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# Creating space and time for innovation - a methodology for building adaptation design appraisal using physics-based simulation tools and interactive multi-objective optimization

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## Abstract

**Purpose** – It is crucial to consider the multitude of possible building adaptation design strategies for improving the existing conditions of building stock as an alternative to demolition.

**Design/methodology/approach** – Integration of physics-based simulation tools and decision-making tools such as Multi-Attribute Utility (MAU) and Interactive Multi-objective Optimization (IMO) in the design process enable optimized design decision-making for high-performing buildings. A methodology is presented for improving building adaptation design decision making, specifically in the early-stage design feasibility analysis. Ten residential building adaptation strategies are selected and applied to one primary building system for eight performance metrics using physics-based simulation tools. These measures include energy use, thermal comfort, daylighting, natural ventilation, systems performance, life cycle, cost-benefit and constructability. The results are processed using MAU and IMO analysis and are validated through sensitivity analysis by testing one design strategy on three building systems.

**Findings** – Quantifiable comparison of building adaptation strategies based on multiple metrics derived from physics-based simulations can assist in the evaluation of overall environmental performance and economic feasibility for building adaptation projects.

**Research limitations/implications** – The current methodology presented is limited to the analysis of one decision-maker at a time. It can be improved to include multiple decision-makers and capture varying perspectives to reflect common practices in the industry.

**Practical implications** – The methodology presented supports affordable generation and analysis of a large number of design options for early-stage design optimization.

**Originality/value** – Given the practical implications, more space and time is created for exploration and innovation, resulting in potential for improved benefits.

**Keywords** Design, Architecture, Decision support systems, Simulation

**Paper type** Research paper

## 1. Introduction

The adaptation of existing buildings is critical for lowering energy use and improving the quality of life in cities (Pardo-Bosch *et al.*, 2019). There is a large ratio of existing buildings globally compared to new construction, and existing buildings are a significant contributor to energy use and Greenhouse Gas (GHG) emissions (Nejat *et al.*, 2015). Building adaptation

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strategies, including refurbishment and adaptive reuse of existing buildings, can provide various benefits (Xu *et al.*, 2011). Improving energy use in existing buildings and increasing indoor thermal comfort is essential for reducing carbon production (Si *et al.*, 2019). It can be concluded from studies that successful building adaptation, and specifically adaptive reuse projects, can result in notable social, economic and environmental benefits (Ma *et al.*, 2012; Sanchez and Haas, 2018; Shahi *et al.*, 2020). These benefits include improving energy efficiency (Xu *et al.*, 2011), financial gains from reduced maintenance and operation cost, improved thermal comfort and the increased useful life of buildings (Langston *et al.*, 2008; Wilson, 2010; Foley, 2012; Smith and Hung, 2015; Tokede *et al.*, 2018). Limited knowledge regarding suitable retrofitting strategies, specifically in housing and the related supply chains, leads to increased experimentation and risks of reduced performance in practice (Swan *et al.*, 2013). Incorporating Building Performance Simulation (BPS) in the design decision-making process is critical but can be challenging for designers lacking expertise in physics-based simulation processing (Singaravel *et al.*, 2018). The design process is complex, and integration with environmental and life-cycle assessment tools can be challenging (Rezaee *et al.*, 2019). Physics-based simulations of multiple design options are also a time-consuming task. The use of computational design methodologies and BIM for option appraisal offers possibilities for physics-based simulation and analytical inputs to be integrated into the early-stage decision-making (Mattern and König, 2018). While these tools can help the speed of analysis times and limit barriers to entry, it is essential to have access to immediate design feedback and comparison metrics to inform design decision-making in the early design and feasibility analysis of a project. This process creates access to non-conventionally accessible design solutions (Singaravel *et al.*, 2018).

There is a gap for a comparative index considering a range of measures and strategies in the building adaptation process. In a typical feasibility analysis process, the prime consultant hires multiple consultants to develop a handful of suitable solutions for the client.Using advanced simulation and decision-making analysis tools, clients and consultants can access a large pool of solutions at an early stage. There is currently no formal and structured process for evaluating, quantifying, and comparing the benefits of building adaptation designs for residential buildings (Gosling *et al.*, 2013). It is important to develop a methodology and index to evaluate building design option appraisal. Multi-Attribute Utility (MAU) decision-making can help process different objectives in the process of considering multiple design variables. Also, Interactive Multi-objective Optimization (IMO) is an effective method in optimizing design decision-making.

This research focuses on adapting dated residential buildings and proposes a methodology for optimizing the feasibility study process. Creating a comprehensive index can enable designers to make educated assumptions about the performance of adaptation measures in the early design stages. The index can further assist in analyzing a large number of cases, enabling the development of future predictive design algorithms. This can improve the quality of design option generation through optimization of various metrics involved. It can also reduce the timeline of feedback from weeks and months to real-time and make feasibility studies more accessible and affordable. To achieve a holistically well-performing building, metrics including energy, indoor thermal comfort, life-cycle, cost-benefit and others can, therefore, be considered and optimized (Si *et al.*, 2019). The basis of this research enables the automation of feasibility studies through parametrization. It facilitates immediate MAU and IMO for adaptive reuse appraisal in architectural design practice and real estate development applications.

## 2. Background

### *2.1 Building adaptation*

Construction materials stocked in the built environment, such as buildings and infrastructure, make up a large part of global material use (EC-European Commission, 2016). Buildings have permanency ranging from 50 to 75 years, and with the lack of timely adaptation measures, increased energy and material consumption, obsolescence and demolition are inevitable (Munaro *et al.*, 2020). These include strategies for extending the use of systems and increasing value in all life cycle phases, and reducing waste (Brown *et al.*, 2019; Foster, 2020; López Ruiz *et al.*, 2020; Munaro *et al.*, 2020).

Canada has committed to reducing energy use in all existing buildings by 40% before 2050 (Generation Energy Council, 2018). Over 3,000 residential towers in Ontario were built between 1950 and 1990 and require the immediate need for retrofitting and renovations to prevent demolition, reduce energy use and carbon emissions, and improve occupant comfort. The obsolescence and redundancy of existing dated residential building stock are critical for sustainable development (Manewa *et al.*, 2016). In addition, the residential sector accounts for 17% of operational energy use in Canada, 20% of which belongs to multi-family housing. 52% of all energy consumed by all 4,878 apartments in Canada is spent on space heating (Natural Resources Canada, 2015). Over 41% of over 20 million single house constructions in the UK have been altered in their lifetime, 25% of which have been modified three or more times (Kinnane *et al.*, 2016). There are many financial, technical and process barriers to building adaptation. These include elevated upfront costs, supply chain and service management barriers, the complexity of design, coordination, and execution of projects (Sebastian *et al.*, 2018). Successful building adaptation projects need to address these barriers through innovation in design and procurement.

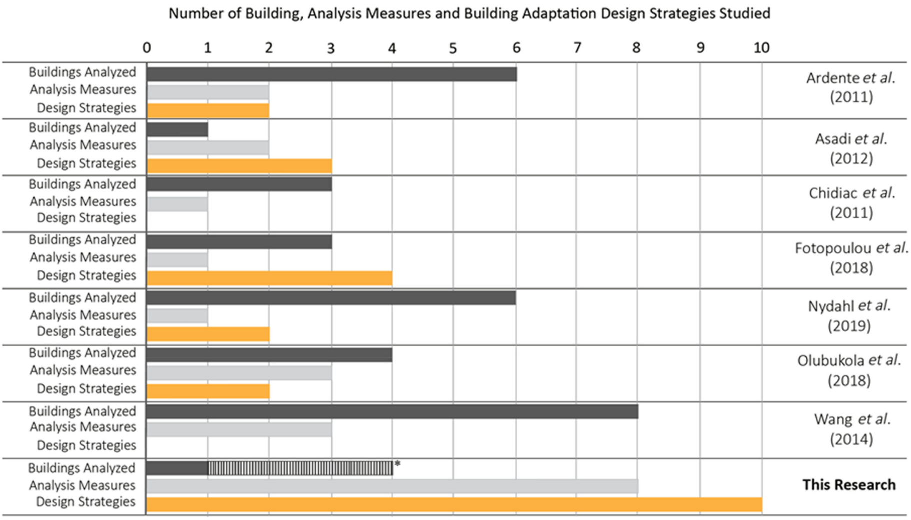
### *2.2 Metrics and indexes for building adaptation design option appraisal*

Many researchers have developed metrics and indexes for benchmarking and understanding the performance of design strategies, individually relating to building adaptation projects. Sustainable building adaptation projects, specifically refurbishment projects, have been researched intensively in recent years. Many methods have been researched and developed for environmental assessment in the integration of simulation tools for design option appraisal of building adaptation projects (Edwards *et al.*, 2019). Ardente *et al.* developed a comparison of numerous factors relating to energy and global warming potential for six different building systems. They demonstrate how each building ranks in terms of energy savings and energy cost return ratio. While no direct index is developed for the application to other sites, they conclude that significant improvements to energy use are obtained as a result of envelope improvements, specifically the replacement of insulation and glazing components (Ardente *et al.*, 2011). Mostavi *et al.* analyzed multiple iterations of insulation and window types to optimize cost and energy use on one building system. Two solutions are presented, one as an ideal system for reduced energy use and one for optimal cost. Through an analysis of three building systems and multiple adaptation design strategies, a mathematical model is developed that can be used to implement retrofit strategies on similar buildings (Mostavi *et al.*, 2018).

Fotopoulou *et al.* investigated design strategies for deep renovation of residential buildings in three various climates. Multiple approaches are analyzed across different regions. Suggestions are made regarding which strategy performs optimally in each region (Fotopoulou *et al.*, 2018). Six strategies are analyzed for their return on the investment opportunity and GHG emissions. The results are presented as guidelines highlighting that energy recovery ventilation was the most desirable refurbishment strategy. No metrics aside from overall conclusions are offered for direct application to other sites, but a methodology for evaluating building adaptation strategies is suggested (Nydahl, 2019). Tokede *et al.* developed a framework for design decision-making through a whole-life cycle analysis. Based on the proposed framework for option appraisal, multiple strategies are simulated for their life cycle performance. The methodology presented can be used to evaluate other similar scenarios (Tokede *et al.*, 2018). Wang *et al.* analyzed multiple scenarios for financial feasibility and created a comparative framework of these metrics against all scenarios (Wang *et al.*, 2014). Dirutigliano *et al.* demonstrated multicriteria decision-making for supporting energy retrofit design decision-making. Retrofit strategy decision-making criteria based on quantitative criteria focused on costs including investment costs, energy savings and reduction of maintenance costs, and qualitative factors including satisfaction of occupants and beautifying the built environment (Dirutigliano *et al.*, 2018). Taillandier *et al.* demonstrate another application of multicriteria decision-making in building adaptation design. With a focus on specific building insulation material, the implemented methodology focused on improving the decision-making process for building owners (Taillandier *et al.*, 2016).

A limited number of researchers have used computational design tools for design optimization of building adaptation projects. Parametric and generative design environments enable optimization of building geometry. This aspect is not typical in building optimization literature (Kiss and Szalay, 2020). The majority focus on different properties and qualities of materials involved, including insulation types and window-wall ratio as examples. Parametric design also enables the designer to test design variation with immediate building performance feedback (Holzer, 2016). In terms of design automation, Sharafi *et al.* developed a matrix-based methodology supporting an automated early-stage design process for modular buildings. Through the developed methodology, the effects of various forms on performance can be compared in the early stage design process. The developed methodology by Sharafi *et al.* can determine life cycle cost, energy efficiency or other quantifiable metrics (Sharafi *et al.*, 2017).

Figure 1 summarizes the number of building systems, measures, and strategies analyzed in the literature. Building systems include the existing conditions, design options and iteration of the same building system in different climates. Analysis measures include the different metrics considered for analysis, including energy use and life cycle as examples. Strategies refer to the design options investigated in each case. Most studies in the literature have investigated multiple building systems, including similar building systems in various climates (Ardente *et al.*, 2011; Fotopoulou *et al.*, 2018; Nydahl, 2019), different construction methods and building sizes (Chidiac *et al.*, 2011) and various budgets (Wang *et al.*, 2014).




**Note(s):** *1 Building System with all strategies applied, and three building systems with the enclosed strategy used for validation

**Figure 1.**
Comparison of the number of building systems, analysis measures and adaptation strategies in the literature review (Ardente *et al.*, 2011; Asadi *et al.*, 2011; Chidiac *et al.*, 2011; Fernandez and Mozas, 2013; Wang *et al.*, 2014; Fotopoulou *et al.*, 2018; Tokede *et al.*, 2018; Nydahl, 2019)

*2.3 Early-stage design optimization*

Fasna and Gunatilake identified many barriers to the successful adoption of energy-efficient retrofits. One of the main identified barriers was the lack of technical knowledge and expertise of designers in the preliminary stages of a project (Fasna and Gunatilake, 2020). Specifically, the design process and decisions made in the first 10% of projects determine up to 80% of the building operation costs after construction (Sharafi *et al.*, 2017). Through early design stage optimization, Kiss and Szalay demonstrated environmental savings of 60–80%. Considering multiple factors, including cost, energy and life-cycle performance, has become common in the past decade. Software interoperability is a significant step in supporting automated design processes and enabling designers to engage with option generation through real-time performance feedback (Holzer, 2016). The initial feasibility and conceptual design phase are essential and foundational steps in the building design process. Preliminary architectural feasibility studies and early-stage design studies analyze environmental opportunities (considering energy use and carbon emission reduction, the extension of building life cycle, etc.) and propose high-level design options in response to the completed analysis (RAIC, 2019).

This process can be time-consuming and complicated due to the necessity of exploring design alternatives (Khan and Awan, 2018). The building design is an iterative process, combining experiential expertise and design exploration. Building Performance Simulation (BPS) and appropriate physics tools enable adequate decision-making in the design process of high-performing buildings (Singaravel *et al.*, 2018). Feasibility studies can take a couple of weeks to several months depending on the complexity of each project, involve multiple stakeholders and specialists, focus on suitability rather than optimization of options, and can be expensive - typically equivalent to 10–20% of the design fee of the project (RAIC, 2019).' A building project's conceptual design or feasibility phase mainly determines factors that contribute to energy efficiency, overall cost, and other performance measures. The early stages of a project, therefore, have the potential to maximize overall building performance (Si *et al.*, 2019).

In an effective early-stage design process, designers in charge must consider multiple factors simultaneously, including spatial, structural, environmental performance, and life cycle effects and life cycle costs, to make optimized decisions (Yuan *et al.*, 2018). The main advantage of applying optimization to building design is the resolution of one scenario that performs well in a range of multiple objectives (Geyer, 2009), and different criteria can be optimized simultaneously (Mela *et al.*, 2012). Optimization is helpful for aspects of building performance that can often be contradictory. For example, balancing the decrease in energy use and an increase in thermal comfort must be balanced with a reduction in heating design capacity and improved life-cycle costs (Si *et al.*, 2019). Zeng and Chini developed a decision-support model for designers for early-stage projects based on energy use, embodied carbon, and cost. The model is designed and optimized for new construction projects, requiring a range of building data and a selection of structural components (Zeng and Chini, 2020).

*2.4 Knowledge gap*

The literature review highlights the importance of building adaptation design appraisal and early-stage design optimization. Integration of physics-based simulation tools has been identified for improving the early-stage decision-making process. It can be summarized that in most studies, a limited number of design strategies are considered, and there is a lack of a methodology that considers a comprehensive range of design strategies and analyzes them simultaneously using multi-objective decision-making methods.

## 3. Methodology

This research aims to develop a methodology for improving building adaptation design decision making, specifically in the case of multi-family residential buildings. As highlighted in the literature, design decision-making can be enhanced by simultaneous consideration of multiple design options and using computational and information-rich design models and accessible simulation tools. The methodology proposed focuses on an initial assessment and validation analysis for creating an interactive indexing tool that can be applied to various similar buildings. It is estimated that there are over 40 significant variations in tall multi-family housing types in Canada in terms of shape, form and range of heights (Tower Renewal Partnership, 2017). Considering ten adaptation strategies, eight performance measures and four orientations, this results in the requirement of 12,800 simulations for a comprehensive analysis of how residential adaptation strategies would perform on the range of existing housing (Table 1). The number of required simulations and processing time is a complex and long-term pursuit, especially when considering a design optimization process.

The proposed methodology is comprised of three stages: (1) building adaptation design option selection and model preparation, (2) design option simulation and (3) result analysis. A case study review, evaluation and selection of residential building adaptation projects are conducted. Selected strategies are modelled in 6D BIM and simulated and analyzed for various metrics. MAU is conducted on the initial results, and through a sensitivity analysis, the decision-maker can decide how to narrow down the search objective as part of the IMO. Further MAU analysis is conducted on a sample decision-maker selection set for demonstration (Figure 2). The presented methodology is intended to increase the efficiency and accuracy of options presented by consultants working in the field of building adaptation. In a typical feasibility design process, designers provide a handful of design options that meet defined criteria. Using this methodology, designers can parse through many design options and filter suitable scenarios for further investigation.

The initial assessment includes analyzing ten adaptation strategies using eight analysis measures on one orientation, requiring 60 simulations. The analysis measures were selected based on industry expertise in collaboration with the industry partners of this study that work in the field of building adaptation, including Diamond Schmitt Architects, Parcel Developments and Entuitive Consulting Engineers. Energy use, life cycle analysis and cost-benefit were highlighted as the top priority strategies in design decision-making. For validation, one adaptation strategy is analyzed on multiple building systems for a total of 18 simulations (Table 1).

Building system one, used to complete the initial assessment, is developed based on the Ellebo Housing State in Denmark (Figure 3). The Ellebo Housing buildings were built in the mid-20th century, and with refurbishments made in the 1990s, the buildings are still a solid base for adaptive reuse (Fernández *et al.*, 2014). Ten residential building adaptation studies are identified from the literature review and are modelled in Autodesk Revit® on building system one. The adaptation design strategies are analyzed regarding environmental performance, life

**Table 1.** Required simulations for tall multi-family housing types and experimental design for validating methodology

| | Building systems | Adaptation strategies | Analysis measures | Orientation | Total simulations |
|---|---|---|---|---|---|
| Comprehensive analysis of all multi-family building types in Canada | 40* | 10 | 6** | 4 | 9,600 |
| Experimental methodology for analysis | 1 | 10 | 6** | 1 | 80.60 |
| Validation of experimental methodology | 3 | 1 | 6** | 1 | 24.18 |

**Note(s):** *Estimate of typical multi-family residential building types common in Canada (Tower Renewal, 2017)
**up to 3 measures are derived from a single simulation in Sefaira

cycle, cost benefits and constructability. These adaptation strategies include restructuring, extending glazing, recladding, enclosing, insulating, adding, relocating, insetting, layering and extending (Figure 3). The building systems are gathered based on built global examples of residential adaptation. For the purposes of simulation and analysis, a consistent location in Toronto, Canada and the same orientation is assumed for all buildings.

The results are categorized in an interactive indexing tool for adaptability to create a basis for understanding the implications of residential adaptation strategies. MAU analysis is used to analyze the building adaptation strategies. The application of strategies on three other building systems and their simulation is used in a sensitivity analysis.

### *3.1 Physics-based simulation tools*

BIM models of all strategies applied to building system one are developed in Revit®, including detailed information regarding construction phase, cost and life cycle phasing with a consistent BIM Level of Development (LOD) of 200. Various physics simulation tools within Revit® and Rhino® Grasshopper® are used to measure the following parameters: energy use, thermal comfort, daylighting, natural ventilation, systems performance, life cycle analysis, cost-benefit and constructability. The selected tools include Sefaira® for energy use, daylighting and systems simulation, Honeybee® for thermal comfort, Autodesk CFD® for natural ventilation, Tally® for life cycle analysis, Sigma Estimates® for costing and the Sustainability ROI Workbook for cost-benefit analysis and scheduling tools in Revit® for determining constructability were used.

### *3.2 Multi-criteria decision making for building adaptation design*

Multi-criteria Decision Making (MCDM) methods are effective for determining optimal solutions in complex problems (Hu, 2019). Common MCDM methods include AHP, MAU, Fuzzy Theory, Case-Based Reasoning, Data Envelopment Analysis (DEA), and less common methods such as SMART, ELECTRE, PROMETHEE, SAW and TOPSIS (Velasquez and Hester, 2013). MCDM has been effectively demonstrated to support complex design decision-making and can be applied effectively for building adaptation projects. For example, Rocchi *et al.* (2018) used a multicriteria sorting approach to account for conflicting objectives regarding insulating

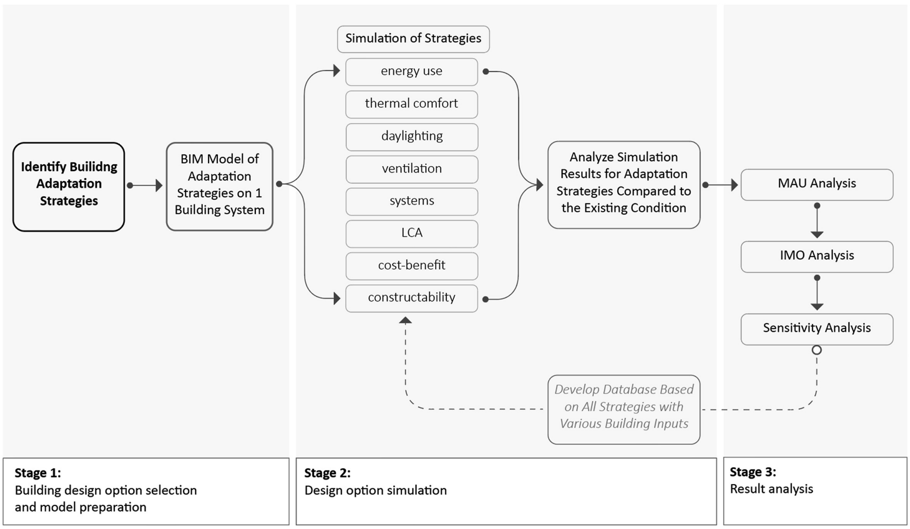



**Figure 2.** Steps in the methodology, including identification of adaptation strategies, simulation, analysis and validation. The future steps of this research will include the development of an extensive database that can be used for future design automation applications

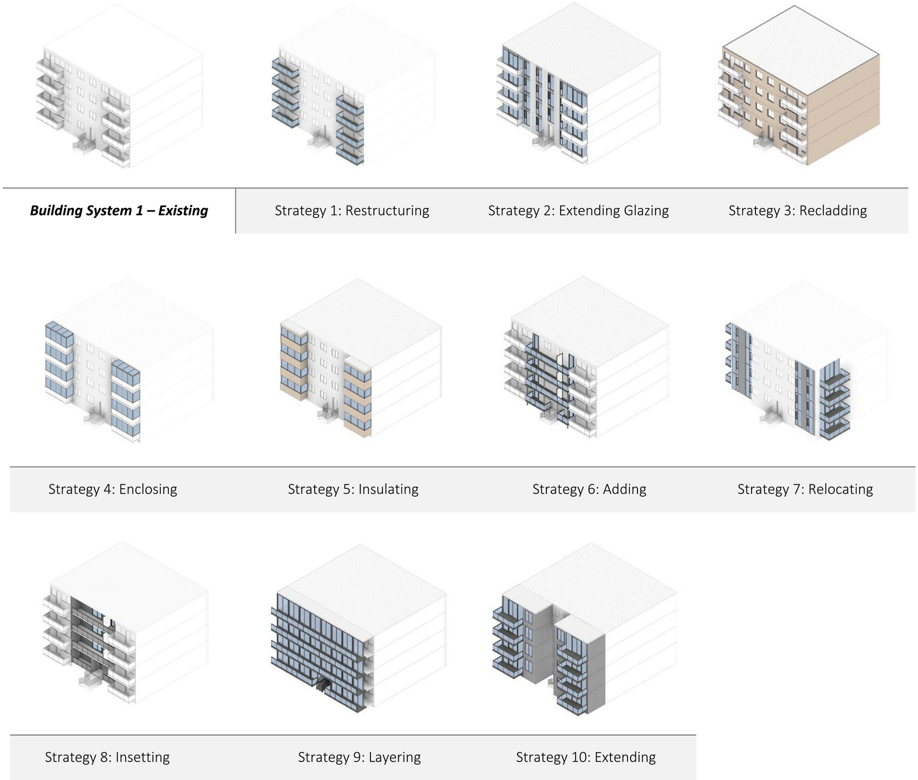



**Figure 3.**
Building system #1, existing condition and 10 building adaptation strategies

materials for retrofitting projects (Rocchi *et al.* (2018)). Also, Motuziene *et al.* used MCDM to examine the environmental impacts of three different building materials, optimizing for cost and carbon emissions (Motuzienė *et al.*, 2016). MAU is an MCDM method that is particularly appropriate for the decision-making methodology in this paper. It allows decision-makers to apply criteria utility values based on their judgement informed by context (Velasquez and Hester, 2013; Verbeke *et al.*, 2018).

*3.2.1 Multi-attribute Utility Analysis.* A Multi-attribute Utility Analysis (MAU) analysis of alternatives, in this case, between multiple building adaptation design strategies, identifies options that perform well on most measures and are used to rank the alternatives identified (Li *et al.*, 2011). MAU analysis requires the determination of weight factor distribution for each of the metrics being analyzed. For each performance measure, a single utility function is determined (between 0 and 1) (Kapur, 2015) to determine the weight and importance of each measure on the overall result.

Based on the simulation of all strategies for performance, the percentage of improvement or decline of each strategy compared with the existing conditions of building system one is analyzed. While energy use and cost are determined as the most important factors for decision-making by experts from the industry partners of this research, various weights per strategy are used for demonstration. The multi-attribute utility for design option $x$ is:

$$v\ (x) = \sum_{i=1}^{n} w_i v_i(x_i) \tag{1}$$

where $v_ix_i$ is the value of design option $x$ on the $i_{th}$ attribute, $w_i$ is the importance weight of the $i$th attribute and is a constant for each iteration, and $n$ is the number of different attributes (Von Winterfeldt and Fasolo, 2009).

*3.2.2 Interactive Multi-objective optimization.* Interactive multi-objective optimization is applicable for applications where the decision-maker is heavily involved, such as a building design process. In an Interactive Multi-objective Optimization (IMO), a solution scenario is repeated multiple times using various iterations for achieving desirable Pareto optimal solutions. In the optimization process, the decision-maker receives preliminary feedback regarding the performance of various options. The decision-maker can specify preferences and explore interesting areas of the search to arrive at preferable solutions. An IMO allows the decision-maker to learn about the interdependencies and relationships between various objectives and make informed decisions based on the feasibility of solutions (Xin *et al.*, 2018). It is a way of finding a good human-machine balance in design decision-making.

In an IMO, the decision-maker specifies preferences progressively in phases to alter and guide the search results. No global preferences are required as the decision-maker can adjust and alter the search scope through a better understanding of the outcomes in each step. Since the decision-maker is actively involved and interactively adjusting the search, the computational complexity is significantly reduced. Through the interaction with the optimization algorithm, the decision-maker can learn about the parameters that affect the results of the problem and can adjust their preferences. Interaction patterns can be categorized into two groups of interaction after a run and interaction during the run of the optimization algorithm. In this research, we will focus on interaction of the decision-maker after the run of each phase in the optimization process. The comparison of objectives can be conducted through various means, including the definition of weights and analyzing trade-offs, amongst others. Varying weights are used to test results based on value function (utility function) with MAU. As a scalar function, value function allows the evaluation of all solutions and their comparison in a quantitative manner (Branke *et al.*, 2008).

The IMO methodology assumes that the decision-maker can provide preference by a value on a scalar function, and the weighted metrics are used to find Pareto optimal solutions. The value function provides a comprehensive ranking of design options, and the optimal solution is the decision-maker's most suitable solution:

$$y\ (x) = \sum_{i=1}^{n} vw_i y_i(x_i) \tag{2}$$

where $y_ix_i$ is the value of design option $x$ on the *ith* attribute, $vw_i$ is the varied importance weight of the *ith* attribute, and $n$ is the number of different attributes (Von Winterfeldt and Fasolo, 2009). Sliders are incorporated within the IMO interface as a graphical way to change the values of $vw_i$, and therefore presenting optimal solutions for each case.

### *3.3 Sensitivity analysis*

The parameters that are expected to have the highest impact on the variation of the percentage of change results include size, complexity, and distribution of strategies in buildings. A comprehensive sensitivity analysis on various building systems, orientations and climates is required for widespread methodology adoption. For limited validation in this research, three built building systems composed of various building adaptation design strategies are selected. One adaptation strategy is chosen for the validation of results. The enclosing strategy is modelled on the south face of the building instead of other adaptations. The existing building, as-built building adaptation, and the implementation of the enclosing strategy are demonstrated in Table 2. Building systems 2–4 are modelled in Autodesk Revit® with a consistent LOD of 200 necessary for analysis (Liu *et al.*, 2019), similar to building

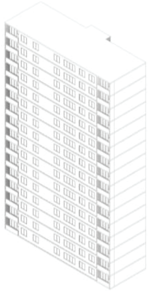
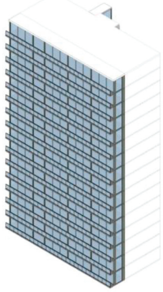
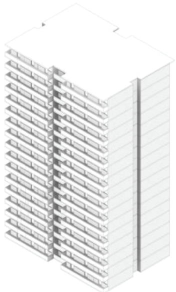
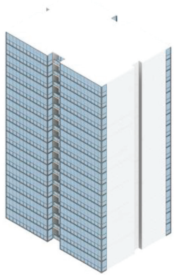
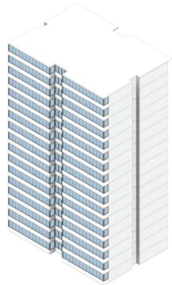
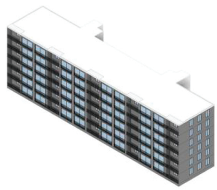
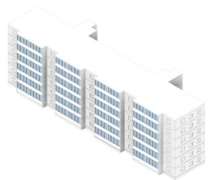
| Building Systems | Existing | As-Built Building Adaptation | Enclosing Building Adaptation Strategy on Existing |
|---|---|---|---|
| **#2:** Block G,H,I, Lacaton & Vassal, Bordeaux, France<br>**Original Construction:** 1950s<br>**Adaptation:** 2016<br>**Original Function:**<br>Inset Balconies<br>**New Function:** Layered Balconies |  |  |  |
| **#3:** Piazza-Flat, A3 Architects, Gorinchem, Netherlands<br>**Original Construction:** 1975<br>**Adaptation:** 2009<br>**Original Function:** Cantilevered Balconies<br>**New Function:** Added/ Enclosed Balconies |  |  |  |
| **#4:** Gruentenstrasse, Lattke Architects, Augsburg, Germany<br>**Original Construction:** 1966<br>**Adaptation:** 2013<br>**Original Function:** Cantilevered Balconies<br>**New Function:** Added/ Inset Balconies |  |  |  |

**Table 2.**
Existing, as-built building adaptation strategy, and enclosing building adaptation strategy on building systems 2, 3 and 4

system 1. Building systems 2, 3 and 4 are analyzed for all similar measures as building system 1. The improvements and downfalls of the enclosing strategy from the base case are analyzed and demonstrated for validation of methodology. All building systems are modelled and simulated in the same orientation and have all been simulated with locations set to Toronto, Canada, for consistency.

## 4. Results

Energy, daylighting and systems simulation is completed within Sefaira® using EnergyPlus®. The following are the general model inputs: building area of 1,170 m$^2$, fan coil units and central ventilation, occupant density of 50 $m^2$/person, the equipment power density of 5 W/$m^2$, a lighting power density of 10 W/$m^2$, heating setpoint at 18C, air changes of 0.2 L/s.m. The existing wall U-factor is set at 0.57 W/$m^2$K, and the existing glazing *U*-factor is set at 3.3 W/$m^2$K with an SHGC of 0.4. Any area with new wall construction or recladding assumed a U-factor of 0.1 W/$m^2$K and new glazing at 0.8 W/$m^2$K with SHGC: 0.6. Energy Use Intensity (EUI) is selected as a measure for comparison of energy use. The existing condition had a total EUI of 123 kWh/$m^2$/yr, compared to recladding, demonstrating a 2.1% improvement and enclosing a 2.4% improvement.

Thermal comfort is calculated as the average percentage of time occupants would be comfortable without air conditioning on an extremely hot week in Toronto, Canada. Results for recladding demonstrate a 20.8% increase in thermal comfort and a 10.4% increase for enclosing. Average Daylighting Factor (DF) is selected as a measure for comparison of daylighting. The existing condition and recladding demonstrated an average DF of 4.12% and enclosing an average DF of 2.07%, a decrease of 49% in DF as a result of the balcony enclosure.

For natural ventilation, areas that are not being ventilated (0 m/s) and comfortably ventilated (0.15–0.9 m/s) are measured. There were no changes made to the opening in the recladding strategy, but enclosing demonstrated a 1% improvement of natural ventilation. The natural ventilation simulations are based on 15 km/hr winds with an outdoor temperature of 20 ℃. Single units are isolated and simulated for comparison between different openings, layouts and building heights are overall massing wind flow is not taken into consideration. For systems simulation using Sefaira® for Autodesk Revit®, the heating equipment design capacity is selected as an appropriate measure in a cold climate. Recladding requires a heating equipment design capacity of 66.1 W/$m^2$, 3.5% improvement from the existing condition, and enclosing needed 61.1 W/$m^2$, a 12.2% improvement.

The primary metrics for LCA analyzed include smog formation potential, acidification potential and Global Warming Potential (GWP). GWP is selected as the primary measure for comparison of strategies and 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. The various life cycle stages considered in Tally® calculations include product, maintenance and replacement, end of life and potential of reuse afterlife of building, including energy recovery and material recycling (Module D) (Cays, 2017; De Wolf *et al.*, 2017). Required operational energy data includes energy use intensity (kWh/$m^2$/year) and total electricity demand (kWh). 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). Existing building system one is estimated to have a total global warming potential of 3,213,745 kgCO2eq and a primary energy demand of 65,322,390 MJ. Recladding shows a reduction in GWP of 1.9% as compared to the existing condition over the life cycle of the building, and enclosing shows a 2.6% increase in life cycle impacts.

The Net Present Value (NPV) was selected as a measure of comparison, and recladding demonstrated an NPV of $41,388 while enclosing has an NPV of $53,198. The cost factor for required labour, equipment, and materials is used to understand each strategy's constructability. The results for all simulations are summarized in Table 3. The results for the percentage of change in performance for all strategies compared to the existing base case are analyzed and demonstrated in Figure 4.

According to the initial assessment, energy use and natural ventilation are most consistently improved across all strategies. Daylighting had the most significant variance amongst the strategies, with an improvement of 190% for insetting and a decrease of 74% in layering. The two strategies of recladding and enclosing experienced a positive NPV, while the rest experienced a negative NPV ranging from −0.2% to −115%. Heating equipment

| | Energy use | Thermal comfort | Daylight | Ventilation | Systems | LCA | Cost-benefit | Construct-ability factor |
|---|---|---|---|---|---|---|---|---|
| | EUI ($kWh/m^2/yr$) | % of time comfortable (Extreme hot week | Daylight factor (Average %) | % of area ventilated | Heating equipment design capacity ($W/m^2$) | Global warming potential ($kgCO_2eq$/ millions) | NPV ($/thousands) | Labour/Material/ Equipment cost ($/thousands/100) |
| Existing | *122.8* | *54.5* | *1.9* | *79.6* | *69.6* | *3.2* | *−5.2* | *10* |
| Restructuring | 122.8 | 54.5 | 1.9 | 79.6 | 69.6 | 3.2 | −74.2 | 84.1 |
| Extending glazing | 116.2 | 55.4 | 1.9 | 84.7 | 66.8 | 3.1 | −41.0 | 405.3 |
| Re-cladding | 120.2 | 64.9 | 1.9 | 79.6 | 66.1 | 3.1 | 41.4 | 68.3 |
| Enclosing | 120 | 49.8 | 2.0 | 80.8 | 61.1 | 3.3 | 53.2 | 62.5 |
| Insulating | 96.9 | 49.8 | 1.7 | 80.8 | 41.8 | 2.8 | −5.3 | 121.8 |
| Adding | 156 | 45.5 | 2.1 | 87.6 | 97.7 | 3.0 | −70.4 | 143.5 |
| Relocating | 125 | 57.2 | 3.2 | 88.6 | 74.2 | 3.3 | −67.0 | 680.2 |
| Insetting | 90.6 | 55.8 | 5.5 | 84.5 | 46.6 | 2.6 | −257.4 | 303.4 |
| Layering | 115.9 | 58.3 | 0.5 | 69.2 | 59.0 | 3.3 | −597.1 | 548.1 |
| Extending | 117.1 | 47.4 | 1.1 | 94.8 | 75.1 | 3.2 | −542 | 510.2 |

**Table 3.**
Simulation Results of Energy, Thermal Comfort, Daylighting, Ventilation, Systems, Life Cycle and Cost-Benefit for Existing Building System 1 Demonstrated for All Strategies. Percentages of improvement for each measure compared to existing condition is demonstrated for all strategies being compared

design capacity also had a significant variance of −40% for adding and a 40% improvement for insulating, and 33% for layering. Other strategies for systems performance had a modest gain or decrease in performance in the −10%–10% range. For energy use and ventilation, most strategies experienced an improvement. Layering and extending strategies while experiencing mutual improvements in energy use and independent improvements in other measures collectively performed lower than other strategies.

Ten iterations of MAU analysis are conducted for varying weights per strategy for demonstration. The ranking and utility factors for each strategy are presented in Table 4. The MAU Analysis results for existing, recladding and enclosing are based on equal weights for all measures and are presented in option 1. Various weight distributions have been tested for: (1) option 2 demonstrates results for 50% weight of energy and equal for all others, (2) option 3 shows 50% weight of thermal comfort and balanced for all others, (3) option 4 demonstrates 50% weight of daylighting and balanced for all others, (4) option 5 demonstrates 50% weight of ventilation and equal for all others, (5) option 6 demonstrates a 50% weight of systems and balanced for all others, (6) option 7 shows a 50% weight of life cycle and balanced for all others, (7) option 8 demonstrates a 50% weight of cost-benefit and equal for all others, (8) option 9 demonstrates a 50% weight on constructability and equal for all others, and (9) option 10 demonstrates a 40% weight on energy use, a 40% weights on cost-benefit, and equal distribution of weight on all others.

The iterations are presented to the decision-maker in an interface that enables an easy search through the data, a sample of which is demonstrated in Figure 5. The interactive interface enables the decision-maker to participate in an IMO process and get the ranking of each design options after determining the required weights of each metric. Going through the results using an interactive interface will allow the decision-maker, a project designer, stakeholder or client, to better understand the metrics driving the results and the prioritization of a design option in each defined scenario.

Further, a sensitivity analysis (identifies the most reliable metrics in determining optimal design decisions using this methodology. The enclosing strategy is examined on building systems 2, 3 and 4, and compared to results in building system one examined previously. The simulation results are presented in Table 5. The percentage of change in performance in regard to each metric, compared to the base of each of the four building systems investigates, is demonstrated in Figure 6. The analysis a consistent and reliable analysis of improvements for strategies regarding energy use, ventilation, life cycle analysis, systems, and cost-benefit. Prediction of thermal comfort, daylighting and constructability based on the developed

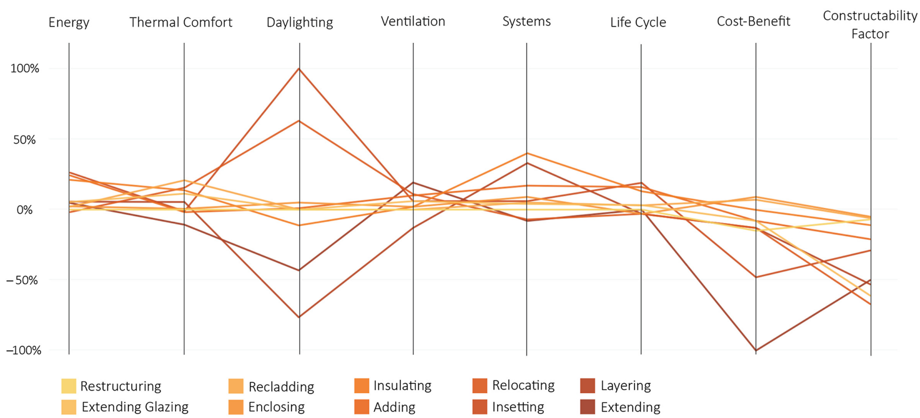



**Figure 4.** All strategies - % of change in performance of each measure is demonstrated in comparison to the existing condition of building system 1. Each line represents one adaptation strategy, identified by colour

**Table 4.** MAU analysis results for existing and strategies – based on various strategy weights

| | Option 1 | Option 2 | Option 3 | Option 4 | Option 5 | Option 6 | Option 7 | Option 8 | Option 9 | Option 10 |
|---|---|---|---|---|---|---|---|---|---|---|
| *Weight of measures* | | | | | | | | | | |
| Energy | *12.5%* | *50%* | 7.2% | 7.2% | 7.2% | 7.2% | 7.2% | 7.2% | 7.2% | *40%* |
| Thermal comfort | *12.5%* | 7.2% | *50%* | 7.2% | 7.2% | 7.2% | 7.2% | 7.2% | 7.2% | 3.4% |
| Daylighting | *12.5%* | 7.2% | 7.2% | *50%* | 7.2% | 7.2% | 7.2% | 7.2% | 7.2% | 3.4% |
| Ventilation | *12.5%* | 7.2% | 7.2% | 7.2% | *50%* | 7.2% | 7.2% | 7.2% | 7.2% | 3.4% |
| Systems | *12.5%* | 7.2% | 7.2% | 7.2% | 7.2% | *50%* | 7.2% | 7.2% | 7.2% | 3.4% |
| Life cycle | *12.5%* | 7.2% | 7.2% | 7.2% | 7.2% | 7.2% | *50%* | 7.2% | 7.2% | 3.4% |
| Cost-benefit | *12.5%* | 7.2% | 7.2% | 7.2% | 7.2% | 7.2% | 7.2% | *50%* | 7.2% | *40%* |
| Constructability | *12.5%* | 7.2% | 7.2% | 7.2% | 7.2% | 7.2% | 7.2% | 7.2% | *50%* | 3.4% |
| *Sample iteration results: Utility factor* | | | | | | | | | | |
| Existing | 52.5 | 51.4 | 51.4 | 44.3 | 44.3 | 51.4 | 51.4 | 53.4 | 65.1 | 52.3 |
| Restructuring | 49.3 | 49.6 | 49.6 | 42.5 | 42.5 | 49.6 | 49.6 | 48.7 | 55.5 | 48.9 |
| Extending glazing | 47.6 | 49.7 | 49.0 | 41.2 | 41.2 | 49.5 | 49.3 | 49.0 | 42.8 | 50.6 |
| Re-cladding | 53.5 | 52.5 | 52.5 | 44.9 | 52.0 | 53.1 | 52.7 | 55.3 | 61.8 | 54.2 |
| Enclosing | 54.4 | 53.0 | 50.6 | 46.1 | 52.9 | 54.4 | 51.9 | 56.2 | 70.1 | 54.8 |
| Insulating | 53.0 | 56.2 | 56.2 | 43.0 | 52.2 | 60.3 | 54.5 | 53.7 | 49.8 | 56.3 |
| Adding | 46.8 | 43.6 | 52.6 | 41.2 | 41.2 | 39.6 | 49.4 | 49.4 | 50.1 | 44.5 |
| Relocating | 45.7 | 47.2 | 48.7 | 50.2 | 49.9 | 46.1 | 46.9 | 47.0 | 30.0 | 48.1 |
| Insetting | 54.3 | 58.1 | 52.1 | 72.7 | 53.8 | 53.7 | 56.5 | 45.0 | 42.7 | 49.8 |
| Layering | 36.5 | 43.6 | 43.8 | 24.3 | 39.6 | 45.0 | 41.8 | 21.9 | 28.8 | 30.0 |
| Extending | 34.8 | 42.3 | 38.5 | 27.9 | 45.4 | 39.6 | 41.3 | 22.8 | 19.8 | 30.9 |

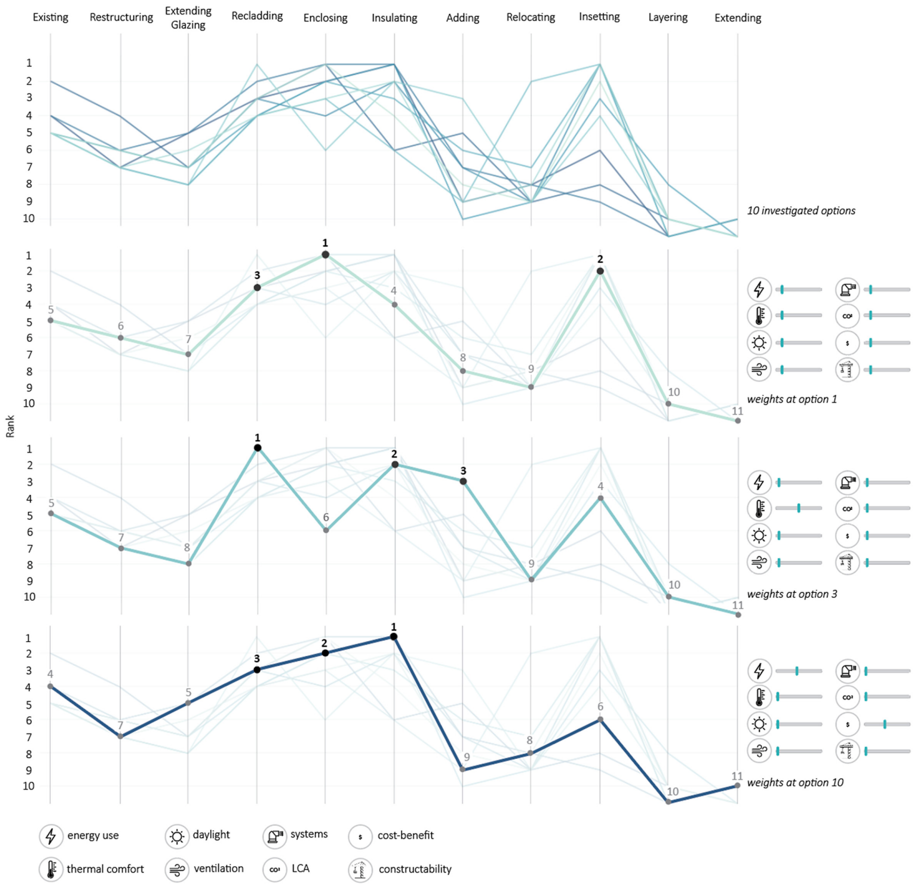



**Figure 5.** All strategies analyzed through 10 varying weight options using of MAU. Ranking of options are numerically represented for each set. Enclosing, insulating, and recladding, are the three strategies that are consistently high performing across the ten varying weight scenarios

matrix is not accurate and can differ based on the form and material complexity of the existing building. The methodology can be used to generate and analyze a large number of cases and design variations suitable for early-stage design optimization.

The results are validated using analysis of the enclosing strategy on building systems 2, 3 and 4. Results demonstrate an overall correlation of improvements for energy use, ventilation, cost-benefit and a similar correlation for constructability. Thermal comfort is varied across building systems, with building systems 1 and 4 having a decrease of 9% and 24% respectively and building systems 2 and 3 having improvements in the range of 3%. For daylighting, building system 1 demonstrates an increase of 5% and building systems 2, 3 and 4 show significant decreases in quality of daylighting due to enclosing. Buildings systems 1, 2 and 3 also show a negative contribution to the global warming potential of 0.18%–3.00%, while building system 4 has a small improvement in global warming potential of 0.1%. Constructability based on the intensity of labour, material and equipment used in building systems 2–3 varies in the range of −0.5% to −6.3% and correlates with building system "1's score of −5.2% (Table 5).

Based on the initial simulation results, ten iterations of MAU and the sensitivity analysis, the decision-maker can narrow down the search criteria for further analysis. For demonstration, recladding, insulating, and enclosing have been selected as the top three

| | Energy use | Thermal comfort | Daylight | Ventilation | Systems | LCA | Cost-benefit | Construct-ability factor |
|---|---|---|---|---|---|---|---|---|
| | EUI (kWh/$m^2$/yr) | % of time comfortable (Extreme hot week | Daylight factor (Average %) | % of area ventilated | Heating equipment Design capacity ($W/m^2$) | Global warming potential (kg $CO_2$ eq/ millions) | NPV ($/thousands) | Labour/Material/ Equipment cost ($/thousands/100) |
| Building system 1: *Existing* | 122.8 | 54.5 | 1.9 | 79.6 | 69.6 | 3.2 | −5.2 | 10 |
| Building system 1: *Enclosing* | 120 | 49.8 | 2.0 | 80.8 | 61.1 | 3.3 | 53.2 | 62.5 |
| Building system 2: *Existing* | 99 | 55.3 | 4.62 | 94.6 | 44.1 | 611.7 | 0 | 23 |
| Building system 2: *Enclosing* | 89 | 57 | 3.72 | 99.3 | 42.6 | 612.8 | 93,960 | 33.8 |
| Building system 3: *Existing* | 106 | 5.4 | 2.30 | 91.2 | 49.8 | 312.5 | 0 | 31 |
| Building system 3: *Enclosing* | 85 | 8.5 | 119 | 93.2 | 40.2 | 313.6 | 60,320 | 61.4 |
| Building system 4: *Existing* | 101 | 47.6 | 4.22 | 81.7 | 48.5 | 735.7 | 0 | 12 |
| Building system 4: *Enclosing* | 83 | 35 | 2.76 | 98.5 | 42.8 | 735.1 | 18,235 | 88.3 |

**Table 5.**
Simulation results of energy, thermal comfort, daylighting, ventilation, systems, life cycle and cost-benefit for building system 1 and enclosing strategies on building systems 2, 3 and 4

highest performing strategies. Lifecycle, energy use and cost-benefit were selected as the three main decision drivers based on industry expert input. They are also high ranking in terms of reliability of results based on sensitivity analysis. The results in Figures 5 and 7 are for demonstration of the methodology being applied and can be customized based on decision-maker preferences.

Enclosing, insulating, and recladding, are the three strategies that are consistently high performing across the ten varying weight scenarios. Based on this, 30 iterations of MAU are

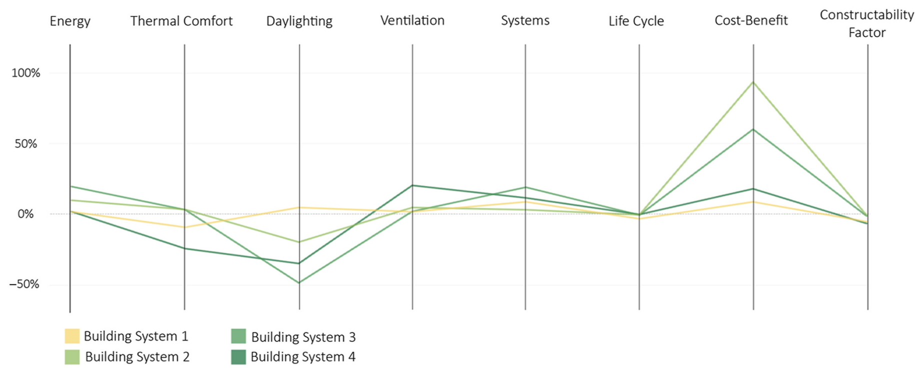



**Figure 6.** Simulation results for enclosure strategy of all building systems compared with existing condition of each building system – simulation results of energy, thermal comfort, daylighting, ventilation, systems, life cycle and cost-benefit for existing and enclosing strategy

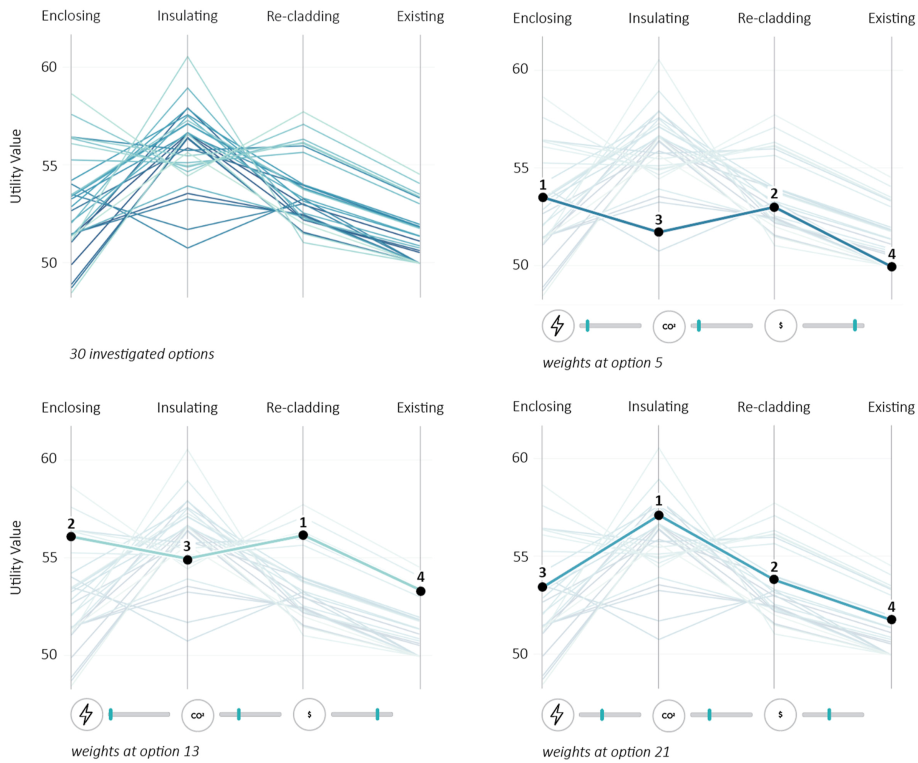



**Figure 7.** Interactive MAU analysis. All strategies were analyzed through 30 varying weight options using of MAU. The ranking of options is numerically represented for each set

conducted for varying weights on each of the three selected metrics, and the results are demonstrated in Figure 7. Similar to the previous MAU interface presented in Figure 5, the MAU interface in Figure 7 will enable project stakeholders to alter the importance of the three metrics with the most significant impacts identified, energy use, carbon emissions and cost, and to understand which of the three most suitable design options identified in this demonstration, enclosing, insulating and recladding, are prioritized.

## 5. Discussion

This research examines the use of multiple tools and develops an index that can be used to gain a holistic perspective on the performance of building adaptation projects. The methodology presented in this research addresses the need to consider computational tools and make decision-making accessible to designers and decision-makers in the early stages of a project. The main goal of this research was to develop, examine and apply a methodology for early-stage design decision-making for building adaptation projects using multiple physics-based simulation tools and decision-making tools such as MAU and IMO. Based on findings presented in Figure 5 and the filtered results in Figure 7, the design options that achieve optimal performance to varying degrees based on metric prioritization are the recladding, enclosing and insulating strategies. It is worthwhile to compare the results of this exploration to the existing database of residential building adaptation. The building permits regarding enclosure-related adaptations and alterations in multi-family housing in the City of Toronto have been studied. The percentage of each of the top five strategies from total adaptations has been demonstrated in Figure 8.

Based on the existing trends, restructuring, including balcony and guard repairs, has been the most common strategy over the past decade, followed by the enclosure, recladding, and reglazing with a large gap. Th is research demonstrate that restructuring is not the most optimal design strategy to pursue any of the investigated optimization metrics. It can be assumed that the prevalence of restructuring is due to the perceived aesthetic improvements and addressing of structural failure needing immediate attention. It can be concluded that access to this methodology and integration with practice can allow the decision-makers and designers to better understand the design options and consider them more holistically in

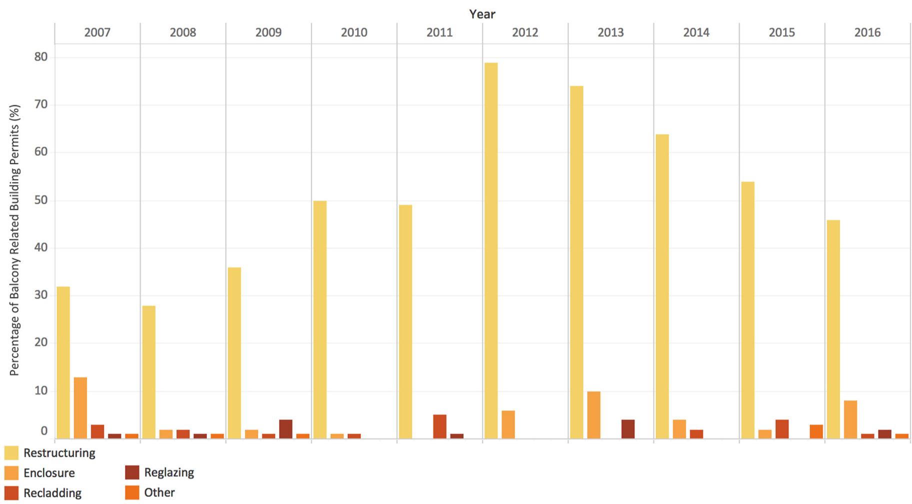



**Figure 8.**
Types of enclosure-related adaptations to multi-family housing in the city of Toronto based on the city of Toronto permit database (City of Toronto, 2019)

terms of environmental performance and return-on-investment benefits. This comparison highlights the practicality of this process in illuminating new possibilities and gaining more insight regarding prevalent strategies.

The presented methodology contextualizes and quantifies the potential benefits of integrating technical performance information for enabling the consideration of large number of design options in the early stages of a design process, as well as highlighting the efficacy of developing an index through this methodology that can be applied to other similar projects. The application of this research will clarify strategies through which performance-conscious decision-makers and designers can apply simulation tools and decision-making methodologies to help supplement their workflows for achieving optimal design combinations and hitting specific performance targets. Since there are high stakes in the early design process, it is important that data-driven tools and methodologies be implemented by or in conjunction with experienced designers that are able to actively contextualize the design suggestions and effectively filter through the data in an interactive process, such as the IMO implemented in this research, to achieve the benefits of multidisciplinary performance feedback.

The comparison between the status quo and the results from this research highlights the decision-making improvements that can be enabled by data-driven design analysis. Without the use of tools and methodologies presented in this research, including simulation feedback and decision-making tools, the decision-maker would potentially miss out on design options with potential savings on multiple fronts, such as energy use, life cycle impacts and better financial performance. The main advantage of the methodology presented in this research is its demonstrated flexibility and accessibility and its applicability to a range of building adaptation projects.

Data-driven design decision-making tools are helpful in supplementing a designer's ability to make optimal and informed decisions. The application of this methodology can improve the performance of a specific design problem while highlighting how a range of objectives might interact and affect the performance of each design option. It is acknowledged that the goals, objectives, and strategies will need to be refined based on findings in a design process. In this process, the decision-maker needs to be present and supported by data-driven feedback. A framework for this interaction needs to be present even as more complex data management techniques and evolutionary algorithms are integrated for design decision-making.

## 6. Conclusion

Using MAU analysis to rank adaptation strategies based on their overall performance, various weight scenarios were considered, and IMO was used to demonstrate the efficacy of interaction of decision-makers with the process. Prioritizing strategies in various scenarios results in the ideal option oscillating between recladding, enclosing, insulating and in-setting. A sensitivity analysis demonstrated that some metrics are more reliable for performance prediction than others. Based on this initial iteration, it was demonstrated that the decision-maker could filter the results to understand the data better and incorporate their own preferences in the process. For demonstration, in-setting was eliminated from the top-performing design strategies and energy-use, LCA and cost-benefit were selected as the main metrics for decision-making. Through the second round of MAU analysis, the decision-maker was able to make a more precise differentiation based on the varying weights of the objectives. In the search for optimal design decision-making using innovative tools and simulations, it is important that the decision-maker and designers integrate their experiences and design sensibilities in the process, and future methodologies and tools to improve the engagement and participation of decision-makers in developed algorithms.

The presented research provides the basis for computational and complex form-finding processes that navigate complex building adaptation projects. It is acknowledged that successful building adaptation projects often contain a mix of a variety of solutions. An example of this could be the recladding of one elevation, insulating failing northern balconies and enclosing most eastern balconies. For a scalable application, data collection and analysis need to be expanded to accommodate different building types, including the analysis of the effects of geometry, location and building materials on the efficacy of different building adaptation strategies. Developing a comprehensive database with sensitivity analysis on the parameters that are expected to have the highest impact on result variation will improve the scalability and applicability of the proposed methodology. A comprehensive database can also develop automated design tools using evolutionary or heuristic algorithms for developing complex design solutions.

Ability to assess multiple design strategies using quantifiable measures impacting building adaptation design decision-making is critical for improving the widespread implementation of building adaptation projects. Building adaptation option appraisal using physics-based simulation and analysis tools and the use of MAU analysis and IMO for optimal decision-making can be applicable for design decision-making. The quantifiable comparison of building adaptation strategies presented in this research can, therefore, assist the evaluation of overall environmental performance and economic justifications for future adaptation projects and facilitates a timely analysis of the success of existing building adaptation projects. A comparative metrics also gives designers access to a comprehensive review of design options for decision-making that is not available in a conventional design process. The current methodology is limited to the analysis of one decision-maker at a time. It can be improved to include multiple decision-makers and capture varying perspectives to reflect common practices in the industry. This can be achieved by running multiple MAU analyses simultaneously using the same developed methodology and analyzing the trade-offs between the strategies suitable for each stakeholder. In addition, the application of this methodology is limited to consultants familiar with advanced modelling and simulation tools. In further developments of this work, with iterative analysis of typical building types and intensive data collection and analysis, it will be possible to develop algorithms for predicting possible outcomes without individual simulation. A developed tool using this methodology and appropriate databases will broaden the accessibility and affordability of advanced design decision-making.

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