in an Adaptability Index Tool Interface for comparison of the performance and evaluation of all the strategies under study, as examples (Figure 6). The LCA analysis is thus illustrated in that broader context.

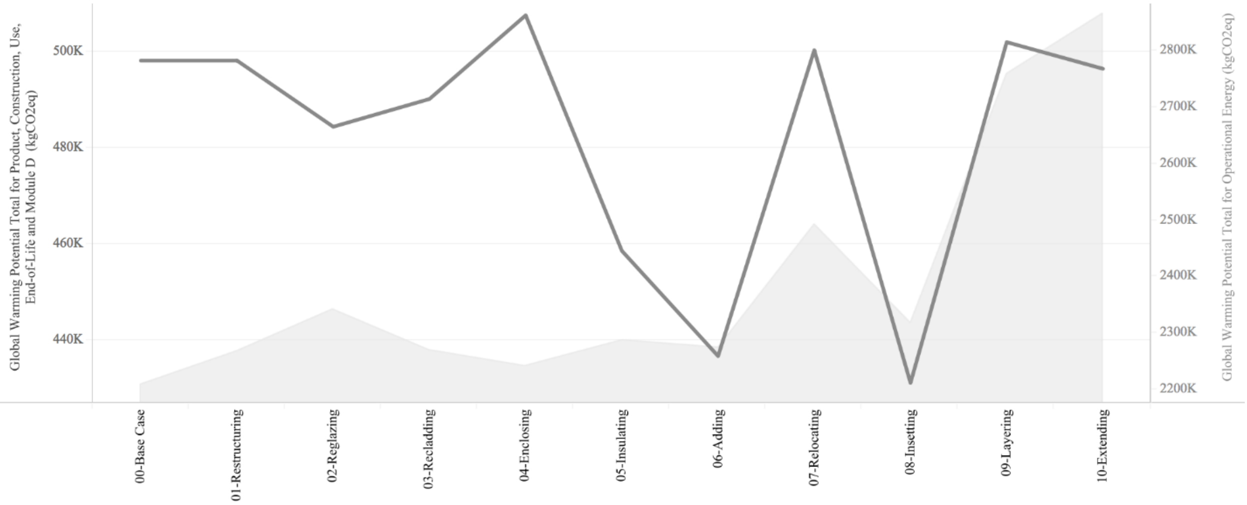


Figure 4: GWP for Product, Construction, Use, End-of-Life and Module D is represented for each strategy (line) in comparison GWP for Operational Energy (area) (kgCO2eq)

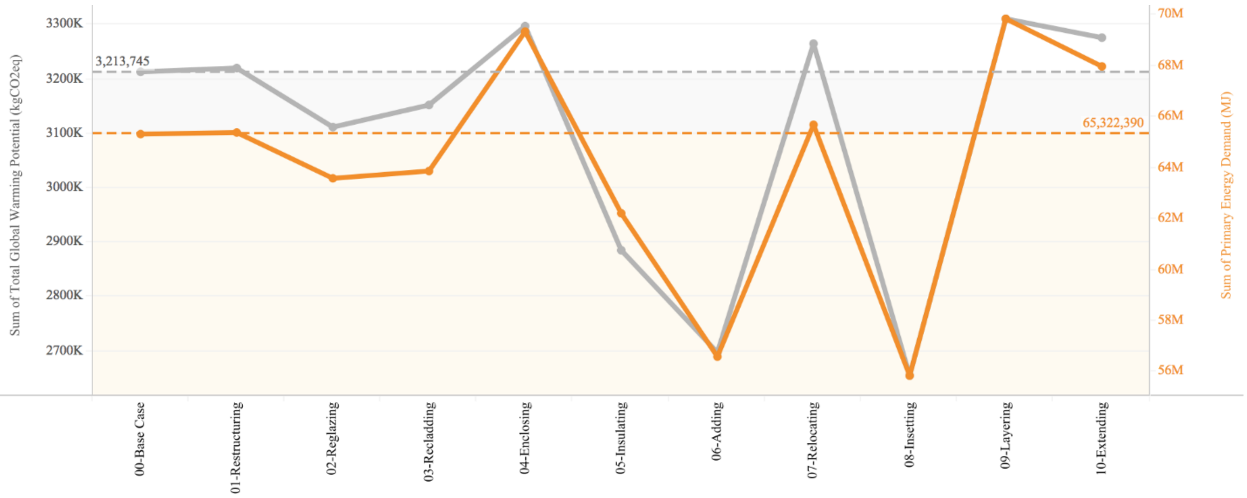
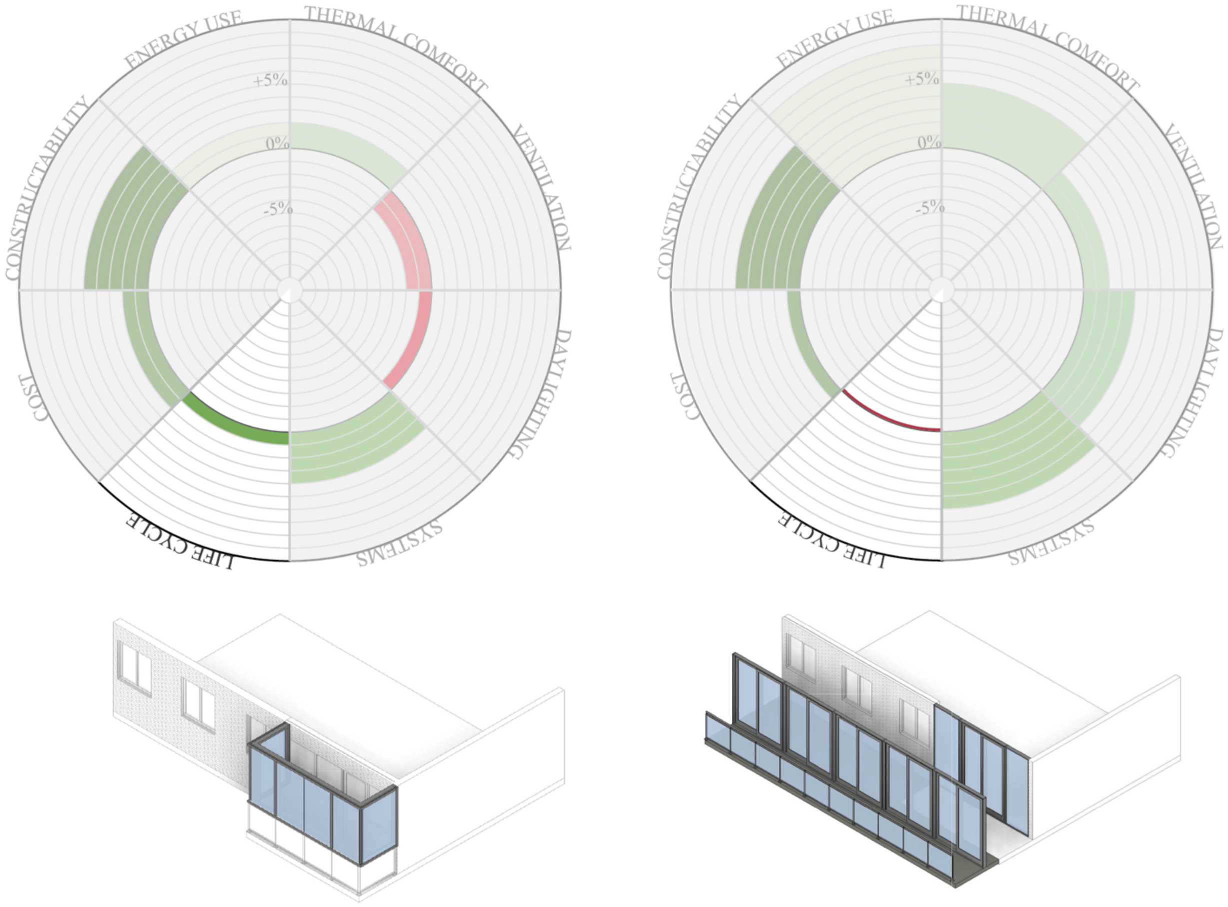


Figure 5: Sum of Primary Energy Demand Total (MJ) and Sum of Global Warming Potential Total (kgCO2eq) for Base Case and Adaptive Reuse Strategies. The dotted orange and grey lines represent the corresponding base case values. Strategies that fall below the orange line show improvements in primary energy demand. Strategies that fall below the grey line show improvements in total global warming potential.



04 – Enclosing 09 – Layering

Figure 6: Adaptability Index Tool Interface Example for Enclosing and Layering, Summarizing Performance Results

4. Conclusion and Future Work

A quantifiable comparison of balcony adaptive reuse strategies evaluates the success of their overall performance and demonstrates environmental as well as economic justifications for future adaptive reuse projects. With the developed comparative metrics, it is possible to understand the strengths, weaknesses and possibilities of each strategy. Identifying advantages and disadvantages facilitates a timely analysis of the success of existing adaptive reuse projects. A thorough comparative tool also enables the determining of best possible options as a design tool for new residential adaptive reuse projects. This enables limited analysis requirements in the early design stages of a project. Challenges for accurate implementation of the tool includes gathering quality data of existing buildings and accurate documentation of components for simulation. The future development of this comparative tool will benefit from more extensive case study analysis, data collection and more complex interdisciplinary efforts.

References

Attia, S., Hensen, J.L.M., Beltrán, L. & De Herde, A. 2012, "Selection criteria for building performance simulation tools: contrasting architects' and engineers' needs", *Journal of Building Performance Simulation,* vol. 5, no. 3, pp. 155-169.

Azhar, S. & Brown, J. 2009, "BIM for Sustainability Analyses", *International Journal of Construction Education and Research,* vol. 5, no. 4, pp. 276-292.

Cays, J. 2017, "Life-Cycle Assessment: Reducing Environmental Impact Risk with Workflow Data You Can Trust", *Architectural Design,* vol. 87, no. 3, pp. 96-103.

Chen, D.A., Klotz, L.E. & Ross, B.E. 2016, "Mathematically Characterizing Natural Systems for Adaptable, Biomimetic Design", *Procedia Engineering,* vol. 145, pp. 497-503.

Chen, S. 2018, "Use of neural network supervised learning to enhance the light environment adaptation ability and validity of Green BIM", *Computer-Aided Design and Applications,* vol. 15, no. 6, pp. 831-840.

Conejos, S., Langston, C. & Smith, J. 2015, "Enhancing sustainability through designing for adaptive reuse from the outset", *Facilities,* vol. 33, no. 9, pp. 531-552.

De Wolf, C., Pomponi, F. & Moncaster, A. 2017, "Measuring embodied carbon dioxide equivalent of buildings: A review and critique of current industry practice", *Energy & Buildings,* vol. 140, pp. 68-80.

Dingman, S. 2018, February 12, -last update*, Toronto condo numbers set new records*. Available: https://www.theglobeandmail.com/real-estate/toronto/toronto-condo-numbers-set-new-records/article37959424/ [2018, July 28].

Finnveden, G., Hauschild, M.Z., Ekvall, T., Guinée, J., Heijungs, R., Hellweg, S., Koehler, A., Pennington, D. & Suh, S. 2009, "Recent developments in life cycle assessment", *Journal of environmental management,* vol. 91, no. 1, pp. 1-21.

Gosling, J., Sassi, P., Naim, M. & Lark, R. 2013, "Adaptable buildings: A systems approach", *Sustainable Cities and Society,* vol. 7, pp. 44-51.

Hensel, M., author. 2013, *Performance-oriented architecture: rethinking architectural design and the built environment,* Wiley, Chichester, West Sussex.

Hoornweg, D. & Pope, K. 2014, "Socioeconomic Pathways and Regional Distribution of the World's 101 Largest Cities".

Kesik, T.J., 2009, *Tower renewal guidelines for the comprehensive retrofit of multi-unit residential buildings in cold climates,* Daniels Faculty of Architecture, Landscape, and Design, University of Toronto, Toronto.

Krygiel, E., 2008, *Green BIM: successful sustainable design with building information modeling,* Wiley Pub, Indianapolis, Ind.

Leblanc, D. 2012, "' Re- skinning' the skyscape", *The Globe and Mail (Index-only),* pp. G.4.

Lehrer, U., Keil, R. & Kipfer, S. 2010, "Reurbanization in Toronto: Condominium boom and social housing revitalization", *disP - The Planning Review,* vol. 46, no. 180, pp. 81-90.

Manewa, A., Siriwardena, M., Ross, A. & Madanayake, U. 2016, "Adaptable buildings for sustainable built environment", *Built Env Proj and Ass Man,* vol. 6, no. 2, pp. 139-158.

Park, J., Kim, K. & Cho, Y.K. 2017, "Framework of automated construction- safety monitoring using cloud-enabled BIM and BLE mobile tracking sensors. (building information model) (Bluetooth low-energy) (Report) (Author abstract)", *Journal of Construction Engineering and Management,* vol. 143, no. 2.

Peters, B. 2018, "Defining Environments: Understanding Architectural Performance through Modelling, Simulation and Visualisation", *Architectural Design,* vol. 88, no. 1, pp. 82-91.

Rosen, G. & Walks, A. 2015, "Castles in Toronto's Sky: Condo-ism as Urban Transformation", *Journal of Urban Affairs,* vol. 37, no. 3, pp. 289-310.

Ross, B.E., Chen, D.A., Conejos, S. & Khademi, A. 2016, "Enabling Adaptable Buildings: Results of a Preliminary Expert Survey", *Procedia Engineering,* vol. 145, no. Complete, pp. 420-427.

Sinha, S., Sawhney, A., Borrmann, A. & Ritter, F. 2013, "Extracting information from building information models for energy code compliance of building envelope", *RICS COBRA Conference 2013,* pp. 10-12.

Tower Renewal Partnership 2017, *Thermal Comfort; Cooling in Apartment Towers*, Tower Renewal Partnership, Toronto, Canada.

Wu, W. & Issa, R.R. 2015, "An integrated green BIM process model (IGBPM) for BIM execution planning in green building projects" in *Building Information Modeling: Applications and Practices*, pp. 135-165.