Developing design option assessment methods for high-rise residential building adaptation projects

by

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Author's Declaration

This thesis consists of material all of which I authored or co-authored: see Statement of Contributions included in the thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

I understand that my thesis may be made electronically available to the public.

Statement of Contribution

Chapter 3 of this thesis has been incorporated in a journal article published by Sustainable Cities and Society[1]. The paper is co-authored by myself, Professor Carl Haas, Professor Chris Bachmann, and Mansour Esnaashary Esfahani. I developed the paper's methodology and research design in collaboration with Mansour Esnaashary Esfahani, and with guidance from Professor Haas and Professor Bachmann. I completed the data collection, visualizations and illustration presented in the paper; Mansour Esnaashary assisted with the first draft of the article and preliminary data analysis.

Chapter 4 of this thesis has been incorporated within journal article and has been submitted to the Journal of Architecture for publication. The article is co-authored by Professor Haas, Professor Beesley and myself. Professor Haas, Professor Beesley and I developed the methodology and experimental design. I completed all data collection and analysis. The paper was co-written with Professor Haas with guidance from Professor Beesley. Chapter 5 has also been incorporated as a journal article and submitted to Engineering, Construction and Architectural Management for publication. The article is co-authored by Professor Haas, Professor Beesley and myself. Professor Haas and I developed the methodology and experimental design. I completed all simulations, data collection, analysis and co-wrote the paper with Professor Haas. Professor Beesley has provided guidance in the process of the work.

Chapter 6 is an overview of the material included in Appendix A. Material included in Appendix A is based on a conference paper submitted to ISARC 2020 and has been compiled and developed further within a journal article submitted for publication to Automation in Construction. The article has been developed in collaboration with Entuitive Consulting Engineers, the industry partners of this research. The methodology and research design was created by myself, Patryk Wozniczka from Entuitive and Professor Haas. Patryk Wozniczka and I developed the initial algorithm, carried out the experiments, simulations and collected all data. I completed the data analysis, visualization and illustrations included in the paper, and completed the writing of the article. Christopher Rausch developed the algorithm and data analysis relating to structural analysis and contributed to the writing of the article. Ian Trudeau, associate at Entuitive, has been actively overseeing the project and ensuring the industry relevance of results.

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[1] Shahi, S., Esfahani, M. E., Bachmann, C., & Haas, C. (2020). A Definition Framework for Building Adaptation Projects. *Sustainable Cities and Society*, 102345.

Abstract

Adapting existing buildings is complex, but it can reduce the ratio of operating-to-embodied energy and the amount of demolition and construction waste. There has been a growing interest in the adaptation of existing buildings over the past decade as a response to changing environmental conditions and resource depletion. A cohesive perspective on project scope definition, design option assessment, tools and techniques for improving building adaptation is demonstrated. A definition framework is developed first, enabling consistent categorization of building adaptation projects. Then, a decision-making framework is presented for supporting generation, evaluation and selection of multiple conceptually orthogonal design options as a basis for future computational design optimization and detailed design. Lastly, a methodology is developed to improve building adaptation design decision-making by considering multiple environmental and financial parameters, using physics-based simulation tools and decision-making frameworks including multi-attribute utility and interactive multi-objective optimization. The combination of frameworks and methodologies presented in this thesis have been demonstrated to be useful in clarifying building adaptation project scope and definition, and early-stage design and feasibility decision-making. This thesis marks a reference for the future development of interactive and computational tools for improving the proliferation and performance of building adaptation projects.

Keywords: building adaptation, adaptive reuse, design appraisal, design optimization, physics-based simulation tools, multi-attribute decision making

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1. Introduction

1.1 Background and Motivation

Building adaptation, including refurbishment and adaptive reuse of existing buildings (P. Xu et al., 2011), can significantly reduce the GHG emissions produced by the built environment that currently contribute 40% of all emissions (Nejat et al., 2015; P. Xu et al., 2011). Successful building adaptation projects can result in notable social, economic and environmental benefits including: (1) improving energy efficiency, (2) increasing financial gains from reduced maintenance and operation costs, (3) improving occupant thermal comfort, and (4) increasing the useful life of buildings (Foley, 2012; Langston et al., 2008; Ma et al., 2012; Smith & Hung, 2015; Tokede et al., 2018; P. Xu et al., 2011). Adaptation can lead to a reduction of waste material, preservation of natural resources, improvements in energy use and carbon emissions, and the conservation of embodied energy compared to demolition and new construction (Yung & Chan, 2012). Adaptation projects can also improve the quality and comfort of existing buildings, leading to improved occupant satisfaction and preservation of cultural and social values of historical buildings (Chan et al., 2015c; Remøy & Wilkinson, 2012). Building adaptation is typically less expensive than demolition and new construction and can also improve the economic viability of dated buildings (Chan et al., 2015b; Langston et al., 2008; Shipley et al., 2006; Wadu Mesthrige et al., 2018a).

Adaptation of existing buildings has increased over the past decade as a response to changing environmental conditions and requirements for reducing energy use and construction and demolition waste (Pardo-Bosch et al., 2019). It serves as an alternative to our status-quo linear approach of design and construction with the inevitable end-of-life option of demolition. Building adaptation changes an existing building through refurbishment or adaptive reuse. Refurbishment is the process of improving the current conditions and may include retrofitting, rehabilitation or renovation work (Kamaruzzaman et al., 2016). Adaptive reuse can include conversion and material reuse strategies, which extend the useful life of existing buildings (Shahi et al., 2020). Conversion can be defined in terms of a range varying from repurposing of the main structure for another use to the reuse of building systems and components (Bullen, 2007; Conejos et al., 2013; Passer et al., 2016; Wilson, 2010). To move to a circular built environment, there is a need to incorporate adaptation of buildings to facilitate continual loops of resources, products and materials in construction (Stahel, 2016).

Despite the proliferation of adaptation projects, evaluation of design options has been limited in practice, and the success of the designs executed is questionable. This is likely due to the lack of a disciplined framework and limited design professional resources allocation. Based on literature review, a limited number of adaptation strategies are often considered for assessment. While there are many guidelines and models developed for evaluating a building for its adaptation potential to varying degrees (Conejos et al., 2015), there is a gap for clearly identifying an adaptation project scope and a methodology for considering a range of measures and strategies for a specific condition. Specifically, there is no formal and structured process for evaluating, quantifying, and comparing the benefits of building adaptation designs for residential buildings (Gosling et al., 2013). Early in the design process, considering a broad range of strategies is a necessary prelude to a successful generative and detailed design process.

The systematic consideration and evaluation of design strategies in the early design stages can lead to increased design performance (Blizzard & Klotz, 2012). Through early design stage optimization, Kiss and Szalay demonstrated environmental savings of 60-80% compared to traditional design methods (Kiss & Szalay, 2020). The early stages of building design, especially of a building adaptation project, are complex and involve various metrics (Conejos et al., 2015; F. W. H. Wong et al., 2009). For an effective early-stage design, it is essential to consider multiple factors simultaneously, including environmental performance and life cycle impacts (Yuan et al., 2018), as examples. To achieve optimal design options, solutions must be reached that perform well for a range of multiple objectives (Geyer, 2009; Mela et al., 2012). Typical design option optimizations reviewed in literature often consider a limited number of options (Kiss & Szalay, 2020), highlighting the need to consider computational design methodologies for design option generation and simulation to optimize multiple factors simultaneously. Automated design option generation and optimization based on set spatial constraints, energy use, and Life Cycle Analysis (LCA) and Life Cycle Costing (LCC) can be applied using computational tools in early-stage design (Tugilimana, Thrall, Descamps, et al., 2017).

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 use of computational design methodologies and Building Information Modeling (BIM) for option appraisal offers possibilities for physics-based simulation and analytical inputs to be integrated into the early-stage decision making (Mattern & König, 2018). The design process is complex, and integration with environmental and lifecycle assessment tools can be challenging (Rezaee et al., 2019). Physics-based simulations of multiple design options is also a time-consuming task. While these tools can help the speed of analysis times and limit entry barriers, it is essential to have access to immediate design decision-making tools for 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), and highlights the importance of novel methodologies for design option appraisal.

1.2 Research Objectives

The proposed research aims to improve the scope definition and design decision-making process for building adaptation projects. Identified factors that can contribute to these improvements include a clear framework for consistently defining and determining building adaptation project scopes and decision-making frameworks and methodologies that can simultaneously consider multiple factors. Application of this research could begin to address the gap in accurate building adaptation project definition and design option assessment, and enable architects and engineers to design and implement higher-performing designs. It could make complex retrofitting and renovation projects feasible in the long term, and could increase the speed at which building adaptation is addressed. Implementing the methodologies developed in this thesis in the industry could have the following benefits: (1) optimized decision-making and real-time feedback regarding design options, (2) ability to provide high-quality services, to expand quickly and to address a market need, (3) ability to accommodate limited project fees due to gains in speed and quality, (4) ability to optimize fund allocation to a larger number of buildings. This research's scalability should contribute to strengthening a circular economy in construction through mitigation of demolition and release of embodied energy in existing buildings and extending their life cycles.

Based on the outlined motivation, the current study will address the following objectives:

1. Develop a definition framework for building adaptation projects that will serve to clarify the scope of such projects.

2. Develop a decision-making framework for supporting the generation, evaluation and selection of multiple building adaptation design options.

3. Develop a methodology to improve building adaptation design decision-making through application of physics-based simulation tools and multi-objective analysis.

1.3 Premise

Two key premises of this research are:

1. A comprehensive framework for clearly defining building adaptation projects can improve quality of adaptation project scopes and that this can improve project performance.

2. Design decision-making framework and methodologies can improve quality of design outcome and improve speed of analysis.

1.4 Research Scope

The proposed research is divided into two distinct sections. In the first section of the study, a decision-making framework and methodology for early-stage design feasibility analysis is developed to understand and identify the scope of primarily multi-resident building adaptation projects. The framework considers the different aspects of such building adaptation projects and highlights the need to understand the variety of project scopes and in various types of building adaptation projects. In the second stage of this work, a framework is developed for the generation, evaluation and selection of design options and validated with a functional demonstration of residential high-rise adaptation projects. In the second phase, the concepts and methods are further developed into a comprehensive methodology for building adaptation design decision-making and include physics-based simulation and multi-objective decision-making tools. It is reasonable to expect that while the research scope is limited to multi-resident-projects for its validation, that the frameworks developed may be generalized to some extent, and then adapted and applied to other types of building projects.

1.5 Methodology

The methodology of this thesis for contributing to improving design decision-making is demonstrated in **Figure 1-1.** The methodology starts with the literature and case study review in phase one. A functional demonstration of a project definition demonstrates the efficacy of the developed framework. In phase two, a framework is developed for defining scope of building adaptation projects. In phase three, a decision-making framework is developed using multi-attribute utility theory (MAUT). Further, physics-based BIM simulation tools, MAUT, Interactive Multi-objective Optimization (IMO) and Sensitivity Analysis (SA) are used to appraise building adaptation design options based on their environmental and economic performance. Validation of the developed framework and methodology is demonstrated through residential building adaptation projects. The steps of the methodology are outlined below:

1. Literature Review: Conduct a comprehensive literature review on a range of topics related to the issues discussed in the thesis, including: (1) building adaptation project definition, (2) role of building adaptation in a circular economy, (3) residential building adaptation, (4) building adaptation feasibility analysis, and (5) BIM simulation tools.

2. Case Study Analysis: Select relevant residential building adaptation projects and conduct a case study analysis.

3. Model Development: Create 6D BIM models of case study buildings for analysis.

4. Physics-based Simulations: Conduct physics-based simulations and collect data for the modelled case buildings' performance in terms of various environmental and economic performance measures.

5. Analysis: Analyze the collected data using MAUT, IMO and SA.

4. Validation: Validate the proposed framework and methodology using a functional demonstration of the design of a residential building adaptation project.

5. Documentation and dissemination: Document and present the findings of this research in peer-reviewed journals, conferences and reports.

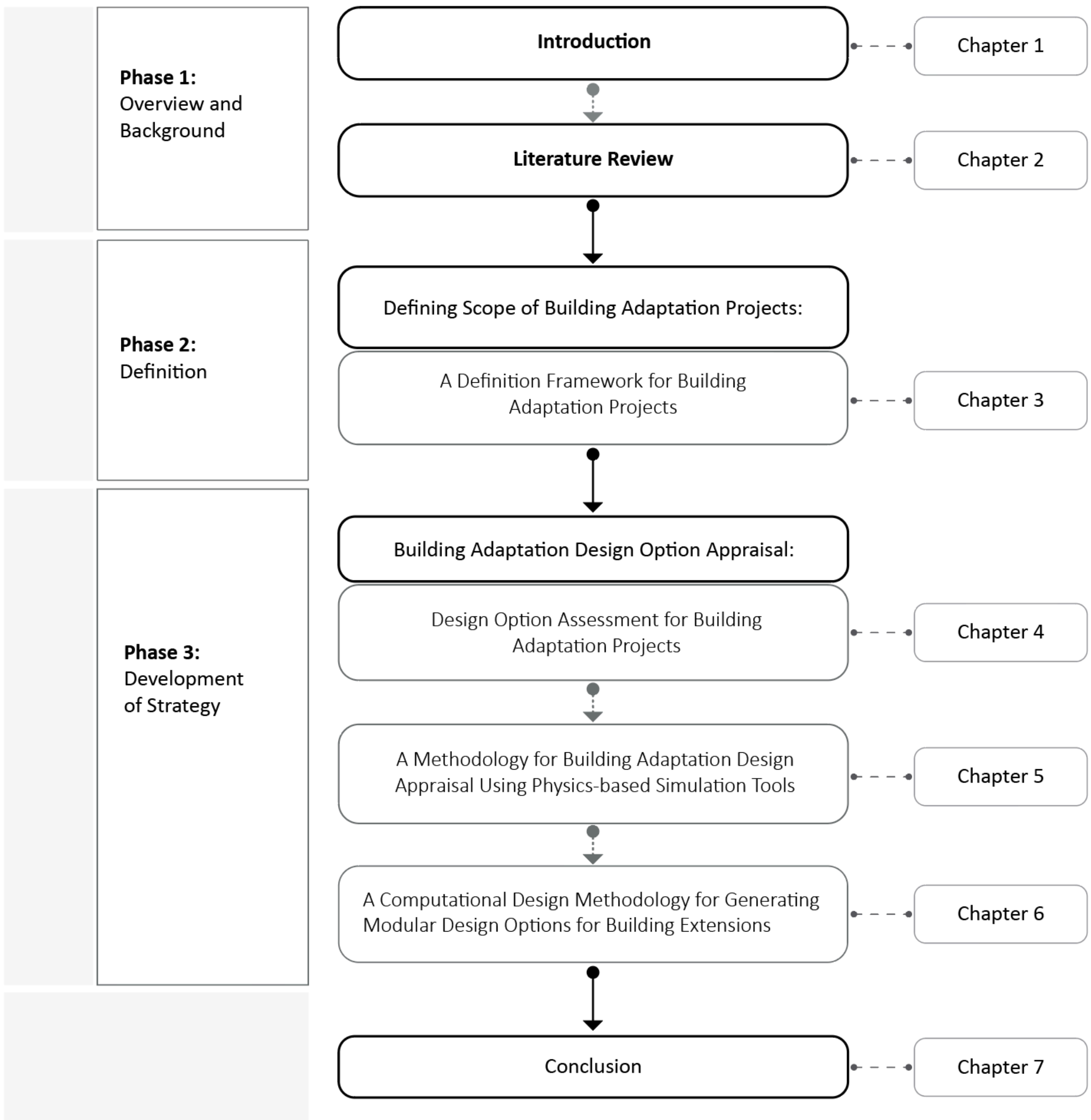


Figure 1-1: Thesis methodology and structure

1.6 Thesis Organization

This thesis is organized into six chapters and two appendices. In **Chapter One**, an overview of the background and motivation for the project, research objectives, scope and methodology are provided.

In **Chapter Two**, the literature review and background information are presented.

In **Chapter Three**, a comprehensive study of different building adaptation project scopes and definitions is conducted. A definition framework for clarifying project scopes is presented and validated through multiple examples.

In **Chapter Four**, a framework for the generation and evaluation of building adaptation design options are presented. The framework is validated through demonstration of adaptation of multi-family residential projects.

In **Chapter Five**, a methodology for integration of physics-based simulation tools and decision-making tools for a comprehensive analysis of design options is presented. The methodology is validated through the functional demonstration of a specific residential building adaptation project.

In **Chapter Six**, an overview of a computational design methodology for integrating modular construction in building adaptation is presented. The details of this investigation are presented in **Appendix A**.

In **Chapter Seven**, a summary of this research, contributions, limitations and recommendations for future work are provided.

In **Appendix A**, a partial development of future work outlined by this research is presented. A computational design methodology for integrating modular construction in building adaptation projects is developed in close collaboration with Entuitive Consulting Engineers. The detailed results of this study are provided in **Appendix B**.

The results of conducted simulations in **Chapter Five** are summarized in **Appendix C**.

2. Literature Analysis

2.1 Building Adaptation Project Definition

Many aspects of building obsolescence affect the quality and performance of a building after its useful life. These include reduced environmental, economic, functional and social performances (Langston et al., 2008; Ren et al., 2015). A building facing obsolescence is often economically unsustainable, has low occupant comfort and satisfaction, and has increased energy use and water consumption. Responsive, appropriate, and timely building adaptation and renewal are essential in extending a building's effective life span. Building adaptation can provide considerable environmental, social and economic benefits, making it a sustainable alternative to demolition and new construction (Conejos et al., 2013; Noorzalifah & Kartina, 2016).

Adaptation of existing building stock can lead to a reduction of waste material, preservation of natural resources, improvements in energy use and carbon emissions, and the conservation of embodied energy compared to demolition and new construction (Yung & Chan, 2012). Adaptation projects can also improve the quality and comfort of existing buildings, leading to occupant satisfaction and preservation of cultural and social values of historical buildings (Chan et al., 2015c; Remøy & Wilkinson, 2012). Building adaptation is typically less expensive than demolition and new construction and can improve the economic viability of dated buildings (Chan et al., 2015b; Langston et al., 2008; Shipley et al., 2006; Wadu Mesthrige et al., 2018a).

The scope of building adaptation projects can be broad and varies between each project. Scope variations are due to many factors, including the type and scale of buildings, existing conditions and requirements for adaptation, and construction activities conducted during these projects (Thuvander et al., 2012). Many different terminologies are used in the literature and industry to specify building adaptation projects' scope. The variability in the definition of building adaptation projects reflects the broad scope of these projects. Some of the terminologies often used to describe aspects of building adaptation include refurbishment, retrofitting, rehabilitation, renovation, restoration, modernization, conversion, adaptive reuse, material reuse, conservation, and preservation, amongst others. These terminologies are often used interchangeably due to overlapping scopes and lack of clarity for their appropriate uses (Douglas, 2006). Many examples in the literature refer to similar adaptation projects in terms of type, scale, and construction, but use different terms to describe the adaptation scope. For example, Passer et al. (2016) and Zaragoza-Fernandez et al. (2014) use the terms refurbishment and rehabilitation, respectively, to describe window replacements and insulation improvements in existing buildings (Fernández et al., 2014; Passer et al., 2016).

Adaptation is defined as changes to an existing building to alter its capacity, function or performance (Douglas, 2006), and it is understood across multiple studies as an environmentally sustainable alternative to both demolition and new construction (Conejos et al., 2015; Douglas, 2006; Langston et al., 2008). Adaptation addresses the need for an existing building to better suit the existing use by addressing occupant requirements make it more fitting for a proposed use (ICOMOS, 2013). Retrofitting involves the redesign and reconstruction of an existing building to meet environmental performance requirements not anticipated in the initial design. This can involve the replacement of failing or outdated building components. It can also accommodate changes that were not anticipated at initial construction and incorporate new technologies relevant to the building (Douglas, 2006; Iselin & Lemer, 1993; L. Wong, 2016). Adaptation strategies extend the functional life of existing buildings that are have degrading energy performance or are obsolete in use through reuse or re-purposing. This can be defined in terms of a range varying from re-purposing the main structure to updating building components and HVAC systems (Bullen, 2007; Conejos et al., 2013; Langston, 2012; Langston et al., 2008; Wilson, 2010). Adaptation projects are complex, and their evaluation needs to include performance improvements, social, economic, legal and political metrics.

In the context of residential building adaptation, it is important to address strategies for adaptation—strategies that can address various use requirements—as well as retrofitting requirements that concern environmental performance requirements. Strategies for adaptation and retrofitting of balconies are mainly concerned with refurbishment and conversion. Refurbishment involves changes and alterations to a building restricted to non-structural improvements and often consists of the building envelope directly (Douglas, 2006). These changes can be focused on retrofitting and are directed at modestly addressing changes in occupant requirements and environmental requirements. While refurbishment is often limited to the building exteriors, it does not concern the load-bearing structure or interior layouts. Conversions concern more intrusive changes to an existing building, often involving structure and interior layouts (Giebeler et al., 2012).

There are multiple guidelines and models developed for evaluating a building for its adaptive reuse potential. The Adaptive Reuse Potential (ARP) provides a ranking for adaptive reuse potential in existing buildings by predicting the optimal timing for adaptive reuse (Langston, 2012). The adaptSTAR is another model that provides a weighted checklist of metrics that can facilitate the adaptive reuse of a building, ranging from structural, economic and legal metrics (Conejos et al., 2015). While these models help assess the conditions that make a building suitable for adaptive reuse, further studies need to examine the efficacy of building adaptation strategies. It can be concluded from studies in this field that successful adaptation projects can result in notable social, economic and environmental benefits (Langston et al., 2008; Schultmann & S., 2007; Smith & Hung, 2015; Wilson, 2010). The complexity of these projects can be summarized in a multitude of conditions and issues that need to be addressed. The metrics for decision-making of building adaptation designs are understudied. Most decision-making regarding the planning, design and construction of adaptive reuse of buildings is limited to the experts in the field and experience with the status quo (Gorse, 2009).

2.2 Circular Economy in the Built Environment: Role of Building Adaptation

Construction materials stocked in the built environment, such as buildings and infrastructure, make up a large part of global material use (Commission, 2016). Buildings have a 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). A Circular Economy (CE), as relevant to the built environment, refers to a regenerative approach to construction processes and systems that improve material use and minimize environmental impact. 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). Currently, the global economy is only 8.6% circular, with most Construction and Demolition Waste (CDW) being recycled or used as backfilling (Wit et al., 2019).

The construction industry has a great potential for adopting CE principles and is a leading sector in this field, and CDW reduction is a priority in most global CE policies (Brambilla et al., 2019; López Ruiz et al., 2020). The focus of CE in the built environment is on utilizing technological advances in design, construction and planning to address the economic and environmental issues of finite resources (Anastasiades et al., 2020; Munaro et al., 2020), the issue of demolition and resulting CDW (Jaillon & Poon, 2014), and increasing sustainability and resiliency in buildings and cities. A CE in the built environment needs to address these issues while contributing positively to economic growth (Lieder & Rashid, 2016; López Ruiz et al., 2020).

An effective circular economy in the built environment can be achieved by implementing a range of strategies in building design and demolition mitigation (López Ruiz et al., 2020). These strategies include reducing the use of materials and extending their useful life, reducing waste production and minimizing carbon production in multiple building life cycle phases. There is a need for facilitating adaptability and reuse of buildings and materials, and to focus on the process of design for disassembly (DfD), design for adaptability (DfA), transformation and reuse as strategies to implement the continual loops of use of resources, products and materials (Stahel, 2016) and design for Modular Construction (MC) that can enable long-term effective building adaptation (i.e. reuse, refurbishment).

The design of the built environment significantly influences reusability and waste generation. Munaro et al. demonstrate that circular economy practices are best adopted for design optimization in early-stage design. They also highlight the important role of policy and life cycle optimization for improving the circularity of the built environment (Munaro et al., 2020). Anastasiades et al. and Hossain et al. suggest the adoption of DfD and DfA, as well as modular and prefabricated construction, are the main strategies for implementing circular construction practices and the continual circulation of building materials (i.e. extension of building service life) (Anastasiades et al., 2020; Hossain et al., 2020). In general, more than half of the total CDW can be reduced by the adoption of prefabricated systems (Jaillon & Poon, 2014; López Ruiz et al., 2020). Computational design tools models can improve the functionality of these designs (Hossain et al., 2020). Design decision-making using brute-force search and Pareto-optimality, are effective means for considering multiple objectives, improving the overall quality and circularity of design decisions.

2.2.1 Residential Building Adaptation

With a sudden increase in population and urbanization at the beginning of the 20th century, housing became a critical issue. Within the utopian ideologies of the period, the multi-family highrise was regarded as an efficient machine for meeting the needs of increasing populations and changing family structures. The balcony's key roles in mass post-war multi-family projects can be summarized as having the aim to articulate a relationship between the individual to the larger collective and a bridge from the private to the public (Koolhaas, 2014). In this period, balconies had gained their reputation for providing fresh air and visibility for the working and middle class. They were regarded as an advantage to the typical residential unit in dense urban environments.

The rise in the balcony in the 20th century was a way for the suburbanization of the urban environment through the replication of the suburban ideals within a dense housing block. In this way, the balcony replaced the typical suburban porch while the open space of apartment neighbourhoods was advertised as a “collective backyard” (Kesik, 2009). The ideas of sun-filled towers with indentations as large outdoor spaces punctured through the building incorporating plants and seating, implying social interactions. Small forms were investigated first by Le Corbusier in L’Immeuble Villa in 1922 (Koolhaas, 2014). By the 1930s, the balcony was recognized as a tool for increasing light, openness, and outdoor activities in modern towers. The balcony was seen to increase the productivity and quality of life of residents. (Overy, 2007).

The 1950s to the 1970’s marked the peak of the predominance of the balcony. In the design of mid-20th century residential towers, decreasing attention was given to the relation between the inside and outside. In highrise housing developments, collective outdoor spaces such as outdoor terraces and gallerias were eliminated and replaced by the balcony as cantilevered projection (Vayssiere, 1988). The balcony’s architectural position in the mid-20th century was reduced to a singular repetitive element and deprived of a relation to other architectural elements, resulting in criticism as an add-on, and devoid of any architectural character. Meanwhile, the balcony was still believed to function as a means for expressing individuality in the changing and automatized society. This expression of the individual and creating relationships between the inhabitants and their cities became a vital new function of the balcony (Bofill et al., 1988).

In the 1950s, the balcony was a common feature of the residential tower in the City of Toronto. From the 1960s to the late 1970s, there was an increase in the popularity in the use of balconies in residential buildings in the region. The use of balconies was minimized in the 1980s and 1990s, 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 included high numbers of towers possessing 40% to 100% of balcony coverage and minimal buildings with no balconies. Similar patterns have been ongoing from the 2000s onwards, with the increase in the city’s condo construction. Towards the middle and end of the 20th century, the fascination with the balcony-clad tower block and potentials of self-expression was quickly replaced with low-income housing ideas favourable to large populations of new immigrants (Harris, 1996).

Within the downtown core, housing guidelines have changed drastically from former requirements of 90% open space (City of Toronto, 2019). The increase in density, variation and flexibility within housing units are seen as a strategy to create multi-faceted and diverse tower neighbourhoods. New infill, providing much-needed housing options for current residents and the city at large, provided both at the grade level or as extensions to the towers, can give better definition and form to the open areas and in-between voids of the tower in the park morphology of tower neighbourhoods. Examples of how building adaptation strategies can improve the overall building include creating extensions to the balconies, as examples of adding density and more flexibility to the existing housing stock (Kesik, 2009).

Currently, most of the 20th-century high-rise concrete towers in Canada have reached the end of their lifecycle in terms of structural integrity and environmental performance. High-rise residential towers are typically rigid in structure, limiting their use and making them prone to obsolescence. During the last decades, limited improvements have been made in structural integrity and environmental performance to the building envelope and balconies of residential towers. Therefore, the obsolescence and redundancy of existing dated residential building stock are identified as critical issues 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 4878 apartments in Canada is spent on space heating (Natural Resources Canada, 2015). Single-family and house alteration and reconstruction are common, with 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). Extending the life cycles of affordable housing stocks and improving their quality and efficiency is essential for improving housing affordability.

Canada has committed to reducing energy use in all existing buildings by 40% before 2050 (Generation Energy Council, 2018). Also, over 450,000 residential units in the City of Toronto's aging multi-family housing infrastructure alone require immediate retrofitting and renovations to prevent demolition, reduce energy use and carbon emissions, and improve occupant comfort. This effort involves advancement in current processes and workflows and methods for automation and optimization, to be able to address the required market in an efficient and timely manner. Dated residential towers house over 1 million residents in the Greater Toronto Area and make up the majority of affordable housing options. More than 22,000 residential units were built within the City of Toronto in 2018, and has increased 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 et al., 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, the ongoing popularity of apartment unit ownership, and the provincial plan for future development (Lehrer et al., 2010; Rosen & Walks, 2015). With shrinking unit sizes and despite the rising expense of cantilevered balcony construction, the balcony remains an attractive feature of dense urban living.

Feasibility studies that determine early-stage design direction, can take a couple of weeks to several months depending on each project's complexity, involve multiple stakeholders and specialists, focus on suitability rather than optimization of options, and can be expensive. Preliminary architectural feasibility studies help clients understand the possibilities for developing a site or the improvement of an existing building, and (1) present possibilities for change or development (considering existing conditions and planning requirements, possible use, setbacks, etc.), (2) determine financial opportunities and merit of the investment (considering potential project cost, ROI, etc.), (3) analyze environmental opportunities (considering energy use and carbon emission reduction, (4) the extension of building life cycle, etc.), (5) and propose high-level design options in response to the completed analysis.

According to the Royal Architectural Institute of Canada, the feasibility cost is 10-20% of the design fee, which is 5.8% of the construction cost (RAIC, 2019). Assuming an average construction cost for a residential tower retrofit project at CAD 17.5M (ERA Architects, 2017), each adaptation project's feasibility study cost will be roughly CAD 100K. There are 3.9M apartment units in Canada that need retrofitting by 2050 (Canada Mortgage and Housing Corporation, 2017). Based on this data, a total of 20,000 buildings in Canada need retrofitting by 2050. The feasibility cost for each building is CAD 100K, leading to a Total Addressable Market (TAM) of CAD 2B in Canada only. US has a population of 327M, almost 10X Canada, assuming a modest multiple of 5X the TAM in North America is CAD 10B.

Through market research and speaking with multiple professionals, the pain-points of architects and engineers related to feasibility studies are as follows: (1) the process is time-consuming because of various stakeholders involved, making decision-making difficult, (2) requires the involvement of many different professionals, making the synthesis of analysis into suitable options difficult, (3) inability to optimize decision-making due to lack of a large enough database, resources and concentrated in-house knowledge, (4) interest in improving existing offerings related to existing buildings but unable to expand due to limited project fees. Meanwhile, building owners, developers and municipalities define their pains as: (1) the feasibility process is time-consuming and complicated, (2) need to understand the feasibility of improvements for a large number of existing buildings in a short amount of time, (3) dealing with limited budgets, requiring optimization of fund allocation.

2.2.2 Case Studies of Residential Adaptation

The following five case studies demonstrate various degrees of the building adaptation strategies. The case study buildings are modelled in 6D BIM for the analysis in later phases of this research. The existing condition, extent of demolition, and new construction have been outlined in Table 2-1. The context and scope of work for each project are described below.

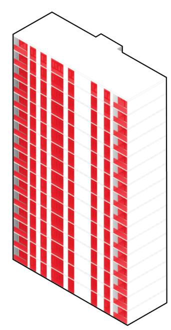
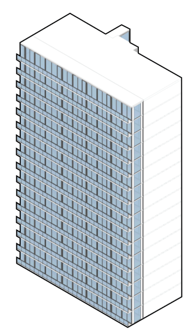
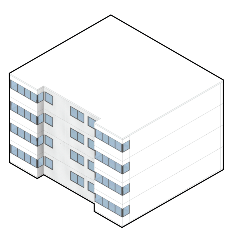
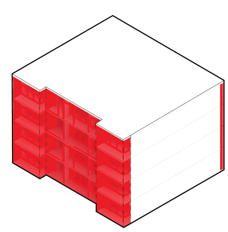
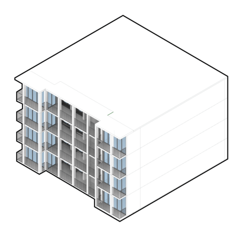
The Ellebo Housing Estate is comprised of collective blocks arranged around a large communal outdoor court. The buildings were built in the mid-20th century, and with refurbishments made in the 1990s, the buildings are still a solid base for adaptive reuse. In the 1990s, performance improvements to the building's envelope and systems were introduced, and the balconies were also enclosed to extend living spaces. The buildings at Ellebo Garden were extended, balconies were added, large portions were re-clad, and glazing was extended. These adaptation strategies have improved the buildings in terms of interior spatial arrangement, connections to the exterior and environmental performance (Fernandez & Mozas, 2013).

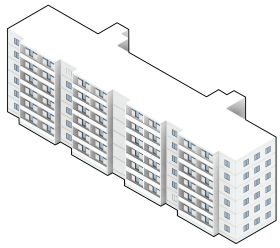
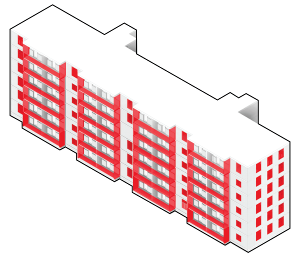
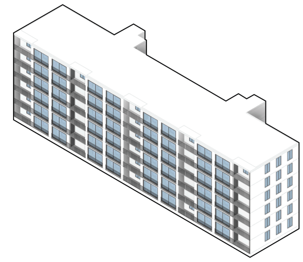
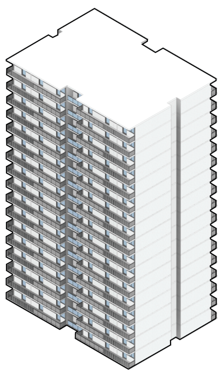
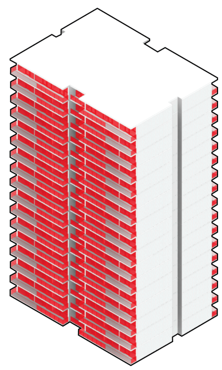
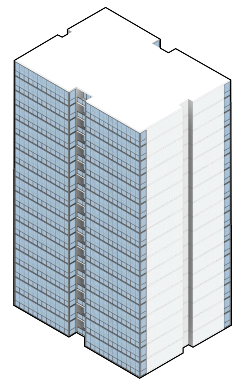
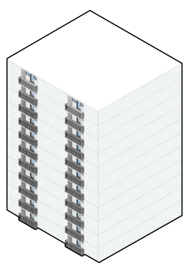
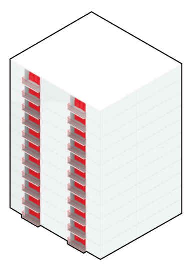
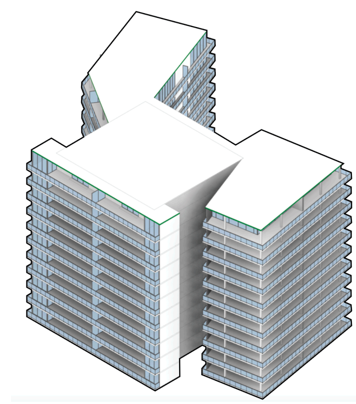
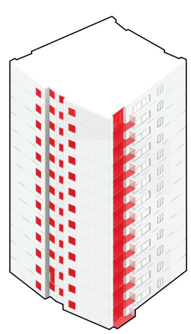
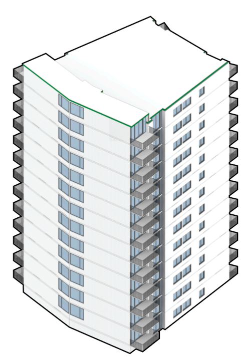
The Weberstrasse tower has been extended in the north by the addition of studio apartments and loft apartments. On the interior, multiple apartments have also been joined to form larger apartments. In this process, balconies have been extended and relocated to make them more suitable for the new apartments. The adaptive reuse strategies implemented include the extension of the building, adding and relocating balconies, re-cladding and extension of glazing (Batthyany & Shramm, 2013).

The Block G, H, I project was completed as a part of a more extensive development to transform existing inhabited social housing buildings in Bordeaux, France. The existing buildings were built in the early 1960s, and house 530 dwellings. In the adaptation and extension of this project, winter gardens and expanded balconies were added to improve the overall quality of each unit in terms of improved building envelope, light, use and views. This project was successful in terms of physical and economic transformations to existing buildings, while transforming them to suitable and desirable living units with improved environmental and comfort performance and context relevance. The adaptive reuse strategies implemented include extension, addition and layering the balcony, and re-cladding and extension of the glazing (Lacaton et al., 2011).

Le Chesnaie highrise state is a highrise complex in Saint-Nezaire designed in the 1960s. The buildings were dated and highly prone to demolition and were restructured to accommodate the well-preserved solid construction, the building's inhabitants, and plan for its future. The adaptive reuse strategies implemented at Le Chesnaie include the extension of the building, adding balconies to the existing and the extension of existing glazing (Lacaton et al., 2011). A layer of exterior spaces is added to the existing building to improve the existing units' spatial quality. Each unit is extended by a new balcony, protected by a glass enclosure. Operable glass panels at each balcony and the roof panels can open up the winter gardens for ventilation and better connection to the communal court. The adaptation strategies implemented include extension, addition and layering the balcony, and re-cladding and extension of the glazing (Hughes, 2013).

Table 2-1: Complex residential refurbishment and adaptive reuse strategies demonstrated in the existing phase, scope of demolition and the refurbished building including retrofitting, adaptive reuse and new construction scope.

Case Studies	**Existing Building**	**Scope of Demolition**	**Retrofit/ Adaptive Reuse/ New Addition**
Case Study 1: Block G, H, I, Lacaton & Vassal, Bordeaux, France **Original Construction:** 1950s **Adaptation:** 2016 **Original Function:** Inset Balconies **New Function:** Layered Balconies			
Case Study 2: Ellebo Garden 1, Adam Khan Architects, Ballerup, Denmark **Original Construction:** 1950s **Adaptation:** 2020 **Original Function:** No Balconies **New Function:** Added/ Extended Balconies			

Case Study 3: Gruentenstrasse, Lattke Architects, Augsburg, Germany **Original Construction:** 1966 **Adaptation:** 2013 **Original Function:** Cantilevered Balconies **New Function:** Added/ Inset Balconies			
Case Study 4: Piazza-Flat, A3 Architects, Gorinchem, Netherlands **Original Construction:** 1975 **Adaptation:** 2009 **Original Function:** Cantilevered Balconies **New Function:** Added/ Enclosed Balconies			
Case Study 5: Le Chesnaie Tower, Lacaton & Vassal, Saint-Nezaire, France **Original Construction:** 1950s **Adaptation:** 2016 **Original Function:** Inset Balconies **New Function:** Added/ Extended Balconies			
Case Study 6: Weberstrasse Tower, Winterthur, Switzerland **Original Construction:** 1960s **Adaptation:** 2009 **Original Function:** Cantilevered Balconies **New Function:** Added/ Relocated/ Extended Balconies			

2.2.3 Building Adaptation Feasibility Analysis

In a traditional building adaptation feasibility and early design process, many uncertain factors need to be examined. Project requirements, including budgets, timelines, spatial requirements and performance benchmarks, are taken into account. The analysis of the building's existing conditions, including building geometry, overall condition, and areas for improvement, are also considered. Preliminary design options are developed by the design team and often analyzed by various consultants that can include energy consultants, LCA consultants and cost consultants, as examples. The design team and specialty consultants go through an iterative process to develop suitable design options, and the results are shared with the client for feedback. This process can take many months to complete depending on project complexity, often leading to suitable, non-optimal design options **Figure 2-1**.

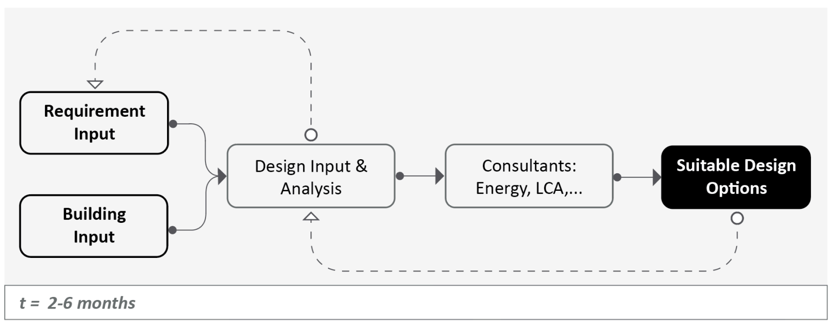


Figure 2-1: Traditional Design Methodology

The extended timeline for the building adaptation feasibility process cannot meet the increasing demand due to key aging urban building stock, requirements for improved energy efficiency and spatial quality, and construction and demolition waste mitigation. For example, more than 3000 residential towers were built between 1950-1990, accommodating more than 65% of middle- and low-income communities, as the primary source of affordable housing in Ontario (Smetanin et al., 2019). These buildings were built with low energy standards and have reached the end of their useful life and require adaptation at different scales. In 2019, a ten-year CAD 1.3B co-investment fund was set up for Toronto Community Housing Corporation (TCHC) for adaptation, including retrofitting and rehabilitation. Still, only 21 buildings out of the 2100 TCHC buildings were adapted in 2019 (Pelley & Lee-Shanok, 2019). In addition, in building adaptation design processes, future adaptability and reusability for improving the built environment's resiliency and circularity are often not considered, which can be addressed using modular construction.

2.2.4 Design Option Assessment in Building Adaptation

To address sustainability concerns in construction and emerging technologies, building professionals can evaluate more design alternatives than in the past (Clevenger & Haymaker, 2011). As argued here, they may not evaluate enough alternatives. Integration of systems thinking, requiring designers to consider the entire systems, component and the relationships in the design process, and the simultaneous consideration of multiple attributes instead of an exclusively reductionist approach while leading to sustainable designs (Blizzard & Klotz, 2012) has contributed to this potential increase. One challenge in practice is implementing unfamiliar design options that can introduce levels of risk, including cost increases and difficulty with permit processes as examples, and designers typically consider design strategies based on pre-determined principles, often overlooking unfamiliar strategies (Y. C. Liu et al., 2003). A satisfactory design strategy is an integrated response to a series of diverse issues, which are often a result of uncertainties about design objectives and priorities (B. Lawson, 2006). Therefore, it is necessary to understand the importance of design management (Austin et al., 1999) and to optimize amongst conflicting objectives in complex building projects.

Ideally, conceptual design processes go through the two steps of diverging and converging, through which alternative design concepts are generated and then evaluated and distilled. The generation of a wide range of design strategies is aimed at considering all valuable concepts. The evaluation and restricting of design strategies in the second step aim to enable meaningful consideration of design decisions (Y. C. Liu et al., 2003). After generating a large pool of design strategies, selecting evaluated strategies for further consideration is essential for making sure they can be further evaluated and considered in a meaningful manner. There are many frameworks developed for the generation and narrowing down of design concepts. These include Cross and Pugh's work, highlighting that the number of divergent strategies needs to be decreased to one-to-few solutions by the end of the design stage (Cross & Roy, 1989; Y. C. Liu et al., 2003; Pugh, 1991). This idea is based on the premise that designers should be equipped to develop the broadest possible range of concepts in a short amount of time. Also, they need to evaluate and modify strengths in each strategy to achieve better results.

Researchers have developed approaches to improve the process and breadth of design option assessment in building adaptation projects to accomplish these goals. Recent studies on building adaptation option appraisal are analyzed using analysis methods, cases, and strategies deployed. Tokede et al. investigate the effects of applying strategies of airtightness, insulation and smart metering for variations of an office building. Variations in the base-case considered include setting, expanding, relocating and retrofitting. Strategies for analysis include life cycle appraisal and net present value analysis for evaluating the success of the various strategies in different building iterations (Tokede et al., 2018). Chidiac et al. focused on analyzing three wall constructions, including brick veneer and concrete construction and building height with a range of 2 to 12 meters. Energy modelling was used to measure lighting systems and HVAC's effect on each case considered (Chidiac et al., 2011).

Asadi et al. used multi-objective optimization and energy modelling on a single base case to determine the effects of varying window types, wall insulation, roof insulation and addition of a solar collector (Asadi et al., 2011). Wang et al. used multi-objective optimization, energy modelling and life-cycle analysis to analyze a single base case with eight scenarios of varied budgets ranging from $60k to $250k. Strategies of lighting, HVAC and smart controls were used on each of the cases to determine feasibility (Wang et al., 2014). Fotopoulou et al. used energy modelling on a single base case in 3 different climates. They aimed to determine the success of wall insulation, window replacement, the addition of a sunspace and a double-glazed façade on the performance of buildings in each climate (Fotopoulou et al., 2018). Nydahl et al. used LCA to determine the effects of 6 strategies compared to the base case in a two-storey residential building. The strategies were analyzed using HVAC, re-glazing, insulating and renewable energy (Nydahl & A., 2019). Ardente et al. (2017) examined six different buildings compared to their base cases for the addition of insulation, re-glazing, HVAC retrofits and the addition of renewables. Life cycle analysis and processing of existing energy use data were used to determine strategies' success (Ardente et al., 2011).

Table 2-2: Selection of Building Adaptation Option Appraisal Studies – demonstrating different numbers of analysis methods, analysis cases and strategies investigated.

Authors	**Analysis Method Considered**	**Strategies**	**Analysis**	**Building Typology Considered**	**Compared with the Base Case**	**Climate Analyzed**	**Major Results**
(Tokede et al., 2018)	Life Cycle Appraisal, NPV	Contracting, Expanding, Reconfiguring, Retrofitting of Base Case	- Airtightness, insulation, smart metering system	Office Building	No	UK	*- None of the four strategies can return the investment over 20 years.* *- Insulation-focused adaptive reuse strategies have the most promising cost-saving in office buildings in the UK.*
(Chidiac et al., 2011)	Energy Modeling	12 storey brick veneer and concrete, two-storey brick veneer,12 storey curtain wall	- Lighting System, HVAC	Office Building	Yes	Ottawa, Edmonton, Vancouver	*- Considering multiple strategies in a building retrofitting is essential for reducing energy use.*

(Asadi et al., 2011)	Multi-objective Optimization, Energy Modeling	Base Case, - Window type, Wall insulation, Roof insulation, Solar Collector	- Insulation, Renewable energy	2 Storey Residential House	Yes	Portugal	*- Development of models, including multi-objective mathematical models investigated in this research, can support decision making in the evaluation of building retrofit strategies.*
(Wang et al., 2014)	Multi-objective Optimization, Energy Modelling, Life Cycle-Cost Assessment	Base Case with 8 Scenarios of Varied Budgets ($60k - $250k)	- Lighting, HVAC, Smart Controls	Generic	No	South Africa	*- Considering the combination of retrofitting strategies enables the implementation of cost-effective and efficient adaptive reuse projects. - Life-cycle cost analysis can lead to a substantial analysis of retrofitting strategies.*
(Fotopoulou et al., 2018)	Energy Modeling	- wall insulation, window replacement, sunspace, double glazed facade	Base Case in 3 climates (Bologna, Athens, Riga)	Residential Tower	Yes	Multiple (Europe)	*- Energy savings are significant in the winter in southern climates, while northern climates show increased savings in the summer. - Balcony additions are effective in reducing energy use and are successful in improving the formal qualities of dated buildings.*
(Nydahl & A., 2019)	Life Cycle Analysis	Base Case with 6 Scenarios of strategies in 3 Climates	HVAC, re-glazing, insulating, renewable energy	2 Storey Multifamily Residential	Yes	Sweden, Poland	*- Retrofitting windows resulted in considerable improvement in operation energy.*
(Ardente et al., 2011)	Life Cycle Analysis, Processing Energy Use Data	6 Different Buildings' Base Case and Adaptive Reuse Case	Insulating, Reglazing, HVAC, Renewable	Public Buildings	Yes	Multiple (Europe)	*- Improvements to the building envelope, including thermal insulation and efficient windows, had the most significant effect on reducing energy use and lowering GWP.*

Analyzing this research foundation indicates that life cycle appraisal, energy use and costing are the most common analysis methods. It can also be observed that most studies have analyzed multiple cases. These can include similar cases in various climates (Ardente et al., 2011; Fotopoulou et al., 2018; Nydahl & A., 2019), different construction methods and building sizes (Chidiac et al., 2011), and various budgets (Wang et al., 2014). While there is variety in the type of base-case and strategies analyzed, there is an indication of a lack of clarity in selecting metrics.

In any building adaptation project, the decision-making process is concerned primarily with selecting the appropriate refurbishment or adaptive reuse strategies through selective criteria (Brandão de Vasconcelos et al., 2016). With the increase in the importance of building adaptation projects, and adaptive reuse projects specifically, there has been an increase in studies focusing on analyzing the performance and benefits of various adaptation strategies. Through analysis of state-of-the-art on retrofitting projects specifically, Ma et al. (2012) illustrated a three-step decision-making phase of pre-retrofit planning, retrofit implementation and post-retrofit verification. Pre-retrofit activities primarily consider strategies for determining if an adaptation project is suitable. After a retrofit project is identified as a suitable alternative to demolition and new construction within pre-retrofit planning, identifying possible retrofit measures and prioritizing measures are suggested based on energy simulation, risk assessment, and cost-benefit analysis (Ma et al., 2012).

2.2.5 Design Optimization Metrics

Design optimization is the process of considering and evaluating design alternatives that impact the overall performance of a design. Energy use, life cycle impacts, and structural efficiency are important factors in evaluating a design strategy's success and can be considered adequately in the early stages of design. Mathematical optimization in building design has been applied extensively in literature to evaluate cost, energy use and thermal comfort (Aparicio Ruiz et al., 2014; Hamdy et al., 2013; Pal et al., 2017). Eleftheriadis et al. also demonstrated that optimizing structure and interior layouts in early-stage design for life cycle impacts can reduce carbon emissions by 10-50% and improve cost performance by 2-5% (Eleftheriadis et al., 2018). Ghisellini & Ulgiati suggest the superiority of building adaptation, specifically refurbishing, as an alternative to new construction while suggesting that a framework for integrating LCA and LCC and optimizing the design decision making process for building adaptation projects is required (Ghisellini & Ulgiati, 2020).

2.3 BIM Simulation Tools

2.3.1 Building Information Modeling

BIM (Building Information Modeling) is a method for design, documentation, and performance analysis of structures and systems. BIM models are also used for optimization and data visualization of building data. Benefits of BIM include interoperability of software, resulting in high levels of flexibility and adaptability in the way stored building element information and data can be used (Pezeshki & Ivari, 2018). BIM processes are also beneficial in design and construction processes enabling improved collaboration and cooperative working measures, increased productivity, and precision. Improved efficiencies achieved through clash detection, costing accuracies, and accelerated design and documentation processes are also notable benefits. Lastly, interactive simulation and analysis abilities in all project stages are important benefits of BIM-enabled processes (Chi et al., 2015; Porter et al., 2018).

Improved collaboration in the design process is mainly achieved by the seamless integration of various parties involved and the consolidation of their efforts. Highly integrated processes in BIM enable the identification of problems and gaps in development in preliminary design stages. This process reduces risks, duplication of work, and allows the preliminary stages' distribution of efforts with more efficiency in the final documentation of solutions (Bueno et al., 2018). Limiting data duplication, redundancy and improving precision also enables analytical tools (Pezeshki & Ivari, 2018). The benefits result in BIM and its connected tools to be an ideal means for architectural, structural and systems design optimization, visualization, cost estimation, code review, fabrication documentation, construction management, conflict detection, occupancy and facilities management, as well as end of life recycling and waste management (Chi et al., 2015).

2.3.2 Simulation

Accurate performance simulation and scientific visualization are challenging tasks as they require multi-disciplinary skills (Regt, 2014). While any simulation tool is based on specialized knowledge, their accessibility and ease of integration bring great value when used in a project's design and analysis stages. Simulation tools are most useful when multiple parameters are analyzed simultaneously to contribute to optimized design decisions. Feedback regarding design decisions in the pre-construction stage, and analysis of building performance in the occupancy stages, helps designers, architects, and engineers better understand the designed environment and its performance (Peters, 2018).

With advancements in analysis tools regarding quantity, accessibility and interoperability, feedback regarding various performance parameters are becoming increasingly dependable (Peters, 2018). Energy, lighting, acoustic, heat and air flow studies can inform the impact of design projects on occupants and the environment. Structural, code, cost, and constructability analysis can also help designers make informed decisions (Peters & Peters, 2018). The simulation calculation comprises a series of computations of mathematical equations that studies the system under given circumstances, often over a period of time (Sokolowski & Banks, 2009). To complete a simulation, the key steps are accurate modelling, simulations calculations, visualization, and data analysis. The model itself is primarily a representation used to analyze and understand the parameters being studied. The model must also create an abstraction of environmental and contextual realities to be used in the analysis.

2.3.4 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 (S. Chen, 2018; Krygiel, 2008). BIM and BPS processes are being increasingly integrated to analyze and predict various performance measures while communicating through images and analyzed data. Simulations evaluate and analyze various performance metrics to advance understanding regarding the multiple factors influencing design and facilitate optimized decision-making (Attia et al., 2012; Peters, 2018). The integration of simulation tools with BIM in this manner is beneficial from preliminary stages of a design process (S. Chen, 2018).

BIM integration with BPS has been made possible through easy exchange between BIM software and simulation tools. For example, Autodesk Revit® includes built-in BPS software and multiple plug-ins 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 and daylighting analysis. Autodesk Revit® also hosts other simulation plug-ins, 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 plug-ins that allow a seamless flow of data between Autodesk Revit® and their tools. In this process, the plug-ins easily communicate geometric and contextual data to simulation engines, and analysis results are either transferred back and visualized in the BIM software (S. Chen, 2018) in the case of Autodesk CFD®. Alternatively, they are housed and organized as iterations on the cloud, in the case of Sefaira®.

The application of simulations in BIM includes the ability to find relationships, map similarities and differences, and to 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. There have been increasing efforts in improving the integration, interoperability and communication of simulation tools. Burrohapold is developing a tool for

McNeel's Rhino® Grasshopper® as a "Smart Building Analyzer" that can simulate and analyze energy use, thermal comfort, daylighting, acoustics, security, safety and circulation simultaneously. Through simulation and visualization, and working at a multi-disciplinary 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 the development of comprehensive tools that, aside from measuring energy and carbon, can also predict occupant-centric measures, including productivity, health, and well-being. 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 the ability to customize codes, allow users' participation in the development and customization of tools within BIM (Azhar & Brown, 2009; Peters, 2018; Sinha et al., 2013).

2.3.5 Energy Use

Energy assessment tools integrated in BIM software can facilitate optimized environmental decision-making in initial design stages. It is the most efficient time to make good sustainable decision-making (Azhar & Brown, 2009). BIM tools incorporate comprehensive data regarding a building's geometry, systems information, materials, environmental and contextual data required to analyze overall performance (Azhar & Brown, 2009; Bueno et al., 2018). This facilitates limited time investment, efforts and skills required to carry out simulations (Barrett et al., 2013; Bueno et al., 2018). Since BIM can process, analyze, visualize and share multidisciplinary information, it has proven to be a useful tool for verifying and optimizing thermal performance in buildings (Natephra et al., 2017; Sinha et al., 2013).

In energy simulation, a reliable thermal engine for computational calculation of heat flow is key. EnergyPlus® is an energy calculation engine validated by the US Department of Energy. It uses detailed geometric information to confirm accuracy of resulting calculations (Mackey, 2015). Sefaira®, as well as Ladybug® and Honeybee® plugins for Rhinoceros® Grasshopper®, create understandable visualizations and interfaces to interact with the EnergyPlus® engine (Roudsari et al., 2013).

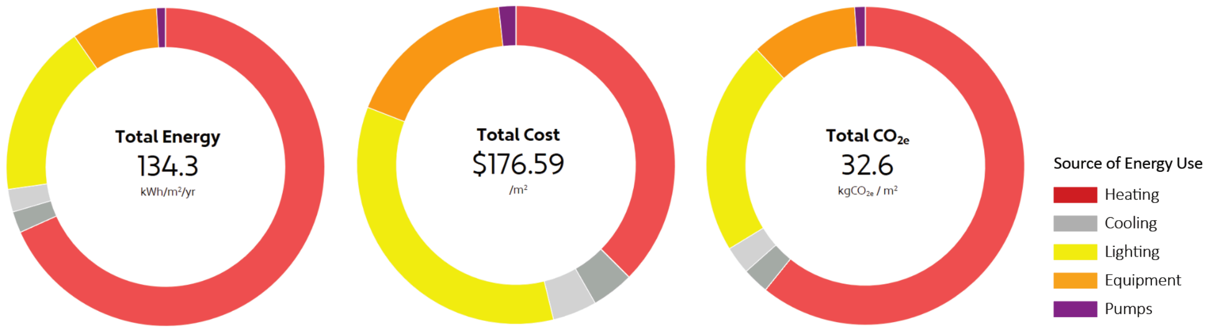


Figure 2-2: Energy Use Simulation for Existing Base Case Building – Autodesk Revit® and Sefaira®

2.3.6 Thermal Comfort

Thermal comfort is defined by ASHRAE Standard 55 as an occupant satisfaction measure determined by state of mind, and as the calculation of balance of heat transfer energy (ASHRAE, 2017). The heat generated by occupants and relative humidity and occupant clothing insulation levels are balanced against heat transfer contributions by conduction, radiation and convection (Fanger, 1970). Thermal comfort is influenced by physical building parameters as well as occupant physiological and psychological influences. The main factors that affect thermal comfort include air temperature, relative humidity and air velocity, and metabolic rate and clothing (Natephra et al., 2017).

Thermal comfort calculation follows two different methodologies based on the physical laws involved in human energy balance. The second takes statistical correlations between collected occupant data to predict comfort levels. Thermal comfort calculations are typically expressed in terms of the percentage of time occupants are comfortable measured by Predicted Percentage of Dissatisfaction (PPD). Predicted Mean Value (PMV) predicts comfort levels based on occupant votes across various thermal sensation measures. PMV uses poll testing, and Adaptive Models use extensive occupant surveys to determine analysis models. Autodesk CFD® uses the PMV model to calculate thermal comfort, and Honeybee® for Rhinoceros® Grasshopper® uses the adaptive model. Adaptive thermal comfort models used in this research, embedded in Honeybee® tools, are focused on passive design strategies, including the consideration of natural ventilation, solar gain and thermal mass calculations (Mackey, 2015). **Figure 2-3** demonstrates thermal comfort temperatures for various times of the day.

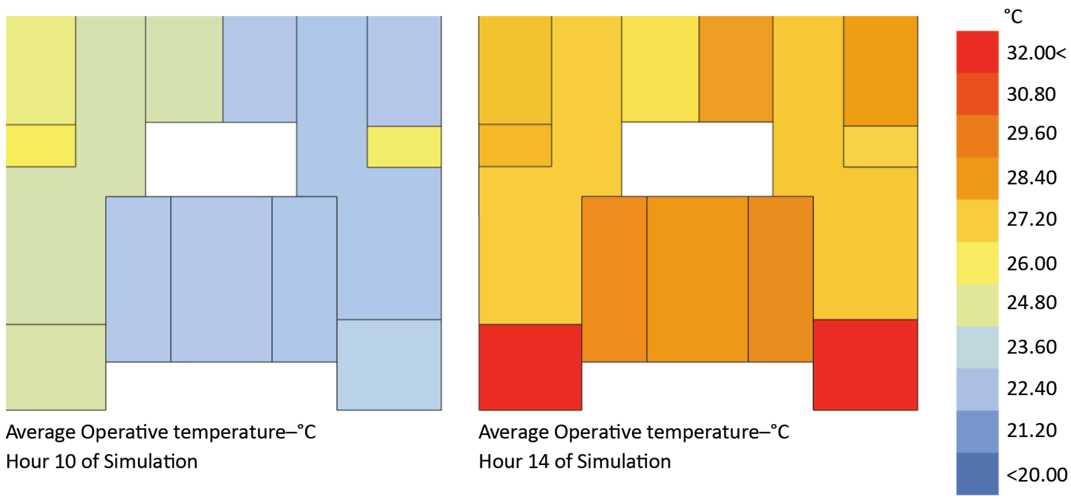


Figure 2-3: Thermal Comfort Simulation for Existing Base Case Building Honeybee® Plugin for Grasshopper®

2.3.7 Ventilation – CFD

Computational Fluid Dynamics (CFD) is useful in analyzing buildings' ventilation due to its ability to simulate fluid flow in between complex geometries (Porter et al., 2018). CFD is a branch of fluid mechanics used to analyze and solve problems involving fluid flows. It is applicable in architecture, urban planning, and environmental engineering for understanding air flow in the environment (Blocken et al., 2009). Air movement in naturally ventilated buildings is typically a result of density due to variations in temperature. In internal ventilation, the combination of ambient air through interior openings and exterior openings causes buoyancy-driven natural ventilation. CFD models help in simulating and communicating these flows. While many researchers and practitioners subcontract the CFD simulations to consultants or specialists, this slows down the design process and does not provide the process's interactivity. BIM models are useful starting points for complicated calculations, such as CFD calculations. Recent attempts in integrating CFD within existing BIM software has made CFD more accessible to design professionals (Fukuda et al., 2015; Kaijima et al., 2013). **Figure 2-4** demonstrates airflow patterns in a typical unit in the base-case building and highlights significant points of airflow between different rooms and from the outside.

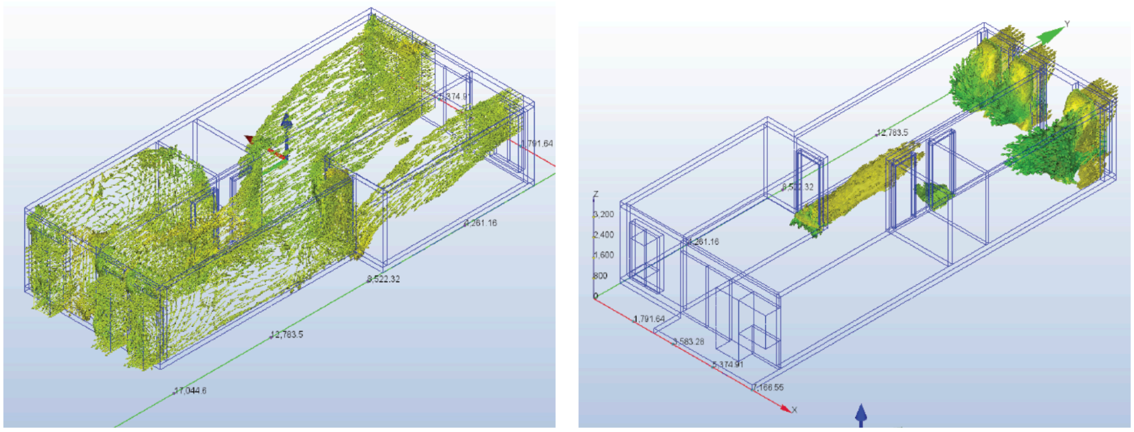


Figure 2-4: CFD Simulation for Existing Base Case Building Autodesk Revit® and CFD®

2.3.8 Daylighting

Daylighting plays a vital role in environmental performance and occupant comfort in buildings. Many available simulation tools analyze daylighting performance in buildings. They can help make data-driven decisions and communicate decisions with stakeholders and clients through effective visualization (BWBR, 2014). CAD environments are commonly used to convert geometry information to daylighting models for simulation. BIM software has embedded capabilities for daylighting analysis and has overcome the inefficiencies of converting geometry from CAD software to simulation engines by using accurate and embedded information. BIM software simplifies geometry and mainstreams the communication of data in daylighting analysis.

An example of this is with Radiance® and DAYSIM® daylighting engines that are embedded within Sefaira®, a plug-in for daylighting analysis within Autodesk Revit®. Since no geometry alterations are required within these BIM tools, real-time analysis becomes more effective (Kota et al., 2014). Through this plug-in, information from BIM is transferred in real-time within the one tool, and various metrics, including Spatial Autonomy (SA) and Annual Sunlight Exposure (ASE), are analyzed simultaneously (BWBR, 2014). In **Figure 2-5**, the number of hours receiving adequate daylight amount and distribution are portrayed in a sample simulation.

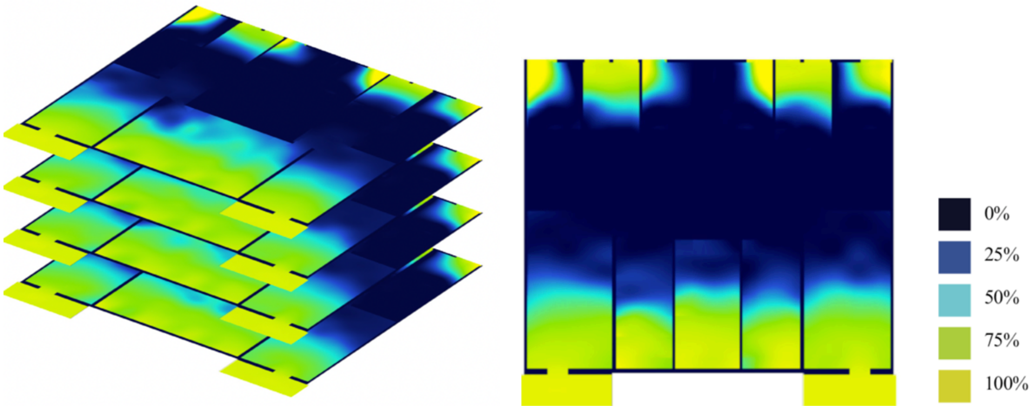


Figure 2-5: Daylighting Simulation for Existing Base Case Building – Autodesk Revit® and Sefaira®

2.3.9 Systems

Integrating HVAC simulation to optimize building performance early in the process is important for evaluating design options. Sefaira Systems®, an example of a systems simulation software integrated with BIM, optimizes designs and provides accurate simulations using EnergyPlus® engines and detailed HVAC templates. Simulating, analyzing, and comparing the performance of HVAC and systems design can begin to justify optimization of building form, envelope systems, and HVAC sizing, leading to reduced cost of operations and allows for the optimization of building performance from early on. Other benefits of systems simulation include integrating space requirement information and the implication of HVAC systems early in the design process (Sterner, 2015). **Figure 2-6** shows heating, cooling, heat rejection and air handling simulation of a sample simulation.

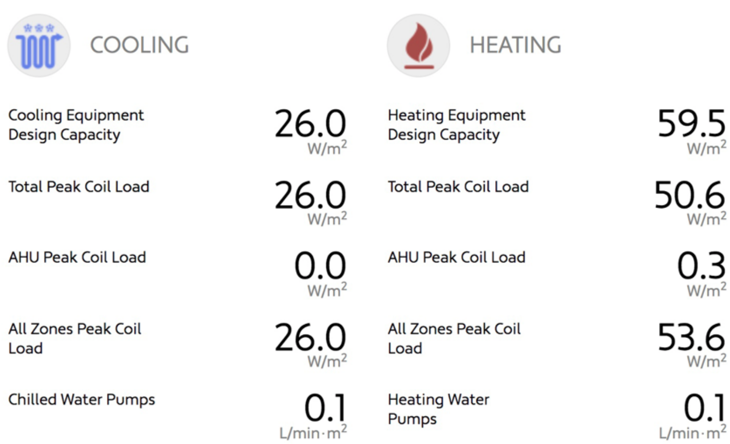


Figure 2-6: Systems Simulation for Existing Base Case Building – Autodesk Revit® and Sefaira®

2.3.10 Life Cycle

BIM can be used to conduct accurate Life Cycle Analysis (LCA) and help better understand the life cycle of projects in the design, construction, maintenance, and operation stages of a building (Jeewoong Park et al., 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). Many LCA tools for BIM effectively overcome these challenges and are validated for accuracy, including GaBi® and Tally®, amongst others (Wu & Issa, 2015). Tally® is an integrated tool within Autodesk Revit®. 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.

Cost estimation is typically conducted by taking manual takeoffs from drawings or input information into customized cost estimation software. Aside from the potentials for human error and redundancy of information, this can be costly and time intensive. Quantity takeoffs, material information, counts and measurements can be readily extracted from a BIM model. In this process, the cost estimate will be live and responding to design changes. The two significant strategies into which information can be categorized in BIM for costing include material takeoffs, enabling the pricing of materials, and tallying building elements. This allows categorizing elements and the collective cost of their embedded materials (Pezeshki & Ivari, 2018).

The embedded information of materials, quantities, and construction of a BIM structure enables the categorization of this data and cost estimation. This makes cost estimation more accessible to designers and engineers involved in the project. Within BIM, embedded information and workflows enable free and accurate cash ow analysis, quantity takeoffs, cost estimating, cost forecasting and scheduling (Hwang et al., 2012; Kim & Grobler, 2013; Pezeshki & Ivari, 2018). Calculation of maintenance costs and facility expansion can also be incorporated within BIM for life cycle costing (Oskouie et al., 2012). Equations for cost estimation can be combined with an automatic collection of quantity and geometric data from a building. Therefore, it can be automatically updated as a live representation of the cost information (K. Liu et al., 2013).

2.3.11 Constructability

Constructability is defined as the evaluation of a design and its overall requirements in terms of ease of construction. Constructability of a building can be improved by optimizing the design, planning, and construction (Zhong & Wu, 2015). Constructability can be evaluated in terms of challenges that can increase project time and budget (Sidwell, Francis, 1996). Problems leading to lowered constructability include exceeding time and cost, duplication of time and resources, lack of integration of various disciplines involved, and information exchange. BIM can improve the lack of proper information exchange and enhance relationships between the design and construction industries, significant contributors to constructability (Kordestani Ghaleenoe et al., 2017).

Constructability can be evaluated based on standardization, simplicity in construction and integration of elements. Standardization of building elements, including component sizes, connection details and layout, can be a lead indicator of constructability. Secondarily, constructability can be measured by determining the simplicity in construction systems and installation requirements. Lastly, the possibility for integration and combination of multiple elements together in a single element for facilitating pre-fabrication, factory construction and ease of installation on site are measures for determining constructability. Examples include pre-cast concrete external walls, curtain walls, or pre-fabricated parts of a building such as pre-fabricated wet units in the residential context (Zhong & Wu, 2015).

Improvements in the performance of buildings can be achieved by considering the parameters for improving constructability in the preliminary stages of a project using BIM (Zhong & Wu, 2015). Through BIM, constructability can be optimized through new modes of communication and fabrication. Identifying repetition, duplication, the number of variants, and clash detections are embedded tools within BIM that can facilitate evaluating the constructability of a given design. Levels of standardization, the number of various components, types of construction and details can be readily identified, scheduled and quantified in BIM. The difficulty of construction, through initial assessment of detail requirements and error detection and identifying possibilities for pre-fabrication and integrating systems coordination for this process, are possible within BIM (Mostafa et al., 2018).

2.4 Knowledge Gap

There is a lack of a clear and consistent use of building adaptation terms and project scope definition observed in the literature, leading to costly confusion in academia and industry. Most decision-making regarding the planning, design and construction of building adaptation projects is limited to the experts in the field and experience with the status quo. Further, it has been demonstrated in the preceding review that a limited number of adaptation strategies are considered for assessment in the literature and practice, and assessment is typically narrowly based on energy use improvements such as increased insulation, new windows and integration of renewable energy. In this review, the importance of building adaptation design appraisal and early-stage design optimization has been highlighted. It can be summarized that there is also a lack of a methodology that considers a comprehensive range of design strategies and analyzes them simultaneously for multiple objectives.

A comprehensive definition framework can be used as a reference for future researchers and practitioners to clearly and consistently define the scope of work in their building adaption projects. To address gaps regarding design option appraisal in practice and theory, a decision-making framework must be developed for supporting generation, evaluation and selection of multiple conceptually orthogonal design options as a basis for future computational design optimization and detailed design. A decision-making framework for supporting generation, evaluation and selection of multiple conceptually orthogonal design options can address the gap in practice and theory and serve as a basis for future computational design optimization and detailed design. Integration of physics-based simulation tools have been identified for improving the early-stage decision-making process. Currently, no formal and structured process exists for evaluating, quantifying, and comparing environmental, life cycle and financial benefits of building adaptation design. The development and adoption of a clear and consistent definition framework can avoid the high costs arising from codes, specifications, and project descriptions that confuse these definitions. The metrics for decision-making of adaptive reuse are also understudied.

3. A Definition Framework for Building Adaptation Projects

OVERVIEW

Building adaptation encompasses a range of construction activities that improve existing building conditions and extend the effective lives of buildings. The scopes of building adaptation projects vary, and may include rehabilitating failing structures, improving environmental performances, and changing functional uses. In order to address multiple aspects of building adaptation, different terminologies are used in the literature and in practice, including refurbishment, retrofitting, rehabilitation, renovation, restoration, modernization, conversion, adaptive reuse, material reuse, conservation, and preservation, amongst others. These terminologies are often used interchangeably with overlapping definitions, causing a lack of clarity in the addressed scope of work. An extensive literature review of terminologies related to building adaptation was conducted and the most common and applicable terminologies were identified. Recent definitions, applications, and scope for the identified terminologies are reviewed. Based on this classification, a definition framework is developed enabling precise categorization of building adaptation projects, and application is demonstrated in multiple case studies. The proposed definition framework is a valuable reference for future researchers and practitioners to clearly and consistently define the scope of work in their building adaption projects, and thus avoid the high costs arising from codes, specifications, and project descriptions that confuse these definitions.

3.1 Introduction

Many aspects of building obsolescence affect the quality and performance of a building after its useful life. These include reduced environmental, economic, functional and social performances (Langston et al., 2008; Ren et al., 2015). A building facing obsolescence is often economically unsustainable, has low occupant comfort and satisfaction, and has increased energy use and water consumption. Responsive, appropriate and timely building adaptation and renewal are essential in extending a building's effective life span. Building adaptation can provide considerable environmental, social and economic benefits, making it a sustainable alternative to demolition and new construction (Conejos et al., 2013; Noorzalifah & Kartina, 2016).

Adaptation of existing building stock can lead to a reduction of waste material, preservation of natural resources, improvements in energy use and carbon emissions, as well as the preservation of embodied energy in comparison to demolition and new construction (Yung & Chan, 2012). Adaptation projects can also improve the quality and comfort of existing buildings, leading to occupant satisfaction as well as preservation of cultural and social values of historical buildings (Chan et al., 2015c; Remøy & Wilkinson, 2012). Building adaptation is typically less expensive than demolition and new construction and can improve the economic viability of dated buildings (Chan et al., 2015b; Langston et al., 2008; Shipley et al., 2006; Wadu Mesthrige et al., 2018a).

The scope of building adaptation projects can be broad and varies between each project. Scope variations are due to many factors, including type and scale of buildings, existing conditions and requirements for adaptation, and construction activities conducted during these projects (Thuvander et al., 2012). Many different terminologies are used in the literature and in industry to specify the scope of building adaptation projects. The variability in the definition of building adaptation projects is a reflection of the broad scope of these projects. Some of the terminologies often used to describe aspects of building adaptation include refurbishment, retrofitting, rehabilitation, renovation, restoration, modernization, conversion, adaptive reuse, material reuse, conservation, and preservation, amongst others. These terminologies are often used interchangeably due to overlapping scopes and lack of clarity for their appropriate uses (Douglas, 2006). There are many examples in the literature that refer to similar adaptation projects in terms of type, scale, and construction, but use different terms to describe the adaptation scope. For example, Passer et al. (2016) and Zaragoza-Fernandez et al. (2014) use the terms refurbishment and rehabilitation, respectively, to describe window replacements and insulation improvements in existing buildings (Fernández et al., 2014; Passer et al., 2016).

The objective of this chapter is to develop a definition framework that avoids costly confusion by enabling clear and consistent use of building adaptation terms based on the characteristics and scope of each project. The proposed definition framework can be used as a reference for future researchers and practitioners to clearly and consistently define the scope of work in their building adaption projects. It is acknowledged that the adoption of a clear and consistent definition framework can avoid the high costs arising from codes, specifications, and project descriptions that confuse these definitions.

To achieve this objective, this chapter first identifies the most common terminologies relating to building adaptation projects, investigates their definitions, and categorizes them based on their applications. An extensive literature review of terminology related to building adaptation is conducted and the most common and applicable terminologies are identified. The identified terminology includes building refurbishment, retrofitting, rehabilitation, renovation, adaptive reuse, conversion, and material reuse. Literature review on the identified terminology is conducted using published peer-reviewed journals and conference papers from 2015 to the present.

An overview and definition breakdown for each term is provided. The typical scope for each term is identified, and common strategies are demonstrated along with examples of their application. Our findings suggest all building adaptation projects can be divided into the two major categories of refurbishment and adaptive reuse. These two major categories are further broken down into several subcategories including retrofitting, rehabilitation, and renovation for refurbishment, and building conversion and material reuse for adaptive reuse. The definition framework is developed using this categorization. Several case studies of building adaptation projects are used to validate the framework through functional demonstration.

The remainder of this chapter is structured as follows. Section 2 describes the research methodology and the results of the literature analysis. In section 3, the results of building adaptation project categorization, the definition of various terms, and the developed definition framework are presented. The function of the definition framework is presented in section 4 by conducting a case study analysis. Lastly, section 5 concludes with the key results of this study, research limitations, and lessons learned.

3.2 Literature Review Methodology

The literature review methodology consists of the following two steps: (1) Determining the most common terminologies used to describe building adaptation projects; and (2) Analyzing the literature related to the determined terms.

3.2.1 Determining Common Building Adaptation Terminologies

Common building adaptation terminologies were selected from several relevant terminologies present in the literature. Refurbishment, renovation, retrofit, rehabilitation, adaptive reuse, conversion, modernization, material reuse, and revitalization were considered as the relevant terminologies based on the authors' experience in the field of building adaptation. The scope of this research does not include historical and heritage restoration and terms related to these topics were omitted (e.g., preservation and conservation). The Scopus search engine was used to find the number of published articles, including peer-reviewed journal articles and conference papers, which include each term in their title. The terms 'adaptive reuse' and 'material reuse' were searched as phrases; the word 'building' was added before other relevant terms and phrases being searched (e.g., building renovation).

As presented in Figure 1, there are over 1600 papers published from 2011-2020 involving the selected terminologies including retrofitting, renovation, rehabilitation, refurbishment, material reuse, building conversion and adaptive reuse. In order to conduct a thorough analysis of definition used in a range of different studies, the scope of this literature review is limited to published articles from 2015 to 2020. In addition, through preliminary analysis it was concluded that technical terminology related to building adaptation and project scopes have been changing significantly over time. Thus, recent literature was selected for an in-depth analysis to capture current usage.

The number of published articles regarding relevant terms between 2015-2020 are as follows: (1) building refurbishment: 168, (2) building retrofit: 292, (3) building rehabilitation: 115, (4) building renovation: 311, (5) adaptive reuse: 99, (6) building conversion: 49, (7) building modernization: 33, (8) material reuse: 93, and (9) building revitalization: 23. The authors identified common terminologies as those for which there were close to, or more than, 50 articles published, so that broad geographic and temporal trends could be identified. Hence, revitalization and modernization were excluded, and refurbishment, retrofitting, rehabilitation, renovation, adaptive reuse, and material reuse were included.

3.2.2 Analyzing the literature related to chosen building adaptation terms

The information about the number of published articles related to the most common terminologies in the past five decades was retrieved from the Scopus database. An overview of how the focus of research on building adaptation has changed over time and which terms were of most interest among researchers is presented in **Figure 3-1**. It can be observed that the average number of published articles about building adaptation from 2001-2010 and from 2011-2020 is approximately 10 and 40 times the average number of publications in the 1970s, respectively. Interpreting trends, in the context of increased world populations, wealth and academic publishing rates from 1970 to 2020 is challenging. However, the increase in research in this field may partly be due to building adaptation gaining acceptance during the past two decades as a sustainable approach to asset and urban management. Concepts of building refurbishment, retrofitting, rehabilitation and renovation are more established. The average number of published articles regarding these topics is 2.75 times more than the average number of publications regarding adaptive reuse, material reuse, and building conversion from 2010-2020. In addition to these broad subject and temporal trends, geographic and cultural differences can be revealing.

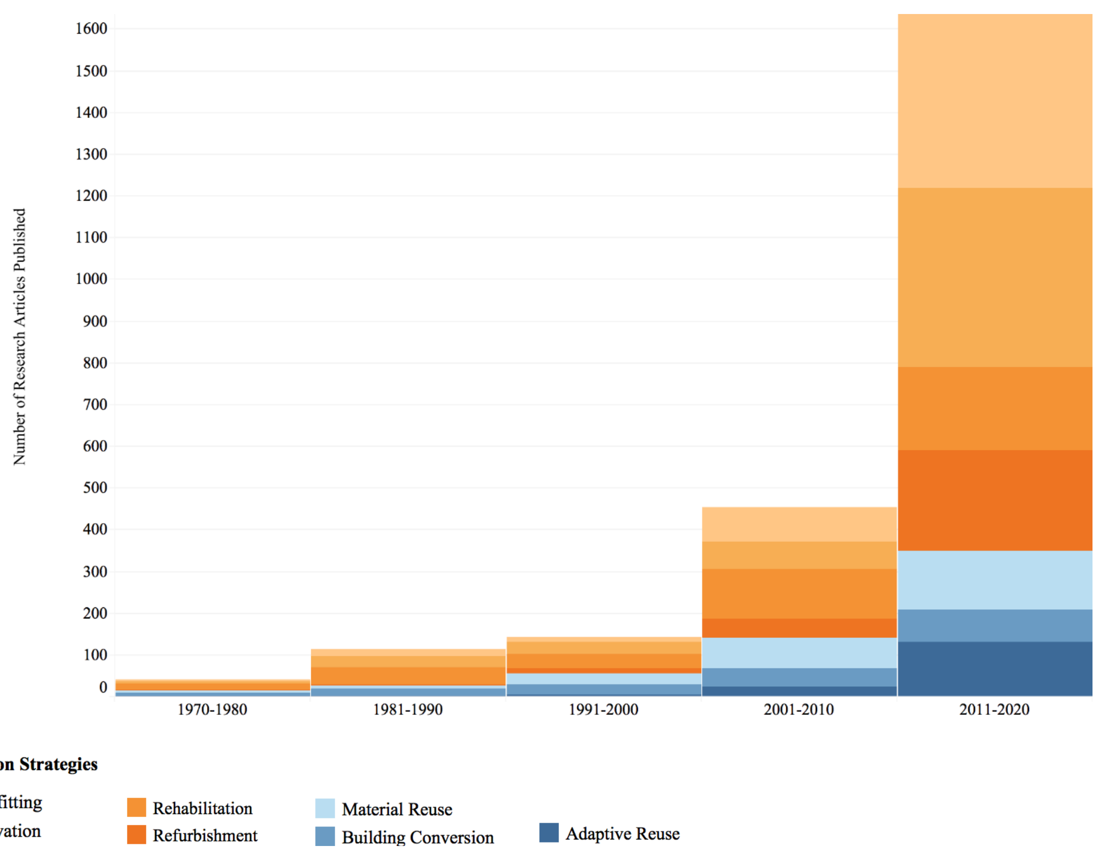
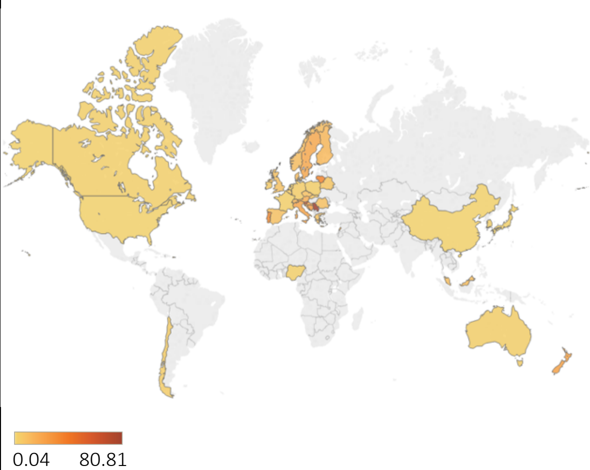
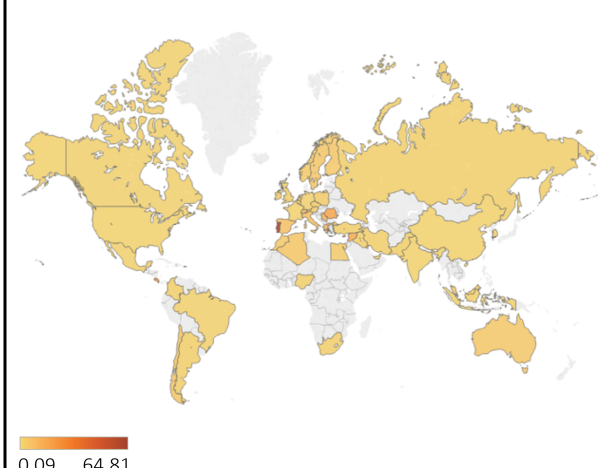


Figure 3-1: Number of research articles published on the most common adaptation terminology.

To explore geographic differences, the number of published articles related to the most common terminologies was retrieved and categorized per country of focus from 2015 to the present. The number of articles was normalized by dividing it by the country's Gross National Product (GNP). **Table 3-1** illustrates how the most common terminologies were adopted around the world and how different countries have contributed to the published articles during the past five years. Based on **Table 3-1**, building refurbishment is of more interest in North America, Europe, China, and Australia; and Europe is the main contributor by publishing 90% of the published articles.

As shown in **Table 3-1** sections b, c and d, the terms building rehabilitation, retrofitting, and renovation are used all around the world, and all continents have contributed to publishing with these terms. On average, Europe, Asia/Australia, America, and Africa have published 75.2%, 15.03%, 6.16%, and 3.61%, respectively, of the total published articles regarding building rehabilitation, retrofitting, and renovation. North America, Eastern Asia, Europe, Russia, and Australia have made the largest contribution of publications on adaptive reuse and building conversion by publishing almost 97% of the published articles (**Table 3-1** sections e and f). Material reuse has a similar distribution to adaptive reuse and building conversion; an exception to this finding is Canada's lack of contribution to material reuse, however compensated by research on this topic in South America (**Table 3-1** section g). The summary of terminologies associated with building adaptation projects is presented in **Table 3-2**. A summarized definition, scope and advantages for each category are presented.

Table 3-1: Number of published articles in countries demonstrated per one trillion dollars of GNP: (a) refurbishment, (b) rehabilitation, (c) retrofitting, (d) renovation, (e) adaptive reuse, (f) conversion, and (g)

a) Refurbishment	b) Rehabilitation
	

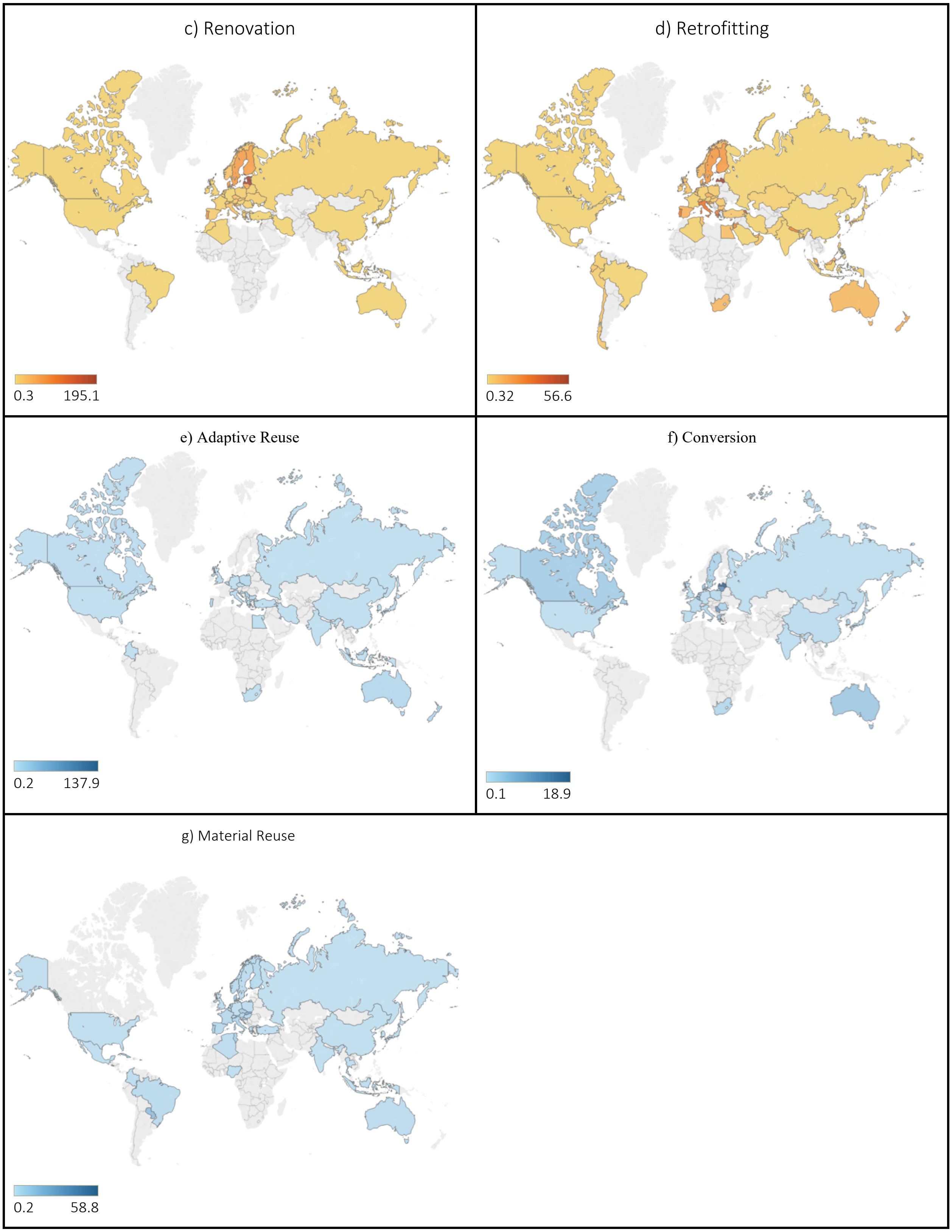

c) Renovation
0.3
195.1
d) Retrofitting
0.32
56.6
e) Adaptive Reuse
0.2
137.9
f) Conversion
0.1
18.9
g) Material Reuse
0.2
58.8

Table 3-2: Summary of the definition of building adaptation terminologies.

Category	Definition	Scope	Advantages	Key References
Refurbishment	Building refurbishment is the process of improving the existing conditions of a building for the existing use. It can include the restoration of the previously acceptable conditions or making improvements to the existing systems, including the addition of energy-efficient strategies and renewable energy production.	• Repair • Maintenance • Building Upgrade • Energy Efficiency	• Reducing the life cycle impact of existing buildings	(Ghose et al., 2017; Institute of Historic Building Conservation, 2019a; Passer et al., 2016)
Retrofitting	Building retrofitting involves the addition or upgrading of an existing building with features or capacities that it was not initially constructed with, to improve energy use and efficiency. Retrofitting focuses mainly on improvements to the envelope, systems and the addition of renewable energy sources.	• Energy Efficiency • Building Envelopes • Replacing HVAC Systems • Addition of Renewables	• Improving energy efficiency • Improving occupant comfort	(Albatici et al., 2016; Antoine et al., 2016; Ma et al., 2012)
Rehabilitation	Building rehabilitation involves the process of repairing, altering, or adding to a deteriorating building to make it compatible for use. Rehabilitation always involves elements that are damaged or deteriorating, and often includes the structure but can involve system, building openings and envelope.	• Damaged structures • Deteriorating systems, envelope and openings	• Avoiding demolition • Increasing building safety • Extending the life cycle of buildings	(Brás et al., 2017; Garrido et al., 2016)
Renovation	Renovation is the process of replacing or fixing the outdated components or remodeling the interior spatial layout of existing buildings.	• Remodel • Energy efficiency • Aesthetic appearance • Interior design	• Improving appearance and occupant comfort • Restoring energy efficiency	(Ástmarsson et al., 2013; Jensen & Maslesa, 2015)
Adaptive Reuse	Adaptive reuse is the process of reusing an obsolete and derelict building by changing its function and maximizing the reuse and retention of existing materials and structures.	• Change the function of buildings • Rehabilitation • Renovation • Retrofitting • Material reuse	• Preventing demolition / decreasing waste • Increasing economic/ social performance	(Bullen & Love, 2011; Conejos et al., 2011; Langston et al., 2008)
Conversion	Building conversion is the strategy of adapting obsolete and abandoned buildings that do not satisfy their users or are not used anymore by changing their function.	• Change the function of buildings • Rehabilitation • Renovation • Retrofitting	• Decreasing material use and greenhouse gas emission • Increasing living quality	(Purwantiasning et al., 2013; Živković et al., 2016)
Material Reuse	Material reuse is the process of partially repairing or refurbishing recovered materials from existing buildings to use them more than once for different purposes.	• Recover and reuse existing materials	• Minimizing waste • Decreasing material and energy use	(Kralj & Markic, 2008; Jungha Park & Tucker, 2017)

Lastly, the titles and abstracts of all relevant research and ontological articles since 2015 have been reviewed. These articles were reviewed and analyzed in depth. The results of this literature review are summarized in **Table 3-3**. In order to effectively compare the articles and identify the scope of each terminology, the focus and strategy of each article is characterised by column and row membership.

Regarding refurbishment, retrofitting, rehabilitation, and renovation, the articles mainly focus on improving the sustainability of existing buildings by conducting different adaptation strategies (e.g., replacing the windows, improving insulation, reinforcing building structure, and using renewable sources of energy). Most of the articles relating to adaptive reuse and building conversion investigate the impacts of changing the function of the buildings and reusing their materials on overall sustainability improvement. Additionally, some articles focus on the impacts of policies and regulations on adaptive reuse and building conversion, advantages and disadvantages of these projects, development of decision-making methodologies, and explain strategies for improving the performance of these projects. As such, the focus of articles associated with material reuse is mainly on the sustainability, advantages and barriers of material reuse, investigation of the potential of material reuse, and strategies to maximize the material reuse (e.g., deconstruction and disassembly) considering the reuse and recycling strategies.

Table 3-3: Summary of literature review for building refurbishment, rehabilitation, retrofitting, renovation, adaptive reuse, building conversion, and material. reuse.

	Reference	***Focus***																										
		Sustainability				Material Reuse/ Recycle				Building Envelope					Building MEP			Building Structure		Change of Function						Waste/ Material Management		
		Environmental	Economic	Social	Policy	Challenges/Barriers	Strategies to Maximize	Potentials	Deconstruction	Cladding Replacement	Window Replacement	Insulation Improvement	Solar Shading Integration	Energy Transfer Ratio	HVAC	Lighting/Electrical	Active Systems	Structural Reinforcement	New Structure Addition	Industrial to Residential	Industrial to Commercial	Other to Residential	Commercial to Other	Other to Other	Other to Commercial	Waste Management	Reuse	Recycle
Refurbishment	(Vilches et al., 2017)	•									•	•			•													
	(Passer et al., 2016)	•									•	•																
	(Schwartz et al., 2016)	•	•								•	•		•														
	(Ali et al., 2018)	•	•									•		•		•		•										
	(Ghose et al., 2017)	•									•	•	•	•	•	•												
	(Kamaruzzaman et al., 2016)	•										•			•	•												
	(Sesana et al., 2016)	•									•	•			•													
	(Lidberg et al., 2016)	•										•			•													
	(Brandão de Vasconcelos et al., 2016)	•	•								•	•																
Rehabilitation	(Saez & Shivanagari, 2019)																									•		
	(Thibodeau et al., 2019)																									•		
	(Alba-Rodríguez et al., 2017)	•	•								•							•								•		
	(Garrido et al., 2016)																	•										
	(Brás et al., 2017)			•														•										
	(C. P. Almeida et al., 2018)																									•		
	(R. Almeida et al., 2015)	•	•								•																	
	(Brás & Gomes, 2015)	•										•						•										
	(Alonso et al., 2017)	•								•									•									
	(Abbas et al., 2018)		•															•	•									
Retrofitting	(Albatici et al., 2016)	•	•	•							•	•			•		•											
	(Antoine et al., 2016)	•		•							•	•			•		•											
	(Mata et al., 2018)	•	•								•	•			•	•												
	(Pasichnyi et al., 2019)	•	•								•	•			•	•												
	(Raimondi et al., 2016)	•									•	•	•	•	•	•			•									
	(Ferrari & Zagarella, 2015)	•	•								•	•			•	•	•											
	(Garay et al., 2017)	•									•	•																
	(Pardo-Bosch et al., 2019)	•	•								•	•			•	•	•											

	(Hagentoft, 2017)	•									•	•																
	(Mauro et al., 2015)	•	•								•	•	•		•													
Renovation	(Helander & Singh, 2016)	•																										
	(Jensen et al., 2018)	•									•	•			•	•												
	(Ferrari & Zagarella, 2015)	•	•								•	•		•	•											•		
	(Thomsen et al., 2015)	•		•						•	•	•			•			•										
	(Andrić et al., 2017)	•									•	•																
	(Serrano-Jimenez et al., 2017)	•								•	•	•			•													
	(Dalla Mora et al., 2018)	•	•								•	•			•	•		•										
	(Ding et al., 2019)																									•		
	(Fotopoulou et al., 2018)	•								•																		
	(Mateus et al., 2019)	•	•								•	•		•	•		•											
	(Milić et al., 2019)		•								•	•																
	(Ramírez-Villegas et al., 2019)										•	•			•													
Building Conversion	(Živković et al., 2015)	•	•	•																		•						
	(Wadu Mesthrige et al., 2018a)			•																•								
	(Ren et al., 2015)		•		•																•							
	(Chan et al., 2015a)		•	•																•	•							
	(Chan et al., 2015b)			•	•															•	•							
	(Chan et al., 2015c)				•															•	•							
	(Ojikpong et al., 2016)		•	•																					•			
	(Petković-Grozdanovića et al., 2016)																			•								
	(Cianci & Molinari, 2018)			•																		•						
Adaptive Reuse	(Günçe & Misirlisoy, 2019)	•	•	•																				•				
	(Sanchez & Haas, 2019)	•	•																				•					
	(Li et al., 2018)		•		•															•	•							
	(Tam & Hao, 2019)	•	•	•																				•				
	(Remøy & Wilkinson, 2012)	•	•		•																	•						
	(Haidar & Talib, 2015)		•		•																			•				
	(Dewiyana et al., 2016)	•																		•								
	(Rodrigues & Freire, 2017)	•	•																						•			
	(Al-Obaidi et al., 2017)	•		•																					•			
	(Louw, 2016)	•	•	•																	•							
	(Celadyn, 2019)	•																						•				
Material Reuse	(Park & Tucker, 2017)						•	•																			•	
	(Hosseini et al., 2015)	•	•	•		•	•	•																			•	•
	(Cruz Rios et al., 2019)	•				•																					•	
	(Diyamandoglu & Fortuna, 2015)	•	•						•																		•	
	(Rose & Stegemann, 2018)							•	•																		•	•
	(Sakaguchi et al., 2016)								•																		•	
	(Kozminska, 2019)						•		•																		•	
	(Nußholz & Whalen, 2019)		•				•		•																		•	
	(Ng & Chau, 2015)	•							•																		•	•
	(Sanchez & Haas, 2018)	•	•																								•	

3.3 Results: A Definition Framework

This section is divided into four subsections. The first subsection presents the results of categorizing the terminologies related to building adaptation projects based on the literature review. The second subsection explains the definition, scope of application, and barriers to implementation for each type of building adaptation. The provided definitions for terminologies are summarized in the third section. Lastly, the definition framework is presented.

3.3.1 Categorization of Building Adaptation Projects

The categorization of definitions, demonstrated in Figure 3-2 and **Table 3-4**, is derived from the extended literature review conducted, analysis and comparison of terms described in detail in the following sections. Figure 3-2 illustrates a categorization of building adaptation projects. As shown in this figure, building adaptation can be subdivided into the two major categories of refurbishment and adaptive reuse. The two terms are further broken down to explain the detailed scope of refurbishment and adaptive use, respectively. A summarized description of terminology categorization in described in the following. Building refurbishment defines the process of improving the existing conditions of buildings and making improvements for the existing use (Hassan et al., 2017). Building retrofitting, renovation, and rehabilitation are defined as subcategories of building refurbishment. The term adaptive reuse covers the concepts of building conversion, including reusing an existing building for a *different use*, and the reuse of salvaged materials in a building for a *different use* (i.e., material reuse). Building retrofitting covers non-structural strategies, while rehabilitation always involves a structural scope. Building renovation, conversion and material reuse can involve both structural and non-structural elements.

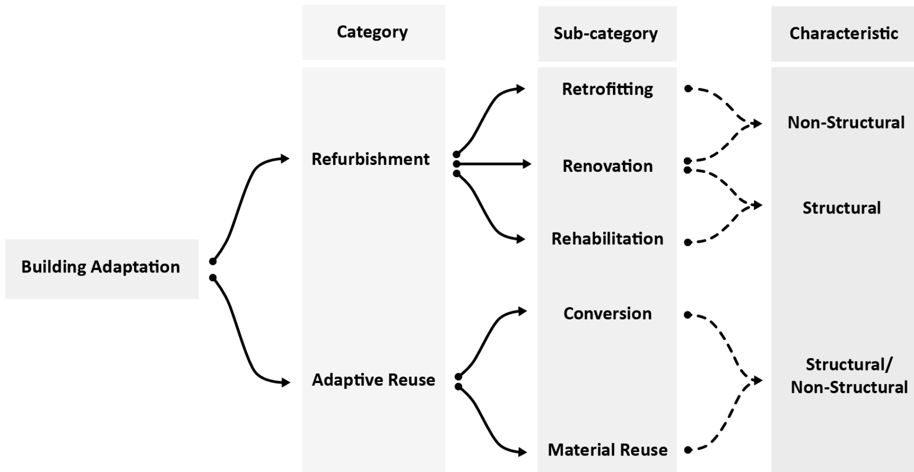
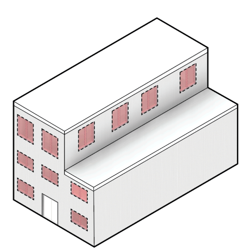
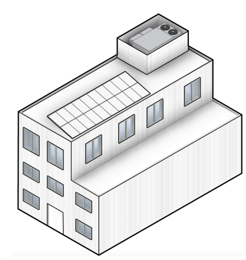


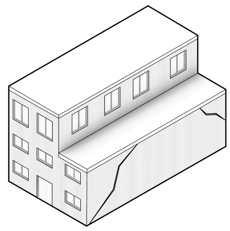
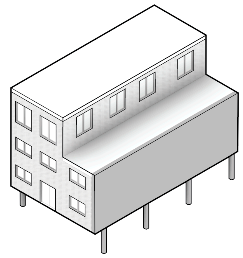
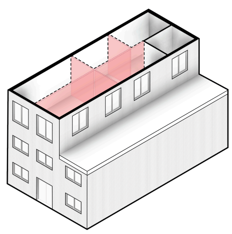
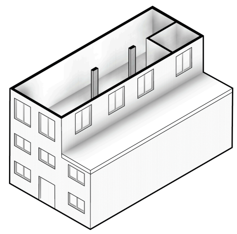
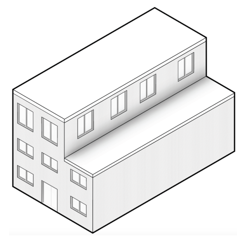
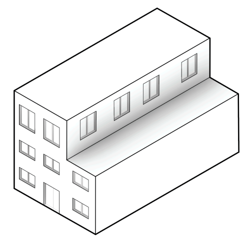
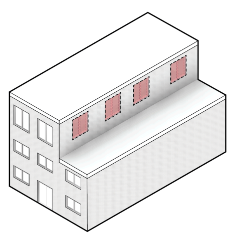
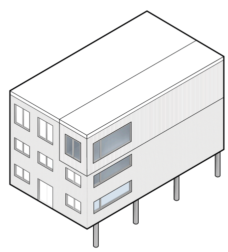
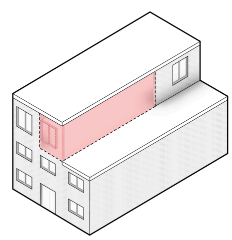
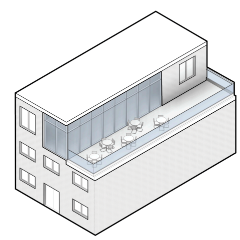
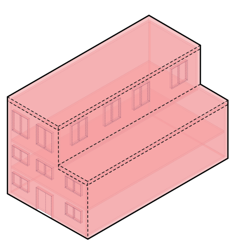
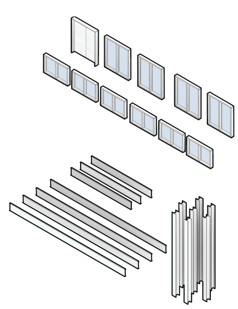
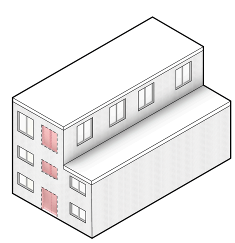
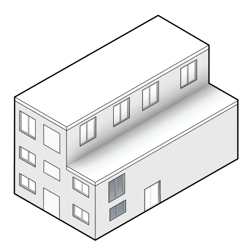
Figure 3-2: Breakdown of Building Adaptation in Two Categories of Refurbishment and Adaptive Reuse. Each of the categories are divided into the subcategories of Retrofitting, Renovation, Rehabilitation, Conversion and Material Reuse, tagged by their structural characteristic.

3.3.2 Definition of Terminologies

An overview of the scope involved in each terminology is represented visually in **Table 3-4**. All terminologies are separated by the identified categories of refurbishment and adaptive reuse. For each terminology, examples are provided for each applicable area of improvement. The existing and adapted building condition is demonstrated for each example, with the applicable demolition scope of each highlighted in red.

Table 3-4: Scope of application associated with different subcategories of building refurbishment and adaptive reuse.

Adaptation Terminology		Structural Improvements		Other Improvements	
		Existing Building	Adapted Building	Existing Building	Adapted Building
Refurbishment	Retrofitting	-----	-----		
				Replacing windows, increasing insulation and addition of renewable energy sources and efficient HVAC	

<table>
<tr><td rowspan="4"></td><td rowspan="2">Rehabilitation</td><td></td><td></td><td rowspan="2">----</td><td rowspan="2">----</td></tr>
<tr><td colspan="2">Reinforcing of failing structuring</td></tr>
<tr><td rowspan="2">Renovation</td><td></td><td></td><td></td><td></td></tr>
<tr><td colspan="2">Changing the interior layout, replacing walls with columns</td><td colspan="2">Replacing exterior cladding</td></tr>
<tr><td rowspan="4">Adaptive Reuse</td><td rowspan="2">Conversion</td><td></td><td></td><td></td><td></td></tr>
<tr><td colspan="2">Converting spaces through an addition</td><td colspan="2">Changing use of the building and converting interior/exterior spaces</td></tr>
<tr><td rowspan="2">Material Reuse</td><td></td><td></td><td></td><td></td></tr>
<tr><td colspan="2">Demolition and retrieval of salvageable materials for reuse</td><td colspan="2">Removal and reuse of building materials in the same building</td></tr>
</table>

3.3.3 Refurbishment

Building refurbishment is defined as the process of improving the existing conditions of a building and may include the addition of elements for the improvement of energy efficiency. Refurbishment can be used to address a range of scopes, including maintenance, repair work, and alteration (Institute of Historic Building Conservation, 2019a). Refurbishment is mainly involved in improving the environmental and operating costs of existing buildings. Increasing insulation and window replacements are highlighted as the most common refurbishment strategies, followed by mechanical system upgrades and changes to the building, including window-wall ratio and structure.

Incorporating energy-efficient mechanisms, including thermal improvements to the building envelope, and improving system performance, covers the most common definition of building refurbishment in the literature. These strategies can include thermal recladding, re-glazing, alteration of wall-window ratio, incorporating new HVAC systems and technologies, and providing electrical upgrades (Ghose et al., 2017; Kamaruzzaman et al., 2016; Passer et al., 2016; Sesana et al., 2016). These changes have direct improvements in overall energy usage, amongst other benefits such as improved building quality and aesthetics (Lidberg et al., 2016). Building refurbishment can additionally refer to the addition of active systems, such as renewable energy production (Brandão de Vasconcelos et al., 2016) and the addition of passive systems including solar shades (Ghose et al., 2017; Passer et al., 2016).

Other approaches to the definition of refurbishment work include the scope of building repair work, renovations and alterations, and structural rehabilitation in addition to making environmental improvements. Building refurbishment projects can be divided into three categories to include minor, medium and major refurbishment works. Minor refurbishment considers the next five years and involves maintenance and repair objectives that are economically justified within this shorter time frame. Medium refurbishment considers the extension of the economic life of the building by 15 years and involves the improvement of building finishes and services and excludes structural repairs. Major refurbishment considers the life of the building beyond 15 years and involves significant alterations to an existing building, including structural, to make it comparable to a newly constructed building (European Commission, 1998; Hassan et al., 2017).

The focus of building refurbishment can be summarized as reducing the life cycle impact of existing buildings (Schwartz et al., 2016). Building refurbishment is the umbrella term of retrofitting, rehabilitation and renovation, which are further explored in this chapter as various facets. Retrofitting involves the addition of new materials and elements that were not part of the existing building in order to bring about environmental efficiencies. Rehabilitation addresses the need to improve the failing aspects of an existing building, mainly involving the structure (Vilches et al., 2017). Building renovation work focuses on the aesthetic aspects of refurbishment and can include structural or non-structural improvements.

3.3.3.1 Retrofitting

Existing buildings make up the largest portion of the built environment, with a major segment built before energy conservation considerations (Albatici et al., 2016; Paradis, 2012) and hence are not compatible with modern standards of energy efficiency (and comfort). A large portion of the existing building stock is, therefore, in need of reconstruction. In the existing building stock, 50% of energy used is spent on space heating and cooling and more than 15% is spent on water heating (Pasichnyi et al., 2019). Therefore, the reduction of space heating and cooling demand, and the introduction of active energy generation can contribute positively to the reduction of carbon dioxide emissions from buildings. Heat loss in buildings through walls, roofs and floors as well as glazed areas results in 60% of energy use in a typical building. Most of this energy is lost because of a lack of adequate insulation; therefore, the addition of thermal insulation is highlighted as one of the most efficient strategies in retrofitting (Garay et al., 2017).

Building retrofitting can be defined as a subcategory of building refurbishment, with a focus on additions to the existing building for improving energy efficiency and performance. Retrofitting activities involve the following categories: reducing heating and cooling demands, improving HVAC efficiency, and integrating active and renewable energy systems. Building retrofits, therefore, involve the addition or upgrading of an existing building with features or capacities that were not included in initial construction (Antoine et al., 2016; Eames et al., 2014; Imaz, 2019; Institute of Historic Building Conservation, 2019b; Ma et al., 2012).

Retrofitting involves a balance of various elements to achieve optimal results. Retrofitting is highly efficient when a whole building strategy is examined but can also be comprised of singular strategies or strategies phased throughout several years. Retrofitting of buildings includes passive and active strategies. Insulation of walls, roofs and floors, the addition of more efficient windows or green roofs on existing buildings, draught-proofing of fenestrations, and installation of more energy-efficient doors and windows are examples of passive building retrofitting strategies (Ferrari & Beccali, 2017; Kamaruzzaman et al., 2016; Passer et al., 2016; Sesana et al., 2016). Installation of new or more efficient heating or cooling systems, solar panels lighting control systems (e.g., sensors and LED lighting), high-efficiency mechanical systems, smart controls and metering systems for building management systems, and upgrading of piping systems are examples of active retrofitting strategies.

Retrofitting measures aim at reducing operative energy demand, and the reduction of lighting loads is becoming increasingly important, particularly the effect of natural daylighting optimization (Raimondi et al., 2016). Other examples include the addition of cooling systems or replacement with in-ground or passive cooling strategies, the addition of renewable energy systems, including photovoltaics and geothermal heating, and reduction of water use, including efficient water fitting and smart controls (Albatici et al., 2016; Brandão de Vasconcelos et al., 2016; Institute of Historic Building Conservation, 2019b). Inclusion of passive systems and technologies including smart metering systems and intelligent occupant controls for improvement of occupant comfort as well as improvements to the energy efficiency of the building, is also part of retrofitting (Albatici et al., 2016).

Benefits of retrofitting include reduced dependence on energy sources, improvements to indoor air quality and comfort, and reduction of global warming potential. Other benefits include a reduction in maintenance and repair costs and overall improved socio-economic well-being of the existing building stock (Pardo-Bosch et al., 2019). In the process of retrofitting, costs and payback regarding each strategy ultimately lead to a feasibility assessment and decision making process (Albatici et al., 2016). Barriers to retrofitting include a lack of understanding of benefits and access to reliable information and financial models. These include high costs, risk management and long pay-back periods, amongst others. Other identified obstacles include the complexity involved in large-scale retrofitting projects, lack of clear definitions and scopes, and lack of expertise in the industry (Pardo-Bosch et al., 2019). The large-scale implementation of energy efficiency strategies can be extended to include "multi-system nexus," life cycle improvements and socio-economic well-being (Pasichnyi et al., 2019). Active retrofitting options that include systems upgrades and mechanical systems are highlighted as more most effective compared to passive strategies involving the building envelope (Ferrari & Beccali, 2017).

In contemporary retrofitting projects, it is essential to consider net-zero strategies and the importance of limiting waste to landfills (Ferrari & Beccali, 2017). An important aspect of the proliferation of retrofitting projects lies in the reduction of risks and uncertainties. The retrofitting strategies studied include insulation of walls and attics, heating systems, the addition of smart monitoring systems and photovoltaic panels (Pardo-Bosch et al., 2019). The importance of integrated evaluation of not only energy efficiency but life cycle costs, quality of materials, and overall durability, is paramount. While some strategies can provide instant reductions in energy demands, they might have demanding life-cycle costs and effects such as increased global warming potential. Therefore, careful consideration regarding life cycle implications and costs are required (Hagentoft, 2017).

3.3.3.2 Rehabilitation

Rehabilitation typically involves the repair and restoration of basic systems and the structure of a deteriorating building to the status of a previously acceptable condition. Rehabilitation is therefore undertaken to make a building compatible with continued use. The scope of work for a rehabilitation project refers to strengthening or replacing deteriorating or damaged structural elements, repairs to the building envelope, roof and openings. For mechanical and electrical systems in a building, parts are either replaced or entire systems are rebuilt. In the process of a rehabilitation project, building systems are updated to local codes and necessary adjustments are made (Coffey, 1994). Building rehabilitation can include structural strengthening or replacement of structural components (Garrido et al., 2016). Rehabilitation work at the scale of the building envelope is focused on reducing discomfort due to relative humidity, air and water leakage, and structural failures (Brás et al., 2017).

The focus of rehabilitation projects is mainly on structural measures, as well as waste management strategies, including recycling and reusing materials. Rehabilitation is often not concerned with the improvement and replacement of building systems. Also, rehabilitation is not typically focused on building envelope improvements, while the scope of window or cladding replacement can overlap with the need for structural rehabilitation. Rehabilitation is equally focused on environmental and economic benefits while addressing social benefits. The management of the construction and demolition waste in rehabilitation work is highly important. In the process of rehabilitation, the two main activities conducted are the dismantling of troubled areas, and remediation and new construction work (Sáez & Osmani, 2019). The scope of building rehabilitation projects can include direct rehabilitation of the structure and the combination of rehabilitation with other refurbishment strategies and the integration of new construction (Thibodeau et al., 2019).

The rehabilitation efforts defined here focus on structural repairs that will make buildings safe and habitable. In order to determine the viability of a rehabilitation project, both economic and life cycle assessments are compared to the option of demolition and new construction (Alba-Rodríguez et al., 2017). Rehabilitation work is most influential for improving the environmental life cycle due to the prevention of demolition (Thibodeau et al., 2019). The environmental impact of rehabilitation of a failing structure is estimated to be approximately 60% less than demolition and new construction (Alba-Rodríguez et al., 2017). Furthermore, rehabilitation of old buildings is regarded as a way to prevent de-population in urban centers and to prevent abandonment of old buildings (Almeida et al., 2018).

3.3.3.3 Renovation

According to the literature shown in **Table 3-1**, the term building renovation is most commonly used in European countries. The definition of building renovation and the scope of the activities associated with renovation varies across countries. For example, in Austria and Switzerland, renovation is recognized as a range of simple maintenance and modernization works for improving occupant comfort. In Finland, building renovation is focused on renewing the heating systems of the existing buildings to fix damaged components and improve occupant comfort. In France, the majority of renovation projects are dedicated to improving existing energy efficiency measures of buildings that have degraded over their lifecycle. These renovations include renewing the building envelope's insulation, replacing windows with double glazed ones and fixing HVAC systems. Renovation activities in Germany are usually conducted to meet market demands, to make buildings more attractive for users, or to address building shortfalls acknowledged by building inspecting officials. In Sweden, the main trend of renovation projects is to repair or replace the heating systems, water management and sewage systems, and electrical systems of existing buildings to restore them to their original conditions (Itard & Meijer, 2008; T. Vainio et al., 2002).

Based on the various scopes of renovation projects studied, renovation can be defined as the process of replacing or repairing outdated components or remodeling the interior spatial layout of existing buildings. Renovation addresses conditions that are no longer economical or energy-efficient, or do not satisfy the occupants or users while keeping the function of the building intact. The goal of a renovation project is to restore a building's original conditions, or improve a building's architectural aspects and appearance for enhanced comfort levels and attractiveness (Ástmarsson et al., 2013; Jensen & Maslesa, 2015).

The majority of research studies have considered renovation projects that focus on environmental sustainability by improving the energy efficiency of the buildings. The main problem with considering energy efficiency improvement as a strict requirement for renovations is that other focuses of building renovation include occupant comfort, architectural quality and economic feasibility (Per et al., 2018). To address this problem, recent research studies, particularly in Sweden, have focused on the social and economic sustainability of renovating existing buildings (Thuvander et al., 2012; T. H. Vainio, 2011). Based on these findings, a building should be renovated if it no longer satisfies the requirements of energy, economic, and/or social sustainability. For example, an energy-efficient building can be renovated if its interior design does not satisfy the occupants anymore to address social sustainability or it is not economically viable, therefore jeopardizing its economic sustainability (Femenías et al., 2018).

3.3.4 Adaptive Reuse

Adaptive reuse is defined as the process of extending the useful life of historic, old, obsolete, and derelict buildings. Adaptive reuse also considers new use requirements, socio-cultural demands, and environmental regulations. Adaptive reuse projects seek to maximize the reuse and retention of existing structures and fabrics as well as to improve economic, environmental, and social performance of buildings (Bullen & Love, 2011; Conejos et al., 2011; Langston et al., 2008; Larkham, 2002). These characteristics makes adaptive reuse a sustainable alternative to demolition and new construction (Sanchez & Haas, 2019; Sugden & Khirfan, 2017). In summary, adaptive reuse projects have two different aspects: (1) changing the function of a building or some parts of the building, which is known as building conversion, and (2) recovering and reusing existing materials of a building, which is referred to as material reuse. The following two sections explain the concept and scope of these terms.

3.3.4.1 Conversion

The concept of building conversion became well-known in the 1970s when many industrial buildings in the downtown cores of Western cities were abandoned due to the shift of manufacturing to developing countries. Rapid and fundamental changes in the politics of developed countries during the 20th century led to the majority of industries from developed countries moving to developing and underdeveloped countries (Chan et al., 2015a; Ren et al., 2015). As a result of this movement, industrial buildings were abandoned and dilapidated over time. Thus, building conversion emerged as a sustainable alternative to reuse the abandoned industrial buildings for different purposes instead of demolition and new construction (Cantell, 2005). Building conversion became particularly common in Great Britain, France, Germany, and the United States.

Building conversion is the strategy of adapting obsolete and abandoned buildings, which do not satisfy their users or are not used anymore, by changing their function (either partially or entirely) (Purwantiasning et al., 2013). Building conversion is similar to building refurbishment, including a similar scope with the addition of changing the function of buildings. Many previous studies used the term building conversion for projects that changed the function of a building from a particular type to another. Converting buildings from industrial to residential or commercial (Chan et al., 2015a; Petković-Grozdanovića et al., 2016; Ren et al., 2015; Wadu Mesthrige et al., 2018b), residential to commercial (Ojikpong et al., 2016), and commercial to any type (Abdullah & Will, 2015; Remøy & Wilkinson, 2012; Sanchez & Haas, 2019) are among the most popular types of conversion in the literature. A building conversion project can be guided by the following three principles: (1) selecting the new function as a long-lasting alternative, which is compatible with the users' requirements, building's characteristics and spatial layout, as well as the environmental, economic, and social characteristics of the surrounding area, (2) designing the project to be compatible with the historical background of the building, new codes, regulations, architectural and aesthetic qualities of the surrounding buildings, and (3) considering the requirements of sustainable development to enhance the sustainability performance of the building (Loures & Panagopoulos, 2007; Živković et al., 2016).

By reusing existing buildings and preventing demolition, building conversion results in environmental advantages including (1) reducing construction waste, (2) consuming fewer natural resources and raw materials, (3) decreasing energy consumption, (4) emitting less greenhouse gases, (5) controlling urban sprawl, and (6) conserving embodied energy (Conejos et al., 2013; Langston et al., 2008; Sanchez & Haas, 2019; Yung & Chan, 2012). Regarding social advantages, building conversion can improve safety, quality of living, occupant health (Aigwi et al., 2018; Shen & Langston, 2010). Building conversion can also enhance the property value of a building and its surrounding buildings, increasing the economic viability of the building, and generating 25% more jobs per square meter (Chan et al., 2015a; Sanchez & Haas, 2019).

The scope of building conversion projects is broader than building refurbishment, and therefore faces more challenges and uncertainty. For example, owners and investors often refuse to consider conversion because of the higher risk of return on investment compared to new construction (Shipley et al., 2006). Also, the probability of cost and time overruns is higher in building conversion projects since they usually deal with vacant and old buildings that have many unknown conditions. Encountering latent defects, contamination and hazardous materials, and structural instability are examples of unknown conditions that can dramatically increase the cost and duration of these projects (Bullen, 2007).

As such, a series of regulatory challenges must be addressed, particularly regarding heritage buildings. Regulatory challenges include obtaining required permissions to change the function of a building, satisfying the requirements of building code regulations, and complying with laws and regulations regarding heritage buildings. According to the literature, the process of obtaining required permissions and certificates to start a building conversion project could double the project time and increase the cost by 30% (Yung & Chan, 2012). Furthermore, several technical and functional challenges should be considered (Bullen, 2007). For example, changing the interior spatial layout or exterior appearance of a building can be limited by the structural layout therefore limiting the range of new functions that can be considered for the building.

3.3.4.2 Material Reuse

The construction industry is responsible for 40% of global resource consumption (Pacheco-Torgal et al., 2014) and is the main contributor of waste generation (Zhao et al., 2010). The scarcity of natural resources required to produce new materials (Cruz Rios et al., 2019) and high amounts of waste generation (Jungha Park & Tucker, 2017) are two serious threats facing industries in general, and the construction industry in particular. Waste management is a sustainability strategy that helps reduce the amount of resource consumption and waste generation by maximizing the recovery of waste materials and minimizing landfill disposal as much as economically and technically possible. This strategy is focused primarily on reducing the amount of material consumption, and then reusing or recycling existing materials (Kralj & Markic, 2008; Jungha Park & Tucker, 2017).

The definitions of these terms (i.e., reduce, reuse, and recycle) in the context of the construction industry are highlighted. Reduce is defined as the decrease in the use of construction materials during new construction or building adaptation projects. Achieving this goal requires improving the performance of materials during the production phase, as well as the strategies of building design and construction by leveraging new technologies and tools (e.g., building information modeling (BIM) in the design stage, and off-site prefabrication for construction stage) (Thomsen et al., 2015). Reducing material use is mainly associated with the process of new construction or with a new addition during a building adaptation project.

Material reuse and recycling are closely related to the building end of life (i.e., demolition or deconstruction). Since building demolition and adaptation both contribute to waste generation (Diyamandoglu & Fortuna, 2015), material reuse and recycling apply to both kinds of projects. Reuse is defined as the process of partially repairing or refurbishing recovered materials to use them more than once for different purposes (Kralj & Markic, 2008; Jungha Park & Tucker, 2017). The recovered materials can be reused as if their condition is satisfactory for new purposes. The recovered materials from a building can be either reused in the same building during the building refurbishment or adaptive reuse or be sent to a marketplace to be sold and reused in different projects either within or outside the construction industry. The latter approach is considered when adapting a building is not valuable and the building is demolished (De Brito & Dekker, 2004; Hosseini et al., 2015).

Recycling aims to convert waste materials into new materials or objects through comprehensive remanufacturing (Kralj & Markic, 2008). Although recycling has received more attention in the construction industry to date, and the recycling rates of some construction materials has risen above 90%, the problems associated with natural resource consumption and construction waste production are not entirely mitigated. Recycling rates are based on the amount of waste sent to recycling companies rather than the actual amount of recycled materials (Rose & Stegemann, 2018). Even if the recycling rate is representative, recycling is not the most sustainable approach in waste management since it is still highly wasteful and usually decreases the quality of materials. In other words, materials entail a loss of utility after recycling. Energy and natural resource consumption, pollution generation, and greenhouse gas emissions are less for reuse. In addition, reusing materials saves more costs by consuming less energy and resources, provides revenue from selling used materials, and does not down-cycle the materials (Kralj & Markic, 2008; Roussat et al., 2009). For example, a lumber beam can still be reused as a beam after recovery, while the beam would be chipped for producing chipboards during a recycling process, which have less utility than a lumber beam (Rose & Stegemann, 2018). Hence, recycling should be considered only when material reuse is not possible (Stahel, 2016).

While material reuse has many advantages, several technical and organizational barriers make its implementation in the construction industry difficult. Technical barriers include a lack of design of existing buildings for easy deconstruction and disassembly (Durmisevic & Binnemars, 2014; Tingley & Davison, 2012), requiring excessive time and labor compared to demolition, having the risk of encountering contaminated materials during deconstruction (Hosseini et al., 2015), uncertain quality of recovered materials (Coelho & de Brito, 2011), large sizes and heavy weights of construction materials, which limits their mobility, and unique conditions of each building for disassembly (Kibert, 2016). Other challenges and organizational barriers to reuse include a lack of effective regulations for promoting material reuse (Durmisevic & Binnemars, 2014), a lack of financial support from governmental agencies (e.g., municipalities) (Kozminska, 2019; Nußholz & Whalen, 2019), the low cost of material disposal that makes it more economical option in light of higher initial cost of material reuse (Coelho & de Brito, 2011), the necessity of having a suitable on-site storage for storing the recovered materials (Denhart, 2010), and a lack of robust and practical marketplaces (salvage yards) to accommodate selling and buying recovered materials (Rose & Stegemann, 2018).

There are strategies highlighted in the literature that allow stakeholders involved in the construction industry to eliminate barriers and promote material reuse: (1) designers can consider the requirements of design for deconstruction and disassembly and try to maximize the reuse of recovered materials; (2) builders can implement novel methods and technologies during construction and deconstruction to facilitate reusing recovered materials and disassembling used ones, respectively; and (3) policymakers can make reuse of materials economically competitive by increasing the costs of material disposal, provide financial incentives to accommodate material reuse, and legislate facilitating regulations to promote deconstruction and incorporation of recovered materials in new construction (Hosseini et al., 2015; Kralj & Markic, 2008; Kühlen et al., 2016; Jungha Park & Tucker, 2017; Rose & Stegemann, 2018).

3.3.5 Definition Framework

Based on the comprehensive literature review analysis and the categorization conducted for building adaptation terminologies, a definition framework was developed to facilitate identifying the type of terminologies involved in adaptation projects. Within this framework, it is possible to include aspects of refurbishment in all building adaptation projects. Building adaptation projects can, therefore, be defined as ranging from being exclusively refurbishment focused, to containing a combination of multiple adaptive reuse and refurbishment strategies. The framework first determines if the building under study is undergoing a change of use, and then determines the inclusion of material reuse. After determining the primary category of building adaptation definition, the framework further breaks down refurbishment into it multiple sub-categories. The framework considers aspects of improvement for each subcategory, including structural and energy use improvements, to suggest more detailed definitions.

3.4 Case Study Analysis

The definition framework is validated through functional demonstration on several building adaptation case studies. As a sample, the scope of one of these case studies and adaptation strategies considered during adaptation is explained comprehensively and the application of the framework is demonstrated by identifying the type of adaptation terminologies involved in the case study (**Figure 3-3**). The steps taken to use the framework are summarized in **Table 3-5**.

The transformation of “530 Dwellings” was completed as a part of a more substantial development to transform existing inhabited social buildings in Bordeaux, France. The existing buildings were built in the early 1960s. In the adaptive reuse and extension of this project, winter gardens and expanded balconies were added in order to primarily improve the overall quality of each unit in terms of the improved building envelope, light, use and views. This project was successful in terms of physical and economic transformations to an existing building while transforming it into suitable and desirable living units with improved environmental and comfort performance and context relevance (Lacaton et al., 2011). In order to maximize natural daylighting, large windows were added to the south façade as well as an extension to add winter gardens and balconies to all the units. There were no significant structural activities done to the existing building, and a separate new external structure was built to support the new building envelope, winter gardens and balconies.

The application of the definition framework is demonstrated in **Figure 3-4**.This adaptation project can be categorized as a combination of adaptive reuse and building refurbishment. Building conversion is the applicable subcategory of adaptive reuse and retrofit and renovation are the relevant subcategories of building refurbishment that were involved in this project. The same procedure (reviewing the scope and adaptation strategies of the project and identifying the adaptation terminologies) was conducted for other case studies. These results are summarized in **Table 3-6**.

Figure 3-3: Transformation of "530 Dwellings" is an adaptation of three 1960s housing blocks (Ruault, 2019).

Table 3-5: Steps for using the developed definition framework for the case study:

Steps	Question	Answer
1	Are there any **Improvements** made to the building in terms of structure, energy use, and/or architecture (spatial layout, organization or aesthetics)?	**Yes.**
2	Are there any aspects of **Reuse** involved in the project, including change of use or reuse of materials?	**Yes.** Balconies added and existing balconies changes to winter gardens. The building was partially *Converted.*
3	Are any of the **Materials** reused?	**No.** There is no *Material Reuse* in this project.
4	The two primary categories of ***Refurbishment*** and ***Adaptive Reuse*** are involved in this Building Adaptation project.	
5	Is the existing **Structure** altered or enhanced?	**No.** There is no *Rehabilitation* in this project.
6	Are there **Energy Efficiency** measures implemented?	**Yes.** Improved glazing and insulation have been added. The building is *Retrofitted*.
7	Are there any **Architectural** improvements implemented?	**Yes.** The entire building has been re-clad, the entrance and lobby have been improved, the aesthetic quality of the entire building has been improved. The building is *Renovated.*
8	Has the **Function** of the building changed?	**Yes.** Balconies were added and existing balconies changes to winter gardens. The building was partially *Converted.*
9	The secondary definitions of ***Retrofitting, Renovation*** and ***Conversion*** apply to this Building Adaptation project.	

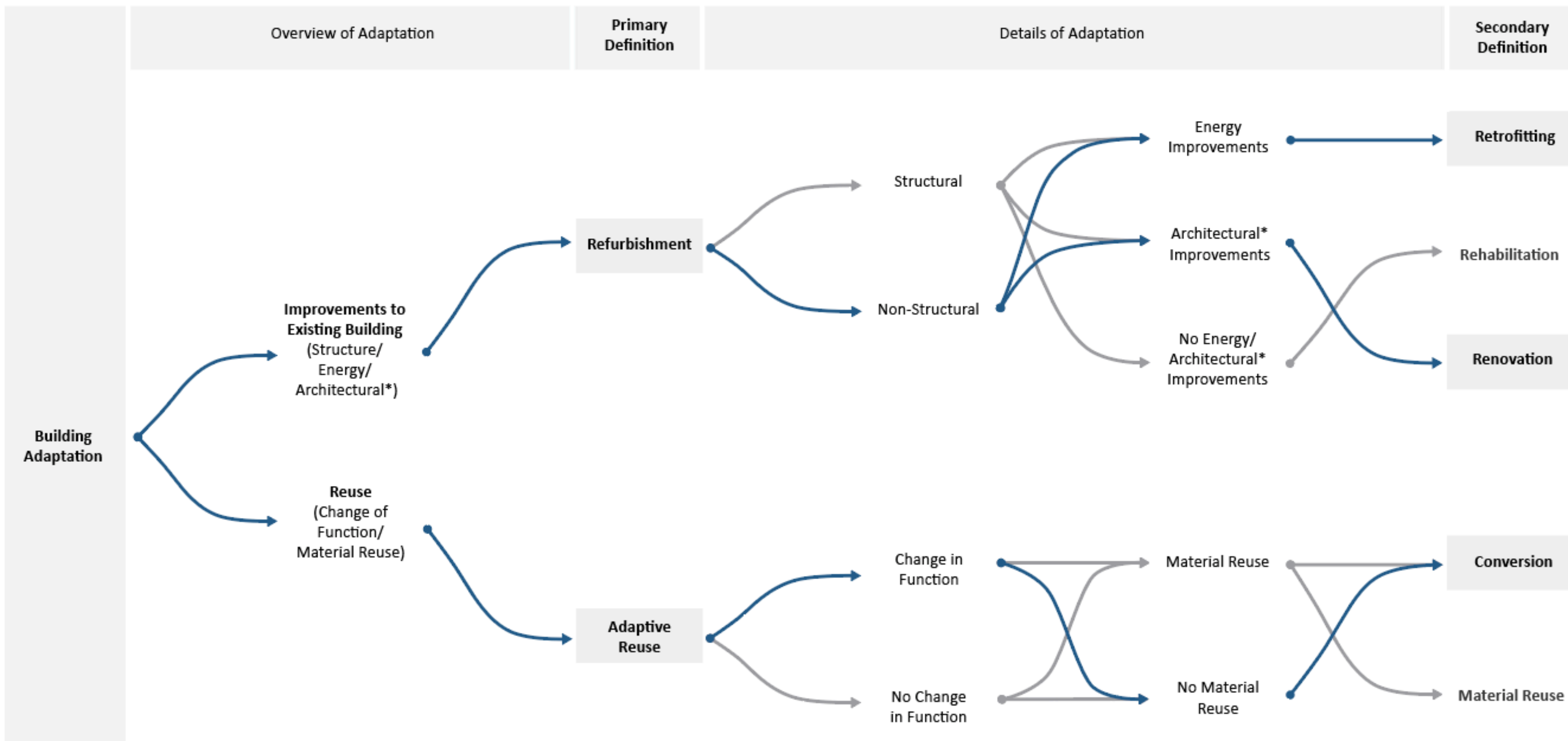


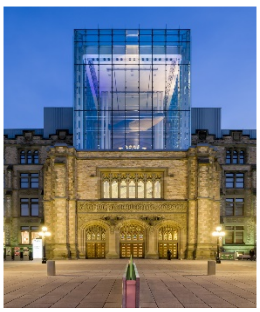
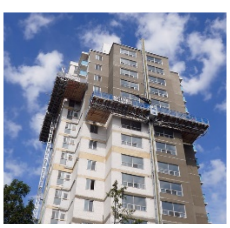
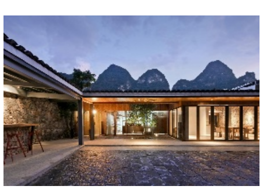
Figure 3-4: Definition Framework for Determining the Scope of a Building Adaptation Projects

A combination of any of the different illustrated paths can be applied to a building adaptation project. The 530 dwellings project illustrated in Figure 3 and Table 5 is used as a demonstration.

- Demonstration of definition of scope of 530 dwellings in Bordeaux, France
- All other options not applicable to 530 dwellings in Bordeaux, France

*Architectural improvements include: spatial (i.e. layout, organization, etc.) and aesthetic (i.e. finishes, coverings, etc.) improvements

Table 3-6: Demonstration of developed definition framework in multiple building adaptation case buildings.

Case Study		**Adaptation Scope**	**Terminologies**
	The Senate of Canada Building Ottawa, Canada, 2019 Diamond Schmitt Architects + KWC Architects (Arban, 2019)	● Train station to a government building ● Material reuse ● Replaced windows ● Increased energy efficiency ● Rehabilitated structure ● Remodeled and constructed interior spaces	● Refurbishment: - Rehabilitation - Renovation - Retrofit ● Adaptive Reuse: - Conversion - Material Reuse
	Canadian Museum of Nature in Ontario Ottawa, Canada, 2010 KPMB Architects (Arban, 2010)	● No change in use ● No material reuse ● Renovated the interiors ● Structural improvements ● Improved building performance ● Added new spaces ● Enlarged windows to improve daylighting	● **Refurbishment:** - Rehabilitation - Renovation - Retrofit
	Advertising Office M adrid, Spain, 2019 Casa Josephine Studio (Imaz, 2019)	● Motorcycle workshop to office ● No material reuse ● No structural improvements ● Interior remodeling	● **Refurbishment:** - Renovation ● **Adaptive Reuse:** - Conversion
	Ken Soble Tower Hamilton, Canada, 2021 ERA Architects (ERA Architects, 2019)	● No change in use ● No material reuse ● Recladding of façade and adding insulation ● Replaced elevators and HVAC systems ● Replaced all windows ● Removed balconies	● **Refurbishment:** - Renovation - Retrofit
	XY Yunlu Hotel Guangxi, China, 2019 Atelier Liu Yuyang (Yuyang, 2019)	● Farmhouse to a hotel ● No material reuse ● Structural improvement ● Renovated building interior ● Improved daylighting with larger windows	● **Refurbishment:** - Rehabilitation - Renovation ● **Adaptive Reuse:** - Conversion

3.5 Discussion and Conclusion

Many different terminologies are used in the literature and in industry to specify the scope of building adaptation projects, but not always consistently. This research found that the terms refurbishment, retrofitting, rehabilitation, renovation, adaptive reuse, and material reuse have been used commonly over the past five years (2015-2020). To enable clear and consistent use of building adaptation terms moving forward, this chapter contributes a definition framework based on a comprehensive literature review of peer-reviewed journal articles and conference proceedings. It is expected that the developed definition framework can be used as a reference in academia and the industry to clearly and consistently defining the scope of work of various types of building adaptation projects, with the aim of minimizing the shortcomings of the current overlaps and confusions in applying definitions to a certain scope. The expected benefits from a coherent and consistent reference for terminology related to building adaptation include cost savings and improved efficiency from consistent codes, specifications and project descriptions that would otherwise lead to confusion and redundancies.

At a high-level, we distinguish adaptive reuse from refurbishment by a change in a building's function or use. Adaptive reuse then encompasses building conversion and material reuse, whereas refurbishment encompasses retrofitting, renovation, and rehabilitation. Most of these project scopes can include structural and non-structural modifications, except for retrofitting, which is limited to non-structural changes, and rehabilitation, which is limited to structural changes.

It is not surprising that these terms could be confused or used interchangeably, as they share subsets of various activities: replacing, adding, repairing, remodeling, reusing, and changing use. Moreover, the activities performed within refurbishment projects are a subset of those performed within conversion projects, which additionally include change of use, all of which can take place in conjunction with material reuse during adaptive reuse projects. Finally, the details of the activities themselves are important, particularly the type of improvements being made (e.g., energy-related, non-energy related, or none at all), in order to determine the type of refurbishment being made (retrofitting, rehabilitation, or renovation).

As a response to COVID-19, there has been an increasing number of temporary conversion of various types of facilities to COVID-19-specific care such as medical units, for overflow of COVID intensive care and overflow of non-COVID care, supply storage and homeless shelters. A study by JLL identified 80 temporary facilities across the United States able to accommodate more than

20,000 beds. These facilities range from large arenas and conference centers to office spaces and hotels (Johnson, 2020). The inherent flexibility in such buildings such as flexible open plans, non-centralized HVAC systems and temporary interior divisions make them ideal for temporary conversion. Buildings that are able to incorporate future adaptability and in the response to COVID are able to temporarily convert to other uses, are defined in literature as adaptable buildings. Adaptable buildings are defined as structures that enable alteration strategies, allowing them to respond to changing environments and occupant requirements (Addis & Schouten, 2004; Gosling et al., 2013).

To be truly sustainable and resilient, it is beneficial for a building design to consider future flexibility and opportunities to adapt to occupant's demands and to enable accommodation of future uses (Manewa et al., 2016). There are many identified effective design-based strategies for enabling adaptability. Some of these include the layering of different building systems, accurate documentation, over-designing structural capacity, designing for disassembly, simplicity of structure, systems and plan and modularity. Amongst these, open and accessible plans, over-designing structural capacity, and layering are highlighted by the industry as the most effective strategies to making future adaptive reuse possible (Gosling et al., 2013; Ross et al., 2016).

The current response to COVID-19 highlights the importance of developing buildings that are responsive to circumstantial, environmental and demographic changes (Kinnane et al., 2016). The term "temporary conversion" as sub-category of adaptive reuse and conversion is expected to gain more importance in research and practice post-COVID, as we begin to navigate a new normal with a perspective on other factors that will affect our built environment, including the effects of climate change in the following decades. The scope, definition and application of temporary conversions need to be investigated in depth in the future of this work.

As demonstrated by this chapter's case studies, the proposed definition framework can be used to clearly articulate the project scope by answering a few relatively simple questions. Judging by the exponential increase in published literature on building adaptation projects over the past several decades, we suspect research in this field to continue growing. This growth will make the proposed definition framework a useful reference point, but also suggests it will be important for future researchers to eventually revisit these terminologies to ensure alignment with the potentially changed nature of future project scopes.

4. Design Option Assessment for Building Adaptation Projects

OVERVIEW

Adapting existing buildings to reduce the ratio of operating-to-embodied energy in addition to accommodating new purposes is an attractive alternative to new construction. Typically, due to the lack of a disciplined framework and resource constraints, a limited number of adaptation strategies are considered for assessment. However, early in the design process, the consideration of a large range of strategies is a necessary prelude to a successful generative and detailed design process. To address this gap in practice and theory, a decision-making framework is presented for supporting generation, evaluation and selection of multiple conceptually orthogonal design options as a basis for future computational design optimization and detailed design. First, fundamental adaptation strategies are identified as critical elements of a design language for design generation, and they are demonstrated for a class of multi-unit, multi-story residential buildings characterized by the problematic dominance of underutilized and poorly designed balconies. Selected options are then analyzed in terms of cost, feasibility and relevance. The most desirable strategies are identified through multi-attribute utility theory. Functionally demonstrating these steps in the framework validates its efficacy for application early in the building adaptation process.

4.1 Introduction

The built environment produces about 40% of all greenhouse gas emissions (Nejat et al., 2015). Building adaptation, including refurbishment and adaptive reuse of existing buildings, can significantly reduce these emissions (P. Xu et al., 2011). Successful building adaptation projects can result in notable social, economic and environmental benefits including: (1) improving energy efficiency, (2) increasing financial gains from reduced maintenance and operation costs, (3) improving occupant thermal comfort, and (4) increasing the useful life of buildings (Foley, 2012; Langston et al., 2008; Ma et al., 2012; Smith & Hung, 2015; Tokede et al., 2018; P. Xu et al., 2011).

The early stages of building design, especially of a building adaptation project, are complex and involve numerous requirements (Conejos et al., 2015; F. W. H. Wong et al., 2009). The systematic consideration and evaluation of design strategies in the early design stages can lead to increased design performance (Blizzard & Klotz, 2012). For an effective early-stage design, it is essential to consider multiple factors simultaneously, including environmental performance and life cycle impacts (Yuan et al., 2018), as examples. To achieve optimal design options, solutions must be reached that perform well for a range of multiple objectives (Geyer, 2009; Mela et al., 2012). It is, therefore, necessary to consider design option generation and assessment methodologies for improving the design process of building adaptation projects.

Building adaptation changes an existing building through refurbishment or adaptive reuse. Refurbishment is the process of improving the existing conditions of a building and may include retrofitting, rehabilitation or renovation work (Kamaruzzaman et al., 2016). Adaptive reuse is defined across multiple studies as an environmentally sustainable alternative to both demolition and new construction (Conejos et al., 2015). Adaptive reuse can include conversion and material reuse strategies, which extend the useful life of existing buildings (Shahi et al., 2020). Conversion can be defined in terms of a range varying from repurposing of the main structure for another use to the reuse of building systems and components (Bullen, 2007; Conejos et al., 2013; Passer et al., 2016; Wilson, 2010). In the case of multi-family housing in many northern climates, the balcony becomes the nexus around which building adaptation occurs due to its ubiquity and role in the environmental obsolescence of multi-unit, multi-story residential buildings built since the second world war.

The balcony has been a prominent feature in residential towers in the City of Toronto since the 1950s. **Figure 4-1** demonstrates the number of residential towers built and the role of balconies within those towers from 1950 to 2015. It can be observed that the balcony proliferation patterns of the 1970s included high numbers of towers possessing 40% to 100% of balcony coverage and minimal buildings with no balconies. Similar patterns have been ongoing from the 2000s onwards, with the increase in the condominium construction in the city, highlighting the importance of balconies in contemporary building and ageing building stock in Toronto. Based on a study of 355 balconies in buildings across the city of Toronto, about 50% of balconies are observed to be actively programmed and integrated as an extension of the living unit, 9% are typically used for transitory activities such as smoking, and 41% are unused and vacant (Shahi, 2015).

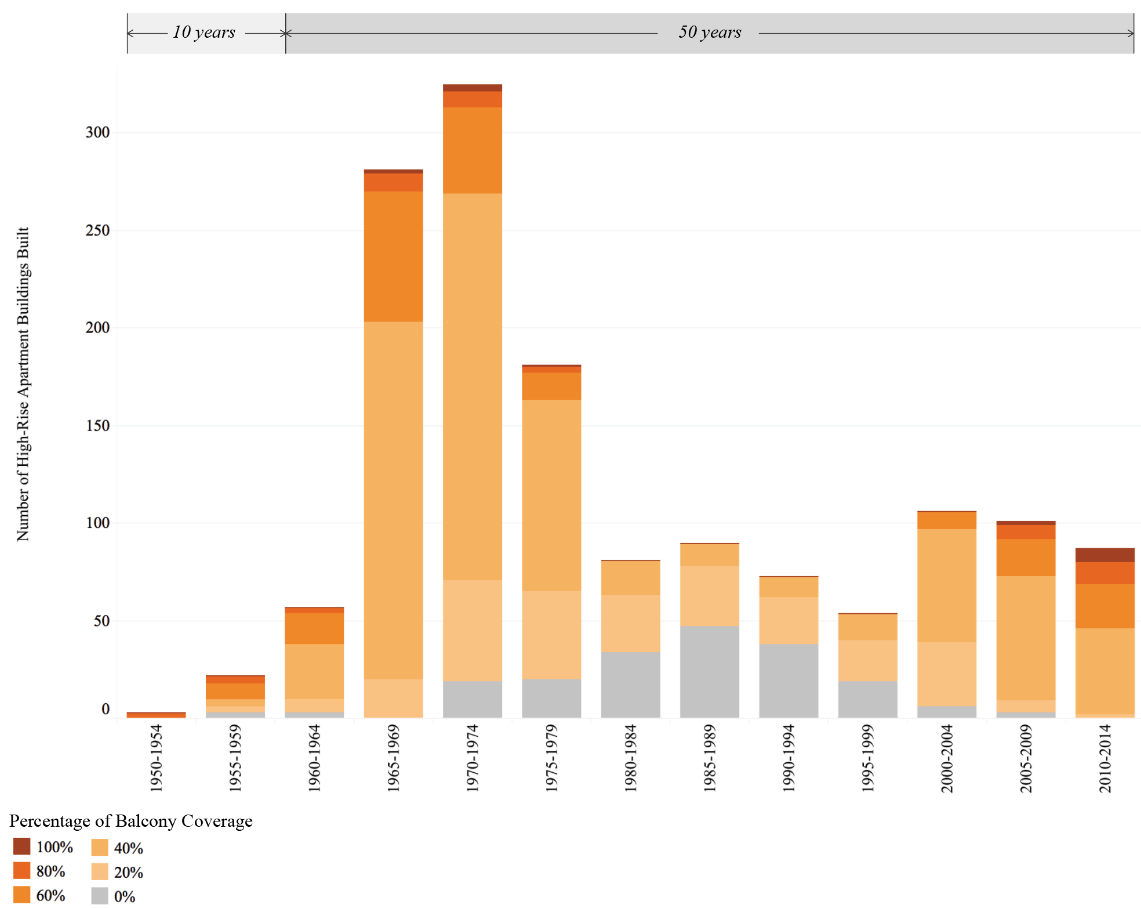


Figure 4-1: Percentage of Balcony Coverages in Residential Towers.

Towers built from the 1950s to 2015 in the Greater Toronto Area are studied based on the data collected from Architectural Conservatory of Ontario (ACO Toronto, 2016)

Mid-20th century housing structures are reaching the end of their designed lives, and there is currently an increased need for their adaptation. The volume of building adaptation and new construction in the residential sector was analyzed for this article across the City of Toronto from

2001-2017, and this provides much of the basis from which its scope for demonstration is derived. In the City of Toronto there has been an increase in the number of balcony related building adaptations compared to all other building adaptations over the last decade. These trends show the importance of balconies in Toronto, and similarly in many northern European cities that experienced baby booms and population influxes post-world war II. Building alterations, interior renovations and additions were studied. In 2001, 52% of all applicable building permit applications studied were related to residential adaptation activities, while 48% were related to new construction. By 2009, adaptation-related projects had increased significantly and, by 2016, made up over 75% of all building permits issued (City of Toronto, 2019). These numbers align with the EU housing construction market, whereby 2014, over 61% of housing construction was allocated to refurbishment up from 49% in 2007 (Brandão de Vasconcelos et al., 2016). In the US, building adaptation rates reached approximately 50% of all building repairs in 2011 and are expected to have increased accordingly since then (Bernstein, 2011; Moschetti et al., 2018) (**Figure 4-2**).

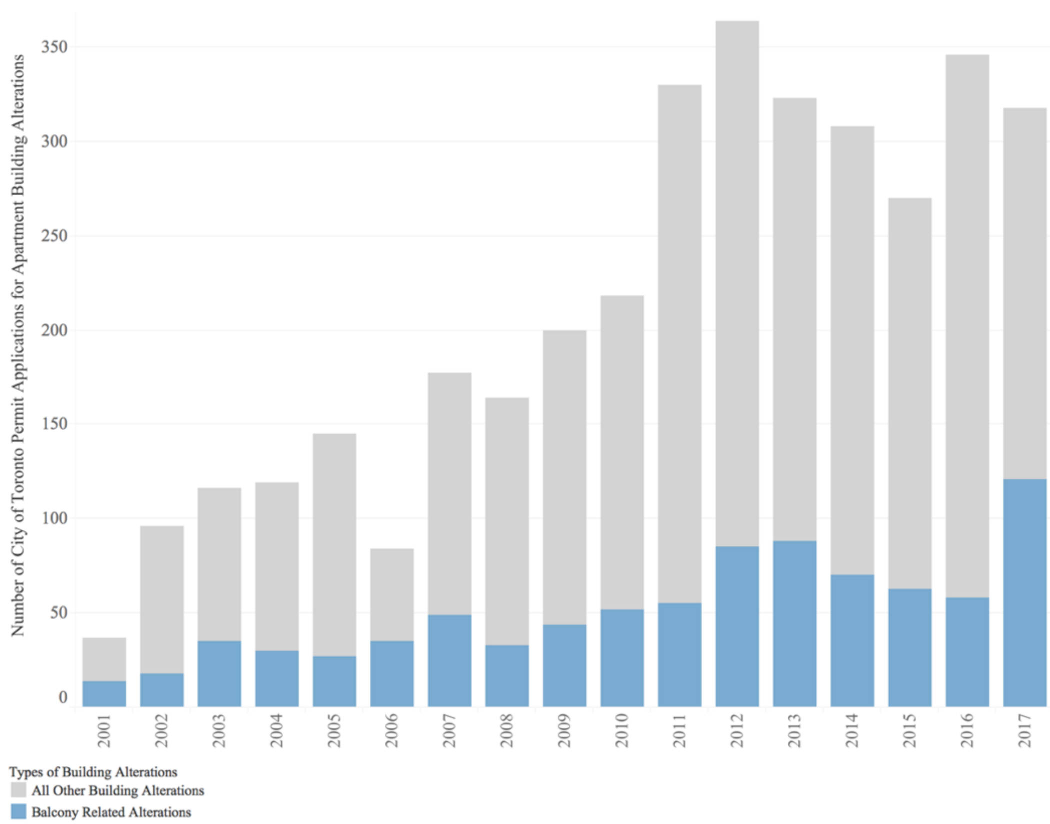


Figure 4-2: Types of building alterations.

balcony related vs. all other building alterations in multi-family housing in the City of Toronto Based on City of Toronto permit database (City of Toronto, 2019).

Despite this proliferation of projects, evaluation of design options has been limited in practice, and success of the designs executed is questionable. This is likely due to the lack of a disciplined framework and the allocation of limited design professional resources, so that a limited number of adaptation strategies are considered for assessment. Early in the design process, the consideration of a large range of strategies is a necessary prelude to a successful generative and detailed design process. To address this gap in practice and theory, a decision-making framework is developed in the following sections for supporting generation, evaluation and selection of multiple conceptually orthogonal design options as a basis for future computational design optimization and detailed design. First, fundamental adaptation strategies are identified as critical elements of a design language for design generation, and they are demonstrated for a class of multi-unit, multi-story residential buildings characterized by the problematic dominance of underutilized and poorly designed balconies.

To do this, six residential adaptation projects are selected based on international presence, complexity and rigour in the integration of building adaptation strategies for design option development at the scale of the balcony and the building envelope. Ten archetypal adaptation strategies are derived from an analysis of a broad representative range of final design cases to create the primary design language in terms of principle dimensions that can be used to define specific, conceptually orthogonal options. All identified strategies are modelled in BIM on one of the building cases, the Ellebo Garden building, for direct comparison. Each building model includes the details of the existing building condition, the demolition scope, and the scope of the new construction. Cost for each phase and the breakdown of cost by equipment, labour and materials are analyzed for prioritizing strategies. Projects are also analyzed based on complexity of construction and the domestic and international precedence, influencing their ease of implementation as measures to narrow down feasible design option for further analysis in later stages. The most desirable strategies are identified through multi-attribute utility theory. Functionally demonstrating these steps in the framework validates its efficacy for application early in the building adaptation process. To further ground this research methodology, it is helpful to begin with a literature review.

4.2 Background

4.2.1 Design Option Assessment in Building Adaptation

To address sustainability concerns in construction and with the help of emerging technologies, building professionals can evaluate more design alternatives than in the past (Clevenger & Haymaker, 2011), though, as argued here, they may not evaluate enough alternatives.

Integration of systems thinking, requiring designers to consider the entire systems, component and the relationships in the design process, and the simultaneous consideration of multiple attributes instead of an exclusively reductionist approach while leading to sustainable designs (Blizzard & Klotz, 2012) has contributed to this potential increase. One challenge in practice is the implementation of unfamiliar design options that can introduce levels of risk, including cost increases and difficulty with permit processes as examples, and designers typically consider design strategies based on pre-determined principles often overlooking unfamiliar strategies (Y. C. Liu et al., 2003). A satisfactory design strategy is an integrated response to a series of diverse issues, which are often a result of uncertainties about design objectives and priorities (B. Lawson, 2006). It is, therefore, necessary to understand the importance of design management (Austin et al., 1999) and to optimize amongst conflicting objectives in complex building projects. An extensive review of multiple approaches for improving the process of design option assessment is presented as part of Chapter 2 on page 18.

4.2.2 BIM and Computational Design Methodologies in Early-Stage Design

Building Information Modeling (BIM), in addition to being a method for design, documentation, and performance analysis of structures and their systems, can also be used for optimization and data visualization of building data. Benefits of BIM for design option analysis include interoperability of software resulting in high levels of flexibility and adaptability in the way stored building element information and data can be used (Pezeshki & Ivari, 2018). Accurate performance simulation and scientific visualization is a challenging task as it requires multi-disciplinary skills (Regt, 2014). While any simulation tool is based on specialty knowledge, their accessibility and ease of integration brings great value when used in early design and analysis stages of a project. Feedback regarding design options in the pre-construction stage can help designers, architects and engineers better understand the designed environment and its performance (Peters, 2018).

With advancements in analysis tools in terms of quantity, accessibility and interoperability, feedback regarding various performance parameters is becoming increasingly dependable, and cost and constructability analysis can also assist designers in making informed decisions (Peters & Peters, 2018). Cost estimation is typically conducted by taking manual takeoffs from drawings or entering information into customized cost estimation software. Aside from the potential for human error and redundancy of information, this can be costly and time-intensive. However, quantity takeoffs, material information, counts and measurements can be readily extracted from a BIM model. In this process, the cost estimate will be live and responding to design changes

(Pezeshki & Ivari, 2018). The embedded information of materials, quantities and construction of a structure in BIM enables the categorization of this data and cost estimation, making cost estimation more accessible to designers and engineers involved in the project. Within BIM, embedded information and workflows enable accessible and accurate cash flow analysis, quantity takeoffs, cost estimating, cost forecasting and scheduling (Hwang et al., 2012; Kim & Grobler, 2013; Pezeshki & Ivari, 2018).

Computational simulation and design tools are beginning to be used for early-stage design optimization and enable the analysis of complex building adaptation strategies, such as building form manipulation, in addition to the more efficient analysis focused on building material characteristics such as insulation and glazing types (Kiss & Szalay, 2020). The consideration of multiple factors including cost, energy and life-cycle performance is increasingly highlighted, as demonstrated by Granadeiro et al., which integrate early design stage automation of building envelope design with energy simulation using grammars (Granadeiro et al., 2013). Yu et al. used genetic algorithms to support automated spatial organization and their analysis in the early stages of design (Yu et al., 2007). The computational time for implementing computational design methodologies for optimization of design options considering a multitude of analysis metrics, such as energy use, daylighting, structural efficiency, life cycle impact, and life cycle cost can be massive and uneconomical on large projects such as multi-family housing. Judicious assessment of a wide range of design options leading up to this stage is a necessary prelude for effective allocation of this massive computing required for computational design optimization.

4.2.3 Knowledge Gap

It has been demonstrated in the preceding review that a limited number of adaptation strategies are considered for assessment in the literature and in practice, and assessment is typically narrowly based on energy use improvements such as increased insulation, new windows and integration of renewable energy. To address this gap in practice and theory, a decision-making framework must be developed for supporting generation, evaluation and selection of multiple conceptually orthogonal design options as a basis for future computational design optimization and detailed design.

4.3 Research Methodology

Such a framework is developed here (**Figure 4-3**). First, fundamental adaptation strategies are identified as critical elements of a design language for design generation, and they are demonstrated for a class of multi-unit, multi-story residential buildings characterized by the problematic dominance of underutilized and poorly designed balconies. Selected options are then analyzed in terms of cost, feasibility and relevance. The most desirable strategies are identified through multi-attribute utility theory. Functionally demonstrating these steps in the framework validates its efficacy for application early in the building adaptation process. While outside the scope of this chapter, the steps for completing further computational design algorithms and simulation tools for optimal design selection are also outlined in the framework to present the contributions of this chapter in their broader design methodology context.

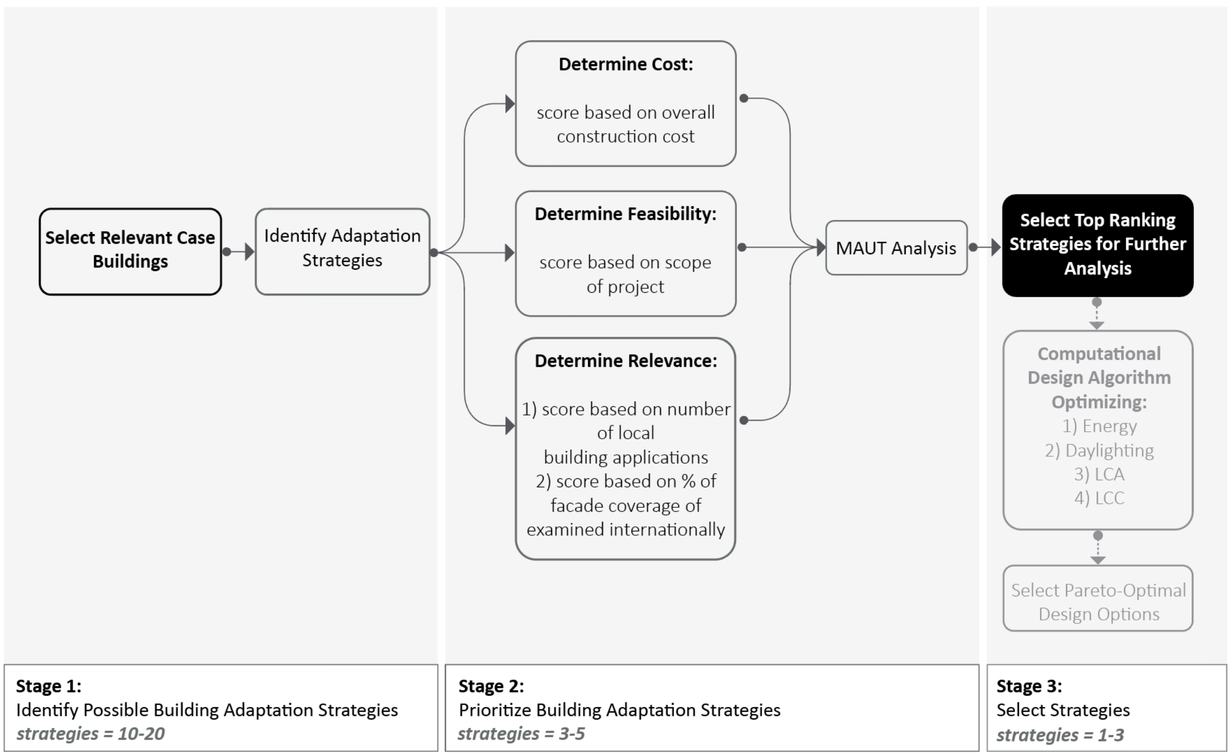


Figure 4-3: Proposed Framework for Developing Building Adaptation Design Option Assessment in Early-stage Design

4.3.1 Identifying Possible Building Adaptation Strategies: Case Study Analysis

Precedent-driven design is a process of generating new design strategies by combining and altering already tested design solutions (Clevenger & Haymaker, 2011). The case study of archetypical building adaptation cases is selected as the primary research strategy, as a suitable methodology for evaluation of buildings, as it is defined as an empirical investigation into the real-life operation of a specific context (Yin, 1993). Due to the unique applications of the case buildings, it is not appropriate for selected data to be directly compared. Therefore, case study analysis can only be used effectively in understanding and articulating underlying patterns (Amaratunga & Baldry, 2001).

The advantage of this methodology is enabling a detailed understanding of reality possible through built examples. Case study analysis is used in this research to demonstrate a detailed examination of building adaptation strategies related to the residential balcony in complex international examples. Common residential building adaptation strategies and their proliferation are studied through analysis of six archetypical projects (Table 2). Building adaptation cases were selected based on observed variation and complexity of adaptable building strategies. A number of common residential building adaptation design strategies are identified from the case studies (Figure 5).

4.3.2 Prioritizing Building Adaptation Strategies: Cost, Complexity and Context

The identified strategies are prioritized based on the analysis of cost, complexity and context. The overall cost of implementing each strategy is calculated, including demolition and new construction. Each of the identified strategies were modelled in 6D BIM as part of variations on a single case building. The 6D BIM models include phase data of existing, demolition and new construction as well as element cost information. Sigma Estimates®, a plug-in for Autodesk Revit®, is used to extract the model data for overall costing analysis of each strategy. The costing information is categorized by the cost of demolition and new construction in Figure 6. Feasibility is analyzed through the understanding of project complexity. The complexity of each strategy is determined by assessing the scope of the project for each strategy. For determining the contextual relevance of each of the strategies, the proliferation of each strategy in international cases studied and locally within the City of Toronto is determined. Context is used here as an empirically validated proxy for building physics studies, which are impractical in this early design phase. Chronologically recent and geographically proximate use in practice is evidence of design options that have been determined to be effective after detailed design for the climatic zone and building stock of a region for which the design option appraisal is conducted. Given the prevalence of urban clusters in our current geography, this is a reasonable addition to an overall early design options appraisal framework.

4.3.3 Application Method for Multi-attribute Utility Theory

The objectives determined for are used for the ranking of strategies using Multi-Attribute Utility (MAU) analysis. MAU is a methodology for evaluating situations with a multitude of goals, usually with varying degrees of importance (Gumasta et al., 2011; Kapur, 2015). The purpose of MAU analysis is to arrive at a combined measure of appeal (utility factor) for an outcome based on a set of alternatives. MAU is most useful when determining which alternative suits a situation the best, based on multiple objectives (Gumasta et al., 2011). An MAU analysis of alternative strategies, in this case, between various residential building adaptation strategies, identifies options that perform well on the identified objectives (Li et al., 2011). The objectives for evaluation include cost, feasibility and relevance of identified strategies.

In an MAU function, for a set of determined values x1, x2, … …, xm (percentage of change for each adaptation strategy), with an attribute of m objectives (performance measures), the overall utility of alternatives are calculated as follows(Kapur, 2015; Li et al., 2011):

$$U(x_1, x_2, \ldots \ldots, x_m) = k_1U_1(x_1) + k_2U_2(x_2) + \ldots \ldots + k_mU_m(x_m)$$
$$= \sum_{i=1}^{m} k_i U_i(x_i)$$

$U_i(x_i)$ = the single utility function of the ith attribute $0 \leq U_i(x_i) \leq 1$.

k_i = the weight of the ith attribute ($k_1 + k_2 + \ldots \ldots + k_m = 1$)

x_i is the computed value of ith attribute i

The Entscheidungsnavi® tool is used for MAU analysis. An MAU matrix is created between identified building adaptation strategies and objectives. For each objective, a single utility function is determined (between 0 and 1) to determine the weight and importance of each measure on the overall result (Kapur, 2015). To determine the top most relevant building adaptation strategies, cost, feasibility and relevance are considered. The demolition, new construction and overall cost are calculated, and strategies are ranked, with the lowest cost having the highest-ranking per each category. The identified strategies are also ranked accordingly to their relevance to the local context, evaluated using analysis of building permit applications in the City of Toronto.

Based on the developed framework, a total of 10-20 identified strategies can be narrowed down to a smaller range for a feasible future computational design optimization using analysis and simulation of design option energy use, life cycle impact and life cycle cost.

4.4 Results

4.4.1 Analyze Relevant Case Studies

The following six case studies demonstrate a range of building adaptation strategies. The context and scope of work for each project are described in the following. The first case is an adaptation project completed in Bordeaux, France, designed by Lacaton & Vassal. The Block G, H, I project was completed as a part of a more extensive development to transform existing inhabited social housing buildings in Bordeaux, France. The existing buildings were built in the early 1960s, and house 530 dwellings. In this project, winter gardens and expanded balconies were added to primarily improve the overall quality of each unit in terms of the improved building envelope, light, use and views. This project was successful in transforming the building and improving environmental and comfort performance. The adaptation strategies implemented include extending the building, adding new balconies and layering on to existing balconies, re-cladding and extension of the glazing (Lacaton et al., 2011).

The second case study, The Ellebo Housing State by Adam Khan Architects in Ballerup, Denmark, is comprised of collective blocks arranged around a large communal outdoor court. The buildings were built in the mid-20th century, and with refurbishments made in the 1990s, the buildings are still a solid base for adaptation. In the 1990s, performance improvements to the envelope and systems of the building were introduced, and the balconies were enclosed to extend living spaces. In the recent adaptation of the Ellebo Garden building, some balconies were extended, balconies were added, significant portions were re-clad, and some of the glazing was extended. These adaptation strategies have improved the buildings in terms of interior spatial arrangement, connections to the exterior as well as environmental performance and comfort (Fernández et al., 2014).

The Gruentenstrasse project is the third case study designed by Lattke Architects in Augsburg, Germany. The project is comprised of two six-storey buildings in Augsburg, Germany, built-in 1966. They are built from a typical mass brick construction, common in Germany between the 1960s and the 1970s. The project improves outdoor spaces of the building and energy. The building was extended, balconies were added, and parts of the glazing was extended. The entire building was also insulated and clad in rough sawn white-painted spruce boards. The existing cantilevering balconies on the south façade were contributing to extensive energy loss due to thermal bridging. The south-facing balconies were insulated and converted to winter gardens, while new balconies were added elsewhere (Lattke & Boonstra, 2014). The Fourth case study, Piazza-Flat, is completed by A3 Architects in Gorinchem, Netherlands, a social housing project built in 1975 by the Service flats Gorinchem Foundation. In 2009, a new outer shell was built, the balconies and were insulated and converted to winter gardens, adding much needed usable living space to the apartments (Architecten, 2019).

Le Chesnaie highrise state is a highrise complex in Saint-Nezaire, France, adapted by Lacaton & Vassal and originally built in the 1960s. The building was dated and highly prone to demolition and reconstruction. The buildings were restructured to accommodate the well-preserved solid construction, and to improve the conditions for the inhabitants. The adaptation strategies implemented at Le Chesnaie include the extension of the building, adding balconies to the existing and partial extension of glazing (Lacaton & Vassal, 2015). The last case study, the Weberstrasse tower, is designed by Burkhalter Sumi Architects in Winterthur, Switzerland. The building has been extended in the north by the addition of studio flats and loft apartments. On the interior, multiple apartments have been joined to form larger apartments. In this process, balconies have been extended in some instances and relocated in others to make them more suitable for the new layouts. The strategies implemented include the extension of the building, adding and relocating balconies, re-cladding and extension of glazing (Batthyany & Shramm, 2013).

Strategies extracted from case study analysis are divided into the two-building adaptation categories of refurbishment and adaptive reuse demonstrated in **Figure 4-4**. Primarily, environmental and structural refurbishment strategies that aim at improving the current condition of residential towers through various strategies 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 spatial conversion, have also been highlighted that aim at improving urban relevance, spatial use, and occupant comfort in addition to environmental and structural improvements. These strategies include (1) addition, (2) in-setting, (3) layering and (4) extending the building at the balcony.

4.4.2 Identify Building Adaptation Strategies

4.4.2.1 Refurbishment Strategies

Based on the identified adaptation strategies in the case studies, the first five strategies are categorized as refurbishment, as they focus on the rehabilitation of the balcony and the retrofitting of the building envelope (Shahi et al., 2020). Restructuring of the balcony focuses on the refurbishment of the failing concrete and reconstruction of the balcony railings. Restructuring is one of the most common strategies for rehabilitating residential towers. It is also one of the least intrusive as it does not involve envelope or interior work (Kesik, 2009). Re-glazing is defined here as the retrofitting of windows and extension wherever applicable. Reglazing can contribute to improved energy performance, daylighting and ventilation. Re-cladding focuses on retrofitting the building envelope and contributes to improving environmental performance and interior air quality. Enclosing balconies using modular glazing systems, for example, can contribute to more comfortable use of balconies while not adding to the thermal load of the existing building. Insulating balconies is a retrofitting strategy focused on thermally enclosing balconies. This strategy can contribute to improved overall thermal performance, reduction of thermal bridging, and improved occupant comfort (Tower Renewal Partnership, 2017) (Figure 4-4).

4.4.2.2 Adaptive Reuse Strategies

The other adaptation strategies identified from the case studies can be categorized as adaptive reuse, focused on conversion of balconies to accommodate changes in spatial requirements and densification or rearrangement of the building layout (Shahi et al., 2020). Addition and relocation of balconies are often a result of interior modifications or envelope redesign (Batthyany & Shramm, 2013), and are common as part of complex building adaptation projects. In-setting of balconies, converting of existing interior spaces into outdoor balcony spaces, are not common due to the reduction of interior space but can lead to improved environmental and comfort performance due to reduced unit depth. Layering and extending of the balcony are the most intrusive strategies and have the highest impact on interior spaces. Layering of the balcony can create environmentally mediating spaces, such as winter gardens and can improve energy efficiency while extending the livable space (Lacaton et al., 2011). Extension of the balcony involves spatial and structural additions and reconfiguration of the existing balcony. This strategy can be a result of densification measures and can lead to the addition of bedrooms or to a single unit or the addition of entire units to an existing building (Figure 4-4).

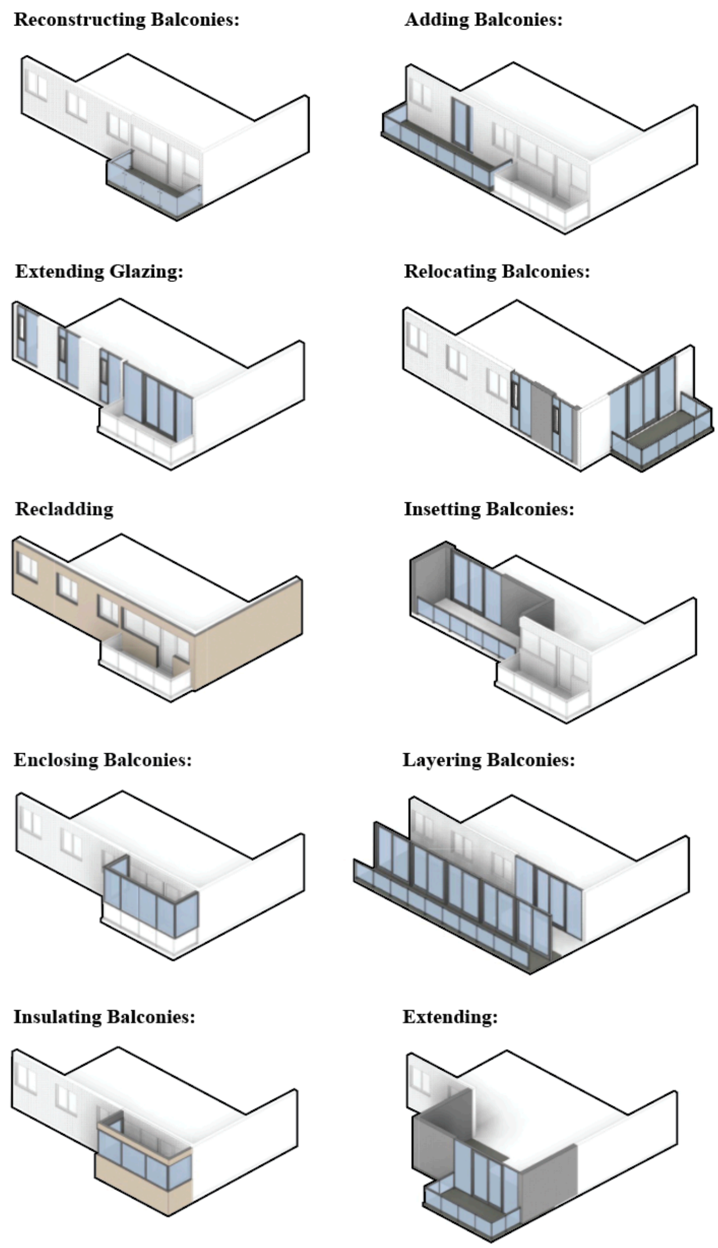


Figure 4-4: Identified Building Adaptation Strategies from Case Study Analysis Refurbishment Strategies (left): Reconstruction, Extending Glazing, Re-cladding, Enclosing and Insulating. Adaptive Reuse Strategies (right): Adding, Relocating, Insetting, Layering and Extending.

4.4.3 Assessment of Building Adaptation Strategies

The selected design options are analyzed in terms of cost, feasibility and relevance to select the most potent strategies for further analysis. For this analysis, each of the identified strategies were modelled in 6D BIM on the existing condition of the Ellebo Garden project, as a case building. The 6D BIM models include the existing building conditions, demolition requirements for each strategy and the new construction scope.

4.4.3.1 Cost

Sigma Estimates®, a plug-in for Autodesk Revit®, was used to extract the model data for overall costing analysis of each strategy. Based on the analysis of demolition and new construction cost, some strategies including re-cladding, enclosing, insulating and adding, have minimal to zero demolition cost with varying scopes of new construction cost. Relocating has the highest cost and scope for both demolition and new construction. In contrast, layering and re-glazing have much higher scopes and cost for new construction compared to their limited scopes of demolition. From the analysis of cost broken down by cost of equipment, labour and materials, it can be observed that while required equipment typically remains proportional, there is variation in the intensity of materials and labour between strategies. Enclosing, insulating, adding, and in-setting are close to having a proportional material and labour cost. Restructuring, re-cladding, in-setting and extending are more labour intensive, and layering and re-glazing can be categorized as being more material intensive. In terms of overall cost, relocating, extension, layering and re-glazing are the most cost-intensive strategies, respectively, and enclosing, re-cladding and restructuring have the lowest total costs (**Figure 4-5**).

4.4.3.2 Feasibility

Feasibility of a project can be evaluated in terms of challenges that can increase project complexity, time and budget (Sidwell & Francis, 1996). The percentage of the building façade involved in each strategy is used as a measure to understand the scope involved in each project. The percentage of the total building façade being adapted, broken down by the percentage of each strategy, is demonstrated in Table 3. Extending is the most intensive of strategies involves 1.25 times of the façade of the building in the project. It is ranked as the most intensive strategy, and the other strategies ranked accordingly for comparison.

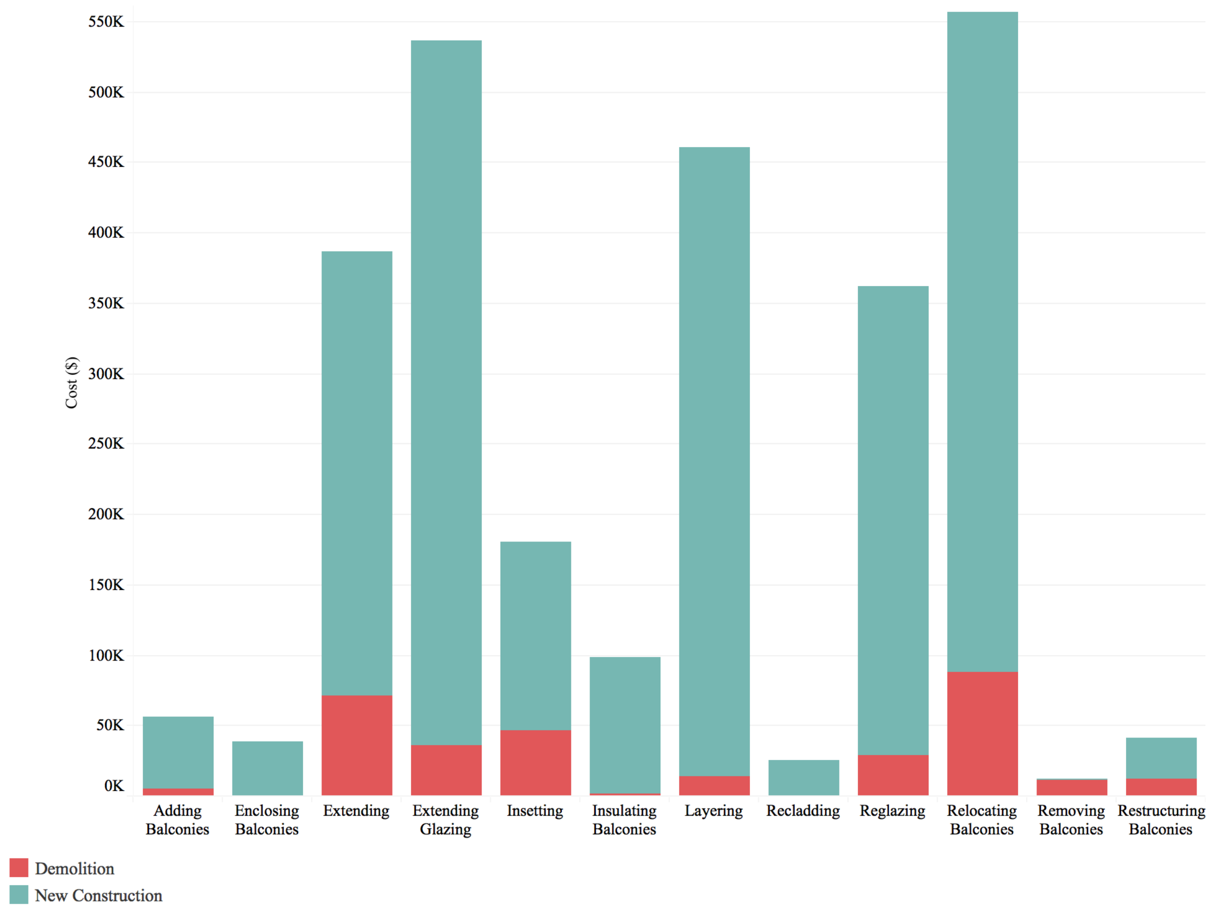


Figure 4-5: Cost of Demolition and New Construction for Each Strategy adopted on a typical 4-storey building based on Case Study #2 (Ellebo Garden 1, Adam Khan Architects, Ballerup, Denmark)

4.4.3.3 Relevance

From 2001 to 2017, there was a recorded number of 3615 building alterations to residential towers in the City of Toronto. Out of these alterations, 25% were related to balconies. 80% of balcony alterations were related to balcony and guard repairs, and 15% were related to balcony enclosures. Other building adaptation strategies in place in the City of Toronto within this period include re-cladding (3%), re-glazing (2%), adding (1%) and extension (1%). Out of the 993 recorded permit applications in the City of Toronto related to building alteration and additions, only six applications involved multiple building adaptation strategies (City of Toronto, 2019). This 0.6 % of applications included a combination of balcony reconstruction, re-cladding and re-glazing (**Figure 4-6**).

The distribution of each of the identified strategies across the various case studies is also demonstrated. It can be observed that Bordeau had the least number of strategies used, with over 65% allocated to layering and about 30% to re-glazing. The majority of case studies used three strategies in the total scope, and Weberstrasse was the most diverse, incorporating five different strategies. Re-glazing is the single strategy common across the different case studies analyzed. Recladding was the second most common strategy implemented, followed by extension. This information is used to conclude which of the case studies are the most relevant to the local context being studied for further analysis.

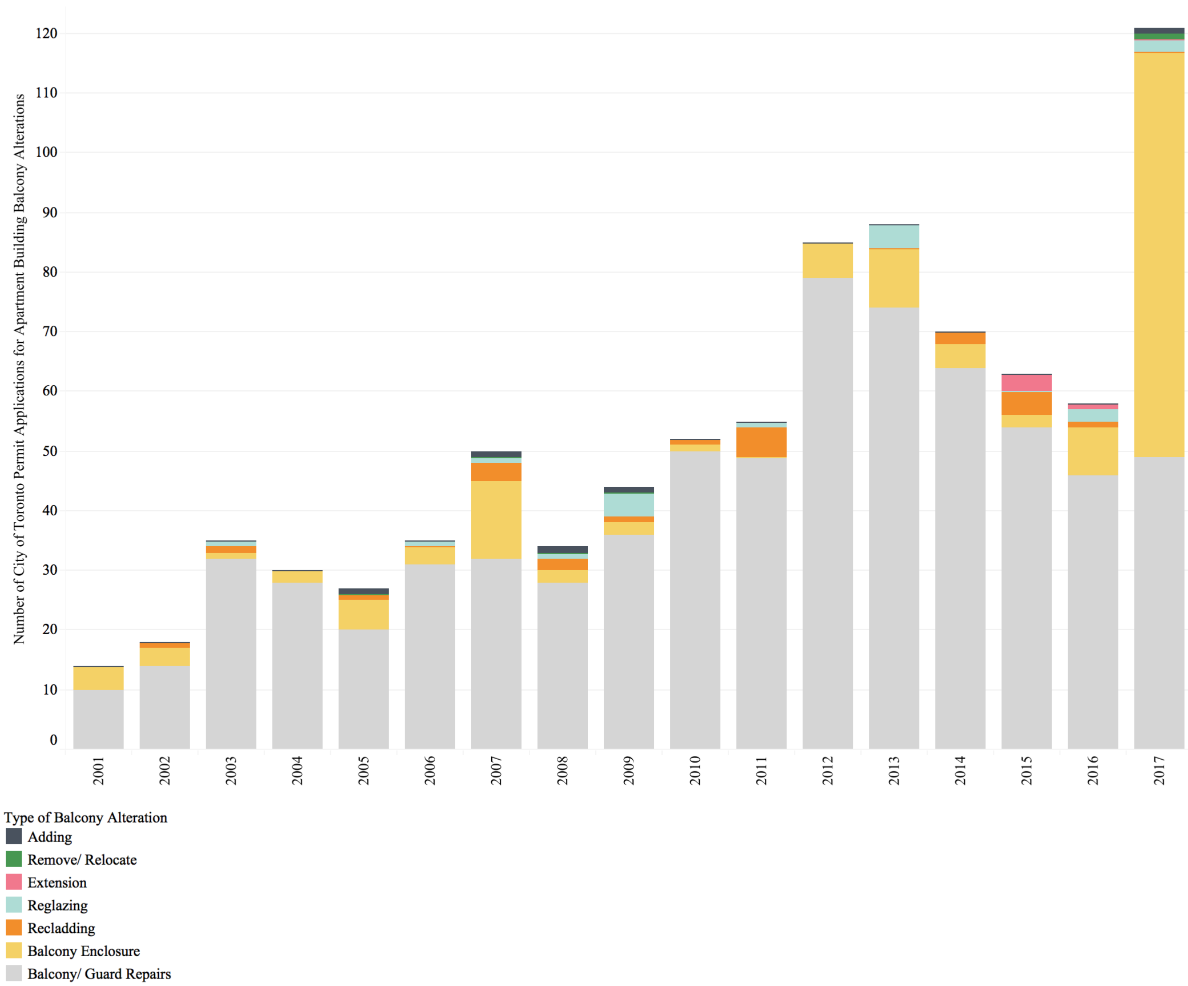


Figure 4-6: Types of balcony alterations in City of Toronto based on the City of Toronto permit database (City of Toronto, 2019).

4.4.3 Ranking Strategies - Application Method for Multi-attribute Utility Theory

The construction cost, feasibility and relevance of all of the strategies are determined and documented in **Table 4-1**. The demolition, new construction and overall cost is calculated, and strategies are ranked, with the lowest cost having the highest-ranking per each category. The details of costing information and analysis are provided in **Appendix C**. Secondly, strategies are ranked accordingly to their relevance to the local context, evaluated using analysis of building permit applications in the City of Toronto. A Comparison of building adaptation strategy ranking in terms of cost and relevance in City of Toronto, with the percentage of each identified strategy in the case studies, can give an idea of which of the case studies are relatable to the parameters being studies. It can be concluded that case 3 is the most relatable building that is studied further for applications in similar projects in Toronto. Cases 2, 3 and 6 also show modest relevance to the context being studied, and case studies 1 and 6 demonstrate minimal relevance. From the analysis of the context, the most common building adaptation strategies observed include restructuring and enclosure. From the analysis, the three strategies, restructuring, enclosing and re-cladding, with the highest-ranking, are identified as prioritized retrofit measures.

Table 4-1: Ranking of Strategies - based on the 4 Identified Objectives, with 0 the most desirable and ten least desirable, determined by the authors. The details of costing information and analysis are provided in Appendix C.

	Cost		***Complexity***		***Contextual Relevance***								
	Total Project Cost (Inc. Demolition, New Construction, Soft Costs, VAT)		**Scope of Project** (% of Façade Coverage)		**Building Permits in the City of Toronto** (% of all Relating to Exterior Alterations from 2001-2017)		**Scope of Project** (% of Façade Coverage)						
	Total	**Ranking**	Total	**Ranking**	Total	**Ranking**	Ellebo	Saint Nezaire	Weberstrasse	Bordeau	Piazza Flat	Gruentenstrasse	Total
Reconstruction	$ 120,535	**1.2**	20%	**1.6**	79%	**1**			3%		7%		10%
Re-glazing	$ 554,162	**5.5**	37%	**2.9**	2%	**9.9**	5%		4%		50%	7%	66%
Adding Glazing	$ 445,970	**7**	68%	**5.4**	0%	**10**	5%	6%	2%	32%		7%	52%
Re-cladding	$ 99,320	**0.1**	73%	**5.8**	3%	**9.6**	51%		43%			61%	155%
Enclosing	$ 92,235	**0.92**	20%	**1.6**	15%	**9.8**					43%		43%
Insulating	$ 171,498	**1.7**	37%	**2.9**	0%	**10**						25%	25%
Removing Balconies	$ 81,530	**0.82**	20%	**1.6**	0%	**10**							0%
Adding	$ 203,068	**2**	21%	**1.7**	1%	**9.9**	22%	23%					45%
Relocating	$ 925,358	**9.2**	71%	**5.7**	0%	**10**			17%				17%
Insetting	$ 416,640	**4.2**	90%	**7.2**	0%	**10**							0%
Layering	$ 597,530	**6**	87%	**6.9**	0%	**10**				68%			68%
Extending	$ 695,863	**7**	125%	**10**	0%	**10**	19%	71%	31%				121%

Using MAUT analysis, the rankings of each of the strategies demonstrated in **Table 4-1** were accounted for, with each of the objectives given equal weights. **Figure 4-7** demonstrates the resultant utility factors for each strategy. Enclosing balconies, reconstructing balconies and re-cladding ranked as the most desirable strategies according to the set objectives. Relocating, removing and layering balconies ranked as the lowest desirable strategies respectively.

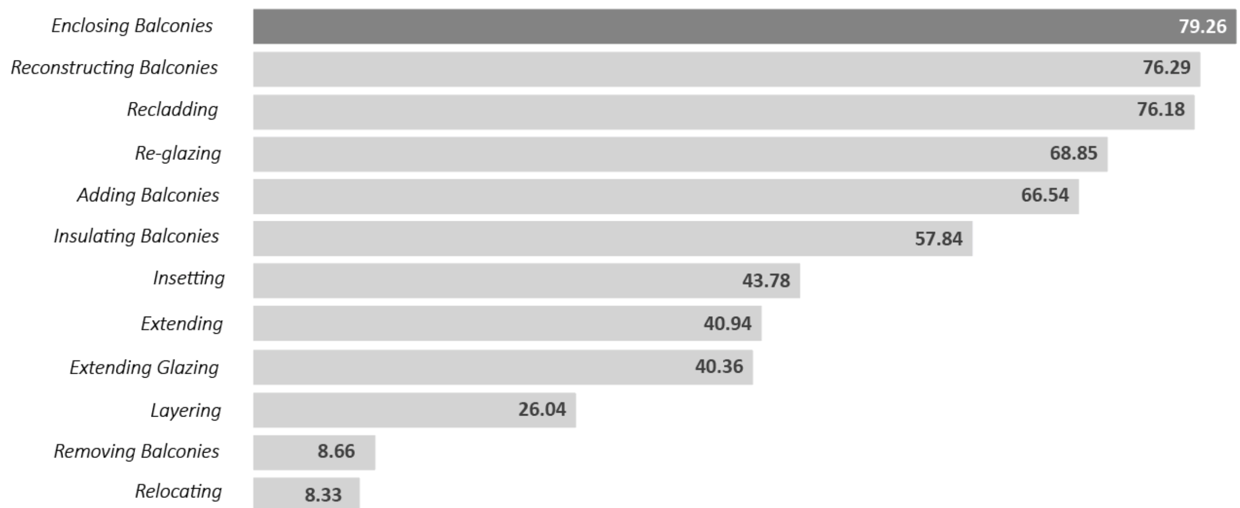


Figure 4-7: Comparison of utility factors for building adaptation strategies.

4.5 Discussion

According to the initial assessment, relocating balconies and extending had the highest demolition costs and relocating balconies and extending glazing had the highest total construction cost. Removing balconies is comprised of mainly demolition costs, and re-cladding, enclosing and adding balconies of mostly new construction costs and make up the lowest overall construction cost, respectively. In terms of complexity, reconstruction, enclosing and adding of balconies have the lowest score while extending is assessed as the most complex. Reconstruction is by far the most common strategy, suggesting ease of logistic implementation, including precedent and ease of permit approvals and construction expertise. Many of the strategies, such as re-cladding, extending and layering are more common in international project with some local precedence. Their success of their implementation can enable their increasing demand in the Toronto residential building adaptation market. Strategies that rank poorly on both local and international relevance, such as removing and relocating balconies are regarded as low priority strategies.

Enclosing balconies, reconstructing balconies and re-cladding of the building envelope are identified as the most relevant building adaptation strategies according to this study and worthy of further implementation in practice. While the lowest ranking strategies, such as removing balconies and relocating, can be negligible in future studies. There are some mid-range strategies that might be of interest for future analysis, such as insulating of balconies and extending. A comprehensive environmental, life cycle and cost-benefit analysis can highlight the benefits of these strategies. This framework suggests the cost and complexities of identified strategies, but it is important to investigate life-cycle cost benefits to make a more comprehensive comparison between desirable strategies.

While this framework does not lead to a comprehensive analysis of design option strategies, it is a useful guideline for the preliminary analysis of design strategies. Understanding that a couple of strategies are more plausible in a given context, such as recladding and enclosing as examples, more focused studies can follow that examine the optimal configuration of each strategy for implementation such as different insulation factors and re-cladding methodologies, or enclosing technologies. With the completing of more comprehensive design analysis on any of the selected strategies, it will be useful to understand that while for example, extending might be an attractive strategy, its implementation will be more difficult because of the identified factors in this study in comparison to enclosing, and significant environmental, life-cycle and cost-benefits need to be achieved to justify its selection for further consideration.

There are currently programs and initiatives developed by municipalities, institutions and industry partners in order to develop policy on the adaptation of existing building stock (Kinnane et al., 2016). In order to facilitate building refurbishment and adaptive reuse, many governments, including Canada and the United States, have provided financial assistance to support energy-efficient improvements (Ma et al., 2012). The International Energy Agency (IEA) has introduced initiatives that encompass policy, finances and technical assistant for adaptive reuse and retrofit projects. These initiatives focus on the reliability of energy-efficient buildings, energy-optimized building renovations and pre-fabrication in building retrofits amongst others (Agency, 2013).

The framework developed for options assessment can be integrated into existing initiatives to promote residential building adaptation. Local programs that can utilize the future developments of this research include The Tower Renewal Project, a City of Toronto initiative which aims to support building upgrades, community development initiatives, and performance improvement programs through the support of the environmental, social, economic and cultural change. The

Tower Renewal Program aspires to achieve improvements through the many initiatives, including High-Rise Retrofit Improvement Support (Hi-RIS) program, the Sustainable Towers Engaging People (STEP) program, and the Residential Apartment Commercial Zoning (RAC) (Tower Renewal Partnership, 2017).

4.6 Conclusion

To be able to implement complex building adaptation projects, comprehensive environmental, life cycle and financial assessments are required to determine the most effective design strategies, which often required computational tools. To make this process feasible, prioritization of building adaptation strategies is an essential process in the building adaptation assessment. The importance of focused studies on building adaptation option assessment and the need to assess and prioritize building adaptation strategies to a building adaptation projects, including refurbishment and adaptive reuse, is highlighted. A literature review of building adaptation option assessment studies indicates a low average number of adaptation strategies considered in most complex studies. A decision-making framework is presented for supporting design strategy generation, assessment and selection for improving the analysis process.

The framework is functionally demonstrated for adaptation of multi-family residential buildings, involving the retrofitting, rehabilitation and conversion of balconies. Six multi-family residential case studies were analyzed, and a total of 10 basic building adaptation strategies were extracted. Identified strategies were modelled individually in 6D BIM on a typical 4-storey case building based on one of the case studies. The cost of demolition and new construction and source of costing, including equipment, labour and materials, were calculated and compared. Three of the ten identified strategies were identified for further analysis in terms of environmental and life cycle performance in future studies. The developed framework when applied to balconies, suggests a bridge between what is possible in terms of applied building adaptation strategies, what is most feasible in terms of cost, and what is possible and prevalent in terms of market application through the analysis of the local context of the City of Toronto. In the framework, adaptation strategies are prioritized for further analysis and increasing the efficacy of the building adaptation process is demonstrated, the selected three strategies include restructuring, enclosing and re-cladding.

5. Methodology for Building Adaptation Design Appraisal Using Physics-Based Simulation Tools

OVERVIEW

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. Integration of physics-based simulations 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 early-stage design feasibility. Ten residential building adaptation strategies are selected and studied on 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. This building adaptation appraisal methodology demonstrates consistent and reliable prediction of improvements for strategies according to energy use, ventilation, life cycle analysis, systems and cost-benefit. Prediction of thermal comfort, daylighting and life cycle benefits based on the developed 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.

5.1 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 strategies, including refurbishment and adaptive reuse of existing buildings, can provide a variety of benefits (P. Xu et al., 2011), and 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 & Haas, 2018; Shahi et al., 2020) including improving energy efficiency (P. Xu et al., 2011), financial gains from reduced maintenance and operation cost, improved thermal comfort and the increased useful life of buildings (Foley, 2012; Langston et al., 2008; Smith & Hung, 2015; Tokede et al., 2018; Wilson, 2010).

Building obsolescence is directly related to the shortcoming of designing prescribed building arrangements, and concrete multi-family housing is an example of this. The limited life cycle of building cause about 60% of all building demolitions in North America (D. A. Chen et al., 2016; Ross et al., 2016). Currently, most of the 20th-century high-rise concrete towers in Canada have reached the end of their lifecycle in terms of structural integrity and environmental performance. Multi-family towers are typically rigid in structure, limiting their use and making them prone to obsolescence. The obsolescence and redundancy of existing dated residential building stock are identified as critical issues for sustainable development (Manewa et al., 2016). During the last decades, limited improvements have been made in terms of structural integrity and environmental performance to the building envelope and balconies of residential towers.

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 lifecycle assessment tools can be challenging (Rezaee et al., 2019). Physics-based simulations of multiple design options is 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 & 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 for a specific condition. Also, there is 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 that can be applied for the evaluating building design option appraisal. MAU decision-making can be useful for processing different objectives in the process of considering multiple design variables. Also, IMO is an effective method in optimizing design decision-making.

The current chapter focuses on the adaptation of 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 early design stages. The index can further assist in the analysis of 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 can make feasibility studies more accessible and affordable. To achieve a holistically well-performing building, metrics including energy, indoor thermal comfort, lifecycle, cost-benefit and others can, therefore, be considered and optimized (Si et al., 2019). The basis of this research enables the automation of feasibility study through parametrization. It facilitates immediate MAU and IMO for adaptive reuse appraisal in architectural design practice and real estate development applications.

5.2 Background

5.2.1 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. In the integration of simulation-tools for design option appraisal of building adaptation projects, many methods have been researched and developed for environmental assessment (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 for optimization of 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 in terms of 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 & A., 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 comparable framework of these metrics against all scenarios (Wang et al., 2014).

There are a limited number of researchers in recent years that 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 & Szalay, 2020), the majority of which 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 be used to determine life cycle cost, energy efficiency or other quantifiable metrics (Sharafi et al., 2017).

Figure 5-1 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 & A., 2019), different construction methods and building sizes (Chidiac et al., 2011) and various budgets (Wang et al., 2014).

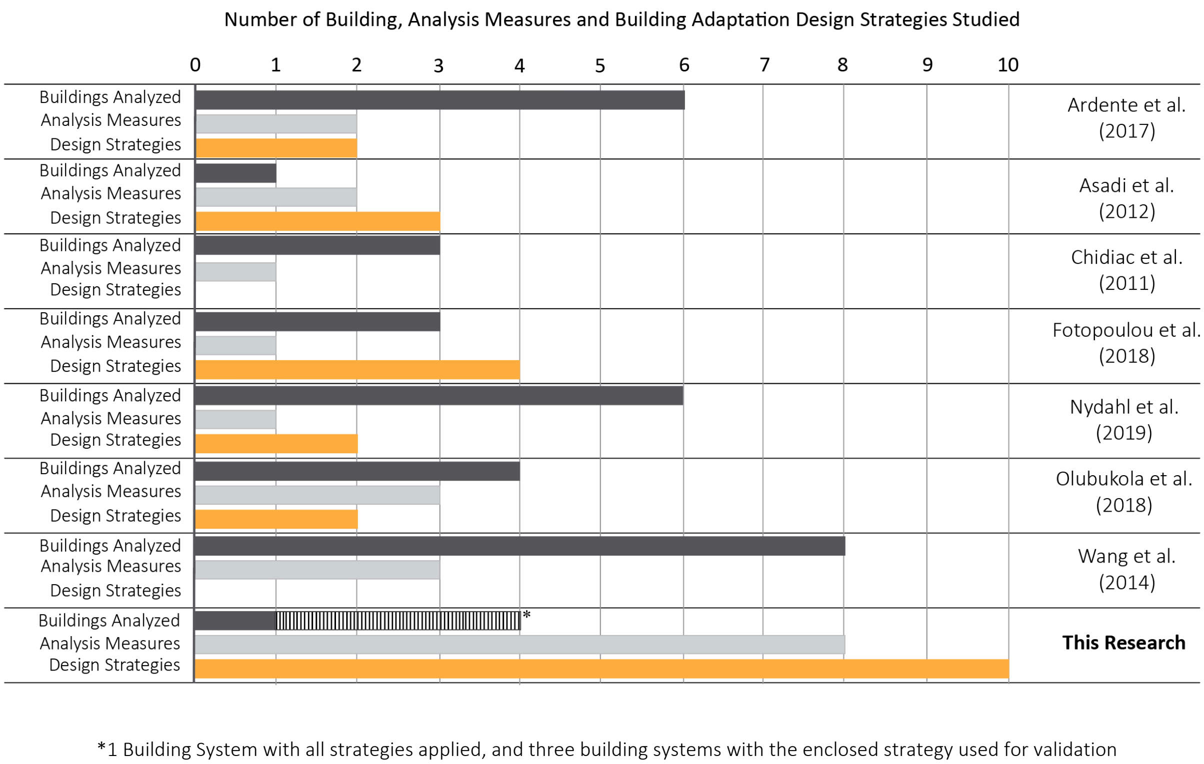


Figure 5-1: Comparison of the Number of Building Systems, Analysis Measures and Adaptation Strategies in the Literature Review.

5.2.2 Early Stage Design Optimization

The design process and specifically, 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 were able to demonstrate environmental savings of 60-80%. The consideration of multiple factors including cost, energy and lifecycle 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 an essential and foundational step 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 & Awan, 2018). 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). Factors that contribute to energy efficiency, overall cost and other performance measures are mainly determined in the conceptual design or project feasibility phase of a building project. 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 be able to 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 useful 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 lifecycle costs (Si et al., 2019).

5.2.3 Physics-Based Simulation Tools

Accurate performance simulation and scientific visualization is a challenging task as it requires multidisciplinary skills (Regt, 2014). Andriamamonjy et al. demonstrate that the seamless exchange of information between different software is important for the success of a construction project (Andriamamonjy et al., 2019). While any simulation tool is based on specialized knowledge, their accessibility and interoperability bring great value when used in the design and analysis stages of a project. Simulation tools are most useful when multiple parameters are analyzed simultaneously as they can contribute to optimized design decisions.

Feedback regarding design decisions in the pre-construction stage and analysis of building performance in the occupancy stages helps designers, architects and engineers better understand the designed environment and its performance. With advancements in analysis tools in terms of quantity, accessibility and interoperability, feedback regarding various performance parameters are becoming increasingly dependable (Peters & Peters, 2018). Energy, lighting, acoustic, heat and airflow studies can inform the impact of design projects on occupants and the environment. Structural, code, cost and constructability analysis can also assist designers in making informed decisions (Peters, 2018; Sokolowski & Banks, 2009).

Improved collaboration in the design process is mainly achieved through the seamless integration of various parties involved and the consolidation of their efforts. Highly integrated processes in BIM enable the identification of problems and gaps in development in preliminary design stages. This process reduces risks, duplication of work and allows the distribution of efforts in the initial stages with more efficiency in final documentation of solutions (Bueno et al., 2018). Limiting data duplication, redundancy and improving precision also enables the accuracy of analytical tools (Pezeshki & Ivari, 2018). The benefits result in BIM and computational design tools to be an important means for architectural, structural and systems design and performance optimization, as well as lifecycle and cost-benefit analysis (Chi et al., 2015).

The integration of BPS tools in the early-stage design process can facilitate the development of efficient and sustainable structures through the simultaneous analysis of multiple parameters (S. Chen, 2018; Krygiel, 2008). Physics-based simulation tools evaluate and interpret different performance metrics to advance understanding regarding the various factors influencing the design and facilitate optimized decision-making (Attia et al., 2012; Peters, 2018). The integration of physics-based simulation tools with BIM and computational design tools in this manner is proven to be beneficial from preliminary stages of a design process (S. Chen, 2018).

Application of physics-based simulations in early-stage design includes the ability to find relationships, map similarities and differences between design solutions, and to 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). New and integrated tools and immersive simulation and visualization capabilities, with the ability to customize codes, allows the participation of users in the development and customization of tools within computational design interfaces (Azhar & Brown, 2009; Sinha et al., 2013).

5.2.4 Knowledge Gap

In the literature review, the importance of building adaptation design appraisal and early stage design optimization has been highlighted. 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 for multiple objectives. Integration of physics-based simulation tools have been identified for improving the early stage decision-making process.

5.3 Methodology

The objective of this research is 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 the use of 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 a variety of 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 gaining a comprehensive analysis of how residential adaptation strategies would perform on the range of existing housing (**Table 5-1**). 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 is conducted. Selected strategies are modeled 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 is able to make a decision about how to narrow down the search objective as part of the IMO. Financial analysis such as return on investments and rental budgets are not considered in this analysis and will be investigated in further stages of the work. Other factors such as durability of design, ease of modifications, mechanical performance will be examined in further stages of this work. Further MAU analysis is conducted on a sample decision-maker selection set for demonstration (**Figure 5-2**).

The initial assessment includes analyzing ten adaptation strategies using eight analysis measures on one orientation, requiring a total of 80 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. For validation, one adaptation strategy is analyzed on multiple building systems for a total of 24 simulations (**Table 5-1**).

Table 5-1: 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	8	4	**12,800**
Experimental Methodology for Analysis	1	10	8	1	**80**
Validation of Experimental Methodology	3	1	8	1	**24**

*estimate of typical multi-family residential building types common in Canada (Tower Renewal, 2017)

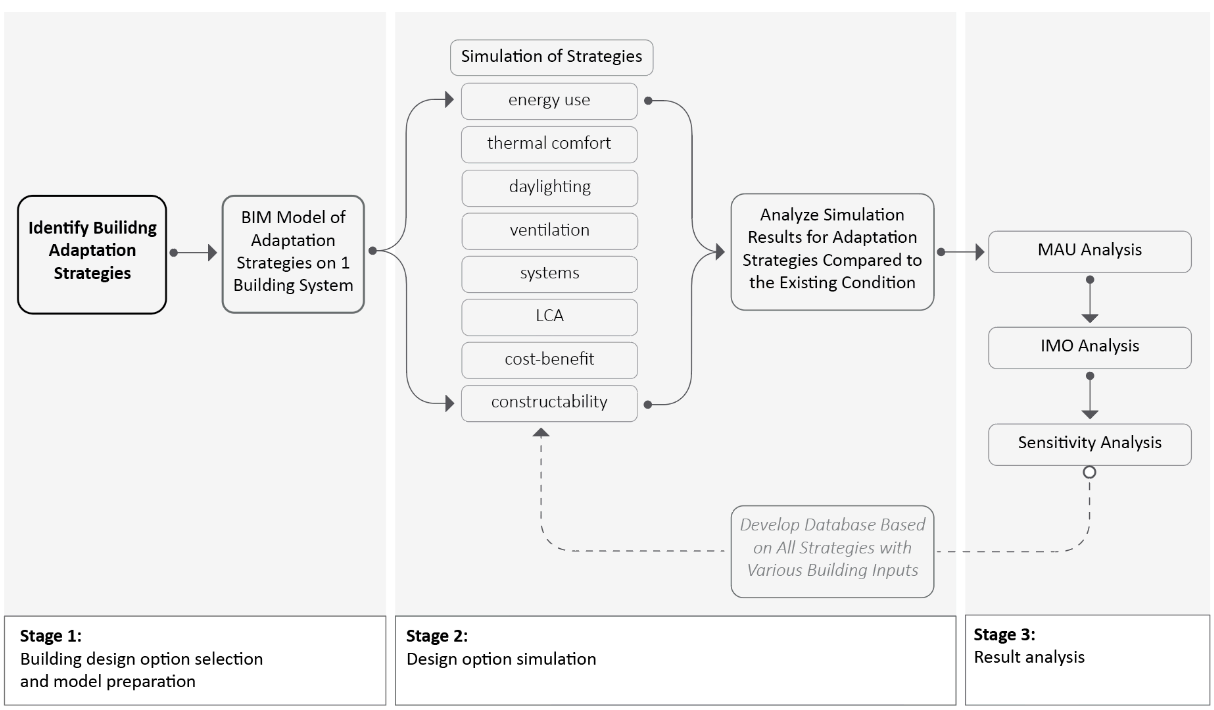


Figure 5-2: Steps in the methodology, including identification of adaptation strategies, simulation, analysis and validation. The future steps of this research will include the development of an extensive database that can be used for future design automation applications. Immediate future steps of the work are highlighted in grey.

Building system one, used to complete the initial assessment, is developed based on the Ellebo Housing State in Denmark (**Figure 5-3**). 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 cycle, cost benefits and constructability. These adaptation strategies include restructuring, extending glazing, re-cladding, enclosing, insulating, adding, relocating, insetting, layering and extending (**Figure 5-3**).

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.

5.3.1 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.

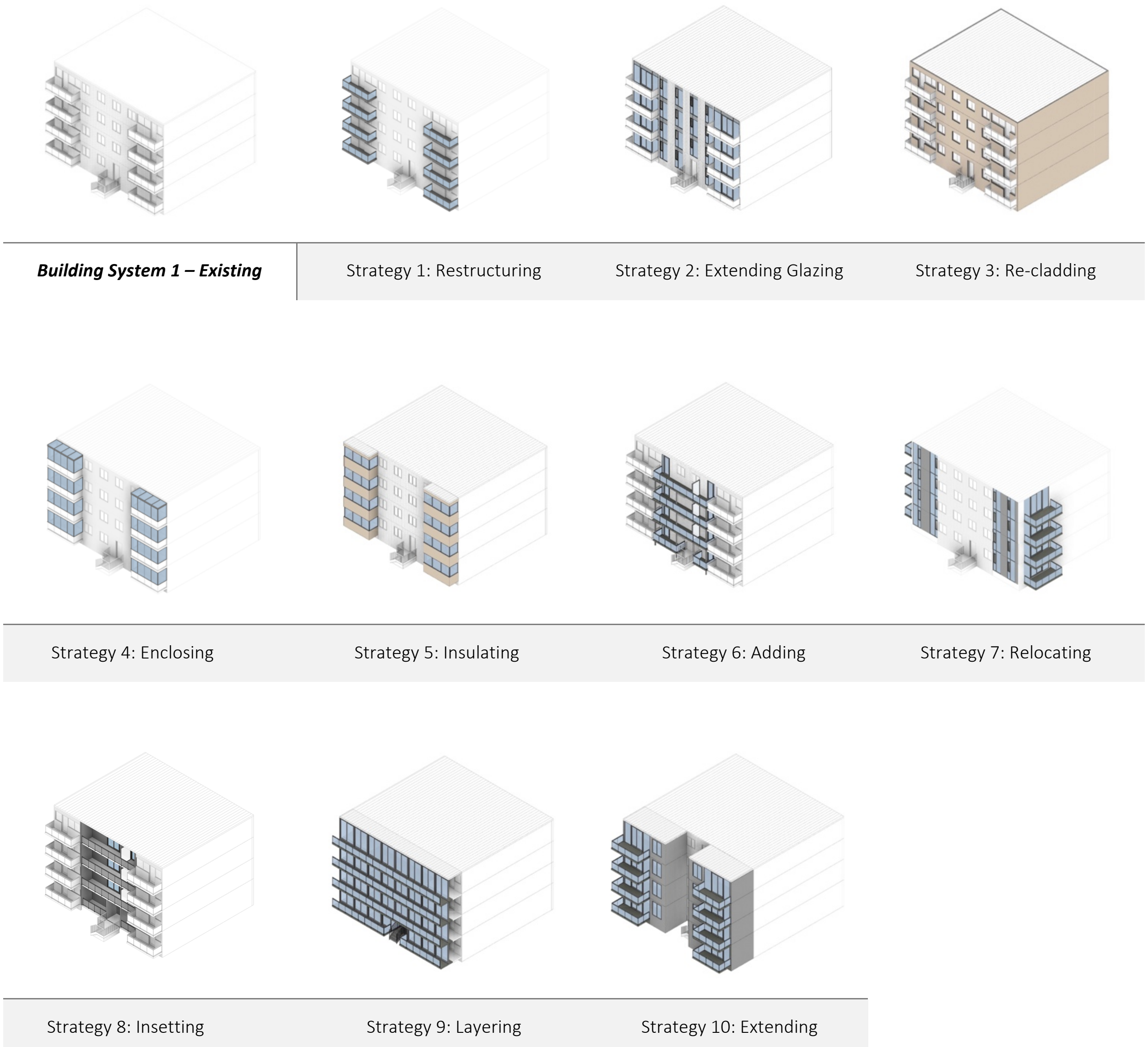


Figure 5-3: Building System #1, Existing Condition and 10 Building Adaptation Strategies

5.3.2 Multi-Criteria Decision Making for Building Adaptation Design

Multi-criteria Decision Making (MCDM) is an effective decision-making tool for determining optimal solutions in complex problems (Hu, 2019). The performance for series of alternatives are determined for a set number of criteria based on determined preferences, or weights, contributing to an overall score (Verbeke et al., 2018). MCDM has been effectively demonstrated for use in complex design decision making and can be specifically applied for determining optimal solutions in building adaptation projects. Rocchi et. al (2018) used a multi-criterion sorting approach to account for conflicting objectives in regard to insulating materials for retrofitting projects (Rocchi et al., 2018). Medineckienė et al. (2011), used the analytical hierarchy process approach to determine a multicriteria assessment for optimal building material cost, construction process and energy use (Medineckienė et al., 2011). 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).

5.3.2.1 Multi-attribute Utility Analysis

MAU is a methodology for evaluating situations with a multitude of objectives, usually with varying degrees of importance (Gumasta et al., 2011; Kapur, 2015). The purpose of MAU analysis is to arrive at a combined measure of appeal (utility factor) for an outcome based on a set of alternatives. MAU is most useful when determining which alternative suits a situation the best, based on multiple objectives (Gumasta et al., 2011). An 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, a variety of weights per strategy are used for demonstration.

5.3.2.2 Interactive Multi-objective Optimization

Interactive multi-objective optimization is applicable for applications where the decision-maker is heavily involved (Luque et al, 2008), 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, based on which the decision-maker can specify preferences and explore interested 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 to make informed decisions based on 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 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 the two groups of interaction after a run, and an 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 of trade-offs amongst others. Varying weights are used to test results based on value function (utility function) with MAU. A value function, as a scalar function, allows the evaluation of all solutions and their comparison in a quantitative manner (Branke et al., 2008).

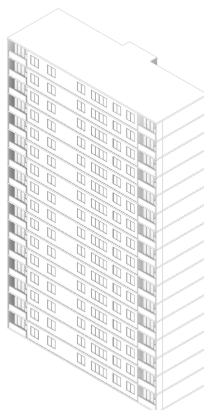
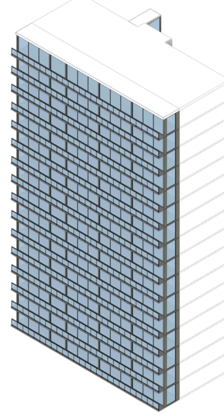
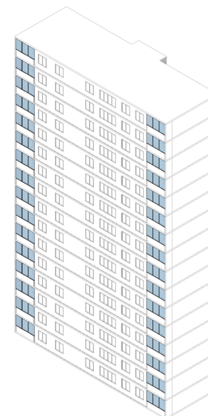
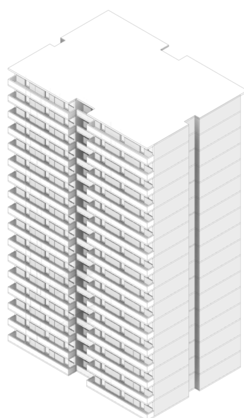
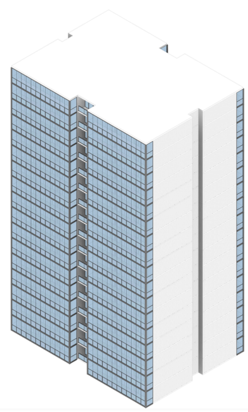
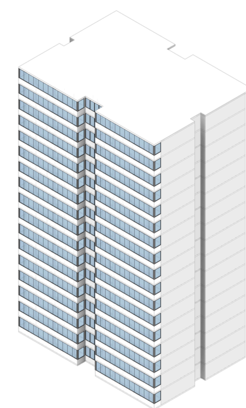
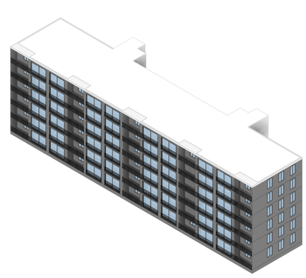
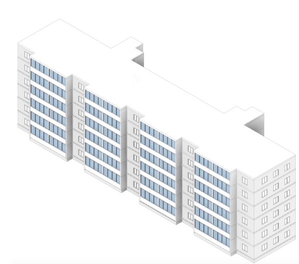
5.3.3 Sensitivity Analysis

The parameters that are expected to have the highest impact on the variation of results of the percentage of change include size, complexity, and distribution of strategies in buildings. Sensitivity analysis determines how the overall outcomes of a model can be allocated to the relative variations and uncertainties of its various inputs (Saltelli, 2002). Sensitivity analysis is used to validate the results for their efficacy and applicability in changing conditions. In this process, the objective is to highlight the most significant factors contributing to uncertainty and extreme outcomes. To ensure the usefulness of the analysis when multiple parameters are involved, it is essential to understand changes as results of varying parameters. To develop a meaningful sensitivity analysis, the required insights from the model must be clearly stated. Sensitivity analysis on different weights of each measure for MAU analysis is conducted to determine which measure that has the most influence on the ranking of the adaptation strategies. Ten option scenarios are identified as a sample.

For further validation, 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 in-lieu of other adaptation. The existing building, as-built building adaptation, and the implementation of the enclosing strategy is demonstrated in **Table 5-2**. Building systems 2-4 are modelled in Autodesk Revit® with a consistent LOD of 200 necessary for analysis (H. Liu et al., 2019), similar to building 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.

Table 5-2: Existing, As-Built Building Adaptation Strategy, and Enclosing Building Adaptation Strategy on Building Systems 2, 3 and 4.

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

5.4 Results

Energy, daylighting and systems simulation is completed within Sefaira® using EnergyPlus®. The following are the general model inputs: building area of 1170 m^2, fan coil units and central ventilation, occupant density of 50 m^2/person, the equipment power density of 5 W/m^2, 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^2K, and the existing glazing U-factor is set at 3.3 W/m^2K with SHGC of 0.4. Any area with new wall construction or re-cladding assumed a U-factor of 0.1 W/m^2K and new glazing at 0.8 W/m^2K 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 re-cladding 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 re-cladding 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 re-cladding 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 balcony enclosure.

For natural ventilation, areas not being ventilated (0 m/s), and comfortably ventilated areas (0.15-0.9 m/s) are measured. There were no changes made to the opening in the re-cladding strategy but enclosing demonstrated a 1% improvement of natural ventilation. The natural ventilation simulations are based on winds of 15km/hr with an outdoor temperature of 20°C. 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. Re-cladding 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. Re-cladding 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 re-cladding demonstrated an NPV of $41,388, while enclosing has an NPV of $53,198. The cost factor for required labour, equipment and materials are used for understanding the constructability of each strategy. The results for all simulations are summarized in **Table 5-3**. The results for the percentage of change in performance for all strategies compared to the existing base case is analyzed and demonstrated in **Figure 5-4**.

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 re-cladding and enclosing experienced a positive NPV, while the rest of the strategies experienced a negative NPV ranging from -0.2% to -115%. Heating equipment 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% to 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. Details of the results summarized in this section are provided in **Appendix C.**

Table 5-3: 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. Details of the results are provided in **Appendix C.**

	Energy Use	***Thermal Comfort***	***Daylight***	***Ventilation***	***Systems***	***LCA***	***Cost-Benefit***	***Construct-ability Factor***
	EUI (kWh/m²/yr)	**% of time Comfortable** (Extreme Hot Week	**Daylight Factor** (Average %)	**% of Area Ventilated**	**Heating Equipment Design Capacity** (W/m²)	**Global Warming Potential** (kgCO2eq / 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

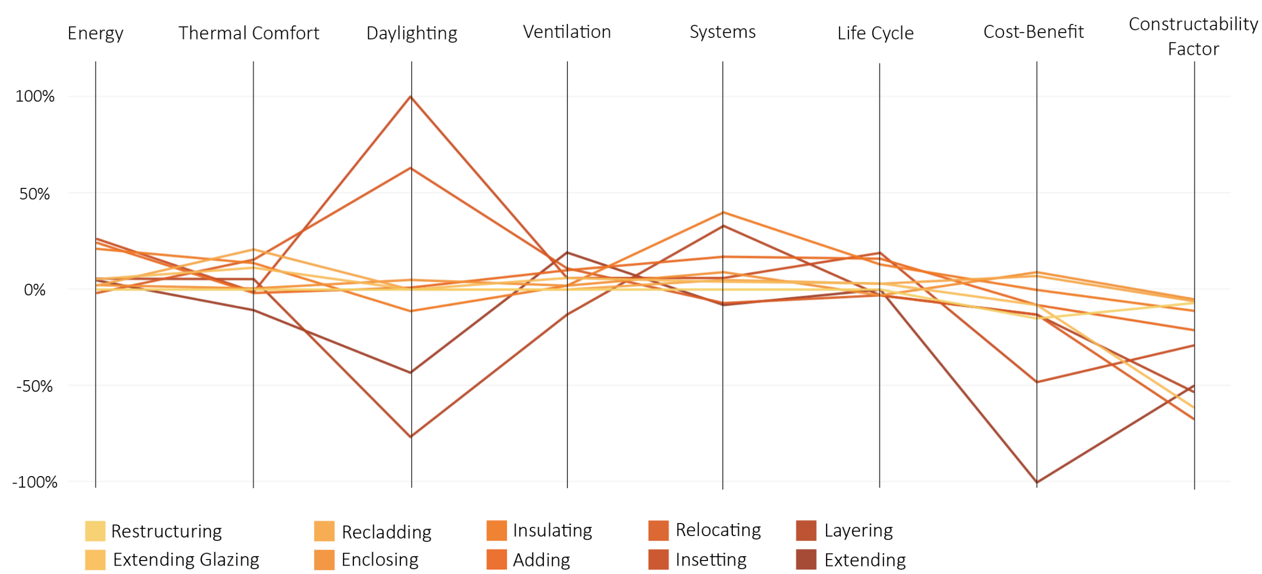


Figure 5-4: All strategies - % of Change in Performance of Each Measure is Demonstrated in Comparison to the Existing Condition of Building System 1. Each line represents one adaptation strategy, identified by colour.

Ten iterations of MAU analysis are conducted for varying weights per strategy for demonstration. The ranking and utility factors for each strategy is presented in **Table 5-4**. The MAU Analysis results for existing, re-cladding 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.

Table 5-4: 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

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 5-5**.**

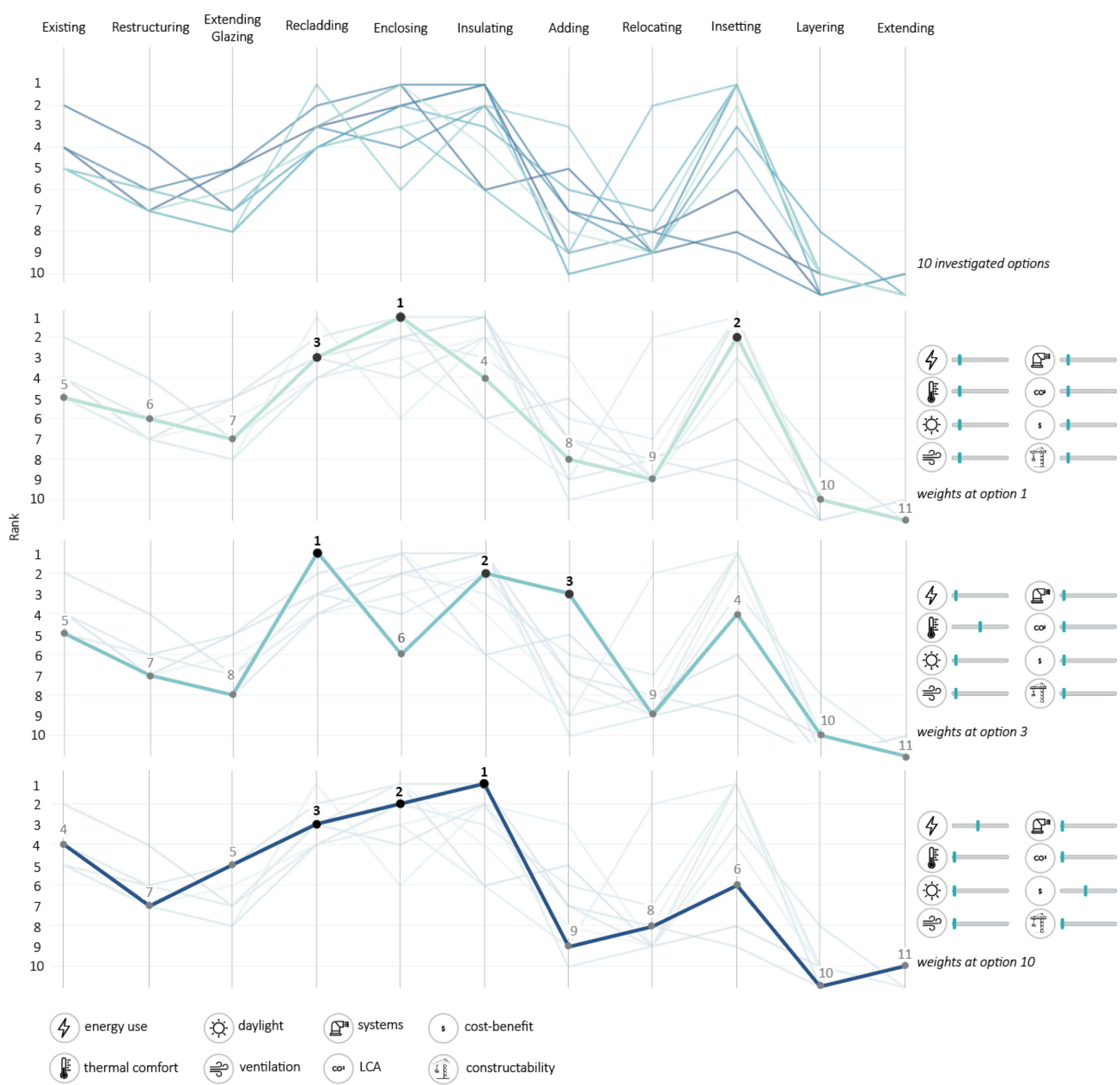


Figure 5-5: All strategies analyzed through 10 varying weight options using of MAU. Ranking of options are numerically represented for each set.

Through the interface, the decision-maker can participate in an IMO process and get the ranking of each of the design options, based on determining the required weights of the metrics. Going through the results using an intractive interface will allow the decision-maker, in this case the project deisgner, to get a better understanding of the metrics that are driving the results.

Further, a sensitivity analysis (identifies the metrics that are most reliable 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 1 examined previously. The simulation results are presented in Table 5-5. The percentage of change in performance in regard to each metric, compared to base of each of the four building systems investigates is demonstrated in Figure 5-6. The analysis demonstrates consistent and reliable analysis of improvements for strategies with regards to energy use, ventilation, life cycle analysis, systems and cost-benefit. Prediction of thermal comfort, daylighting and constructability based on the developed 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 5-5**).

Based on the initial simulation results, ten iterations of MAU and the sensitivity analysis, the decision-maker is able to narrow down the search criteria for further analysis. For demonstration, re-cladding, insulating, and enclosing have been selected as the top three highest performing strategies. Energy use, LCA and cost-benefit have also been selected by decision-maker as the top three strategies in terms of reliability of results based on sensitivity analysis and the importance for the individual investigation of the decision-maker. Based on this, 30 iterations of MAU are conducted for varying weights on each of the three selected metrics, and the results are demonstrated in Figure 5-7.

Table 5-5: 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.

	Energy Use	***Thermal Comfort***	***Daylight***	***Ventilation***	***Systems***	***LCA***	***Cost-Benefit***	***Construct-ability Factor***
	EUI (kWh/m² /yr)	% of time Comfortable (Extreme Hot Week	Daylight Factor (Average %)	% of Area Ventilated	Heating Equipment Design Capacity (W/m²)	Global Warming Potential (kgCO2eq /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

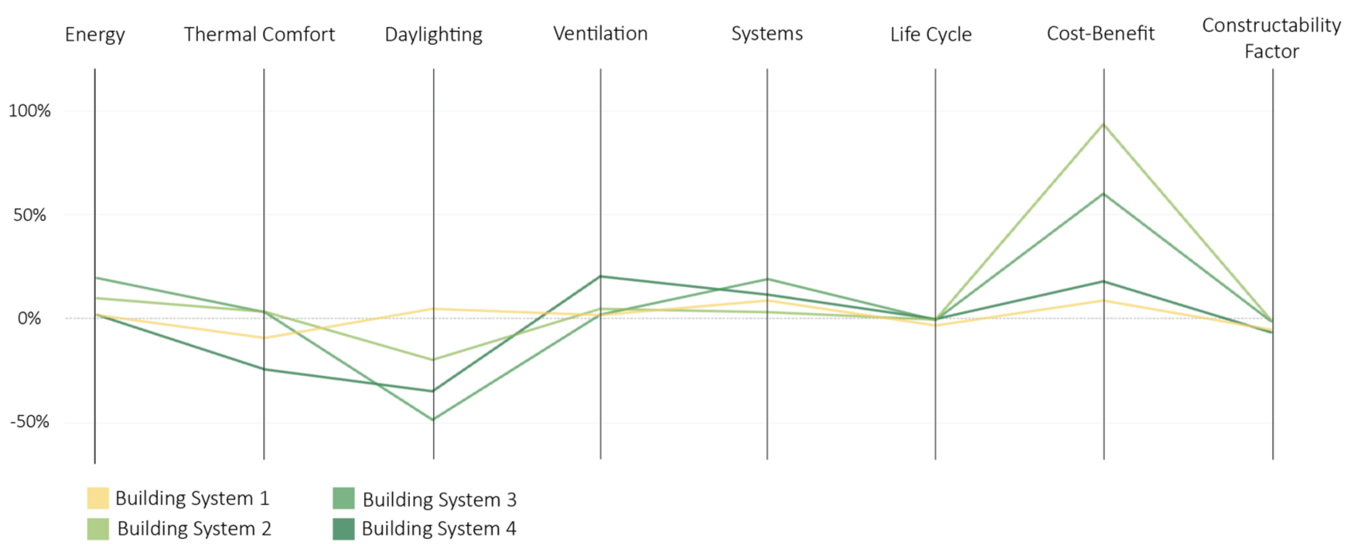


Figure 5-6: Simulation Results for Enclosure Strategy of All Building Systems Compared with Existing Condition of each Building System – Simulation Results of Energy, Thermal Comfort, Daylighting, Ventilation, Systems, Life Cycle and Cost-Benefit for Existing and Enclosing Strategy.

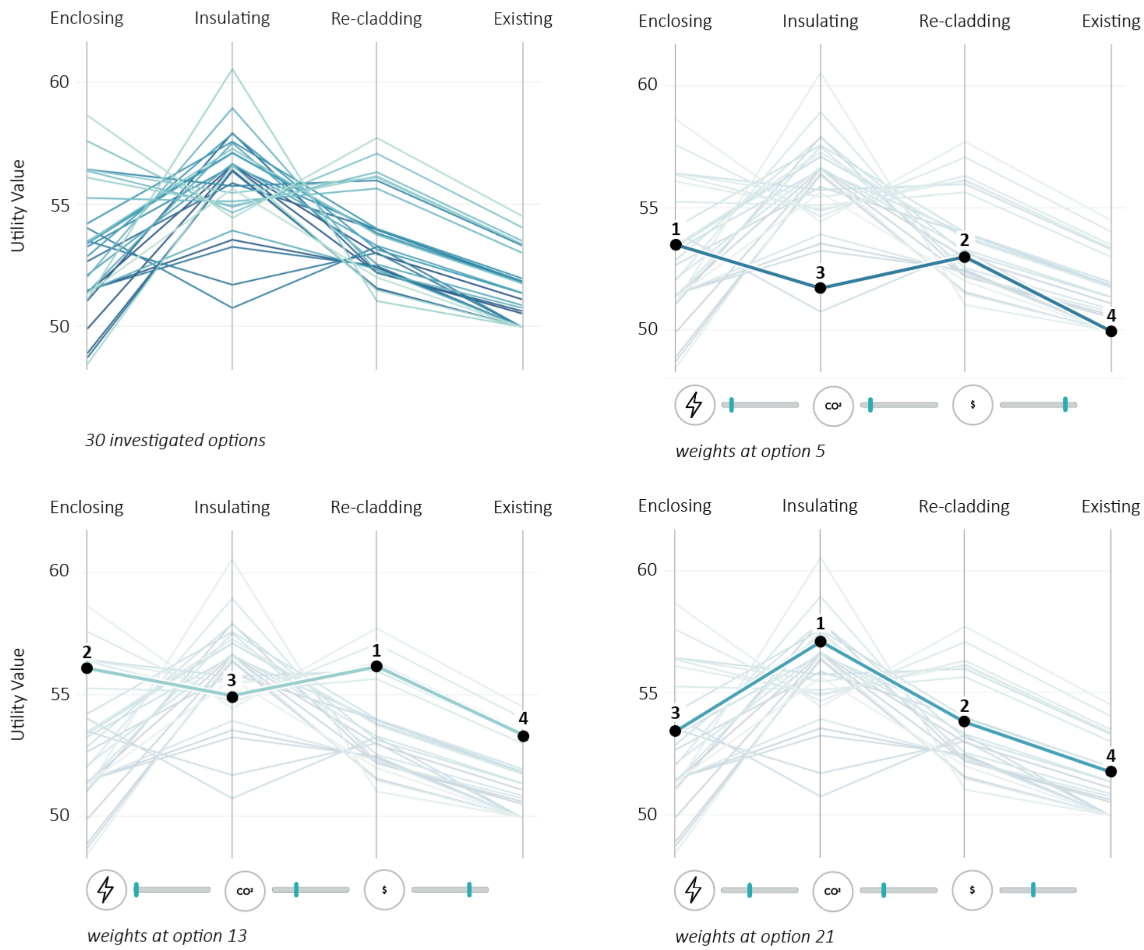


Figure 5-7: Interactive MAU Analysis. All strategies analyzed through 30 varying weight options using of MAU. Ranking of options are numerically represented for each set.

Through the interface, the decision-maker can participate in an IMO process and get the ranking of each of the design options, based on determining the required weights of the metrics. Going through the results using an intractive interface will allow the decision-maker, in this case the project deisgner, to get a better understanding of the metrics that are driving the results.

5.5 Discussion

This research examines the use of multiple tools and developing 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 the use of computational tools and make decision-making accessible to designers and decision-makers in the early stages of a project. The main goal of this chapter 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 5-5, and the filtered results in **Figure 5-7**, 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 has been studied. The percentage of each of top five strategies from total adaptations has been demonstrated in **Figure** 5-8.

Based on the existing trends restructuring, including balcony and guard repairs, has been the most common strategy over the past decade. Followed by enclosure, recladding and reglazing with a large gap. The results of this research demonstrate that restructuring is not the most optimal design strategy to pursue for 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 have better understanding the design options and consider them more holistically in 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.

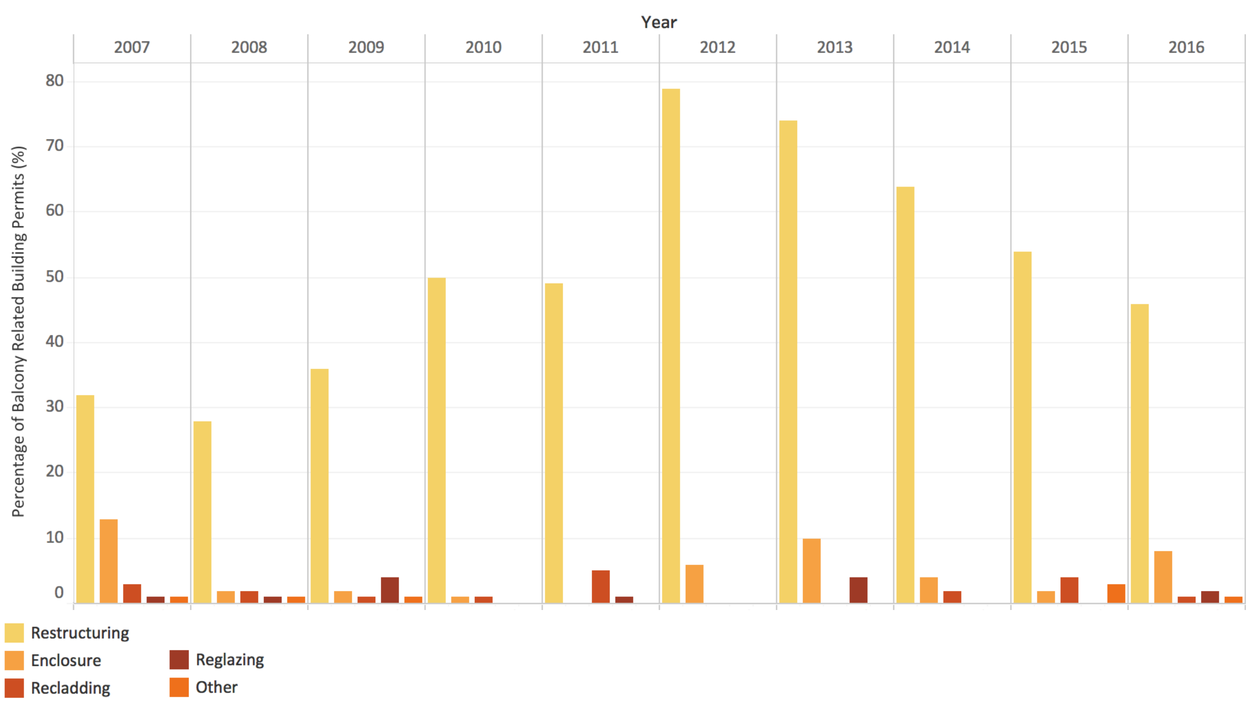


Figure 5-8: Types of Enclosure-Related Adaptations to Multi-family Housing in the City of Toronto Based on the City of Toronto permit database (City of Toronto, 2019).

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 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 combination 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, highlight 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 of 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 in its demonstrated flexibility and accessibility, and the applicability of use to a range of building adaptation projects.

Data-driven design decision-making tools are therefore helpful in supplementing a designer's abilities 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 in a design process, the goals, objectives and strategies will need to be refined based on findings. 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. In the search for optimal design decision-making using innovative tools and simulations, it is important that the decision-maker and designers to integrate their experiences and design sensibilities in the process, and for 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 begin to 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 of failing northern balconies and enclosure of most eastern balconies. For a scalable application, data collection and analysis need to be expanded to accommodate for different building types, including the analysis of the effects of geometry, location and building materials on the efficacy of different building adaptation strategies. A comprehensive database can be the basis of developing automated design tools using evolutionary or heuristic algorithms for developing complex design solutions.

5.7 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-maker with the process. Prioritizing strategies in various scenarios results in the ideal option oscillating between re-cladding, 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 can filter the results to better understand the data and to 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 a second round of MAU analysis, the decision-maker was able to make a more precise differentiation based on the varying weights of the objectives.

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 as well as 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.

Canada has committed to reducing energy use in all existing buildings by 40% before 2050 (Generation Energy Council, 2018). Dated residential towers house over 1 million residents in the Greater Toronto Area alone and make up the majority of affordable housing options (Smetanin et al., 2019). Extending life cycles of affordable housing stocks and improving their quality and efficiency is important for improving housing affordability. This effort requires advancement in current processes and workflows and methods for automation and optimization to be able to address the required market in an efficient and timely manner. Construction and design industries are slow in adopting new technologies, specifically, in taking advantage of workflow management, advanced data and analytics and automation. Application of the methodology developed in this research can begin to address this gap by enabling architects and engineers to design and implement higher-performing designs, can make complex retrofitting and renovation projects feasible in the long term, and can increase the speed in which building adaptation is addressed. The scalability of this research will contribute to strengthening a circular economy in construction through mitigation of demolition and release of embodied energy in existing buildings and extending their life cycles.

This component-based approach to design decision making is limiting as most successful projects are comprised of a complex range of strategies assembled. Challenges for accurate implementation of the tool include gathering quality data of existing buildings and precise documentation of components for simulation. Intelligent modelling systems and mathematical optimization tools can be successful in automating multidisciplinary design optimization. The future of this work includes implementing these methodologies for improving the accuracy and applicability of results through iterative validation. There is concern in the validity of a matrix method for design option appraisal due to the interdependence of some metrics, and this needs to be investigated further. Further development of this work will consider the correlation between measures and will consider in-depth sensitivity analysis for further validation of results. The future steps of this research will include the development of an extensive database and integration of the gathered data to be used in future generative design and design automation processes in a scalable tool.

6. A Computational Design Methodology for Generating Modular Design Options for Building Extensions

Overview

Adaptation of existing building stock is an urgent issue due to aging infrastructure, growth in urban areas and the importance of demolition mitigation for cost and carbon savings. To accommodate the scale of implementation and address the complexity of building adaptation projects, the design decision-making process needs to improve. Computational design methodologies can optimize design decisions driven by spatial, environmental and economic factors. Modular Construction (MC) can also increase efficiencies in the design and implementation of building adaptation projects. An early-stage design computational methodology is developed for integrating MC and design optimization metrics including energy use, daylighting, life cycle impact, life cycle costing and structural efficiency in order to improve the quality of design options and speed of evaluation in building adaptation processes. The extension and recladding of the Ken Soble Tower in Hamilton, Ontario, is used for the functional demonstration of the methodology. Various design options that conform to determining design constraints are evaluated, and pareto-optimal early-stage design options are identified based on life cycle cost and structural complexity. The application of this research can promote the improvement of existing residential infrastructure at increased rates to meet required energy improvements and to address housing affordability needs. This chapter is a brief overview of a journal article included in **C.1**: Energy Modeling Results

6.1 Introduction

Adaptation of existing buildings has increased over the past decade as a response to changing environmental conditions, as well as requirements for reducing energy use and production of construction and demolition waste (Pardo-Bosch et al., 2019). To move to a circular built environment, there is a need to incorporate adaptation of buildings as a means to facilitate continual loops of resources, products and materials in construction (Stahel, 2016). Implementing MC as a building adaptation solution can improve the condition of existing buildings while preparing them for a circular future in which unnecessary demolition is avoided, and the building modules and materials can enter multiple cycles of use (Hossain et al., 2020). The success of MC projects is directly related to appropriate early decision-making due to the planning and coordination focused nature of modular projects. Modular form generation is improved by an automated design processes that provide real-time design feedback (Holzer, 2016). MC has proven advantages in terms of life cycle impacts and life cycle costs compared to traditional construction and can contribute to more energy-efficient buildings through the improved quality of construction (R. M. Lawson et al., 2012). A framework for modular extension to existing buildings, and early-stage automation of designs, therefore, needs to consider multiple factors for optimization.

The conducted literature review highlights the importance of adaptation projects and processes for their improvement. Through early design stage optimization, Kiss and Szalay were able to demonstrate environmental savings of 60-80% compared to traditional design methods. Typical design option optimizations reviewed in literature often consider a limited number of options (Kiss & Szalay, 2020), highlighting the need to consider computational design methodologies for design option generation and simulation for simultaneous optimization of multiple factors simultaneously. Automated design option generation based on set constraints, energy use, and Life Cycle Analysis (LCA) and Life Cycle Costing (LCC) optimization can be applied using computational tools in early-stage design (Tugilimana, Thrall, Descamps, et al., 2017).

Researchers have developed approaches for optimizing building adaptation, modular construction, and have created methodologies for incorporating design optimization metrics and automated early design decision-making. There are currently no studies highlighting a framework for the integration of early-stage design optimization of environmental factors, including energy use and daylighting, Life Cycle Analysis (LCA) and Life Cycle Costing (LCC) for MC, specifically for large-scale building adaptation projects. Therefore, a computational design methodology is developed for integrating MC in building adaptation projects, and for developing optimal design options in the process. The critical aspect of the proposed model is the integration of computational design strategies for simultaneous analysis of MC metrics, energy and daylighting analysis, LCA, LCC and structural complexity analysis. The proposed methodology is demonstrated for the development of design alternatives to the Ken Soble Tower adaptation in Hamilton, Canada.

6.2 Background

In a traditional building adaptation feasibility and early design process, many uncertain factors need to be examined. Project requirements, including budgets, timelines, spatial requirements and performance benchmarks, are taken into account. The analysis of the existing conditions of the building, including building geometry, overall condition and areas for improvement, are also considered. Preliminary design options are developed by the design team and often analyzed by various consultants that can include energy consultants, LCA consultants and cost consultants, as examples. The design team and specialty consultants go through an iterative process to develop suitable design options, and the results are shared with the client for feedback. This process can take many months to complete depending on project complexity, often leading to suitable, non-optimal design options (**Figure 6-1**).

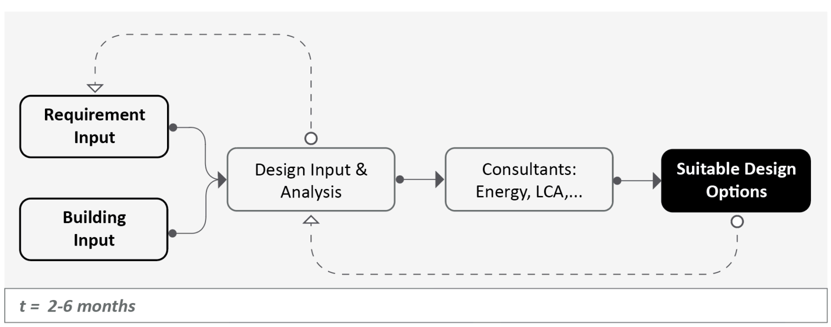


Figure 6-1: Traditional Design Methodology

The extended timeline for the building adaptation feasibility process cannot meet the increasing demand due to key aging urban building stock, requirements for improved energy efficiency and spatial quality, and the need for construction and demolition waste mitigation. For example, there are more than 3000 residential towers built between 1950-1990 accommodating more than 65% of middle-and low-income communities, as the main source of affordable housing in

Ontario (Smetanin et al., 2019). These buildings were built with low energy standards and have reached the end of their useful life and require adaptation at different scales. In 2019, a ten year CAD $1.3B co-investment fund was set up for Toronto Community Housing Corporation (TCHC) for adaptation, including retrofitting and rehabilitation, but only 21 buildings out of the 2100 TCHC buildings were adapted in 2019 (Pelley & Lee-Shanok, 2019). In addition, in building adaptation design processes, future adaptability and reusability for improving the resiliency and circularity of the built environment are often not considered, which can be addressed using modular construction. This literature review highlights the importance of building adaptation for facilitating a circular economy in the built environment. Strategies and processes for improving the efficiency of this process will be reviewed, including modular construction, computational design methodologies, automated early-stage design using design optimization metrics such as energy use, daylighting, structural efficiency, LCA and LCC. An extended literature and background review is provided in C.1: Energy Modeling Results

The success of building adaptation and modular building projects is directly related to appropriate early decision-making due to the planning and coordination focused nature of modular projects and the complexity of building adaptation projects. The following knowledge gaps identified in the literature will be addressed in this research. Computational design methodologies for generating and evaluating multiple analysis metrics are limited. Two studies have been identified that assess multiple metrics, and one that focuses on computational methodologies but does not consider complex building adaptation projects and MC. Studies that demonstrate the use of computational design strategies and modular construction mainly consider the evaluation of either structural efficiency or energy use. There are no tools or methodologies available that integrate various analysis metrics for the early-stage design automation of modular extension and adaptation of existing buildings. The implementation of CE strategies and business models have been proven to be effective in increasing the resiliency and efficiency of the built environment but only at the onset of implementation. Novel methodologies that can address the need for adaptation of existing building stock and the integration of aging infrastructure will help improve the building adaptation design decision making process and facilitating the transition to a circular built environment.

6.3 Computational Design Methodology

A computational design methodology is developed for integrating and evaluating MC in building adaptation projects. An extensive literature review on related topics highlight a gap in consideration of multiple factors for design optimization of modular construction. The methodology is based on creating a finite number of design solutions that meet a set of required data. Energy use, daylighting and carbon emissions will be set as system constraints, and the remaining design combinations will be analyzed based on their LCC and based on structural efficiency as a proxy for complexity to arrive at a set of pareto-optimal design solutions for further selection and analysis by the designer.

This methodology is developed in three stages: 1) analysis, parametrization of existing building and development of an algorithm for the generation of design options, 2) simulation and analysis of generated options for energy use, daylighting, structural complexity, LCA and LCC, and 3) result refinement through a heuristic-guided exhaustive search and selecting pareto-optimal design solutions. Stage one of the framework requires manual work and processing from the project designers for processing the existing building and defining parameters. Through a step-by-step analysis of the building, development of design constraints and processing of user inputs, precise design constraints and rules are developed for algorithm input. In the second stage, the developed algorithm generates design combinations, simulates for environmental analysis and analyzes the conditions of the design combination for life cycle performance and cost. Design options that meet the set criteria are displayed in stage three.

The methodology enables a designer to input preferences for generating and parsing through possible designs for selecting optimal solutions. This methodology suggests possibilities for the incorporation of external databases and previously analyzed cases for the development of databases of all feasible solutions leading to a predictive model of performance feeding the results, to be investigated at a later stage of this work. The first stage requires input from parties involved in the early-stage design process, including the client and designers. The last two stages of the framework are fully automated and can be processed in real-time (**Figure 6-2**).

The developed computational methodology is differentiated by geometric simplicity, integration of automated processes and simulation tools and processing of direct manual user input in various stages. Genetic algorithms are widely used in computational design; in this methodology, the focus has been to incorporate adaptive strategies (specific vs. generic) and topologic modelling strategies. Existing computational interfaces, plugins and frameworks are used in the development of a cohesive tool that integrates existing resources and facilitates integration. The computational design tool is programmed using Grasshopper® visual programming interface, and plugins are used within the interface for energy use simulations and optimization. One-Click LCA® is used for preliminary life cycle emission calculations, and other plugins in Grasshopper®, such as Honeybee® for energy analysis and daylighting, are used. Future development of the framework will involve the incorporation of external databases and analytical cases, creating a database of feasible solutions over time and developing predictive algorithms. The Ken Soble Tower in Hamilton, Canada, is selected as a functional demonstration and is used to demonstrate the functionality of the framework in various stages. The computational methodology is presented in **Figure 6-2**.

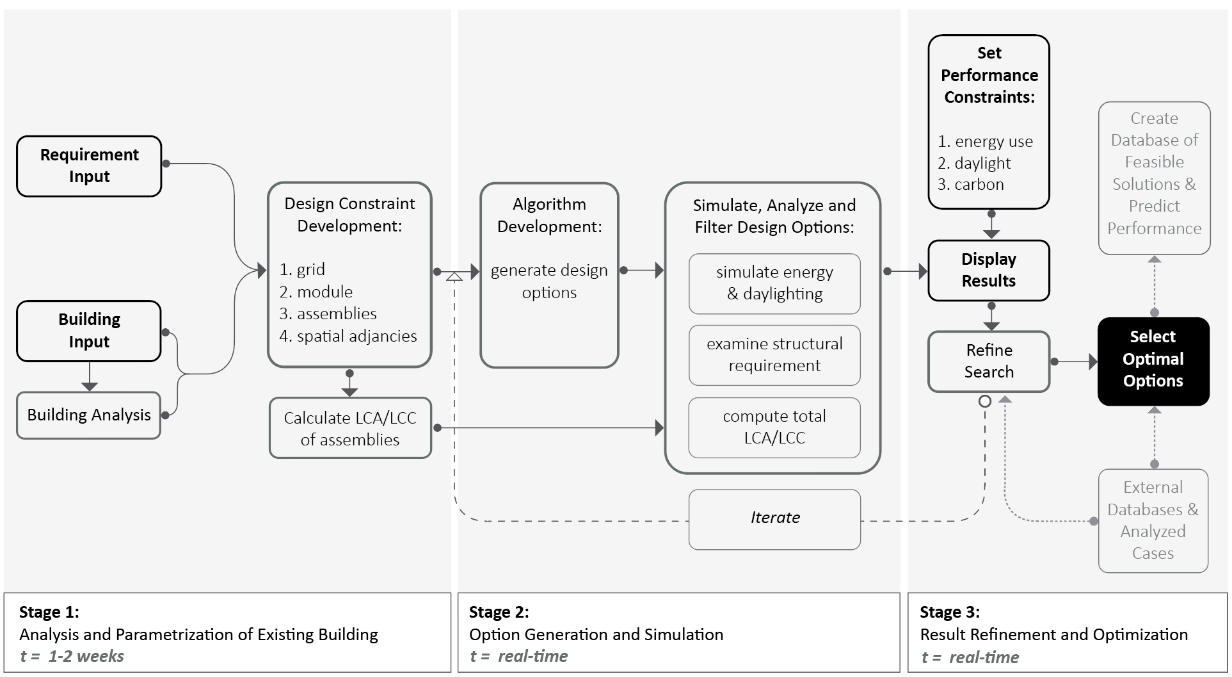


Figure 6-2: Framework for Computational Design Methodology

Details of the three stages of the methodology, demonstrated using the Ken Soble Tower project in Hamilton, Ontario are provided in **C.1**: Energy Modeling Results

Some of the results from the study are demonstrated below in **Figure 6-3**, **Figure 6-4** and **Figure 6-5** and explained in detail in **C.1**: Energy Modeling Results

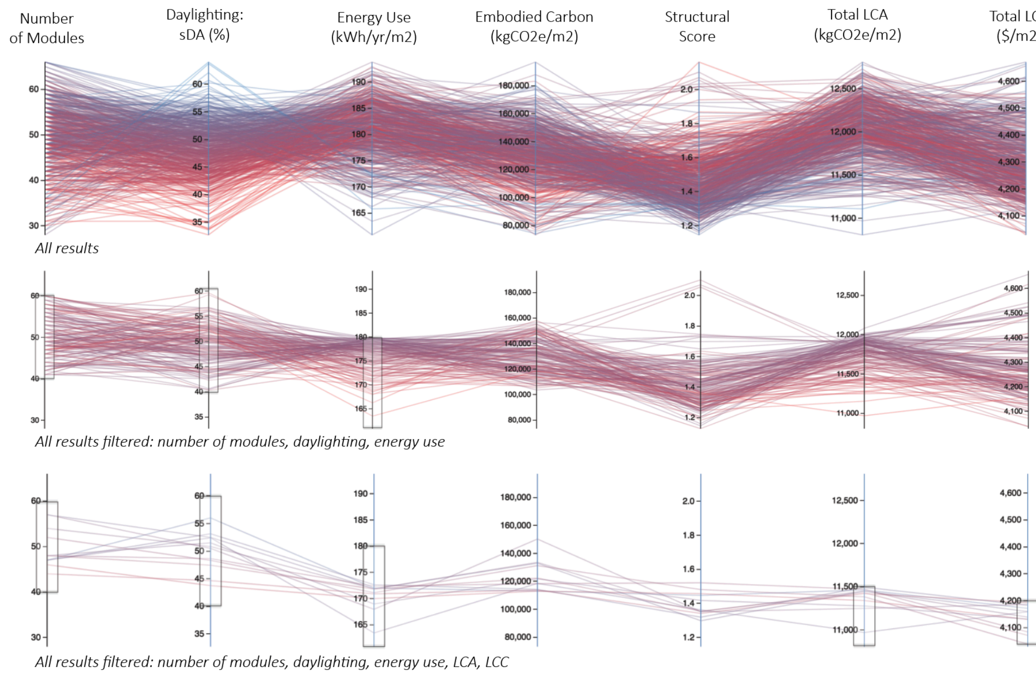


Figure 6-3: All results presented for refinement by user for 1) Number of Modules, 2) Daylighting, 3) Energy Use, 4) Embodied Carbon, 5) Structural Score, 6) LCA and 7) LCC.

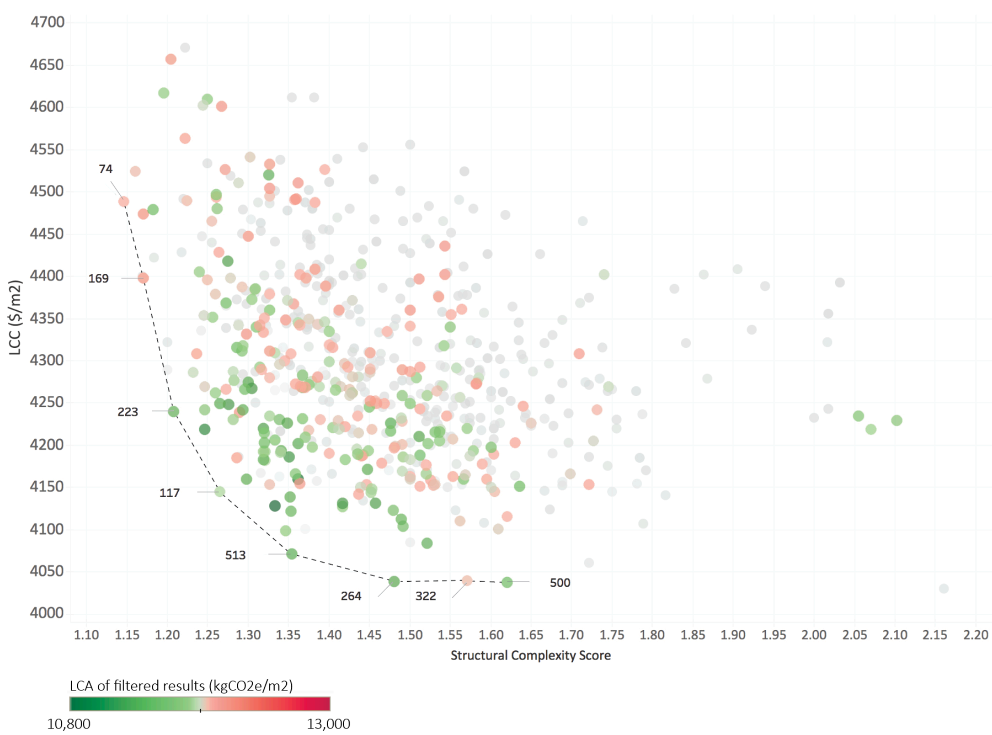


Figure 6-4: LLC ($/m2), Structural Complexity, and LCA (KgCO2e/m2) of Design Permutations (represented by colour range), filtered by selected ranges of embodied carbon, energy savings, daylighting requirements and range of extension. Pareto-optimal design permutations per cost (74, 169, 223, 117, 513, 264, 322, 500). Grey represents all other results.

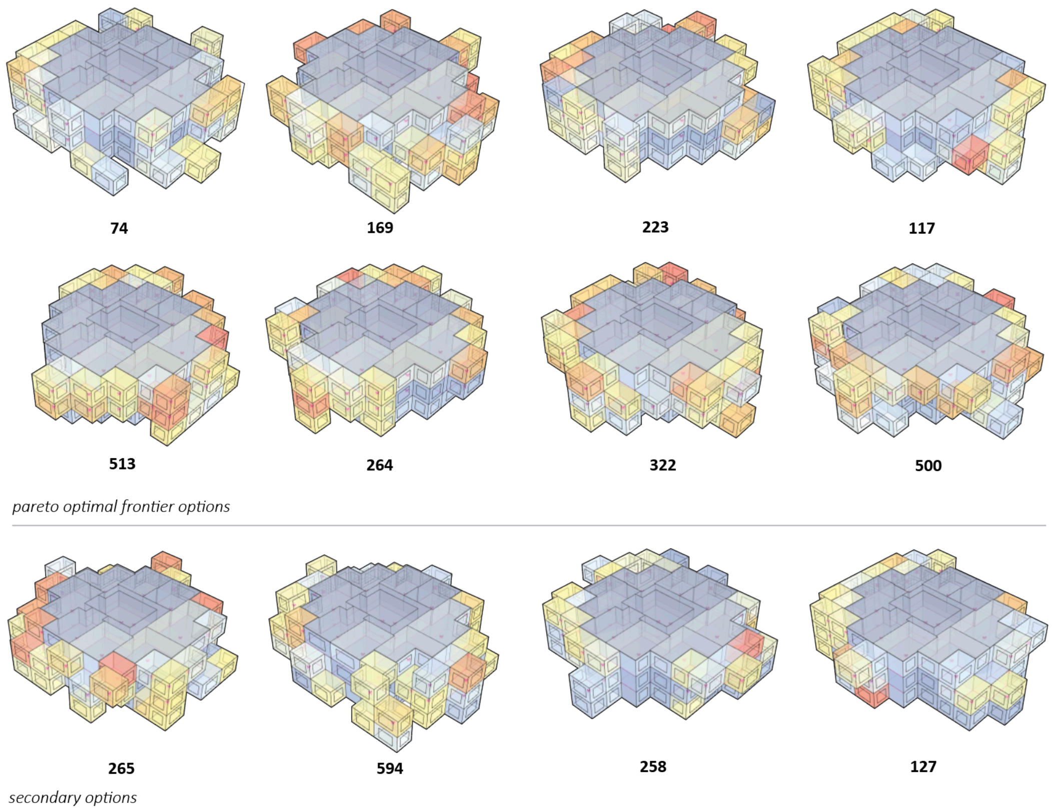


Figure 6-5: Pareto-optimal design permutations (74, 169, 223, 117, 513, 264, 322, 500). The option generation algorithm is limited to three-storeys due to computation limitations.

6.4 Discussion and Application

The main goals of this chapter were to demonstrate an overview of the developed computational methodology for integrating and evaluating MC in building adaptation projects to improve the quality of design options and the speed of evaluation in building adaptation projects. As presented in detail as part of **C.1**: Energy Modeling Results

, the energy use and LCA of generated options for extension to the Ken Soble Tower, are linearly correlated across all generated design options, as was expected due to the significance of operational energy use in a building's overall LCA. However, for design options with a similar LCA, there are significant variations in LCC. For example, for LCA of around 11,760 (KgCO2e/m^2), there are over 25 design options with a range of LCC; from \$4098/m^2 to \$4616/m^2 (**Figure 6-5**,

Figure A-7-14). The variations in LCC correspond to the effect of different materials and assemblies used, as opposed to energy use factors. The variations in Data-driven design option analysis for early stage design, and the resulting variety of LCC per range of LCA highlight the importance of this investigation and multi-objective analysis. Without the use of a computational methodology for design optimization with simulation feedback, there is a potential loss of opportunity in achieving savings in embodied carbon and life cycle impact and environmental performance criteria that are dependent on geometric form generation and material use in MC.

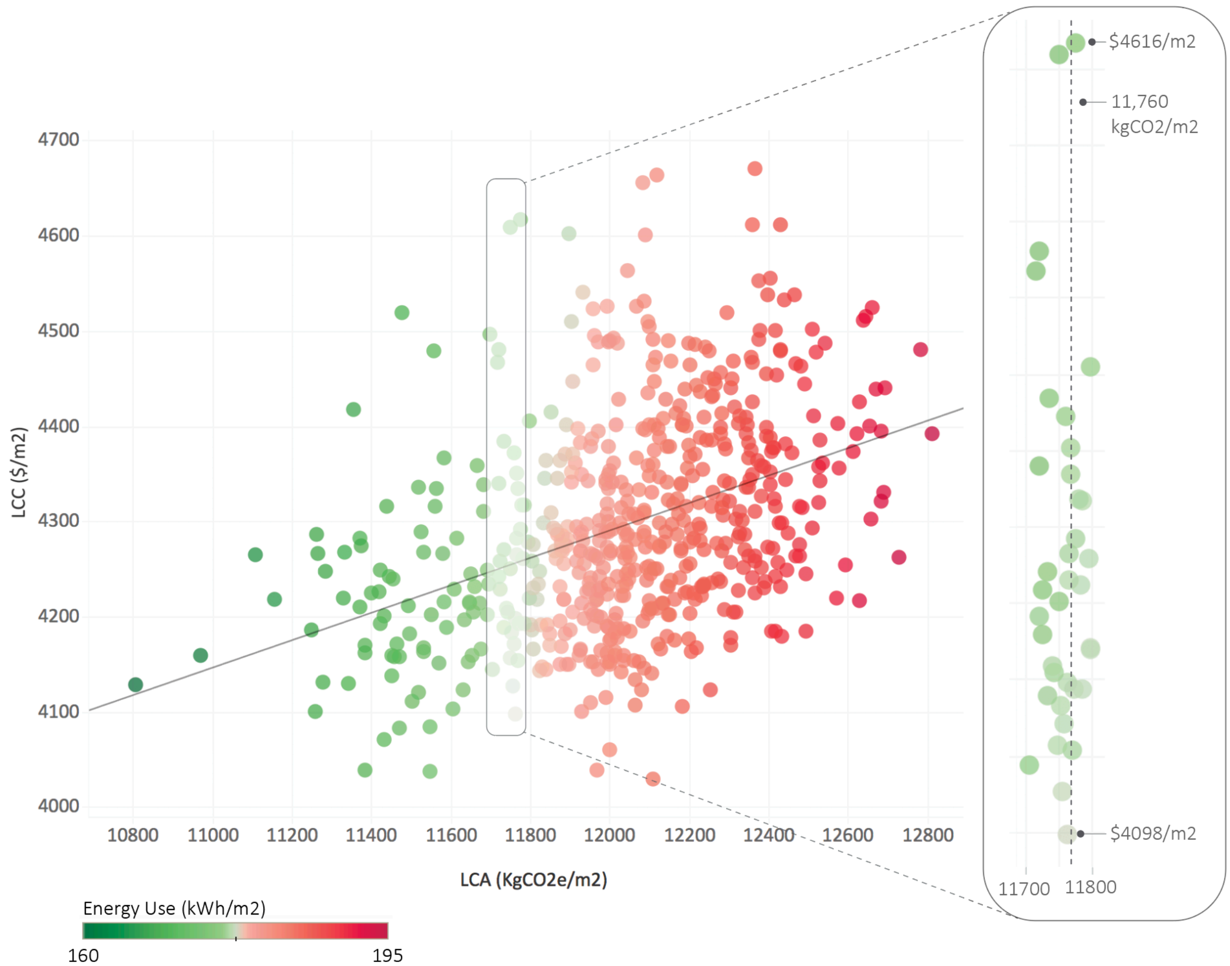


Figure 6-5: LCA (KgCO2e/m²), LCC ($/m²) and Energy Use (kWh/yr/m²) (represented by colour range), all results. Energy use and LCA are linearly correlated; for design options with a similar LCA, there is a variation in LCC from $4098/m² to $4616/m².

The impact of the methodology described is in its versatility and flexibility, making it accessible for designers to use in various contexts, as demonstrated in the functional demonstration. It also has the potential to be used as a preliminary design tool for asset managers who manage existing, aging building stock. The implemented methodology has a modular architecture and can be customized to meet the demands of different types of investigations. In the functional demonstration of this research, it was decided to constrain the generated design options based on embodied carbon, energy savings, daylighting requirements and the number of modular extensions and select pareto-optimal frontier based on LCC and structural complexity. In this investigation, it was important to understand the correlation between LCC and structural complexity as a proxy for design complexity and to select complex design options that are financially feasible and meet the set requirements in terms of performance. However, it is possible to customize the methodology in different ways for designers to improve their workflow based on a variety of objectives, as the modules of the methodology can be adjusted to constrain and analyze for any sets of performance criteria. These include optimizing for lowest cost and most energy efficient options, or the most cost-effective intensive extensions, as examples.

It can be summarized in this study that early design stage multi-objective analysis of various performance criteria, as demonstrated, can enable designers to better understand the design option parameters and conditions that can lead to better performing designs as the designs develop. Simulation-based computational methodologies, as presented in this research, are helpful in supplementing a designer's abilities in developing optimal design options. It is demonstrated in the functional demonstrations that the use of the methodology can improve the performance of a range of design options on multiple metrics and highlighting relationships between various performance metrics. In further development of selected designs, the methodology can be refined and optimized with designer feedback and according to varying project requirements. With extensive use of the methodology and the creation of databases of feasible solutions, it will be possible to use data science and machine learning algorithms to begin to predict the performance of design options in early stage of design processes, limiting the computational time and improving the quality of generated design options. In addition, external databases and previously analyzed cases can be incorporated to improve the overall analysis process. From the stages of the design requirement analysis and constrain development to final selection and design development, the creative process, experience and of the designer is crucial in developing successful building projects. The application of this research in residential multi-family adaptation projects can mitigate unnecessary demolition and promote the improvements to affordable housing assets at increased rates.

6.5 Conclusions

6.5.1 Contributions

Adoption of modular construction in building adaptation projects, specifically as extensions to existing buildings, is an essential step in moving towards a circular built environment and facilitating the continual use of resources in construction. Parameters and limitations in modular design and the opportunity for design optimization highlight the importance of incorporating computational design tools in the design of modular buildings. In this research, a computational design methodology is presented that integrates modular construction in building adaptation projects.

This research contributes towards the improvement of data-driven design generation and multi-objective analysis of early-stage design through the development of a computational design methodology. The methodology also contributes to the improvement in the design process of MC, specifically in the integration with building adaptation projects. Primarily, a heuristic method for creating a finite number of design options that meet defined design criteria is developed. Then, simulation tools are used to analyze the performance and characteristics of each design. Design solution are further constrained based on acceptable range of performance set by the user and final pareto-optimal frontiers are determined for further design development. The efficacy of the methodology is shown in a functional demonstration of an existing residential tower adaptation in Hamilton, Canada. Advantages of the methodology include improved early-stage design workflow, the possibility of improving quality of design decision-making and the increased speed of evaluations. The steps described in the methodology are not bound to specific software mentioned in this study and can be implemented within various computational design interfaces.

6.5.2 Limitations and future work

The limitations of this methodology include a limited analysis of spatial layouts after generation and the ability to account for addition of units, enabling a calculation of increased revenue, and return on investment rates; important factors for feasibility analysis of building adaptation projects. Other limitations of this study include calculation time and computation capacity, highlighting a need to optimize the algorithm for faster analysis in the future. In this study, a one module variant was used, in more complex projects the number of module sizes might need to differ, therefore adding complexity that needs to be considered in the algorithm. The methodology can also be improved by incorporating a user interface for designer input, parsing of data and design option visualization for better accessibility.

Future work will focus on addressing the limitations mentioned and on completing the proposed steps in the methodology not comprehensively investigated in this research—integration of external databases, linking to other analyzed cases, and the creation of an internal database. Selected options be combined to form a database of feasible options that will then be used to build a predictive model and support the assessment of viable options. External Database of analyzed cases – relevant examples are retrieved, and comparison with selected options is possible. The developments in future of this work aim to enhance data-driven, multi-objective design decision making of MC in building adaptation.

7. Summary, Conclusions and Recommendations for Future Work

7.1 Thesis Summary

Adaptation of existing building stock can lead to a reduction of waste material, preservation of natural resources, improvements in energy use and carbon emissions, and the conservation of embodied energy compared to demolition and new construction (Yung & Chan, 2012). Several studies have highlighted numerous other social, economic and environmental benefits of building adaptation projects, including increased financial gains from reduced maintenance and operation costs, improving occupant thermal comfort, and increasing the useful life of buildings. Building adaptation projects are often extremely complex and involve numerous considerations. Therefore, decisions made in the early stages of design are critical, and it is essential to consider multiple factors simultaneously. To achieve optimal design options, solutions must be reached that perform well for a range of multiple objectives. Therefore, it is necessary to consider design option generation and assessment methodologies for improving the design process of building adaptation projects.

In the first phase of this study, a comprehensive literature review is conducted. The analyzed topics include: (1) building adaptation project definition, (2) role of building adaptation in a circular economy, (3) residential building adaptation, including a focus on the obsolescence of the residential balcony and case studies of adaptive residential reuse, (4) building adaptation feasibility analysis, including a focus on design option assessment and design optimization metrics, and (5) BIM simulation tools, including a range of metrics such as energy use, thermal comfort, ventilation, daylighting, systems, LCA, cost and constructability. The highlighted gaps based on this literature review include: (1) a lack of clear definition of building adaptation projects and their scope, and (2) limited design options considered in building adaptation projects and a lack of holistic assessments that focus on a wide range of design optimization objectives.

In the second phase of this study, a framework for the definition of building adaptation projects is defined to enable clear and consistent use of building adaptation terms and correct project scope definition. The framework is determined based on a comprehensive literature review of peer-reviewed journal articles and conference proceedings. It was found that the terms refurbishment, retrofitting, rehabilitation, renovation, adaptive reuse, and material reuse have been used commonly over the past five years. These terms could be confused or used interchangeably, as they share subsets of various activities: replacing, adding, repairing, remodelling, reusing, and changing use. The developed definition framework is useful as a reference in academia and the industry to clearly and consistently define the scope of work of various types of building adaptation projects, intending to minimize the shortcomings of the current overlaps and confusions in applying definitions to clarify scope. The expected benefits from a coherent and consistent reference for terminology related to building adaptation include cost savings and improved efficiency from consistent codes, specifications and project descriptions that would otherwise lead to confusion and redundancies.

In the third phase of the study, a framework and methodologies for building adaptation design option appraisal are investigated. A decision-making framework is primarily presented for supporting design strategy generation, assessment, and selection for improving the analysis process. The framework is functionally demonstrated for adaptation of multi-family residential buildings, involving the retrofitting, rehabilitation and conversion of balconies. Six multiple residential case studies were analyzed, and a total of 10 basic building adaptation strategies were extracted. A more comprehensive methodology for building adaptation design appraisal using physics-based simulation and multi-objective decision-making tools is developed. The detailed results of this analysis are included in **Appendix C.**

Further, an early-stage design computational methodology is developed for integrating modular construction and design optimization metrics including energy use, daylighting, life cycle impact, life cycle costing and structural efficiency in order to improve the quality of design options and speed of evaluation in building adaptation processes. Various design options that conform to determining design constraints are evaluated, and pareto-optimal early-stage design options are identified based on life cycle cost and structural complexity. The details of the computational methodology are provided in **C.1**: Energy Modeling Results

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 set of 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 application of this research can promote the improvement of existing residential infrastructure at increased rates to meet required energy improvements and to address housing affordability needs.

7.2 Conclusions and Contributions:

The key contributions of this study and the conclusions from each stage of the thesis are summarized below.

7.2.1 A Definition Framework for Building Adaptation Projects

In Chapter 3, it was demonstrated that there is a lack of a clear definition guideline for the scope of building adaptation projects. The aim of developing a definition framework was to create a coherent reference for academic and industry projects to clearly and consistently define the scope of work of various building adaptation projects. This aimed to minimize the shortcomings of the current overlaps and confusion in applying definitions to a particular scope. It is expected that the benefits of a coherent and consistent reference can include cost savings and improved efficiency from consistent codes, specifications and project descriptions that would otherwise lead to confusion and redundancies.

Overall, the two distinct categories of adaptive reuse and refurbishment were defined. Adaptive reuse encompasses building conversion and material reuse, whereas refurbishment encompasses retrofitting, renovation, and rehabilitation. Most of these project scopes can include structural and non-structural modifications, except for retrofitting, which is limited to non-structural changes, and rehabilitation, which is limited to structural changes. This study demonstrated that many of these terms were being confused or used interchangeably, as they share subsets of many activities, including: replacing, adding, repairing, remodelling, reusing, and changing use. It was demonstrated that in the details of the activities themselves are essential, particularly the type of improvements being made (e.g., energy-related, non-energy related, or none at all), to determine the type of refurbishment being made (retrofitting, rehabilitation, or renovation).

As demonstrated by case studies, the proposed definition framework can clearly articulate the project scope by answering a few relatively simple questions. Judging by the exponential increase in the published literature on building adaptation projects over the past several decades, we suspect that research in this field continues growing. This growth will make the proposed definition framework a useful reference point and suggests it will be necessary for future researchers to revisit these terminologies in the future to ensure alignment with the potentially changing nature of future project scopes.

In Chapter 4, the prioritization of building adaptation strategies as an essential process in building adaptation assessment is investigated. It is concluded that for implementing complex building adaptation projects, comprehensive environmental, life cycle and financial evaluations are required to determine the most effective design strategies, often requiring computational tools. To make this process feasible, prioritizing building prioritize building adaptation strategies to building adaptation projects, including refurbishment and adaptive reuse, is needed. It is highlighted that in most studies, a low average number of adaptation strategies are considered. The decision-making framework presented supports and contributes to design strategy generation, assessment, and selection to improve the analysis process.

The framework is functionally demonstrated for adaptation of multi-family residential buildings, involving the retrofitting, rehabilitation and conversion of balconies. Six multiple residential case studies were analyzed, and a total of 10 basic building adaptation strategies were extracted. When applied to multi-family residential balconies specifically, the developed framework suggests a bridge between what is possible in terms of applied building adaptation strategies, what is most feasible in terms of cost, and what is possible and prevalent in terms of market application. In the framework, adaptation strategies are prioritized for further analysis and increasing the efficacy of the building adaptation process is demonstrated.

7.2.2 Methodology for Building Adaptation Design Appraisal Using Physics-Based Simulation Tools

In Chapter 5, it was demonstrated that the 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. A methodology is developed for improving building adaptation design decision making, specifically in the case of multi-family residential buildings using simultaneous consideration of multiple design options through computational and information-rich design models and accessible simulation tools. The methodology proposed focuses on an initial assessment and analysis leading to an index that can be applied to a variety of buildings. Building adaptation option appraisal is conducted using physics-based simulation and analysis tools and the use of MAU and MOI analysis for optimal decision-making. Through the functional demonstration of the methodology using a multi-family residential building, it can be concluded that the methodology is specifically successful for analyzing energy use, natural ventilation, LCA, cost-benefit and constructability. The quantifiable comparison of building adaptation strategies presented in this research can, therefore, assist the evaluation of overall environmental performance as well as economic justifications for future adaptation projects and facilitates a timely analysis of the success of existing building adaptation projects. 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. Use of this methodology can enable decision-makers and designers' accessibility to informed design decision making at the early stages of a project and facilitate the proliferation of building adaptation projects.

7.2.3 A Computational Design Methodology for Integrating Modular Construction in Building Adaptation Projects

In Chapter 6, it was demonstrated that computational design methodologies can improve the early-stage design feasibility decision-making process. A developed computational methodology integrated modular construction and design optimization metrics including energy use, daylighting, life cycle impact, life cycle costing and structural efficiency to improve the quality of design options and speed of evaluation in building adaptation processes. This methodology contributed towards the improvement of data-driven design generation and multi-objective analysis of early-stage design. Primarily, a heuristic method for creating a finite number of design options that meet defined design criteria was developed. Then, simulation tools were used to analyze the performance and characteristics of each design. Design solutions were further constrained based on acceptable range of performance set by the user and final pareto-optimal frontiers are determined for further design development.

The efficacy of the methodology was shown in a functional demonstration of an existing residential tower adaptation in Hamilton, Canada. Advantages of the methodology include improved early-stage design workflow, the possibility of improving quality of design decision-making and the increased speed of evaluations. The steps described in the methodology are not bound to specific software mentioned in this study and can be implemented within various computational design interfaces. The details of the methodology are explained in Appendix A and an overview of results is provided in Appendix B.

7.3 Limitations

There are multiple limitations in the research presented as fo:

7.3.1 Definition of Building Adaptation

1. This research was conducted based on a comprehensive literature review limited to academic and peer-reviewed journal and conference publications. The nature of the topic requires a thorough analysis of industry-based publications such as reports, building codes, contracts, etc. to understand the relations, gaps and areas for improvement in the definition framework for a more comprehensive study and scalable findings.

2. It is understood that the use of terminology by professionals in everyday design language and communication between different decision-makers varies. Therefore, a limited study of published material is an inadequate strategy for understanding the range of terminology and nomenclature used to describe projects. A field review and a range of industry and academic-based surveys of experts in this field can further illuminate the gaps in the definition of building adaptation projects.

3. This study was limited to the definition, clarification and justification of the highest used terminology in recent years. Therefore, the results are determined by its backwards-looking nature to terminology and undermine the importance of emerging terms. For example, the current response to COVID-19 highlights the importance of developing buildings responsive to circumstantial, environmental and demographic changes. The term “temporary conversion” as a sub-category of adaptive reuse and conversion is expected to gain more importance in research and practice post-COVID, as we begin to navigate a new normal with a perspective on other factors that will affect our built environment, including the effects of climate change in the following decades. A scalable definition framework needs to consider emerging areas in building adaptation and enable the flexibility to define new terms as they arise.

7.3.2 Building Adaptation Design Appraisal

1. The research design was limited in the range of data collected and analyzed. For a scalable application and a comprehensive index, the effect of different building types,

including the analysis of the impact of geometry, location and building materials on the efficacy of different building adaptation strategies. The conducted sensitivity analysis was also limited and needs to be expanded to encompass many changes, such as building orientations and strategies for a reliable index.

2. The component-based approach to design decision-making investigated in this study is limiting as most successful projects are comprised of a complex range of strategies assembled. Challenges for accurate implementation of the tool include gathering quality data of existing buildings and precise documentation of simulation components.

3. The decision-making tools used in this study were limited to MAU and IMO. It is acknowledged that more robust computational methodologies, such as a brute force search, evolutionary design algorithms and live feedback, are required to achieve optimal results in a building design.

7.3.3 A Computational Design Methodology for Integrating Modular Construction in Building Adaptation Projects

1. The limitations of this methodology include a limited analysis of spatial layouts after generation and the ability to account for addition of units, enabling a calculation of increased revenue, and return on investment rates; important factors for feasibility analysis of building adaptation projects.

2. Other limitations of this study include calculation time and computation capacity, highlighting a need to optimize the algorithm for faster analysis in the future. In this study, a one module variant was used, in more complex projects the number of module sizes might need to differ, therefore adding complexity that needs to be considered in the algorithm. The methodology can also be improved by incorporating a user interface for designer input, parsing of data and design option visualization for better accessibility.

7.4 Recommendations for Future Research

In this section, potential research areas for developing the work presented in this thesis are discussed:

7.4.1 Definition of Building Adaptation

1. There is an exponential increase in published literature on building adaptation projects, and it is expected for research in this field to continue growing. This suggests it will be necessary to revisit these terminologies in the near future to ensure alignment with the potentially changing nature of project scopes.

2. Investigating new terms and sub-categories of adaptive reuse and refurbishment will help identify emerging terms and concepts and avoid confusion. The example of "temporary conversion" as a sub-category of adaptive reuse and conversion is highlighted as a topic requiring immediate attention and integration within the developed framework. Other terms relating to building adaptability and interchangeability will also need more investigation as they gain more traction with the adoption of circular economy practices in the built environment.

3. Examining industry-based publications and reports and conducting field interviews and surveys from academic and industry-based professionals working in building adaptation will be necessary to improve the quality and validate the existing framework and increase its application in practice.

7.4.2 Building Adaptation Design Appraisal

1. It is suggested the methodology needs to be tested for a range of different building types, locations and enclosure assemblies to improve its applicability and scalability to a range of building adaptation projects.

2. Evolutionary and heuristic algorithms can generate design options based on the performance indices developed in this research to create complex design options and a combination of realistic design options comprised of multiple strategies.

3. There is concern in the validity of a matrix method for design option appraisal due to the interdependence of some metrics, and this needs further investigation. Future work can consider the correlation between measures and consider in-depth sensitivity analysis to validate results. The future steps of this research will include the development of an

extensive database and integration of the gathered data to be used in future generative design and design automation processes in a scalable tool.

4. Intelligent modelling systems and mathematical optimization tools can be successful in automating multidisciplinary design optimization can be utilized to develop this work further. Computational design methodologies for generating and evaluating multiple analysis metrics and design generation can be used.

5. Collaboration with programs and initiatives developed by municipalities, institutions and industry partners in expediting and improving adaptation projects, specifically residential projects, can increase the impact of the findings of this research.

6. Pilot projects using the developed methodology can be used to find the gaps in the methodology's scalability in practice.

7. Integrating the research results into an accessible tool with a user-friendly interface can allow the scalability of its use.

7.4.3 A Computational Design Methodology for Integrating Modular Construction in Building Adaptation Projects

1. Future work will include completing the proposed steps in the methodology not comprehensively investigated in this research—integration of external databases, linking to other analyzed cases, and the creation of an internal database.

2. Selected options be combined to form a database of feasible options that will then be used to build a predictive model and support the assessment of viable options. External Database of analyzed cases – relevant examples are retrieved, and comparison with selected options is possible. The developments in future of this work aim to enhance data-driven, multi-objective design decision making of MC in building adaptation.

7.5 Implications for Practice

7.5.1 A Definition Framework for Building Adaptation Projects

There is an increasing need and interest in incorporating design concepts for adaptability as part of circular design principles. The growing importance of preserving and improving existing structures due to their embodied carbon has also led to many research and initiatives by governments and the private sector. With increasing interest and activity in these topics, it will be increasingly important to define and communicate the various aspects of building adaptation in practice. It is expected that coherent and consistent reference to terminology related to building adaptation can include cost savings and improved efficiency from consistent codes, specifications and project descriptions that would otherwise lead to confusion and redundancies.

7.5.2 Building Adaptation Design Appraisal

Multiple methodologies for exploratory building adaptation design generation and appraisal were investigated as a part of this thesis. With an aging existing building infrastructure and a limited time to reach global emission targets, it is essential for developers, architects and engineers to have access to optimal decision-making tools for design and adaptation feasibility analysis. The implication of the research for practice includes improving early-stage design and feasibility analysis workflow, improving the quality of early-stage design decision-making and increasing the speed of feasibility analysis and data-driven design generation. The computational methodologies developed in this research are currently being tested on various existing building typologies and new construction for determining feasibility requirements for a large development in Mississauga as part of continuing collaborations with Entuitive.

7.5 Publications

7.5.1 Peer-reviewed journal articles

- **Shahi, S.**, Esfahani, M. E., Bachmann, C., & Haas, C. (2020). A Definition Framework for Building Adaptation Projects. *Sustainable Cities and Society*, 102345.

- **Shahi,S.**, Beesley, P. and Haas, C. Design Option Assessment for Building Adaptation Projects. *Journal of Architecture.* (Submitted, Under Review)

- **Shahi, S.**, Beesley, P. and Haas, C. A Methodology for Building Adaptation Design Appraisal Using Physics-Based Simulation Tools. *Engineering, Construction and Architectural Management.* (Submitted, Under Review)

- **Shahi, S.**, Woznicska, P., Rausch, C., Trudeau, I., Haas, C. *A Computational Design Methodology for* Implementing Circular Economy in Construction Using Modular Design for Building Adaptation Projects*. Automation in Construction*. (Submitted, Under Review)

- Guerra, B., **Shahi, S.**, Mollaei, A., Skaf, N., Weber, O., Leite, F., Haas, C. Circular Economy Applications in the Built Environment: a Global Scan of Trends and Opportunities*. Journal of Cleaner Production.* (Submitted, Under Review)

- Rausch, C., **Shahi, S.**, Sanchez, B., Dhamani, A., Haas, C. Utilizing Steel Modular Buildings as Structural Assembly Banks: a life cycle analysis perspective. *Journal of Cleaner Production.* (Submitted, Under Review)

7.5.2 Peer-reviewed conference papers

- **Shahi, S.**, Haas, C. and Beesley, P., 2019. A Quantitative Comparison of Adaptive Reuse Strategies of Residential Towers in Northern Climates. In *EG-ICE - 26th International Workshop on Intelligent Computing in Engineering.*

- **Shahi, S.**, Woznicska, P., Rausch, C., Trudeau, I., Haas, C. Energy Performance and LCA-driven Computational Design Methodology for Integrating Modular Construction in Adaptation of Concrete Residential Towers in Cold Climates. In *ISARC 2020 – The 37th International Symposium on Automation and Robotics in Construction.*

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Appendix A: A Computational Design Methodology for Integrating Modular Construction in Building Adaptation Projects

Overview

Adaptation of existing building stock is an urgent issue due to aging infrastructure, growth in urban areas and the importance of demolition mitigation for cost and carbon savings. To accommodate the scale of implementation and address the complexity of building adaptation projects, the design decision-making process needs to improve. Computational design methodologies can optimize design decisions driven by spatial, environmental and economic factors. Modular Construction (MC) can also increase efficiencies in the design and implementation of building adaptation projects. An early-stage design computational methodology is developed for integrating MC and design optimization metrics including energy use, daylighting, life cycle impact, life cycle costing and structural efficiency in order to improve the quality of design options and speed of evaluation in building adaptation processes. The extension and recladding of the Ken Soble Tower in Hamilton, Ontario, is used for the functional demonstration of the methodology. Various design options that conform to determining design constraints are evaluated, and pareto-optimal early-stage design options are identified based on life cycle cost and structural complexity. The application of this research can promote the improvement of existing residential infrastructure at increased rates to meet required energy improvements and to address housing affordability needs.

A.1 Introduction

Adaptation of existing buildings has increased over the past decade as a response to changing environmental conditions, as well as requirements for reducing energy use and production of construction and demolition waste (Pardo-Bosch et al., 2019). There is a need for the reconsideration of our status-quo linear approach of design and construction with the inevitable end-of-life option of demolition. To move to a circular built environment, there is a need to incorporate adaptation of buildings as a means to facilitate continual loops of resources, products and materials in construction (Stahel, 2016).

Implementing MC as a building adaptation solution can also improve the condition of existing buildings while preparing them for a circular future in which unnecessary demolition is avoided, and the building modules and materials can enter multiple cycles of use (Hossain et al., 2020). The success of MC projects is directly related to appropriate early decision-making due to the planning and coordination focused nature of modular projects. Modular form generation is improved by an automated design processes that provide real-time design feedback (Holzer, 2016). MC has proven advantages in terms of life cycle impacts and life cycle costs compared to traditional construction and can contribute to more energy-efficient buildings through the improved quality of construction (R. M. Lawson et al., 2012). A framework for modular extension to existing buildings, and early-stage automation of designs, therefore, needs to consider multiple factors for optimization.

The conducted literature review highlights the importance of adaptation projects and processes for their improvement. Through early design stage optimization, Kiss and Szalay were able to demonstrate environmental savings of 60-80% compared to traditional design methods. Typical design option optimizations reviewed in literature often consider a limited number of options (Kiss & Szalay, 2020), highlighting the need to consider computational design methodologies for design option generation and simulation for simultaneous optimization of multiple factors simultaneously. Automated design option generation based on set constraints, energy use, and Life Cycle Analysis (LCA) and Life Cycle Costing (LCC) optimization can be applied using computational tools in early-stage design (Tugilimana, Thrall, Descamps, et al., 2017).

Researchers have developed approaches for optimizing building adaptation, modular construction, and have created methodologies for incorporating design optimization metrics and automated early design decision-making. There are currently no studies highlighting a framework for the integration of early-stage design optimization of environmental factors, including energy use and daylighting, Life Cycle Analysis (LCA) and Life Cycle Costing (LCC) for MC, specifically for large-scale building adaptation projects. Therefore, a computational design methodology is developed for integrating MC in building adaptation projects, and for developing optimal design options in the process. The critical aspect of the proposed model is the integration of computational design strategies for simultaneous analysis of MC metrics, energy and daylighting analysis, LCA, LCC and structural complexity analysis. The proposed methodology is demonstrated for the development of design alternatives to the Ken Soble Tower adaptation in Hamilton, Canada.

A.2 Background

In a traditional building adaptation feasibility and early design process, many uncertain factors need to be examined. Project requirements, including budgets, timelines, spatial requirements and performance benchmarks, are taken into account. The analysis of the existing conditions of the building, including building geometry, overall condition and areas for improvement, are also considered. Preliminary design options are developed by the design team and often analyzed by various consultants that can include energy consultants, LCA consultants and cost consultants, as examples. The design team and specialty consultants go through an iterative process to develop suitable design options, and the results are shared with the client for feedback. This process can take many months to complete depending on project complexity, often leading to suitable, non-optimal design options (**Figure A-7-1**).

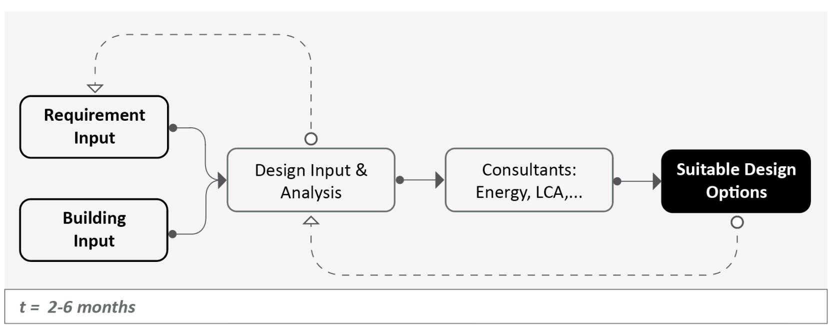


Figure A-7-1: Traditional Design Methodology

The extended timeline for the building adaptation feasibility process cannot meet the increasing demand due to key aging urban building stock, requirements for improved energy efficiency and spatial quality, and the need for construction and demolition waste mitigation. For example, there are more than 3000 residential towers built between 1950-1990 accommodating more than 65% of middle-and low-income communities, as the main source of affordable housing in Ontario (Smetanin et al., 2019). These buildings were built with low energy standards and have reached the end of their useful life and require adaptation at different scales. In 2019, a ten year CAD $1.3B co-investment fund was set up for Toronto Community Housing Corporation (TCHC) for adaptation, including retrofitting and rehabilitation, but only 21 buildings out of the 2100 TCHC buildings were adapted in 2019 (Pelley & Lee-Shanok, 2019). In addition, in building adaptation design processes, future adaptability and reusability for improving the resiliency and circularity of the built environment are often not considered, which can be addressed using modular construction. This literature review highlights the importance of building adaptation for facilitating a circular economy in the built environment. Strategies and processes for improving the efficiency of this process will be reviewed, including modular construction, computational design methodologies, automated early-stage design using design optimization metrics such as energy use, daylighting, structural efficiency, LCA and LCC.

A.2.1 Circular Economy in the Built Environment: Role of Building Adaptation

Construction materials stocked in the built environment, such as buildings and infrastructure, make up a large part of global material use (Commission, 2016). Buildings have a permanency ranging on average 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). A Circular Economy (CE), as it pertains to the built environment, refers to a regenerative approach to construction processes and systems that improves material use and minimizes environmental impact, including strategies for extending the use of systems and increasing value in all lifecycle phases as well as reducing waste (Brown et al., 2019; Foster, 2020; López Ruiz et al., 2020; Munaro et al., 2020). Currently, the global economy is only 8.6% circular, with most Construction and Demolition Waste (CDW) being recycled or used as backfilling (Wit et al., 2019).

The construction industry is a leading sector in the field of CE, and CDW reduction is a priority in most global CE policies (Brambilla et al., 2019; López Ruiz et al., 2020). The focus of CE in the built environment is on utilizing technological advances in design, construction and planning to address the economic and environmental issues of finite resources (Anastasiades et al., 2020; Munaro et al., 2020), the issue of demolition and resulting CDW (Jaillon & Poon, 2014), and increasing sustainability and resiliency in buildings and cities. A CE in the built environment needs to address these issues while contributing positively to economic growth (Lieder & Rashid, 2016; López Ruiz et al., 2020).

An effective circular economy in the built environment can be achieved by implementing a range of strategies in building design and demolition mitigation (López Ruiz et al., 2020). The design of the built environment significantly influences reusability and waste generation. Munaro et al. demonstrate that circular economy practices are best adopted for design optimization in early-stage design (Munaro et al., 2020). Anastasiades et al. and Hossain et al. suggest the adoption of design for disassembly (DfD) and design for adaptability (DfA), as well as modular and prefabricated construction, are the main strategies for implementing circular construction practices (Anastasiades et al., 2020; Hossain et al., 2020). In general, more than half of the total CDW can be reduced by the adoption of prefabricated systems (Jaillon & Poon, 2014; López Ruiz et al., 2020; Stahel, 2016). Computational design tools models can improve the functionality of these designs (Hossain et al., 2020), and design decision-making using brute-force search and pareto-optimality, are effective means for considering multiple objectives, improving the overall quality and circularity of design decisions.

A.2.2 Modular Construction

Compared to traditionally constructed concrete buildings, prefabricated Modular Construction (MC) can reduce environmental impacts, lead to economic benefits with increased on-site productivity and construction quality (Yuan et al., 2018), improve predictability regarding lifecycle costs, energy performance and environmental impact, acoustic quality, airtightness and thermal performance (Sharafi et al., 2018; Z. Xu et al., 2020). Designing buildings for reuse using modular construction, instead of recycling at End-of-Life (EoL), can also reduce life cycle impacts by 88% (Minunno et al., 2020), and facilitates maintenance, repair and reuse during different life cycle stages of a building, minimizing waste generation during construction and deconstruction (Wuni & Shen, 2020). MC can also improve the adaptability of a building through its life cycle with standardization of interfaces and independently fitted elements, allowing interchangeability and making intensive changes to a building in increments manageable (Isaac et al., 2016).

Prefabrication in controlled factory environments is demonstrated to reduce construction waste by 10-15% on average (Z. Xu et al., 2020) and up to 52% (Jaillon & Poon, 2014). Lifecycle greenhouse gas emissions over a 50-year life of a modular building is calculated to be lower on average compared to typical construction (Quale et al., 2012). Through a study optimizing for LCA for MC, Kamali & Hewage demonstrated that modular and prefabricated buildings show significantly improved life cycle performance metrics compared to traditional construction (Kamali & Hewage, 2016), and Mao et al. determined the carbon emissions to be lower by 32 $kgCO_2e/m^2$ compared to traditional construction (Mao et al., 2015). Effective assembly of prefabricated modular units can also improve on-site construction conditions. These improvements include reduced construction pollution, noise and occupant disruptions making it an ideal strategy for dealing with occupied existing buildings and urban areas (Blismas et al., 2006). Reduced construction time is also an important factor, reported from a range of 6-month reduction of construction time in a complex project (Mo et al., 2018) to a 40% reduction in overall project time with conventional construction and disruption to occupants and neighbourhoods are reduced by 30-50% (Hammad et al., 2019; Z. Xu et al., 2020).

While MC has been commonly used in buildings four to eight storeys high, implementation in high-rise buildings is slowly gaining momentum. This includes entire modular buildings or a combination of modular and typical construction (Sharafi et al., 2017). Modular structures in high-rise buildings face the requirement of wind force mitigation, making hybrid structures with a skeletal structure or concrete core common (Lacey et al., 2018). Therefore, existing concrete towers with their over-designed capacities, can be beneficial for the lateral support of modular extensions. A study by Du et al. demonstrates that designers and building owners require more developed and detailed technical and financial performance information for considering MC building adaptation projects such as façade retrofits (Du et al., 2019). Through the analysis and integration of MC design parameters, this research aims to bridge this knowledge gap.

A.2.3 Computation and Automated Early Stage Design

Design decisions made in the first 10% of projects determine up to 80% of the building operation costs after construction, and computational early-stage design methods can improve the architectural, structural and environmental performance of building designs (Sharafi et al., 2017). Yuan et al. demonstrated that a computational design methodology specific to modular construction, can improve constructability and enable design optimization (Yuan et al., 2018). Kiss and Szalay, developed a framework for optimization of early-stage designs for LCA and energy use as part of an automated early stage design process, leading to savings of 60-80% (Kiss & Szalay, 2020). Banihashemi et al. proposed a computational methodology for optimizing structural and other material use, reducing waste in the process (Banihashemi et al., 2018), and Greenbough et al. demonstrated that the integration of computational design tools, in MC specifically, improves the structural engineering design process (Greenough et al., 2019). Schwartz et al. demonstrated that optimal refurbishment design solutions can be obtained from optimizing LCA in early-stage design through a computational and automated design methodology. Their results prove the increased efficiency and accuracy of a consolidated early-stage design tool (Schwartz et al., 2016).

The consideration of multiple factors in early-stage design has become common in the past decade; these include cost, energy and lifecycle performance, amongst others. Granadeiro et al.

integrate early design stage automation of building envelope design with energy simulation using grammars (Granadeiro et al., 2013). Yu et al. used genetic algorithms and design structure matrix to support automated spatial organization in the early stages of design (Yu et al., 2007). Sharafi et al. presented a method for automating early-stage design for modular multi-story buildings through comparison of various forms on performance. They can be used for optimization of design metrics, including spatial or environmental optimizations, defined as constraints. This automated methodology supports designers in generating and analyzing multiple design options simultaneously and enables them to evaluate optimal design solutions (Sharafi et al., 2017).

Computational and parametric design environments enable optimization of building geometry simultaneously with the analysis of various design variations with immediate building performance feedback (Holzer, 2016). Software interoperability is a major step in supporting automated design processes and enabling designers to engage with option generation through real-time performance feedback. In an effective automated early-stage design process, designers in charge must be able to take spatial, structural, environmental performance and life cycle impacts and costs into consideration simultaneously to make optimized decisions. Currently, there are limited studies in supporting an integrated and systematic design process for the design of modular buildings (Yuan et al., 2018) and as modular extensions to existing buildings.

Literature demonstrates examples of applying LCA and energy analysis in a computational tool with geometry represented mathematically or as topologies. Topology optimization is often used in structural design to find an optimized design in a given domain. Design options that do not meet the defined objective are iteratively eliminated after analysis (Tugilimana, Thrall, & Filomeno Coelho, 2017). While energy analysis and environmental performance considerations are becoming common in an automated design process, structural analysis and evaluation is still considered in later stages of design.

Multi-objective optimization allows for choosing a suitable solution but is not common in building optimization literature (Kiss & Szalay, 2020). Obtaining optimal design solutions to complex multi-dimensional and multi-modal problems demands computationally expensive fitness function evaluations, and typical optimization methods are not able to address the issue. To address a structural optimization problem, for example, a single evaluation may require many hours or several days to compute. In a typical genetic algorithm for solving multi-objective solutions, creating of a reasonably sized initial population often needs long periods of calculation time, often making the task unfeasible (Fernandes et al., 2020). Therefore, it is more practical to use heuristic methods to constrain the combinatorial variety and create all possible solutions rather than apply genetic algorithm approaches and further allowing the designer to search the full design space for desirable design solutions.

A.2.4 Knowledge Gap

The success of building adaptation and modular building projects is directly related to appropriate early decision-making due to the planning and coordination focused nature of modular projects and the complexity of building adaptation projects. The following knowledge gaps identified in the literature will be addressed in this research. Computational design methodologies for generating and evaluating multiple analysis metrics are limited. Two studies have been identified that assess multiple metrics, and one that focuses on computational methodologies but does not consider complex building adaptation projects and MC. Studies that demonstrate the use of computational design strategies and modular construction mainly consider the evaluation of either structural efficiency or energy use. There are no tools or methodologies available that integrate various analysis metrics for the early-stage design automation of modular extension and adaptation of existing buildings. The implementation of CE strategies and business models have been proven to be effective in increasing the resiliency and efficiency of the built environment but only at the onset of implementation. Novel methodologies that can address the need for adaptation of existing building stock and the integration of aging infrastructure will help improve the building adaptation design decision making process and facilitating the transition to a circular built environment.

A.3 Computational Design Methodology

A computational design methodology is developed for integrating and evaluating MC in building adaptation projects. An extensive literature review on related topics highlight a gap in consideration of multiple factors for design optimization of modular construction. The methodology is based on creating a finite number of design solutions that meet a set of required data. Energy use, daylighting and carbon emissions will be set as system constraints, and the remaining design combinations will be analyzed based on their LCC and based on structural efficiency as a proxy for complexity to arrive at a set of pareto-optimal design solutions for further selection and analysis by the designer.

This methodology is developed in three stages: 1) analysis, parametrization of existing building and development of an algorithm for the generation of design options, 2) simulation and analysis of generated options for energy use, daylighting, structural complexity, LCA and LCC, and 3) result refinement through a heuristic-guided exhaustive search and selecting pareto-optimal design solutions. Stage one of the framework requires manual work and processing from the project designers for processing the existing building and defining parameters. Through a step-by-step analysis of the building, development of design constraints and processing of user inputs, precise design constraints and rules are developed for algorithm input. In the second stage, the developed algorithm generates design combinations, simulates for environmental analysis and analyzes the conditions of the design combination for life cycle performance and cost. Design options that meet the set criteria are displayed in stage three.

The methodology enables a designer to input preferences for generating and parsing through possible designs for selecting optimal solutions. This methodology suggests possibilities for the incorporation of external databases and previously analyzed cases for the development of databases of all feasible solutions leading to a predictive model of performance feeding the results, to be investigated at a later stage of this work. The first stage requires input from parties involved in the early-stage design process, including the client and designers. The last two stages of the framework are fully automated and can be processed in real-time **Figure A-7-2**.

The developed computational methodology is differentiated by geometric simplicity, integration of automated processes and simulation tools and processing of direct manual user input in various stages. Genetic algorithms are widely used in computational design; in this methodology, the focus has been to incorporate adaptive strategies (specific vs. generic) and topologic modelling strategies. Existing computational interfaces, plugins and frameworks are used in the development of a cohesive tool that integrates existing resources and facilitates integration. The computational design tool is programmed using Grasshopper® visual programming interface, and plugins are used within the interface for energy use simulations and optimization. One-Click LCA® is used for preliminary life cycle emission calculations, and other plugins in Grasshopper®, such as Honeybee® for energy analysis and daylighting, are used. Future development of the framework will involve the incorporation of external databases and analytical cases, creating a database of feasible solutions over time and developing predictive algorithms. The Ken Soble Tower in Hamilton, Canada, is selected as a functional demonstration and is used to demonstrate the functionality of the framework in various stages. The computational methodology is functionally demonstrated in section 4 (**Figure A-7-2**).

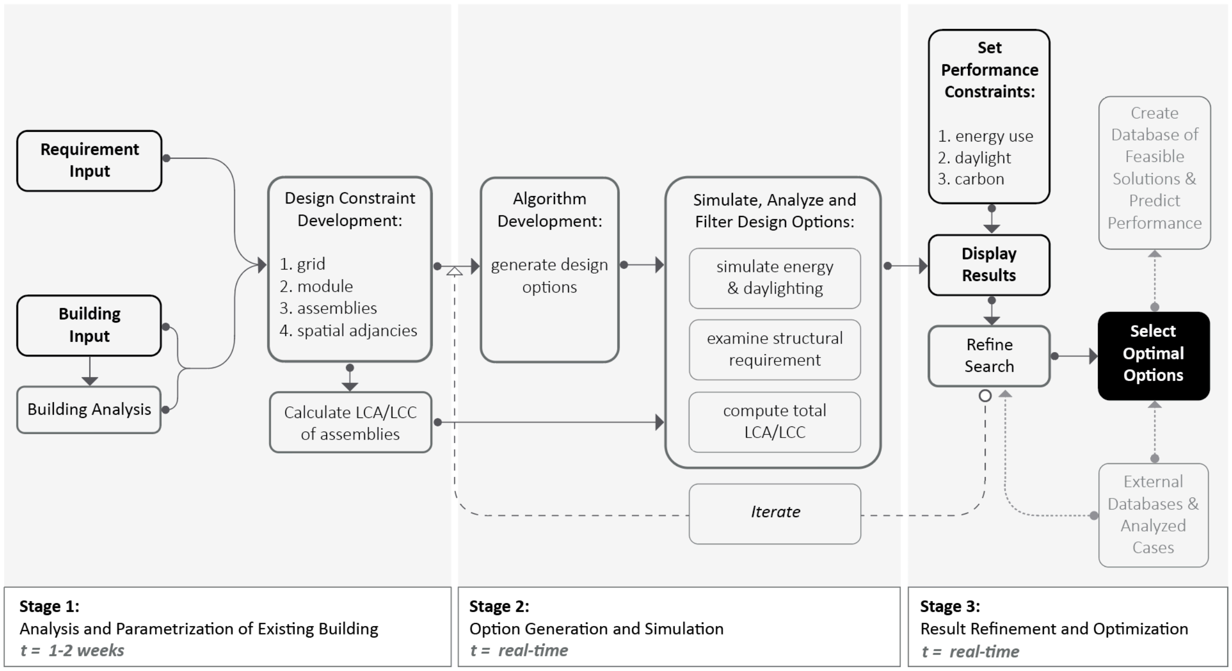


Figure A-7-2: Framework for Computational Design Methodology

A.3.1 Stage 1 – Analysis and Parametrization of Existing Building

The first stage in the methodology is focused on analysis and parametrization of the existing building, as well as the development of design constraints. The design constraints are developed by processing the existing building information, defining design parameters and determining user inputs and requirements. Design parameters are defined based on analysis of the existing building, existing site conditions, and planning requirements and restrictions. Design input includes adaptation strategies to be considered, such as the extension of the building, recladding of the envelope, re-glazing of the windows and enclosing of existing balconies.

For efficient MC design, the fewest number of module variants is required. In the first phase of stage one, the existing building drawings are analyzed, and the geometry of the existing building, including interior spaces and the building envelope, are modelled. The existing structure is analyzed to determine required design parameters, including structural, environmental and spatial shortcomings of the existing building. The existing building is modelled as zones (breps) and aggregated into topological complexes. The building geometry is further discretized into panels and elements at the discretion of the project designer, illustrated as step 1 in **Figure A-7-3**.

Development of design constraints early in the process, such as a speculative grid for modular design, will limit the dimensionality of the design problem leading to a heuristic approach and increased accuracy of generated design options. To acquire this information, the existing building geometry is analyzed in terms of dimensional and spatial constraints for extension, and the dimensions of a typical module are determined. For building extension and recladding for example, the following steps are required: 1) building parameters defining modular extension parameters, module parameters including spatial configurations, connection parameters, and growth patterns and restrictions (**Figure A-7-3**); 2) panel parameters including dimensions of panel divisions, the spatial organization of panels and connection details (**Figure A-7-4**); 3) Determining rules and patterns for unit growth by testing spatial layout using module and panel types, and defining combination of modules and panels for each existing unit type (**Figure A-7-5**).

As part of the existing building analysis in step 4, the LCA of the existing building is determined considering the existing operational energy use standards. After the modules and panels are determined, the life cycle impact per assembly per m2 is determined, not accounting for energy use for each of the modules separately using One-Click LCA® (**Table A-1**). The combination of these modules will be used in the algorithm to determine the LCA of the combined design options in real-time following formula (1) and LCC following formula (2). In the framework, the user can input preferences, review and parse through results and reconfigure priorities based on project data in real-time. The user inputs and determines constraints. The user here is defined as the designer, modeller or client evaluating building adaptation strategies. The building analysis results combined with the input parameters are used to feed the developed algorithm for option generation. The building inputs and analysis, as well as design and user inputs, are combined to create a detailed breakdown of the design constraints for the development of the algorithm in stage 2.

A.3.2 Stage 2 - Option Generation and Simulation

After defining geometry and selecting strategies, a virtual grid of speculative possibilities is computed. The developed algorithm generates adaptation design options by positioning modules and assigning states based on the information stored in the grid, previously determined in stage 1. The design options are generated using Topologic® and the developed algorithm within Grasshopper®. Topologic® is a software modelling library enabling hierarchical and topological spatial representations through non-manifold topology (Aish et al., 2018). Existing geometry is modelled as breps directly modelled or extruded from existing drawings. They are fed as input to the module translating Rhino® 3D brep object to topologic cells, organizing them and forming topologic complexes. The set of options is generated through heuristic-guided exhaustive search, being finite and relatively small, allowing for computation and comparison of all the possible options. Invalid combinations that do not meet spatial requirements are further eliminated, for example long overhangs and inappropriately attached modules (**Figure A-7-6**). A topological structure with cells, also known as object-oriented programming, governs the distribution of modules and assignment of states.

To analyze the performance of the generated design options, multiple adjacent surfaces must be resolved, and pre-determined building assemblies assigned to each surface in step 6. The attachment of multiple modules results in multiple alignment of horizontal and vertical surfaces, and the solving of these adjacencies will eliminate multiple surfaces for a single alignment per vertical and horizontal surface (**Figure A-7-7**). In step 7, defined assemblies are assigned for each single surface (**Figure A-7-8**). With the correct assemblies assigned, heating energy use ($kWh/yr/m^2$) and daylighting, Spatial Daylight Autonomy (sDA) is completed in step 8. SDA is defined as the percentage of yearly occupied time with minimum illuminance threshold reached by daylight, and has been cited in multiple studies as an accurate method for quantifying the daylighting efficiency of a building (Acosta et al., 2019). In addition, data from each design combination including number of module extensions, panel types, extension area, etc. are extracted from the model at this stage (**Figure A-7-9**).

In step 9, the total LCA and LCC of each design option is calculated in real-time. The net environmental impacts for each building adaptation design option consider the LCA of the existing building and consideration of the extension of life by 60 years through building adaptation. The LCA of modules and existing buildings are calculated in line with EN 15978:2011 standards (EN, 2011) for LCA Modules A1 to Module D. The energy use of each compiled design option is calculated inside Grasshopper® in real-time, using the Honeybee® plugin. Honeybee® supports thermodynamic modelling and creates, runs and visualizes the results of energy models using EnergyPlus® and OpenStudio® simulation engines. The number of extension modules is calculated in Grasshopper® in real-time and calculated using the pre-calculated LCA and LCC of each design option, using the formula (1) for total LCA and formula (2) for total LCC:

$$\mathrm{LCA_{total}} = \mathrm{E_i[kgCO_2e]} + \sum\nolimits_A \mathrm{n_A\, E_A\, [kgCO_2e]} + \sum\nolimits_B \mathrm{m_B S_B C_B\, [kgCO_2e]} + \quad (1)$$

$$\mathrm{U_{total}\, [kWh/yr/m^2](U_{factor}[(kgCO_2e)/kWh/yr/m^2])}$$

Where LCA_{total} is total life cycle assessment including, carbon emissions and operational energy use, Ei is the carbon emission of the existing building excluding operational energy use, n is the area of each assembly in each design option, A is the assembly type used in the design option, EA is the emission of type A assembly excluding operational energy use, U_{total} is the total energy use of the building including existing and extension modules, and U_{factor} is the local emission factor, B is accounting for structural impact, m is the number of modules per design option, S is the LCA determined of steel required per module and C is the interpolated complexity score (0.1-0.3) calculated for each design option.

$$\mathrm{LCC_{total}} = \mathrm{E_c}\ [\$/\mathrm{m}^2] + \textstyle\sum_A \mathrm{n_A}\ \mathrm{F_A}\ [\$/\mathrm{m}^2] + \sum_D \mathrm{m_D S_D C_D}\ [\$/\mathrm{m}^2] + \qquad (2)$$

$$\mathrm{U_{cost}}\ [(\mathrm{kWh/yr/m^2})](\mathrm{U_{factor}}[(\mathrm{kgCO_2e})/(\mathrm{kWh/yr/m^2})])\ (\mathrm{U_{carbon}}(\$/\mathrm{m^2/kgCO_2e})]$$

Where LCC_{total} is total life cycle costing including, carbon emissions and operational energy use, E_c is the cost of the existing building excluding operational energy use, n is the area of each assembly in each design option, A is the assembly type used in the design option, FA is the cost of type A assembly excluding operational energy use, U_{cost} is the operational energy cost of the building including existing and extension modules, U_{factor} is the local emission factor, U_{carbon} is the local cost of carbon, D is accounting for structural cost, m is the number of modules per design option, S is the LCC determined of steel required per module and C is the complexity score calculated for each design option.

In step 10, the structural complexity of each module is evaluated. While the development of a computational methodology could include a comprehensive structural design component (i.e., where each module could have its own unique structural system), this methodology adopts a more pragmatic approach of assessing the structural complexity as a function of module topology. A score for structural complexity is a proxy for adding the additional materials required at connections to ensure certain module configurations can be achieved from a structural design standpoint. For instance, a module that is suspended or cantilevered to another module or to the existing building will require additional supports (e.g., larger connections, bracing or awning-type cables). These additional materials not only increase the project cost by adding design complexity and more materials, but they contribute to the overall life cycle inventory (e.g., more volume and mass of materials). As such, the overall LCA and LCC values are increased by a linear factor of the structural complexity, as determined by formulas (1) and (2). A larger structural complexity score will increase the life cycle impacts of a given module configuration. The details of the structural complexity scoring is explained for the case of the functional demonstration and shown in **Figure A-7-10**.

A.3.3 Stage 3 – Result Refinement and Optimization

The results of option generation and simulation are visualized for review of all the generated and evaluated options. The user is able to refine the search for the most viable option by limiting the scope of the investigation (**Figure A-7-10**). After initial refinement, LCC and structural complexity are compared, and pareto-optimal results are highlighted (**Figure A-7-13**) for further analysis.

A.4 Functional Demonstration – Ken Soble Tower

The Ken Soble Tower is a 16-storey multi-unit concrete residential tower built-in 1967 in Hamilton, Ontario. A regional shortage of adequate, affordable housing and the need to reduce energy use and carbon production has led to the adaptation of the tower to Passive House standards currently under construction. In the adaptation, all balconies have been demolished, the envelope has been reclad, and the HVAC systems have been decentralized. In this study, alternative strategies of extension and recladding are investigated as a functional demonstration of the developed computational methodology. Due to computation limitations, only the first three storeys of the building are considered in this analysis.

A heuristic method is used for constraining, combining and generation all possible solutions, allowing the user to explore the created design space. The developed tool in this research creates over 600 design options in a 2-week simulation period, according to a set of predefined design constraints. The breadth of the design space is relatively small due to the imposed constraints. Heuristic methods are applied to minimize the dimensionality of the problem at hand. To assess the performance of each resulting design option, an extended amount of computation required for performing simulations.

A.4.1 Stage 1: Project Parametrization and Analysis

The typical module dimension and the spatial analysis lead to the determination of rules for extension. **Figure A-7-3** demonstrates the points of “growth” in black, and the direction of permitted extension determined by the designer. The grid is determined as derivatives of a, b and z (an exception of envelope extension to a. At the level of the determined module size, panels are broken down and analyzed in terms of joining conditions that include: 1) attachment of a new module to the existing building (e), 2) connection of two modules together (c) and 3) exterior façade (f). Through multiple design exercises, the number of required panel divisions for each panels of a and b are determined for each condition of e, c and f. In the case of the Ken Soble Tower project, the variation of module connections lead to 16 different possible configurations of e, c and f for panel a, seven different possible configurations of e, c and f for panel b as demonstrated (**Figure A-7-4**). Unit growth patterns are also determined by the user by testing spatial layouts for each existing unit using the defined module size and defining combination of possible extensions using modules and panels for each unit (

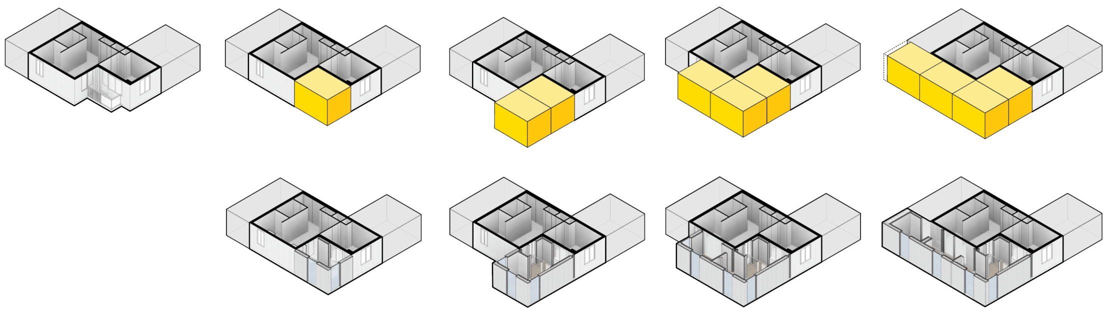


Figure A-7-5). All the different building assembly types used in the study are defined in

Table A-1 and assigned for each single surface. These assemblies include: 1) connecting module floor, 2) exposed floor; 3) exposed roof, 4) exterior wall (solid), 5) exterior wall (glazing), 6) recladding, or 7) connecting interior module wall (Figure 8). The LCA and LCC per unit area (m2) are calculated for each assembly, to be used in real-time analysis of LCA and LCC in stage 2 of the methodology (

Table A-1).

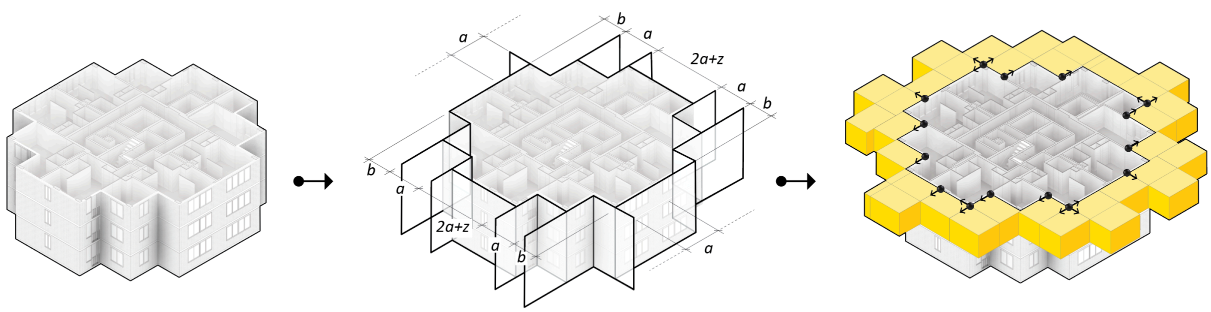


Figure A-7-3: Step 1 – Existing building analysis (demonstrating the first three storeys): 1) Input existing building geometry, 2) Create speculative grid options, 3) Select grid and define module dimensions, 4) Define growth dimensions, direction and starting points based on modular size and interior layout.

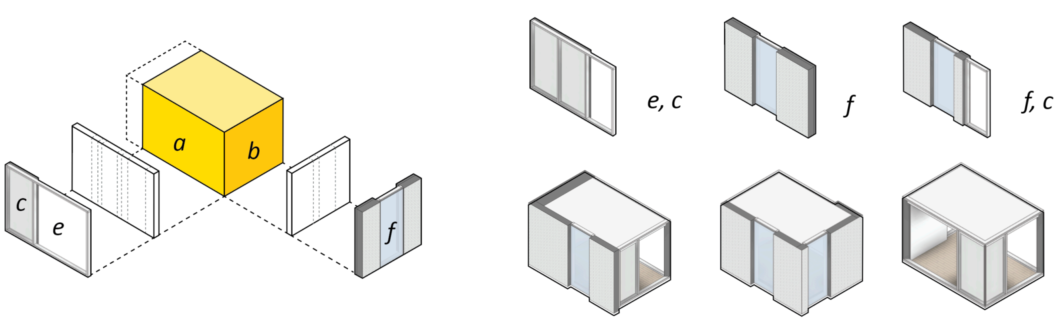


Figure A-7-4: Step 2 – Module and panel parametrization: 1) Define module parameters, 2) Define panel parametrization, 3) Develop module prototypes.

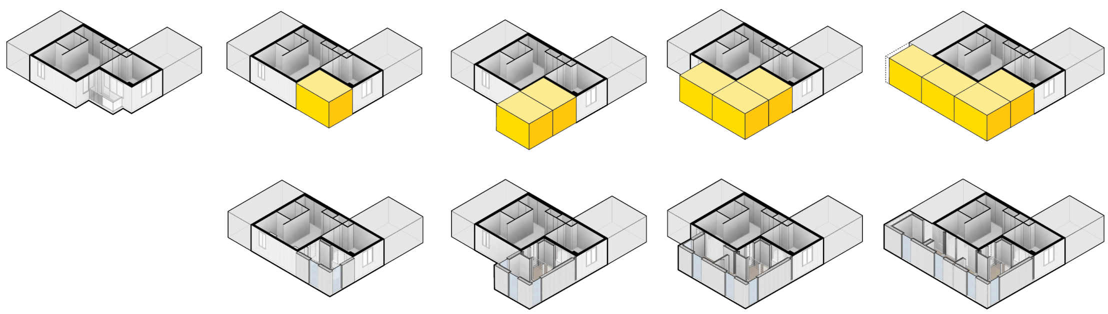


Figure A-7-5: Step 3 – Unit growth patterns: 1) Test spatial layout using module and panel types, 2) Define combination of modules and panels for each existing unit type.

Table A-1: Stage 4 – LCA/LCC of Building Assemblies: 1) Define all building assembly types, 2) Calculate LCA/m^2 for each assembly, 3) Calculate LCC/m^2 for each assembly

Assembly	GWP (kgCO2e)/m^2	Life Cycle Cost ($)/m^2
Connecting Module Floor *- Hardwood flooring, prefinished* *- Concrete, ready mix, 0-2500 psi* *- Plywood, generic, 4-50 mm, 620 kg/m^3* *- Glass wool insulation panel, unfaced, generic, 25 kg/m^3* *- Gypsum board, wallboard, type X, 16 mm)*	51.5	325.5
Exposed Floor (Soffit) *- Hardwood flooring, prefinished* *- Concrete, ready mix, 0-2500 psi* *- Plywood, generic, 4-50 mm, 620 kg/m^3* *- Glass wool insulation panel, unfaced, generic, 25 kg/m^3* *- Gypsum board, wallboard, type X, 16 mm)* *- Flexible waterproofing membrane, from thermoplastic elastomer, on CMU, 2.4 kg/m2* *- Styrofoam insulation, 1.3-3.0 pcf (Dow)* *- Western red cedar bevel siding, clear grade, painted, 1inx6in*	100.0	504.8
Exposed Roof *- Roll formed metal wall and roof panels, 1.0127 lbs/ft2* *- Flexible waterproofing membrane, from thermoplastic elastomer, on CMU, 2.4 kg/m2* *- Oriented strand board (OSB), 0.37in (APA)* *- Glass wool insulation panels, unfaced, generic, 25 kg/m3* *- Styrofoam insulation, 1.3-3.0 pcf (Dow)* *- Gypsum board, wallboard, type X, (16 mm)*	78.2	130.3
Exterior Wall (Solid) *- Gypsum board, wallboard, type X, (16 mm)* *- Glass wool insulation panels, unfaced, generic, 25 kg/m3* *- Plywood, generic, 4-50 mm, 620 kg/m3* *- Styrofoam insulation, 1.3-3.0 pcf (Dow)* *- Plywood, generic, 4-50 mm, 620 kg/m3* *- Air and water barrier system, mechanically fastened, 0.184 lbs/ft2, Tyvek* *- Clay brick, 3.625 x 2.25 x 7.625 in, 37.1 % fly-ash*	56.8	187.8
Exterior Wall (Glazing) *- Window wall curtain wall aluminum framing, 5.9 kg/m2*	51.9	880.2
Recladding *- Plywood, generic, 4-50 mm, 620 kg/m3* *- Styrofoam insulation, 1.3-3.0 pcf (Dow)* *- Plywood, generic, 4-50 mm, 620 kg/m3* *- Air and water barrier system, mechanically fastened, 0.184 lbs/ft2, Tyvek* *- Clay brick, 3.625 x 2.25 x 7.625 in, 37.1 % fly-ash*	46.1	158.2
Connecting Interior Module Wall *- Drywall system with steel studs, incl. mineral wool insulation, painted*	22.0	3.0

A.4.2 Stage 2 - Option Generation, Simulation and Analysis

Possible design combinations are generated within a designated temporal limit for simulation based on set constraints, and combinations that do not meet set spatial requirements are further eliminated (**Figure A-7-6**

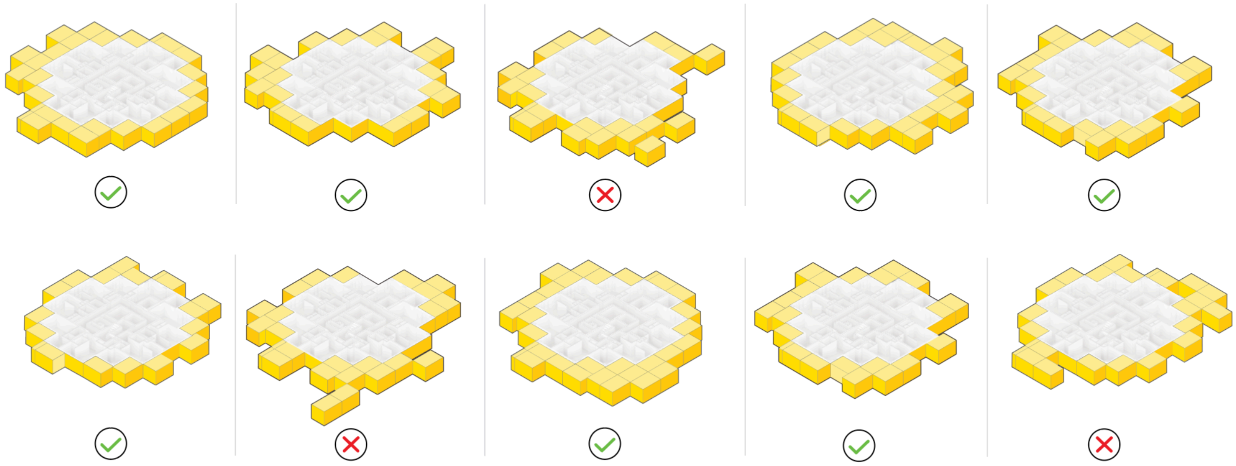


Figure A-7-6). After the design combinations are finalized for further analysis, the geometric adjacencies are resolved. Multiple alignment of horizontal and vertical surfaces in each design combination are identified and eliminated to arrive at a single alignment per vertical and horizontal surface (**Figure A-7-7**). For each resolved surface is identified per assembly type and identified in

Table A-1. The assembly is assigned to enable environmental, LCA and LCC simulation and analysis (**Figure A-7-8**). Using the prepared geometry, the algorithm simulates and calculates heating energy use (kWh/yr/m^2) and daylighting simulation using Honeybee® for Grasshopper®. Spatial Daylight Autonomy (sDA) is used for daylighting analysis of design options. Further, data is collected from each design combination including module numbers, panel types and numbers, extension area for further analysis (**Figure A-7-9**).

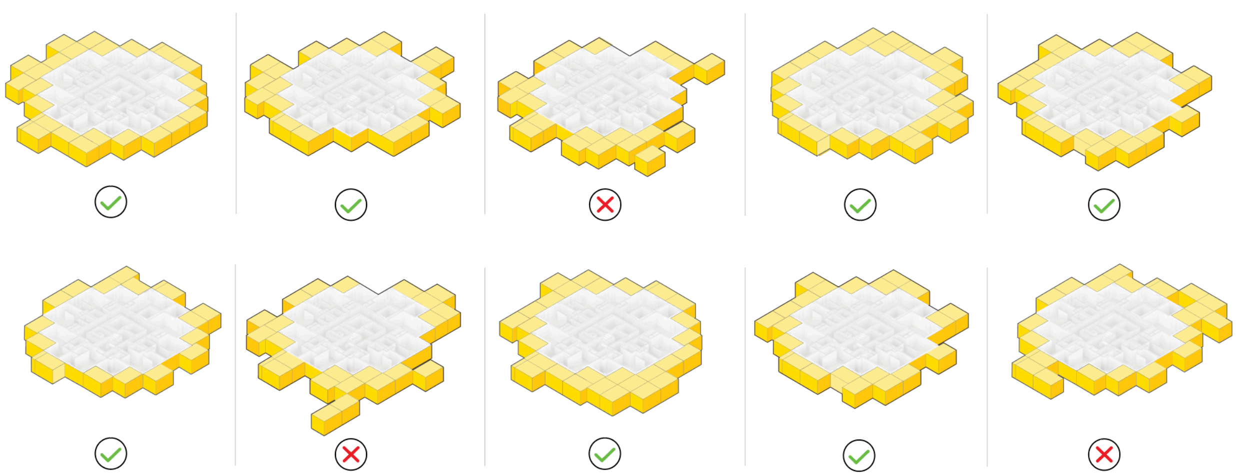


Figure A-7-6: Step 5 – Generate combinations and eliminate invalid configurations: 1) Generate all possible design combinations based on design parameters, 2) Eliminate combinations that do not meet spatial requirements.

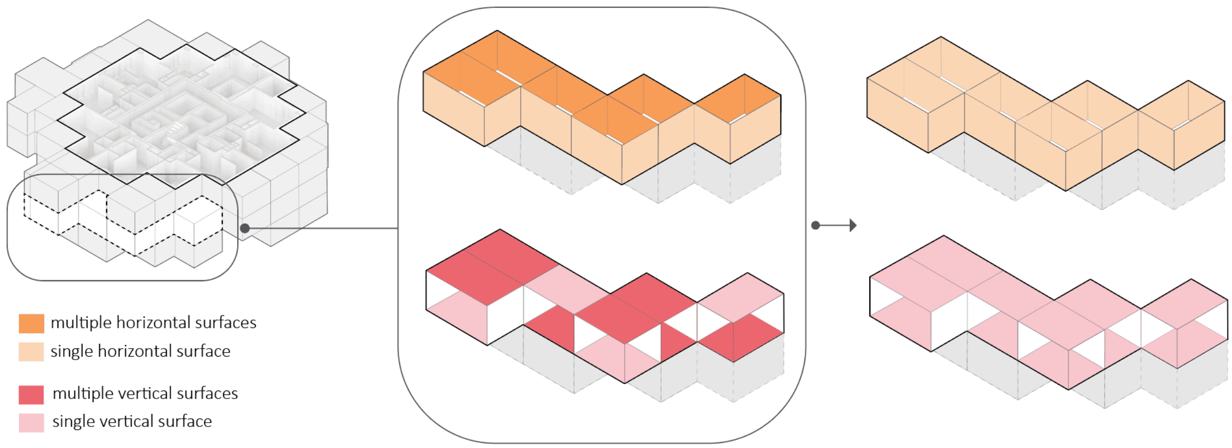


Figure A-7-7: Step 6 – Solve Adjacencies: 1) Identify multiple alignment of horizontal and vertical surfaces in each design combination, 2) Eliminate multiple surfaces and arrive at single alignment per vertical and horizontal surface.

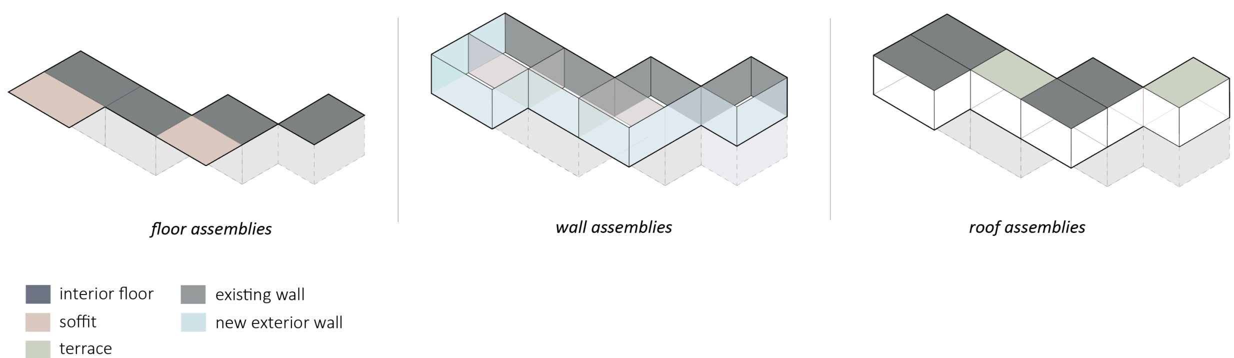
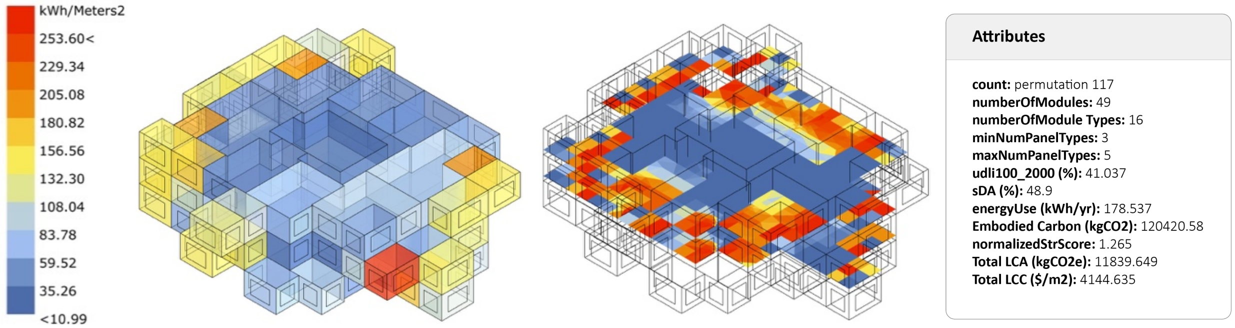
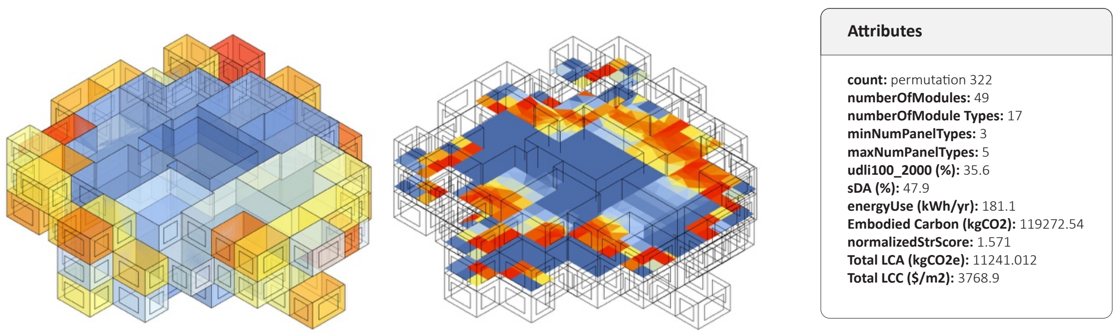


Figure A-7-8: Step 7 – Assign Materials: 1) Assign material assemblies to solved zones in each design combination.



Design Combination #117



Design Combination #322

Figure A-7-9: Step 8 – Simulations and Data Generation: 1) Conduct energy simulations and calculate heating energy use (kWh/yr/m^2), 2) Conduct daylighting simulation and calculate sDA (%), 3) Collect data from each design combination including module numbers, panel types and numbers, extension area.

A.4.2.1 Structural Complexity

The scoring system employed in this work is shown in **Figure A-7-10** and is based on the following conditions. First, as the number of modules supported above a given module increases, so does the structural complexity score. A linear factor of $(+n)$ is assigned to a module for the n number of modules supported above. Effectively, this means that lower modules in a stack will require more support than modules at the top of a stack. For modules at ground level, a score of $(+1)$ is assigned to account for the materials required to tie-into the foundation (i.e., anchor bolts, grout, etc.) Next, complexity is assigned to a module based on the vertical load transfer. No additional scoring is applied when a module is continuously supported from below (i.e., the bottom face of a module is coincident with another module or the existing building). For modules that are not continuously supported, complexity is based on the number of vertical faces that are supported. For rectangular shaped modules with all four sides supported, no additional scoring is assigned as the number of supported vertical sides decreases, the structural complexity increases. A factor of $(4 - f)$ is used for rectangular panels to denote the number of supported vertical sides f. Based on this framework, the lowest structural complexity score would be a value of 0 (for a module on top of a stack, continuously supported below). The highest value for a story height of 6 would be a value of 8 (4 modules supported above, and which is only supported below by one of its vertical faces). The sample scores for a given configuration is shown in **Figure A-7-10**.

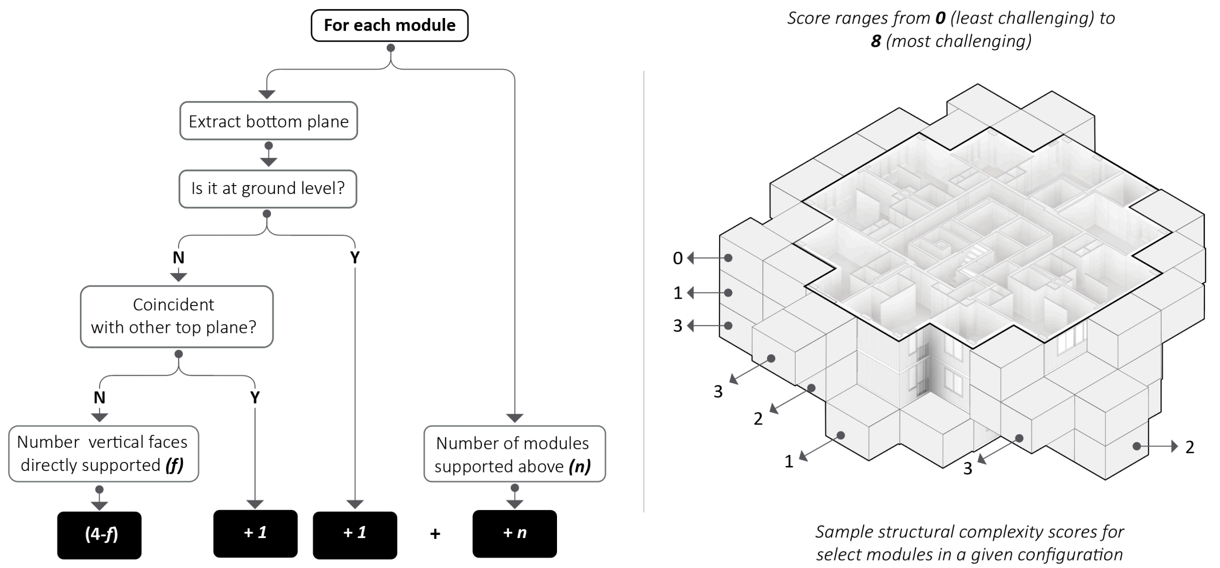


Figure A-7-10: Step 9 – Workflow for calculating structural complexity score: 1) Rank each module in design combination in terms of structural complexity, 2) Combine all scores and normalize for each design combination.

A.4.3 Stage 3 – Result Refinement

Results for the 600 generated design combinations are demonstrated in Figure A-7-11. Constraints are determined for embodied carbon (KgCO2e/m^2), energy use (kWh/yr/m^2) and sDA(%). Based on Toronto Green Standards, a 25% reduction of energy use intensity from the status quo for the achievement of tier 2 is required. The standard is a measure for facilitating sustainable site and building design in the region (City of Toronto, 2020). The existing building has a heating energy use of 243 kWh/yr/m^2 (ERA Architects, 2017), therefore the heating energy use is constrained to below 193.8 kWh/yr/m^2. According to LEED v4, complete points are awarded for a 20% reduction in embodied carbon compared to a reference building. The design options are therefore constrained to the ones having 80% of lowest embodied carbon at 180,000 (kgCO2e/m^2). Also, the minimum average sDA value required for regularly occupied floor areas to qualify for LEED is 40% (US Green Building Council, 2014). Therefore, design options are therefore constrained to sDA of 40% and higher.

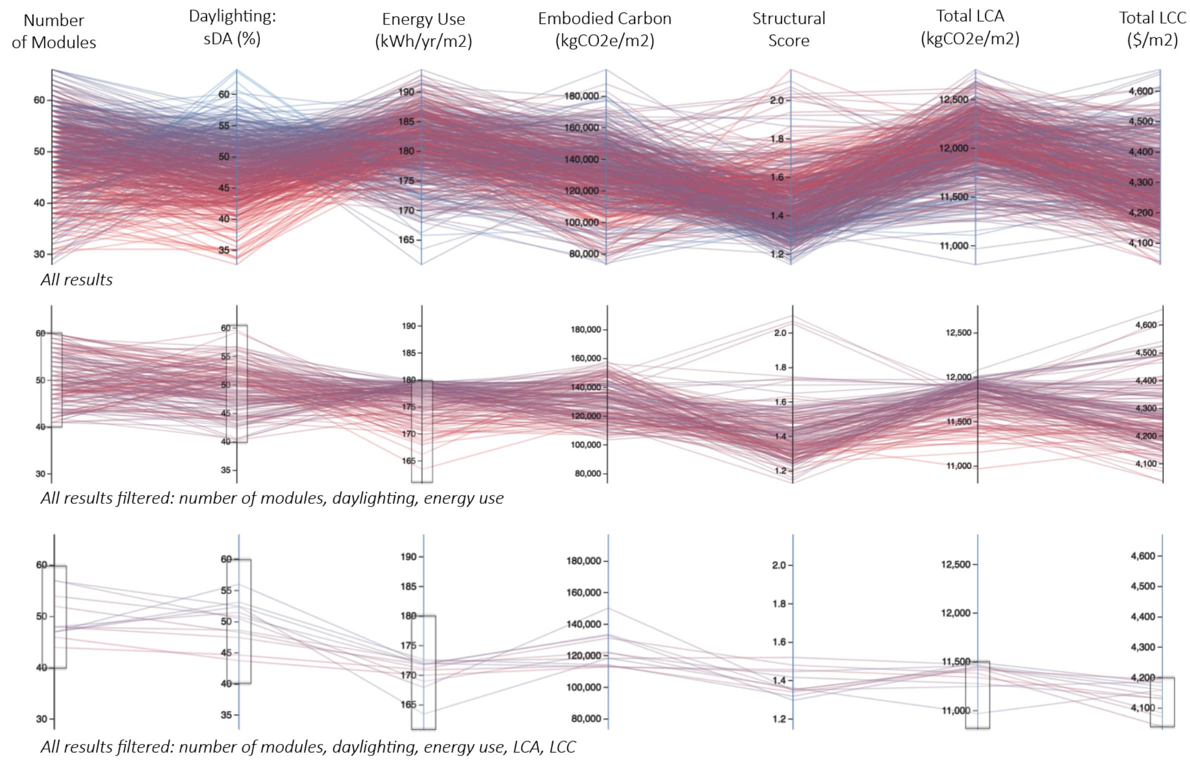


Figure A-7-11: All results presented for refinement by user for 1) Number of Modules, 2) Daylighting, 3) Energy Use, 4) Embodied Carbon, 5) Structural Score, 6) LCA and 7) LCC.

The filtering of results by acceptable ranges or required targets allows the narrowing down of optimal results.

Design options are further analyzed in terms of LCC, encompassing LCA and structural complexity, as a proxy for overall building form complexity. The filtering of results by acceptable ranges or required targets allows the narrowing down of optimal results. **Figure A-7-11** demonstrates all the 600 generated options presented for refinement by the user, and the filtered results primarily by number of module extensions, daylighting and energy use, and in addition by LCA and LCC. Figure A-7-12 represents all the generated design options compared by LCA, LCC and structural complexity. After the set constrains, the remaining results are presented in Figure A-7-13, with the pareto-optimal frontier design options marked including options 74, 169, 223, 117, 513, 264, 322 and 500. The eight pareto-optimal design options are visualized in **Figure A-7-14** for further design exploration by the project designer. Secondary options that performed closely to the optimal frontiers are also presented as further design guidance.

Figure A-7-12: LLC ($/m2), Structural Complexity, and LCA (KgCO2e/m2) of Design Permutations (represented by colour range), filtered by selected ranges of embodied carbon, energy savings, daylighting requirements and range of extension. Pareto-optimal design permutations per cost (74, 169, 223, 117, 513, 264, 322, 500). Grey represents all other results.

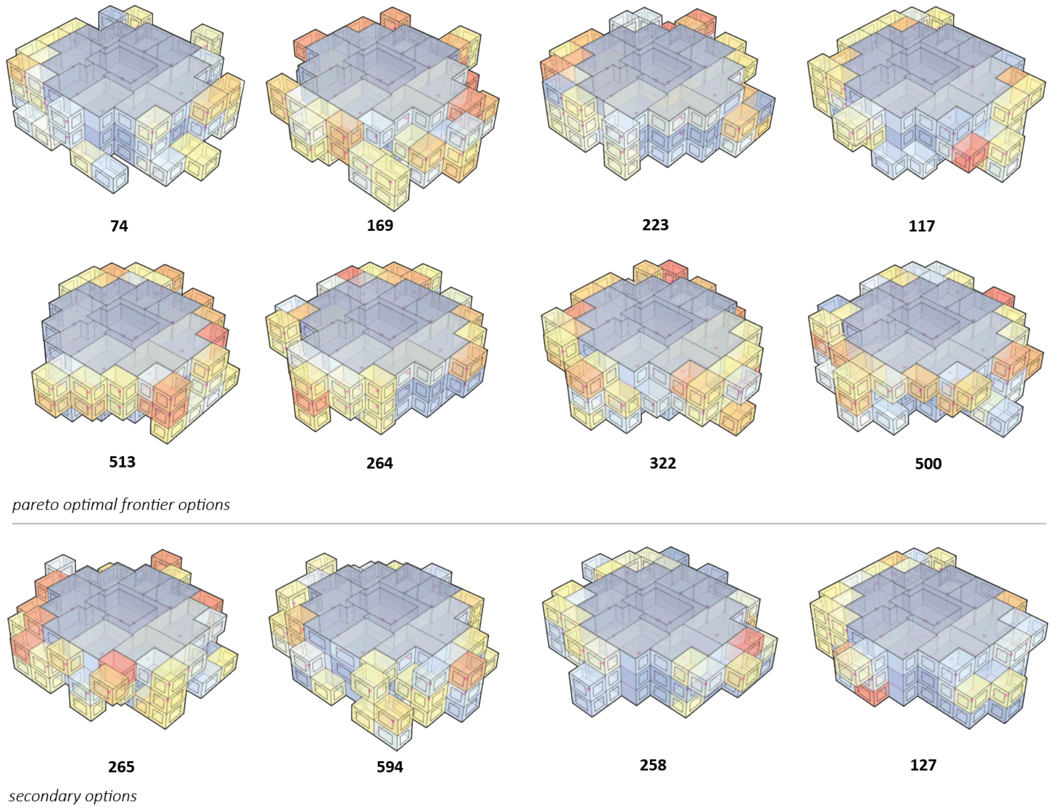


Figure A-7-13: Pareto-optimal design permutations (74, 169, 223, 117, 513, 264, 322, 500). The option generation algorithm is limited to three-storeys due to computation limitations.

A.5 Discussion and Application

The main goals of this research were to demonstrate a developed computational methodology for integrating and evaluating MC in building adaptation projects to improve the quality of design options and the speed of evaluation in building adaptation projects. It was demonstrated that the energy use and LCA of generated options are linearly correlated across all generated design options, as was expected due to the significance of operational energy use in a building's overall LCA. However, for design options with a similar LCA, there are significant variations in LCC. For example, for LCA of around 11,760 (KgCO2e/m^2), there are over 25 design options with a range of LCC; from \$4098/m^2 to \$4616/m^2 (**Figure A-7-14**). The variations in LCC correspond to the effect of different materials and assemblies used, as opposed to energy use factors. The variations in Data-driven design option analysis for early stage design, and the resulting variety of LCC per range of LCA highlight the importance of this investigation and multi-objective analysis. Without the use of a computational methodology for design optimization with simulation feedback, there is a potential loss of opportunity in achieving savings in embodied carbon and life cycle impact and environmental performance criteria that are dependent on geometric form generation and material use in MC.

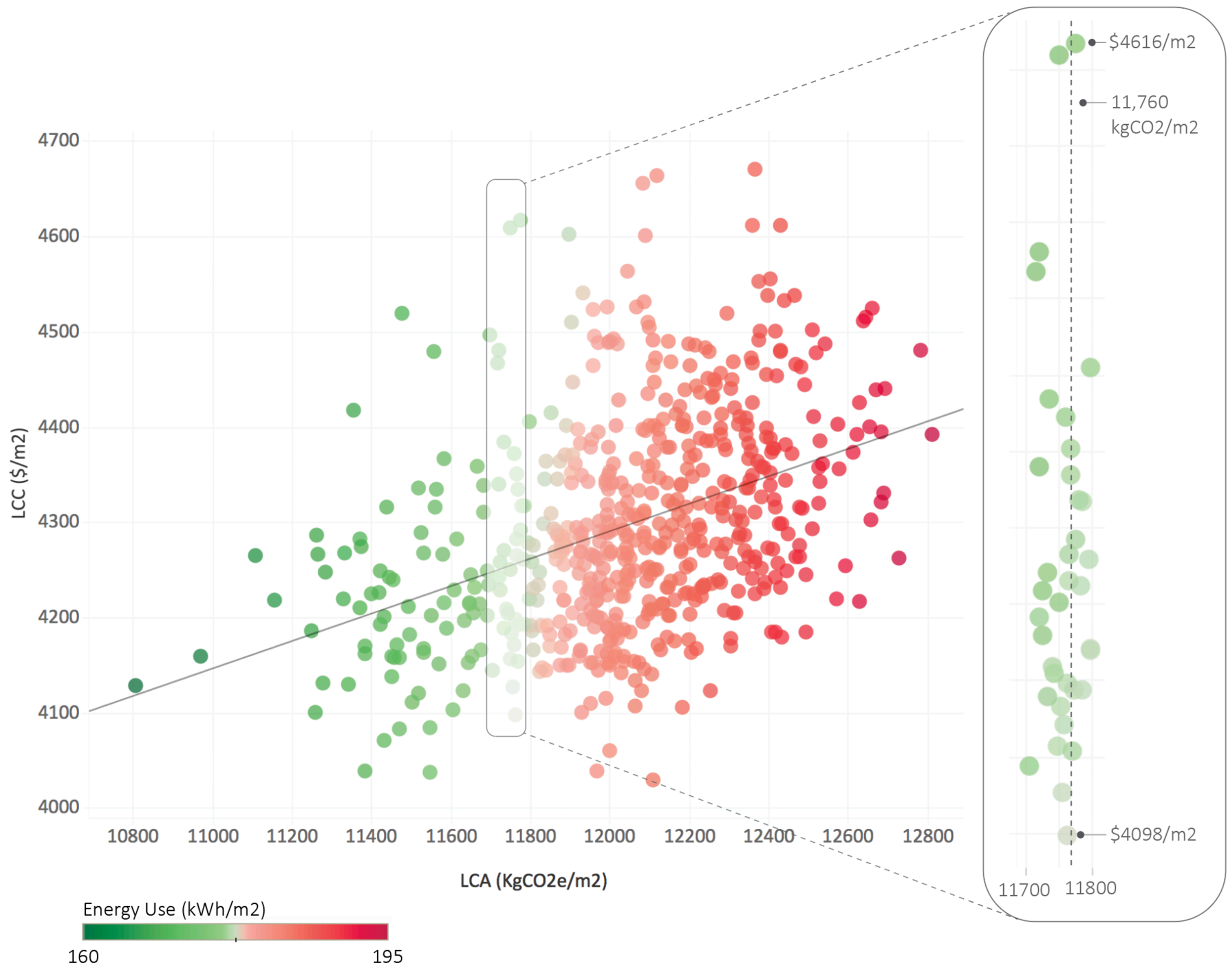


Figure A-7-14: LCA (KgCO2e/m^2), LCC ($/m^2) and Energy Use (kWh/yr/m^2) (represented by colour range), all results. Energy use and LCA are linearly correlated; for design options with a similar LCA, there is a variation in LCC from $4098/m^2 to $4616/m^2.

The impact of the methodology described is in its versatility and flexibility, making it accessible for designers to use in various contexts, as demonstrated in the functional demonstration. It also has the potential to be used as a preliminary design tool for asset managers who manage existing, aging building stock. The implemented methodology has a modular architecture and can be customized to meet the demands of different types of investigations. In the functional demonstration of this research, it was decided to constrain the generated design options based on embodied carbon, energy savings, daylighting requirements and the number of modular extensions and select pareto-optimal frontier based on LCC and structural complexity. In this investigation, it was important to understand the correlation between LCC and structural complexity as a proxy for design complexity and to select complex design options that are financially feasible and meet the set requirements in terms of performance. However, it is possible to customize the methodology in different ways for designers to improve their workflow based on a variety of objectives, as the modules of the methodology can be adjusted to constrain and analyze for any sets of performance criteria. These include optimizing for lowest cost and most energy efficient options, or the most cost-effective intensive extensions, as examples.

It can be summarized in this study that early design stage multi-objective analysis of various performance criteria, as demonstrated, can enable designers to better understand the design option parameters and conditions that can lead to better performing designs as the designs develop. Simulation-based computational methodologies, as presented in this research, are helpful in supplementing a designer's abilities in developing optimal design options. It is demonstrated in the functional demonstrations that the use of the methodology can improve the performance of a range of design options on multiple metrics and highlighting relationships between various performance metrics. In further development of selected designs, the methodology can be refined and optimized with designer feedback and according to varying project requirements. With extensive use of the methodology and the creation of databases of feasible solutions, it will be possible to use data science and machine learning algorithms to begin to predict the performance of design options in early stage of design processes, limiting the computational time and improving the quality of generated design options. In addition, external databases and previously analyzed cases can be incorporated to improve the overall analysis process. From the stages of the design requirement analysis and constrain development to final selection and design development, the creative process, experience and of the designer is crucial in developing successful building projects. The application of this research in residential multi-family adaptation projects can mitigate unnecessary demolition and promote the improvements to affordable housing assets at increased rates.

A.6 Conclusions

A.6.1 Contributions

Adoption of modular construction in building adaptation projects, specifically as extensions to existing buildings, is an essential step in moving towards a circular built environment and facilitating the continual use of resources in construction. Parameters and limitations in modular design and the opportunity for design optimization highlight the importance of incorporating computational design tools in the design of modular buildings. In this research, a computational design methodology is presented that integrates modular construction in building adaptation projects.

This research contributes towards the improvement of data-driven design generation and multi-objective analysis of early stage design through the development of a computational design methodology. The methodology also contributes to the improvement in the design process of MC, specifically in the integration with building adaptation projects. Primarily, a heuristic method for creating a finite number of design options that meet defined design criteria is developed. Then, simulation tools are used to analyze the performance and characteristics of each design. Design solution are further constrained based on acceptable range of performance set by the user and final pareto-optimal frontiers are determined for further design development. The efficacy of the methodology is shown in a functional demonstration of an existing residential tower adaptation in Hamilton, Canada. Advantages of the methodology include improved early stage design workflow, the possibility of improving quality of design decision-making and the increased speed of evaluations. The steps described in the methodology are not bound to specific software mentioned in this study and can be implemented within various computational design interfaces.

A.6.2 Limitations and future work

The limitations of this methodology include a limited analysis of spatial layouts after generation and the ability to account for addition of units, enabling a calculation of increased revenue, and return on investment rates; important factors for feasibility analysis of building adaptation projects. Other limitations of this study include calculation time and computation capacity, highlighting a need to optimize the algorithm for faster analysis in the future. In this study, a one module variant was used, in more complex projects the number of module sizes might need to differ, therefore adding complexity that needs to be considered in the algorithm. The methodology can also be improved by incorporating a user interface for designer input, parsing of data and design option visualization for better accessibility.

Future work will focus on addressing the limitations mentioned and on completing the proposed steps in the methodology not comprehensively investigated in this research—integration of external databases, linking to other analyzed cases, and the creation of an internal database. Selected options be combined to form a database of feasible options that will then be used to build a predictive model and support the assessment of viable options. External Database of analyzed cases – relevant examples are retrieved, and comparison with selected options is possible. The developments in future of this work aim to enhance data-driven, multi-objective design decision making of MC in building adaptation.

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Appendix B: A Computational Design Methodology Results

B.1: Generative Permutation Results

B.1.1 All Results

Permutation Number	Input				Output											
	Number of Modules	Number of Module Types	Min Num Panel Types	Max Num Panel Types	Daylighting [sda (%)]	Energy Use [kWh]	LCA	Embodied Carbon	LCC	Structural Score	Normalized Str Score	Structural LCA	Structural LCC	Corrected LCA	Corrected LCC
permutation0	46	16	3	5	57.702	181.161	11280	109234.7	3967	66	1.435	716.742	267.136	11996.79	4234.525
permutation1	57	16	3	5	52.617	177.595	11091	138975.8	3964	73	1.281	715.177	266.552	11806	4230.828
permutation2	49	13	3	5	45.908	182.989	11416	131706	3960	75	1.531	726.964	270.945	12143.44	4231.413
permutation3	39	14	3	5	39.609	181.16	11347	104150.3	4063	57	1.462	726.941	270.937	12073.47	4333.706
permutation4	41	13	3	5	33.938	186.982	11656	108612.2	3957	72	1.756	731.849	272.766	12387.49	4230.062
permutation5	54	13	4	5	54.478	160.84	10086	134735.1	3860	72	1.333	720.187	268.42	10805.88	4128.479
permutation6	42	15	3	5	47.303	185.249	11553	117684.3	3968	69	1.643	723.584	269.686	12276.6	4237.425
permutation7	46	14	3	5	47.505	181.748	11367	125444.5	4044	61	1.326	718.896	267.939	12085.73	4311.79
permutation8	49	15	3	5	55.165	183.221	11430	135168	3968	75	1.531	724.608	270.067	12154.28	4238.27
permutation9	55	16	4	5	47.561	180.653	11270	137488.6	3921	77	1.4	722.017	269.102	11992.44	4190.042
permutation10	35	14	4	5	49.807	168.935	10545	83479	3835	48	1.371	714.497	266.299	11259.03	4101.066
permutation11	55	14	3	5	52.539	179.362	11176	135095.7	3882	88	1.6	720.911	268.689	11897.25	4150.22
permutation12	54	16	3	5	43.075	182.425	11356	146828.5	3854	84	1.556	723.772	269.756	12079.99	4123.273
permutation13	44	14	3	5	45.146	183.596	11516	124136	4142	63	1.432	718.681	267.858	12234.99	4409.662
permutation14	50	15	3	5	47.373	177.01	11133	136525.9	4146	72	1.44	720.132	268.399	11852.82	4414.854
permutation15	53	17	3	5	50.07	178.298	11106	138214.9	3879	77	1.453	723.14	269.52	11829.04	4148.176
permutation16	49	13	4	5	48.026	178.002	11189	132571	4104	70	1.429	717.336	267.357	11906.61	4371.328
permutation17	41	11	3	5	44.609	183.503	11452	111213.2	3972	66	1.61	722.473	269.272	12173.99	4241.544
permutation18	59	15	4	5	48.192	175.854	10984	148401.6	3954	124	2.102	740.504	275.992	11724.22	4229.53
permutation19	55	15	3	5	43.01	186.925	11636	139942.4	3972	79	1.436	722.953	269.45	12359.18	4241.645
permutation20	46	15	3	5	59.264	174.507	10982	122897	4231	58	1.261	714.755	266.395	11696.82	4497.285
permutation21	47	13	3	5	44.942	185.029	11557	130313.8	4036	77	1.638	727.075	270.987	12283.6	4307.284
permutation22	60	17	3	5	46.473	179.499	11211	151455.6	3954	99	1.65	728.975	271.695	11940.19	4226.177
permutation23	33	13	3	5	46.706	177.963	11138	80639.18	4025	48	1.455	719.263	268.075	11857.38	4293.503
permutation24	49	13	3	5	47.387	174.568	10925	121901.7	3946	75	1.531	722.267	269.195	11647.35	4215.531
permutation25	49	13	3	5	52.375	176.826	11042	126142.7	3995	69	1.408	723.807	269.769	11765.31	4264.939
permutation26	46	16	3	5	43.254	177.926	11162	118513.7	4102	62	1.348	724.454	270.01	11885.97	4371.832
permutation27	36	14	3	5	44.105	180.815	11254	89504.01	3896	54	1.5	721.289	268.83	11975.56	4165.04
permutation28	56	16	3	5	47.589	178.382	11163	144529.5	4018	69	1.232	717.81	267.534	11880.43	4285.775
permutation29	56	17	3	5	45.76	179.739	11200	142044.3	3891	84	1.5	720.61	268.577	11920.82	4159.967
permutation30	54	15	3	5	53.421	188.713	11787	133621.6	4141	75	1.389	723.746	269.746	12510.94	4411.122
permutation31	41	12	3	5	52.801	176.633	11052	109421.8	4048	53	1.293	725.548	270.418	11778.04	4318.193
permutation32	59	16	3	5	51.224	186.548	11642	152062.8	4093	96	1.627	728.288	271.439	12370.19	4364.246
permutation33	30	11	3	5	47.711	181.113	11310	73315.88	3963	50	1.667	719.861	268.298	12030.15	4231.454
permutation34	54	16	3	5	50.559	179.219	11177	131011	3918	85	1.574	722.128	269.143	11899.11	4186.785
permutation35	66	16	3	5	53.026	181.959	11422	196930.9	4221	103	1.561	723.709	269.732	12146.06	4490.393
permutation36	48	14	3	5	47.283	183.476	11452	125052.3	3998	74	1.542	727.151	271.015	12178.71	4269.148
permutation37	47	13	3	5	47.712	181.928	11411	121939.2	4139	65	1.383	722.958	269.452	12134.04	4408.841
permutation38	48	14	3	5	38.634	186.685	11642	130079.1	3989	74	1.542	722.356	269.228	12364.83	4258.189
permutation39	64	20	3	5	51.032	179.81	11251	173539.3	4033	93	1.453	722.47	269.271	11973.59	4301.873
permutation40	42	16	3	5	52.057	173.58	10859	111376.4	3947	62	1.476	722.039	269.11	11580.71	4216.516
permutation41	47	13	3	5	36.338	189.928	11899	128581.3	4155	75	1.596	728.442	271.496	12627.16	4426.394
permutation42	50	14	3	5	54.015	178.465	11123	127014.1	3923	67	1.34	719.85	268.294	11842.46	4191.502
permutation43	45	13	3	5	54.29	185.97	11662	124972	4234	60	1.333	716.391	267.005	12377.98	4500.824
permutation44	35	10	4	5	51.549	172.679	10813	87433.22	4024	42	1.2	710.128	264.671	11523.52	4289.065
permutation45	66	17	3	5	57.448	180.128	11275	180304.5	4078	85	1.288	715	266.486	11989.88	4344.446
permutation46	47	15	3	5	44.413	179.105	11191	114708.8	3989	67	1.426	724.055	269.861	11914.7	4259.273
permutation47	51	17	3	5	56.395	168.657	10636	138000.3	4150	65	1.275	718.301	267.717	11354.5	4417.934
permutation48	47	15	3	5	39.001	184.541	11507	124052.6	3963	74	1.574	722.993	269.465	12230.3	4232.265
permutation49	63	15	3	5	47.048	181.321	11328	171659.6	3994	91	1.444	722.134	269.145	12049.82	4262.953
permutation50	37	12	4	5	44.082	179.836	11247	104232.8	3992	56	1.514	721.892	269.055	11969.25	4261.408
permutation51	50	12	3	5	47.182	183.137	11488	132082.3	4172	76	1.52	729.109	271.745	12217.44	4444.076
permutation52	55	16	3	5	51.04	181.842	11306	139578.9	3873	79	1.436	722.953	269.45	12028.88	4142.25
permutation53	50	15	3	5	54.978	180.214	11273	132189.4	4081	66	1.32	721.628	268.957	11994.68	4350.431
permutation54	46	17	3	5	44.777	183.604	11483	127042.7	4023	71	1.543	721.988	269.091	12205.05	4292.032
permutation55	44	12	3	5	40.449	178.715	11182	121235.1	3935	76	1.727	723.639	269.706	11905.73	4205.165
permutation56	49	16	3	5	49.539	185.682	11526	122896.4	3853	82	1.673	725.926	270.559	12252.14	4123.932
permutation57	46	18	3	5	45.554	176.64	11025	117574.1	3943	63	1.37	715.079	266.516	11740.04	4209.157
permutation58	51	16	3	5	43.226	184.267	11557	136691	4188	71	1.392	721.325	268.844	12278.23	4456.359
permutation59	60	15	3	5	51.599	185.335	11551	162869.7	3971	91	1.517	721.716	268.989	12272.42	4240.019
permutation60	54	16	3	5	52.332	188.719	11819	148079.8	4218	74	1.37	723.268	269.568	12542.27	4487.388
permutation61	52	13	3	5	44.135	191.405	11925	143530.4	4031	83	1.596	731.168	272.512	12655.73	4303.128
permutation62	66	18	3	5	54.172	185.505	11572	168016.2	4050	110	1.667	728.176	271.397	12300.32	4321.287
permutation63	50	15	3	5	49.334	180.855	11284	136702.2	3925	74	1.48	728.074	271.359	12011.66	4196.849
permutation64	52	16	3	5	49.906	177.473	11188	155437.4	4245	67	1.288	714.422	266.271	11902.29	4510.789
permutation65	43	15	3	5	38.193	185.712	11627	132078.8	4104	74	1.721	728.51	271.522	12355.62	4375.112
permutation66	49	13	3	5	53.205	170.856	10706	126307.1	3983	62	1.265	715.471	266.662	11421.35	4249.289

permutation67	35	12	3	5	35.091	179.763	11235	97482.87	3933	54	1.543	722.114	269.138	11956.75	4202.534
permutation68	60	18	3	5	54.119	180.393	11276	153312.8	4022	79	1.317	718.489	267.787	11994.16	4289.88
permutation69	49	15	3	5	45.031	180.467	11240	126530.8	3886	65	1.327	717.04	267.247	11957.01	4153.376
permutation70	48	16	3	5	53.187	184.825	11586	130973.2	4182	62	1.292	720.706	268.613	12306.79	4450.639
permutation71	53	13	3	5	43.937	187.835	11721	143705.8	4017	84	1.585	726.536	270.786	12447.21	4288.091
permutation72	46	15	4	5	33.697	182.515	11394	118568.4	3940	71	1.543	724.479	270.019	12118	4209.859
permutation73	45	15	3	5	45.384	183.754	11472	123877.9	3985	70	1.556	727.187	271.028	12199.66	4256.12
permutation74	48	16	3	5	55.945	179.698	11283	125810	4224	55	1.146	712.219	265.45	11995.55	4488.987
permutation75	54	13	3	5	41.669	188.347	11754	150039.6	4046	83	1.537	723.297	269.579	12477.75	4315.762
permutation76	56	17	3	5	48.701	185.749	11626	151858	4154	93	1.661	730.912	272.417	12356.78	4426.189
permutation77	49	12	3	5	46.898	190.817	11859	127507.9	3981	82	1.673	733.031	273.207	12591.84	4254.648
permutation78	45	12	3	5	42.952	179.795	11235	119596.6	3993	69	1.533	726.614	270.815	11962.06	4263.774
permutation79	36	10	4	5	62.11	165.795	10400	95858.94	4001	48	1.333	707.688	263.761	11108.13	4265.112
permutation80	46	14	3	5	47.968	180.037	11201	114338.8	3830	74	1.609	726.154	270.644	11927.02	4100.754
permutation81	55	16	3	5	49.483	186.07	11670	151714.2	4186	77	1.4	722.017	269.102	12392.33	4455.027
permutation82	46	14	3	5	41.801	187.87	11701	121244.2	3961	73	1.587	728.108	271.372	12428.69	4232.306
permutation83	55	14	3	5	53.636	180.245	11285	147803.8	4074	75	1.364	721.082	268.753	12005.94	4342.447
permutation84	50	16	3	5	54.706	175.004	10930	122998.3	3948	66	1.32	717.058	267.253	11647.39	4215.018
permutation85	51	13	4	5	40.64	179.788	11253	138598.3	4022	74	1.451	720.593	268.571	11973.17	4290.842
permutation86	49	16	3	5	49.622	186.29	11631	137132.5	4075	66	1.347	722.229	269.181	12353.35	4344.348
permutation87	59	17	3	5	56.651	178.705	11184	152414.1	4074	76	1.288	717.628	267.466	11901.15	4341.889
permutation88	49	13	3	5	46.67	186.586	11642	131566.2	4042	70	1.429	721.986	269.09	12364.41	4310.687
permutation89	47	13	3	5	46.386	179.482	11303	129910.9	4221	65	1.383	715.682	266.74	12018.45	4488.018
permutation90	50	13	3	5	51.266	181.186	11317	135468.5	3976	82	1.64	725.257	270.309	12042.22	4246.069
permutation91	57	15	3	5	46.006	184.789	11560	156839.5	4053	86	1.509	725.036	270.227	12284.76	4323.152
permutation92	47	16	3	5	49.905	186.018	11581	121904.3	3988	69	1.468	722.702	269.357	12303.81	4257.488
permutation93	55	16	3	5	50.86	177.644	11099	133507.9	3966	73	1.327	720.147	268.405	11819.23	4234.752
permutation94	52	13	3	5	46.467	188.231	11698	129900.5	3919	67	1.288	716.599	267.082	12414.74	4185.778
permutation95	55	15	3	5	42.632	191.503	11961	152750.8	4126	77	1.4	722.017	269.102	12682.91	4394.716
permutation96	38	12	4	5	38.31	183.575	11464	97025.93	4004	71	1.868	737.377	274.826	12201.35	4278.938
permutation97	54	14	3	5	52.571	178.412	11197	147636.3	4129	69	1.278	720.88	268.678	11918.2	4397.615
permutation98	38	14	3	5	32.696	184.203	11453	101679.3	3835	68	1.789	729.208	271.782	12182.17	4106.714
permutation99	42	10	4	5	39.841	177.229	11105	112702.4	3980	62	1.476	719.324	268.098	11823.94	4248.055
permutation100	55	14	3	5	57.44	189.485	11815	154436.1	4093	79	1.436	720.869	268.674	12535.46	4361.428
permutation101	54	14	3	5	46.748	174.999	10948	143410.3	3946	83	1.537	723.297	269.579	11671.41	4215.228
permutation102	55	16	3	5	48.302	182.288	11426	142062.1	4162	67	1.218	715.273	266.588	12141.5	4428.279
permutation103	51	17	3	5	51.814	182.207	11377	139467.9	3986	74	1.451	716.145	266.913	12093.21	4252.667
permutation104	49	14	3	5	47.426	178.18	11145	118962.4	3994	70	1.429	719.653	268.221	11864.47	4262.101
permutation105	45	12	3	5	51.775	176.429	11049	125776.3	4067	63	1.4	718.097	267.641	11766.81	4334.882
permutation106	49	16	3	5	56.013	180.872	11360	124917.6	4263	65	1.327	724.057	269.862	12084.48	4532.526
permutation107	45	16	3	5	48.75	178.543	11147	115984.3	3962	67	1.489	725.469	270.388	11872.7	4232.011
permutation108	56	18	3	5	49.634	179.201	11211	144375.2	4012	80	1.429	720.818	268.655	11932.19	4280.523
permutation109	42	14	3	5	50.399	181.078	11325	113118.4	4019	63	1.5	719.933	268.325	12045.31	4287.215
permutation110	57	17	3	5	53.689	178.473	11151	141372.7	4020	73	1.281	717.166	267.294	11868.44	4287.156
permutation111	52	12	3	5	56.822	180.685	11278	137701.2	3999	71	1.365	725.198	270.287	12002.77	4269.216
permutation112	56	16	3	5	48.028	183.026	11463	143772.9	4134	77	1.375	719.443	268.142	12182.75	4401.96
permutation113	47	12	4	5	36.466	181.502	11362	124522	4015	76	1.617	724.082	269.871	12085.83	4285.039
permutation114	57	15	3	5	52.029	166.24	10438	150145.1	3951	71	1.246	716.266	266.958	11154.67	4218.388
permutation115	49	16	3	5	45.687	185.829	11603	136933.6	4041	71	1.449	724.86	270.161	12327.8	4310.949
permutation116	40	18	3	5	53.553	170.21	10758	108185.5	4253	53	1.325	717.754	267.513	11475.8	4520.014
permutation117	49	16	3	5	48.878	178.537	11126	120420.6	3879	62	1.265	713.168	265.803	11839.65	4144.636
permutation118	63	17	3	5	52.321	182.986	11447	167222.9	4133	120	1.905	737.676	274.938	12184.79	4408.344
permutation119	38	16	3	5	45.867	177.784	11159	105221.9	4099	54	1.421	713.817	266.046	11873.16	4365.202
permutation120	52	16	3	5	52.036	182.726	11430	134803	4112	68	1.308	719.283	268.083	12148.79	4379.7
permutation121	48	15	4	5	51.501	168.976	10558	121799	3863	68	1.417	719.155	268.035	11277.4	4131.365
permutation122	52	17	3	5	43.74	187.467	11713	145754	4074	85	1.635	727.689	271.216	12440.35	4344.954
permutation123	34	9	4	5	34.943	181.752	11378	94975.58	4007	59	1.735	726.75	270.866	12105.05	4278.318
permutation124	49	14	3	5	53.654	181.884	11365	137040.9	4021	73	1.49	721.222	268.805	12086.04	4289.569
permutation125	57	16	3	5	53.655	182.053	11388	146352.6	4064	74	1.298	715.626	266.72	12103.33	4331.102
permutation126	28	13	4	5	51.584	168.033	10552	75898.89	4024	39	1.393	707.876	263.831	11260.18	4287.546
permutation127	57	14	4	5	52.49	171.867	10732	132988.8	3893	74	1.298	717.617	267.462	11449.28	4160.007
permutation128	59	15	3	5	53.077	191.153	11943	178167.5	4169	90	1.525	725.671	270.463	12669.16	4439.14
permutation129	53	15	3	5	49.236	188.227	11769	133258.4	4176	73	1.377	721.199	268.797	12490.11	4444.633
permutation130	35	16	3	5	45.642	178.174	11123	89487.9	3899	56	1.6	726.862	270.908	11849.68	4170.027
permutation131	58	13	4	5	52.875	168.467	10566	147197.7	3981	74	1.276	717.18	267.299	11283.17	4248.675
permutation132	48	14	3	5	40.354	187.024	11674	134650.9	4004	81	1.688	723.704	269.731	12397.58	4273.295
permutation133	43	14	3	5	46.226	178.833	11276	118020.1	4259	60	1.395	717.509	267.421	11993.45	4526.053
permutation134	55	16	3	5	52.203	191.305	11931	152142.1	4131	78	1.418	724.58	270.057	12655.13	4401.266
permutation135	61	16	3	5	50.461	184.199	11495	156199.2	4026	96	1.574	729.009	271.708	12224.5	4298.017
permutation136	32	10	4	5	43.144	176.5	11035	84385.84	3880	57	1.781	734.545	273.771	11769.38	4154.188
permutation137	58	17	3	5	53.069	176.96	11067	141450.1	3995	73	1.259	714.783	266.405	11782.28	4261.7
permutation138	58	14	3	5	40.371	186.224	11578	144337.4	3908	88	1.517	725.359	270.347	12303.86	4178.803
permutation139	51	18	3	5	50.728	180.748	11308	133128.6	4074	67	1.314	719.309	268.092	12027.12	4342.029
permutation140	43	15	3	5	50.346	170.698	10686	108290.7	3960	58	1.349	713.697	266.001	11399.83	4225.924
permutation141	60	14	3	5	49.061	185.119	11557	156454.6	4045	84	1.4	722.54	269.296	12280.03	4314.604

permutation142	52	15	3	5	42.795	179.818	11250	141749.4	3973	90	1.731	723.529	269.665	11973.77	4242.172
permutation143	48	14	3	5	51.466	186.658	11722	131366	4267	60	1.25	717.252	267.326	12439.47	4533.957
permutation144	54	13	3	5	51.771	187.391	11683	147026	4002	83	1.537	725.426	270.372	12408.51	4271.955
permutation145	59	17	3	5	48.642	183.46	11419	149394.9	3910	89	1.508	725.234	270.301	12144.05	4180.134
permutation146	48	14	3	5	53.477	184.875	11643	134623.1	4346	65	1.354	715.196	266.56	12358.17	4612.468
permutation147	45	14	3	5	44.042	177.096	11063	109881.6	3925	71	1.578	720.115	268.393	11782.84	4193.806
permutation149	38	14	3	5	40.76	180.236	11254	99568.74	3931	58	1.526	722.464	269.268	11976.8	4200.265
permutation150	53	16	3	5	47.503	182.075	11401	133783.1	4120	74	1.396	721.684	268.978	12123.08	4388.88
permutation151	56	16	3	5	47.316	183.545	11439	145788.3	3949	80	1.429	722.864	269.417	12161.75	4218.745
permutation152	62	18	3	5	47.723	190.419	11882	170175.2	4117	126	2.032	739.006	275.434	12620.62	4392.569
permutation153	37	8	4	5	64.022	172.411	10799	95018.7	4069	49	1.324	717.046	267.249	11516.09	4336.101
permutation154	58	17	3	5	58.086	184.262	11522	158505.7	4117	85	1.466	722.048	269.113	12244.2	4385.85
permutation155	52	17	3	5	42.293	182.384	11340	133673.8	3865	75	1.442	722.744	269.373	12062.88	4134.112
permutation156	49	15	3	5	50.64	179.849	11367	136012.3	4391	59	1.204	713.903	266.078	12081.33	4657.027
permutation157	38	14	3	5	40.72	180.936	11291	97557.85	3915	56	1.474	721.116	268.766	12012.23	4183.645
permutation158	57	15	4	5	50.496	167.952	10530	150271.3	3919	77	1.351	718.967	267.965	11248.72	4186.477
permutation159	32	12	4	5	43.915	171.82	10750	80215.06	3889	49	1.531	720.901	268.686	11470.5	4157.979
permutation160	51	16	3	5	46.932	178.844	11165	123894.5	3950	72	1.412	719.588	268.196	11884.6	4218.495
permutation161	58	17	3	5	43.815	188.281	11717	153827.8	3979	91	1.569	726.69	270.843	12443.46	4249.777
permutation162	60	17	3	5	52.82	177.502	11084	149149.4	4008	77	1.283	721.449	268.89	11805.83	4276.652
permutation163	44	11	3	5	44.476	190.386	11934	127222.6	4255	69	1.568	724.773	270.129	12659.04	4524.761
permutation164	49	12	3	5	43.403	186.362	11667	132464.8	4114	95	1.939	737.487	274.867	12404.79	4388.592
permutation165	56	15	3	5	49.576	181.068	11277	143619.9	3907	89	1.589	726.999	270.959	12003.72	4177.591
permutation166	43	15	3	5	43.022	185.09	11652	118986.3	4284	62	1.442	721.349	268.853	12373.49	4552.743
permutation167	30	12	3	5	38.753	179.233	11215	76885.31	3989	48	1.6	718.167	267.667	11933.58	4256.318
permutation169	53	15	3	5	54.475	182.191	11408	137785.6	4132	62	1.17	713.721	266.01	12121.68	4397.878
permutation170	40	14	3	5	42.718	182.907	11440	105902.5	4051	62	1.55	720.668	268.599	12160.76	4319.671
permutation171	54	15	3	5	40.678	184.641	11539	139508.5	4007	85	1.574	728.523	271.527	12267.28	4278.17
permutation172	49	18	3	5	45.639	179.925	11257	133326	4013	65	1.327	717.04	267.247	11974.19	4280.103
permutation173	54	14	3	5	48.339	186.858	11698	136214.1	4185	71	1.315	721.835	269.034	12419.53	4453.941
permutation174	54	15	3	5	47.275	186.145	11610	148455.6	3999	93	1.722	730.189	272.148	12340.54	4271.152
permutation175	60	16	3	5	53.459	174.125	10895	151486.8	4015	82	1.367	717.874	267.558	11613.01	4282.605
permutation176	43	15	3	5	43.919	177.706	11152	117968.1	4080	60	1.395	714.882	266.442	11866.58	4346.274
permutation177	46	13	3	5	47.744	180.984	11373	127975.3	4167	71	1.543	721.988	269.091	12094.71	4435.947
permutation178	51	17	3	5	51.694	183.264	11415	140305.3	3946	75	1.471	718.863	267.926	12133.51	4214.062
permutation179	50	17	3	5	50.569	176.073	11080	136764.6	4138	62	1.24	717.279	267.336	11796.86	4405.453
permutation180	39	15	3	5	52.206	172.064	10739	99046.04	3890	54	1.385	719.064	268.001	11457.61	4158.067
permutation181	42	14	4	5	50.687	170.578	10691	106723.5	3955	62	1.476	727.532	271.157	11418.81	4226.466
permutation182	49	16	3	5	43.44	180.157	11250	133401.4	3960	73	1.49	721.222	268.805	11970.78	4228.687
permutation183	45	13	4	5	44.196	181	11367	126750.5	4128	68	1.511	720.94	268.7	12087.96	4397.085
permutation184	50	15	3	5	46.26	187.703	11711	135977.8	4029	72	1.44	722.42	269.252	12433.44	4298.545
permutation185	60	17	3	5	52.869	175.043	10935	148514.2	3962	82	1.367	723.6	269.692	11658.92	4231.736
permutation186	40	13	3	5	43.091	179.904	11264	109843.2	4048	56	1.4	728.333	271.456	11992.57	4319.004
permutation187	54	13	3	5	48.307	184.134	11577	147138.2	4252	69	1.278	718.758	267.887	12295.45	4519.437
permutation188	46	18	3	5	44.62	183.187	11448	128273.2	4018	76	1.652	722.287	269.202	12170.1	4286.762
permutation189	48	15	3	5	47.387	174.917	10910	120293.6	3855	71	1.479	720.755	268.631	11631.22	4123.35
permutation190	45	18	3	5	51.306	173.013	10782	108510.1	3844	67	1.489	720.371	268.488	11502.3	4112.187
permutation191	46	11	3	5	43.84	176.272	11015	121482.2	3922	66	1.435	716.742	267.136	11731.31	4189.427
permutation192	60	16	3	5	52.592	182.913	11463	164538.9	4157	71	1.183	711.304	265.109	12174.51	4421.935
permutation193	52	13	3	5	44.675	192.973	11999	132343.5	3991	84	1.615	729.423	271.862	12728.76	4263.145
permutation194	61	16	3	5	49.93	191.507	11966	165767.6	4170	89	1.459	726.047	270.604	12692.22	4440.975
permutation195	61	18	3	5	50.614	186.439	11607	158371.3	3981	96	1.574	727.108	270.999	12334.26	4251.786
permutation196	51	15	3	5	48.474	178.608	11238	138805.1	4197	64	1.255	720.04	268.365	11958.25	4465.446
permutation197	38	13	3	5	44.193	173.763	10826	92042.32	3816	57	1.5	721.79	269.017	11547.96	4084.878
permutation198	53	13	3	5	50.694	179.907	11277	144733.6	4067	78	1.472	719.311	268.093	11996.29	4334.931
permutation199	48	12	3	5	47.498	183.102	11400	123841.8	3902	73	1.521	721.822	269.029	12122	4171.121
permutation200	49	16	3	5	50.827	174.217	10950	132540.7	4093	65	1.327	714.731	266.386	11664.87	4359.68
permutation201	46	14	3	5	43.774	184.56	11513	121996.3	3966	70	1.522	721.432	268.884	12234.81	4234.819
permutation202	53	14	3	5	46.518	178.305	11188	142887	4086	66	1.245	715.656	266.731	11903.27	4353.178
permutation203	47	12	3	5	51.289	186.669	11660	127325.2	4090	64	1.362	719.97	268.339	12379.58	4358.781
permutation204	47	17	3	5	49.706	186.459	11706	128561	4211	67	1.426	724.055	269.861	12429.76	4480.649
permutation205	43	16	3	5	42.229	184.23	11489	116753	3956	66	1.535	721.076	268.751	12210.04	4225.119
permutation206	58	17	3	5	54.326	174.632	10958	154901.6	4070	76	1.31	724.005	269.842	11681.67	4339.626
permutation207	44	15	3	5	51.034	180.004	11295	122391.9	4134	60	1.364	719.522	268.172	12014.32	4402.305
permutation208	49	14	3	5	44.285	182.438	11382	132445.8	3940	76	1.551	722.79	269.39	12104.96	4209.851
permutation209	49	16	3	5	44.271	183.859	11463	125216.9	3953	79	1.612	731.447	272.616	12193.99	4226.043
permutation210	56	16	3	5	52.052	179.114	11191	141299	4025	75	1.339	724.682	270.095	11915.82	4295.364
permutation211	48	15	3	5	42.833	185.652	11564	127244.2	3938	77	1.604	723.956	269.824	12288.01	4207.592
permutation212	51	16	3	5	49.733	179.769	11206	129939.7	3896	80	1.569	719.141	268.03	11924.73	4164.482
permutation213	49	15	3	5	52.982	178.871	11253	134017.8	4222	60	1.224	716.741	267.135	11970.15	4489.331
permutation214	51	15	3	5	50.562	184.802	11530	140293.8	3965	79	1.549	725.358	270.347	12255.15	4235.532
permutation215	56	16	3	5	47.308	183.551	11475	145220.6	4049	77	1.375	717.412	267.385	12192.02	4316.67
permutation216	48	12	3	5	54.721	184.26	11494	132627.4	4015	67	1.396	718.621	267.836	12212.24	4282.781
permutation217	55	17	3	5	48.695	187.329	11741	150032.7	4195	82	1.491	726.456	270.756	12467.59	4465.956
permutation218	45	14	3	5	40.549	186.279	11595	117649.6	3936	62	1.378	722.606	269.321	12317.29	4204.964

permutation219	50	16	3	5	47.953	173.362	10834	119469.2	3936	66	1.32	717.058	267.253	11551.04	4202.774
permutation220	58	17	3	5	50.121	186.093	11604	147243.6	4016	75	1.293	719.59	268.197	12323.85	4284.013
permutation221	62	14	3	5	55.755	181.851	11392	169352	4135	83	1.339	717.464	267.405	12109.71	4402.462
permutation222	41	14	3	5	44.181	180.895	11314	113135.9	4024	62	1.512	719.98	268.342	12034.43	4292.136
permutation223	48	16	3	5	55.185	171.781	10742	116724.1	3975	58	1.208	711.474	265.172	11453.43	4240.354
permutation224	45	13	4	5	38.319	179.662	11231	117952.4	3973	69	1.533	721.508	268.912	11952.03	4241.53
permutation225	57	17	3	5	48.329	185.447	11635	158486.8	4198	83	1.456	721.668	268.972	12357.11	4467.387
permutation226	50	14	3	5	51.077	182.539	11390	135669.4	3983	70	1.4	721.392	268.869	12111.53	4251.439
permutation227	51	13	3	5	56.803	176.544	11050	134036.8	4023	67	1.314	723.818	269.773	11774.25	4292.806
permutation228	47	15	3	5	46.182	186.971	11638	121920.2	3956	74	1.574	725.435	270.376	12363.76	4225.999
permutation229	58	19	3	5	50.817	186.887	11710	158504.2	4211	75	1.293	719.59	268.197	12429.61	4479.315
permutation230	48	18	3	5	48.334	174.784	10941	130512.2	3939	64	1.333	714.665	266.361	11655.22	4205.858
permutation231	57	15	3	5	50.258	185.851	11621	156611.4	4124	80	1.404	722.327	269.217	12343.55	4393.179
permutation232	34	10	4	5	63.717	172.146	10744	80509.89	3934	45	1.324	746.702	278.302	11490.49	4212.43
permutation233	47	14	3	5	51.225	177.729	11086	116251.1	3926	62	1.319	714.053	266.133	11800.42	4192.107
permutation234	42	14	3	5	41.989	181.191	11291	111600.1	3891	67	1.595	719.66	268.223	12010.46	4159.505
permutation235	52	15	3	5	47.567	187.264	11690	146423.6	4055	85	1.635	723.269	269.568	12413.45	4324.684
permutation236	59	17	3	5	55.423	185.001	11563	149161.7	4133	69	1.169	714.582	266.331	12277.74	4399.726
permutation237	58	14	3	5	60.246	186.456	11632	156126.3	4079	86	1.483	726.463	270.759	12358.6	4349.829
permutation238	50	15	3	5	45.417	183.09	11457	127821.6	4071	74	1.48	723.448	269.635	12180.13	4340.723
permutation239	39	11	3	5	42.964	184.372	11563	107312	4145	54	1.385	719.064	268.001	12281.96	4413.475
permutation240	57	14	3	5	52.593	179.441	11209	138054	4003	71	1.246	716.266	266.958	11925.24	4269.614
permutation241	48	15	3	5	44.883	178.398	11164	133262.2	3988	75	1.562	720.514	268.541	11884.07	4256.193
permutation242	45	15	3	5	56.081	179.924	11327	118250.4	4297	55	1.222	716.064	266.883	12042.71	4563.833
permutation243	52	16	3	5	49.442	187.66	11723	145330.3	4113	69	1.327	719.777	268.267	12442.92	4381.599
permutation244	55	13	3	5	49.716	181.275	11328	143575.3	4036	94	1.709	732.085	272.854	12060.39	4308.601
permutation245	43	14	3	5	42.249	180.744	11248	109694.5	3876	69	1.605	722.86	269.416	11970.59	4145.384
permutation246	45	14	3	5	46.239	180.002	11371	123521.2	4334	57	1.267	717.205	267.308	12088.48	4601.777
permutation247	54	17	3	5	51.875	184.459	11512	145014.6	4001	80	1.481	723.997	269.84	12235.61	4270.721
permutation248	59	19	3	5	50.837	182.694	11424	153039.2	4073	78	1.322	720.435	268.512	12144.88	4341.802
permutation249	36	14	3	5	42.887	186.037	11617	104215.6	4036	58	1.611	714.709	266.378	12331.79	4302.261
permutation250	51	13	4	5	50.426	173.064	10803	122775.4	3855	69	1.353	715.857	266.806	11518.97	4121.497
permutation251	46	14	3	5	47.309	180.843	11291	126692.5	3933	75	1.63	724.214	269.92	12015.55	4203.258
permutation252	37	11	3	5	47.672	177.865	11189	97922.52	4181	46	1.243	714.969	266.475	11904.38	4447.708
permutation253	48	14	3	5	45.501	185.359	11566	133808.5	4006	72	1.5	726.077	270.615	12292.17	4277.115
permutation254	54	15	3	5	50.442	173.446	10858	136846.4	3998	70	1.296	721.357	268.856	11579.36	4266.627
permutation255	48	13	3	5	44.959	186.125	11577	125424.5	3900	86	1.792	726.363	270.721	12302.87	4170.223
permutation256	47	13	3	5	44.322	179.666	11225	126463.2	3937	73	1.553	724.888	270.172	11950.22	4207.505
permutation257	59	15	3	5	52.948	187.82	11698	161445.8	3987	88	1.492	724.798	270.138	12422.8	4257.5
permutation258	48	18	3	5	48.639	172.369	10751	118339.8	3816	73	1.521	719.45	268.145	11470.01	4083.961
permutation259	57	18	3	5	56.198	176.198	11007	135802.8	3977	71	1.246	712.303	265.481	11719.13	4242.124
permutation260	48	18	3	5	46.891	180.019	11243	130150	3949	66	1.375	720.463	268.523	11963.18	4217.578
permutation261	61	15	3	5	45.319	187.113	11743	183218.5	4270	86	1.41	722.887	269.426	12465.74	4539.178
permutation262	39	13	3	5	45.345	181.857	11435	108496	4202	55	1.41	716.809	267.161	12151.73	4469.595
permutation263	52	16	3	5	46.954	183.889	11528	133839	4161	75	1.442	727.188	271.029	12254.7	4431.562
permutation264	52	14	3	5	48.327	171.135	10659	131228.5	3769	77	1.481	723.733	269.741	11383.05	4039.008
permutation265	50	18	3	5	50.468	178.551	11245	133239.1	4258	58	1.16	712.958	265.725	11957.7	4523.94
permutation266	36	12	3	5	38.218	189.09	11803	103734.2	4051	57	1.583	723.423	269.626	12526.56	4321.039
permutation267	55	18	3	5	55.311	180.403	11284	147825.2	4092	86	1.564	724.134	269.891	12007.95	4361.512
permutation268	43	15	3	5	39.821	181.362	11274	109186.2	3790	74	1.721	725.833	270.524	11999.41	4060.112
permutation269	54	15	3	5	53.025	184.221	11512	132286.8	4087	77	1.426	720.448	268.517	12232.4	4355.051
permutation270	52	15	3	5	48.232	183.384	11409	128176	3898	73	1.404	719.557	268.185	12128.39	4165.987
permutation271	46	13	3	5	43.749	170.008	10615	112963.7	3861	67	1.457	724.747	270.119	11339.73	4130.94
permutation272	41	13	3	5	51.059	186.408	11697	114254.5	4233	61	1.488	719.357	268.11	12416.83	4500.94
permutation273	40	14	3	5	41.993	174.885	10999	108755.8	4071	62	1.55	720.668	268.599	11720.03	4340.074
permutation274	51	18	3	5	46.452	178.778	11154	131728	3899	76	1.49	723.845	269.783	11877.79	4168.722
permutation275	49	15	3	5	51.412	180.887	11378	127325.4	4237	65	1.327	719.364	268.113	12097.33	4504.941
permutation276	34	9	4	5	47.227	179.938	11238	92512.21	3921	57	1.676	721.888	269.054	11960.16	4190.463
permutation277	64	17	3	5	49.998	183.568	11475	171590.6	4075	108	1.688	733.955	273.551	12209.07	4348.481
permutation278	51	14	3	5	47.685	189.237	11762	140934.9	3912	91	1.784	731.406	272.601	12493.23	4184.56
permutation280	43	15	3	5	46.463	178.675	11247	109201.1	4229	57	1.326	713.104	265.78	11960.03	4495.265
permutation281	55	15	3	5	43.02	174.406	10885	147458.6	3835	82	1.491	720.193	268.422	11604.84	4103.503
permutation282	50	17	3	5	47.62	186.06	11675	131225.4	4269	67	1.34	722.144	269.149	12397.61	4538.55
permutation283	40	13	3	5	42.075	181.578	11374	105376.9	4091	60	1.5	722.241	269.185	12096.01	4359.712
permutation284	55	15	4	5	47.599	175.258	10955	136212.6	3959	113	2.055	738.856	275.378	11693.57	4234.283
permutation285	56	14	3	5	52.606	187.825	11735	153492.4	4104	72	1.286	721.237	268.811	12456.28	4372.375
permutation286	46	16	3	5	54.707	179.685	11290	126731.6	4226	58	1.261	717.221	267.314	12007.7	4493.722
permutation287	53	17	3	5	50.918	182.315	11359	143198.3	3926	76	1.434	722.655	269.339	12081.52	4195.701
permutation288	59	17	3	5	50.56	176.907	11071	150449.9	4010	89	1.508	723.284	269.574	11793.95	4279.493
permutation289	35	15	3	5	42.856	180.816	11305	87642.95	4031	50	1.429	719.189	268.048	12024.46	4298.622
permutation290	48	13	3	5	48.69	177.804	11135	119039.5	4043	64	1.333	714.665	266.361	11850	4309.342
permutation291	58	17	3	5	51.092	171.252	10717	153420.6	3935	79	1.362	715.479	266.665	11432.2	4201.486
permutation292	56	18	3	5	47.045	178.834	11210	144434	4082	77	1.375	717.412	267.385	11927.24	4349.232
permutation293	44	18	3	5	43.759	179.185	11159	106756.6	3912	66	1.5	728.274	271.434	11887.21	4182.992
permutation294	61	15	4	5	44.694	179.534	11216	156834.3	3964	109	1.787	732.595	273.044	11948.25	4236.568

permutation295	52	14	3	5	45.31	189.266	11810	141903.5	4075	72	1.385	719.064	268.001	12529.41	4342.871
permutation296	48	13	3	5	58.806	180.52	11345	128009.3	4258	61	1.271	720.169	268.413	12065.14	4526.462
permutation297	49	13	4	5	42.909	183.155	11470	135131.6	4087	78	1.592	723.835	269.779	12194.06	4356.333
permutation298	61	18	3	5	46.909	183.079	11425	155607.9	4025	102	1.672	731.549	272.654	12157.01	4297.233
permutation299	42	16	3	5	49.87	177.107	11074	113708.7	3951	66	1.571	721.758	269.005	11795.74	4219.954
permutation300	40	13	3	5	48.365	174.67	10918	99524.02	3931	64	1.6	716.293	266.968	11634.31	4197.58
permutation301	48	17	3	5	45.008	182.567	11364	132505.2	3876	80	1.667	723.173	269.532	12086.68	4145.872
permutation302	47	15	3	5	46.286	179.679	11229	119641.9	3998	67	1.426	721.609	268.95	11950.21	4266.607
permutation303	53	16	3	5	48.29	183.642	11509	138322.6	4169	73	1.377	719.043	267.993	12228.05	4437.262
permutation304	56	18	3	5	48.848	180.877	11270	146404.8	3894	84	1.5	720.61	268.577	11991.05	4162.933
permutation305	53	15	3	5	49.46	182.523	11448	145360.6	4146	71	1.34	718.075	267.633	12165.92	4413.488
permutation306	43	18	3	5	60.714	176.406	11049	113663.8	4084	54	1.256	716.574	267.073	11765.64	4351.544
permutation307	53	16	3	5	45.341	183.793	11532	142268.2	4162	79	1.491	726.288	270.694	12258.31	4432.7
permutation308	54	15	3	5	48.325	184.826	11492	139908.7	3898	81	1.5	724.474	270.017	12216.67	4167.596
permutation309	53	15	3	5	47.166	185.204	11603	146960.9	4142	83	1.566	723.881	269.796	12326.84	4411.562
permutation310	48	15	3	5	50.92	184.547	11530	131869.8	4047	77	1.604	723.956	269.824	12254.22	4316.477
permutation311	59	17	3	5	49.108	178.356	11152	156572.8	3998	103	1.746	727.42	271.115	11879.38	4269.257
permutation312	42	10	3	5	48.316	188.341	11703	108530.8	3909	67	1.595	727.841	271.272	12431.16	4180.261
permutation313	48	14	3	5	47.927	179.208	11238	124039.1	4120	62	1.292	715.954	266.842	11954.15	4386.902
permutation314	56	16	3	5	45.516	183.122	11450	145642.5	4040	82	1.464	721.734	268.996	12171.71	4308.713
permutation315	50	15	3	5	49.052	177.375	11108	129253.8	4029	70	1.4	723.691	269.726	11831.46	4299.126
permutation316	31	15	3	5	43.953	181.243	11325	78637.71	3972	47	1.516	720.17	268.413	12045.54	4240.511
permutation317	46	14	4	5	35.577	180.569	11311	121442.4	4014	73	1.587	728.108	271.372	12039.37	4285.409
permutation318	56	16	3	5	47.38	187.581	11682	154010.3	3970	113	2.018	733.859	273.515	12415.82	4243.25
permutation319	53	15	3	5	53.186	180.212	11298	140090.8	4160	67	1.264	722.621	269.327	12020.53	4428.924
permutation320	43	12	3	5	45.816	188.17	11798	121058.7	4209	58	1.349	721.623	268.955	12519.52	4478.048
permutation321	64	18	3	5	52.968	189.901	11847	165318.6	4133	99	1.547	726.682	270.84	12573.67	4404.054
permutation322	49	17	3	5	47.882	181.08	11241	119272.5	3769	77	1.571	725.657	270.458	11966.67	4039.375
permutation323	39	15	3	5	46.345	174.989	10924	95247.99	3886	61	1.564	717.833	267.542	11641.55	4153.49
permutation324	49	13	3	5	47.837	183.817	11527	150805.3	4184	76	1.551	718.15	267.66	12244.8	4451.896
permutation325	53	15	3	5	51.116	178.747	11153	135850.5	3927	76	1.434	720.494	268.534	11873.85	4195.605
permutation326	50	16	3	5	51.128	181.468	11393	130681.4	4225	68	1.36	715.816	266.79	12109.19	4491.501
permutation327	40	11	3	5	33.579	180.778	11302	107067	3952	66	1.65	726.088	270.619	12028.32	4223.045
permutation328	63	18	3	5	50.701	180.902	11306	168746.1	4047	127	2.016	736.813	274.616	12042.78	4321.651
permutation329	55	15	3	5	53.713	186.373	11614	140055.7	4018	72	1.309	723.863	269.79	12337.73	4287.57
permutation330	58	15	3	5	49.691	192.725	12057	160292.8	4211	80	1.379	723.794	269.764	12781.08	4480.511
permutation331	47	17	3	5	44.577	186.041	11628	125300.5	4098	61	1.298	720.764	268.635	12348.68	4366.944
permutation332	55	16	3	5	59.677	172.015	10831	150202.7	4209	65	1.182	724.688	270.097	11556.11	4479.411
permutation333	35	13	3	5	53.569	170.888	10728	93195.94	4051	47	1.343	710.571	264.836	11438.51	4315.971
permutation334	56	17	3	5	45.907	181.624	11389	152255.1	4107	86	1.536	721.524	268.918	12110.59	4375.62
permutation335	50	14	3	5	44.386	186.372	11602	129306.9	3959	76	1.52	722.182	269.163	12323.77	4228.158
permutation336	50	16	3	5	54.781	177.63	11158	136366.4	4129	87	1.74	732.458	272.993	11890.13	4401.755
permutation337	41	15	3	5	42.696	187.034	11683	112538.8	4105	61	1.488	722.138	269.147	12405.05	4373.841
permutation338	52	17	3	5	43.227	178.754	11163	129406	3950	80	1.538	720.811	268.652	11883.86	4218.686
permutation339	55	14	3	5	51.842	186.505	11670	151445.9	4121	77	1.4	722.017	269.102	12392.17	4389.751
permutation340	56	11	3	5	56.884	188.103	11784	152980.7	4232	77	1.375	725.606	270.439	12509.15	4502.348
permutation341	54	18	3	5	46.856	176.367	11013	136120.4	3933	83	1.537	729.722	271.973	11742.54	4204.767
permutation342	52	15	3	5	52.575	183.028	11422	130233.3	4021	71	1.365	718.571	267.817	12140.34	4289.104
permutation343	47	14	3	5	53.14	172.66	10778	114224	3916	62	1.319	716.457	267.029	11494.32	4182.899
permutation344	55	16	3	5	46.985	185.669	11624	150034.4	4142	75	1.364	719.004	267.979	12342.82	4410.145
permutation345	53	16	3	5	49.22	179.579	11199	142150.8	3896	90	1.698	725.099	270.25	11924.58	4166.186
permutation346	53	14	3	5	48.943	175.536	10957	134502	3899	72	1.358	718.559	267.813	11675.8	4166.322
permutation347	55	17	3	5	51.804	179.931	11279	144179.1	4111	73	1.327	718.071	267.631	11996.79	4378.835
permutation348	48	15	3	5	45.892	180.854	11275	124523	3921	77	1.604	719.214	268.057	11994.62	4188.741
permutation349	59	17	3	5	51.633	184.377	11546	162044.3	4177	81	1.373	719.803	268.277	12266.25	4445.257
permutation350	48	12	3	5	36.446	186.774	11654	135582.2	3981	78	1.625	726.886	270.916	12381.11	4252.23
permutation351	52	15	4	5	45.482	181.733	11377	131991.7	4079	70	1.346	722.48	269.274	12099.97	4348.054
permutation352	55	15	3	5	46.732	182.639	11399	148790.6	3983	72	1.309	717.605	267.457	12116.95	4250.694
permutation353	55	17	3	5	46.852	182.615	11404	139339.3	4005	71	1.291	719.211	268.056	12123.68	4272.907
permutation354	50	13	3	5	55.598	186.144	11624	138999.6	4133	72	1.44	720.132	268.399	12344.18	4401.766
permutation355	46	14	3	5	42.029	181.231	11378	125945	4134	71	1.543	719.514	268.169	12097.67	4401.67
permutation356	51	12	3	5	47.957	180.242	11272	131324.9	4040	69	1.353	720.317	268.468	11992.57	4308.246
permutation357	55	16	3	5	50.339	175.346	11016	144236.4	4118	72	1.309	717.605	267.457	11733.59	4384.983
permutation358	48	19	3	5	41.63	186.129	11610	134663	4021	75	1.562	718.154	267.662	12327.8	4288.771
permutation359	57	15	3	5	49.953	181.749	11343	143802.3	4013	79	1.386	719.868	268.301	12062.74	4280.956
permutation360	50	16	3	5	54.369	183.977	11462	132545	3955	74	1.48	725.754	270.494	12187.35	4225.338
permutation361	56	16	3	5	48.201	182.268	11374	143010	3983	78	1.393	724.001	269.841	12097.54	4253.238
permutation362	52	19	3	5	46.508	186.196	11588	128300.2	3936	80	1.538	723.007	269.471	12311.36	4205.552
permutation363	53	13	3	5	49.942	177.997	11106	128250.2	3924	70	1.321	719.743	268.254	11825.64	4192.347
permutation364	45	14	3	5	44.151	183.578	11524	140113.2	4210	71	1.578	725.193	270.285	12249.11	4479.818
permutation365	42	14	4	5	52.024	174.661	11001	111840.5	4212	53	1.262	719.257	268.073	11720.31	4480.521
permutation366	50	15	3	5	51.978	185.922	11592	131563.1	4033	74	1.48	725.754	270.494	12317.85	4303.182
permutation367	46	16	3	5	49.696	175.639	10967	117598.4	3933	70	1.522	723.921	269.811	11690.65	4202.408
permutation368	33	13	4	5	43.968	176.464	11053	90364.95	4018	47	1.424	711.67	265.245	11764.84	4283.155
permutation369	47	14	3	5	48.977	181.395	11326	129893.5	3981	69	1.468	720.27	268.45	12046.54	4249.261

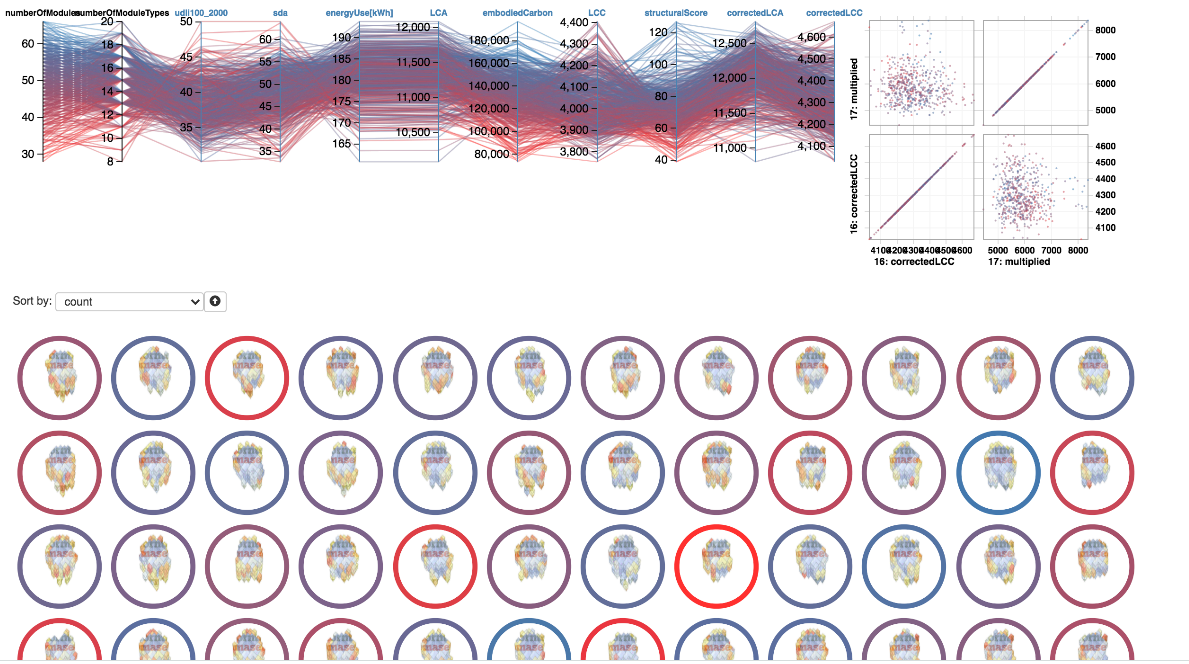
permutation370	56	15	3	5	54.337	172.752	10837	147144.4	4047	72	1.286	721.237	268.811	11558.21	4316.028
permutation371	46	12	3	5	45.507	184.449	11479	119188.7	3894	75	1.63	724.214	269.92	12203.53	4164.297
permutation372	51	16	3	5	47.727	183.5	11496	138098.7	4104	71	1.392	716.859	267.179	12212.62	4371.672
permutation373	52	19	3	5	49.846	177.375	11043	125429.2	3831	70	1.346	718.078	267.633	11760.71	4098.68
permutation374	59	17	3	5	51.897	184.089	11541	161659.7	4181	81	1.373	721.744	269	12262.6	4449.768
permutation375	42	17	3	5	47.871	180.744	11308	109128.1	4047	59	1.405	720.207	268.427	12027.71	4315.275
permutation376	61	19	3	5	48.68	182.999	11477	166770.4	4195	94	1.541	724.374	269.98	12201.81	4465.184
permutation377	48	15	3	5	42	183.21	11417	126557.1	3931	76	1.583	728.225	271.415	12145.46	4202.015
permutation378	41	14	3	5	52.424	177.087	11186	112446.9	4338	51	1.244	710.389	264.768	11896.04	4602.849
permutation379	46	15	3	5	49.674	180.331	11262	126657.4	3984	67	1.457	719.763	268.261	11982.03	4252.153
permutation380	62	13	3	5	53.883	182.209	11417	169368	4108	97	1.565	726.961	270.944	12143.93	4379.155
permutation381	56	18	3	5	44.219	189.034	11766	144864.8	3974	85	1.518	727.226	271.043	12493.26	4245.333
permutation382	43	17	3	5	47.405	178.066	11140	107108.5	4021	67	1.558	724.333	269.965	11863.99	4291.19
permutation383	50	14	3	5	47.294	181.35	11295	123734.4	3918	72	1.44	722.42	269.252	12017.17	4187.423
permutation384	53	15	3	5	39.391	178.913	11153	129644.2	3882	82	1.547	721.241	268.812	11874.69	4150.709
permutation385	31	13	4	5	41.171	179.25	11217	81592.13	4025	44	1.419	710.459	264.794	11927.28	4290.17
permutation386	56	17	3	5	49.844	186.855	11662	144508.7	4087	79	1.411	724.462	270.013	12386.77	4357.354
permutation387	42	14	3	5	41.109	183.41	11426	111079.8	3934	63	1.5	722.65	269.338	12148.52	4202.846
permutation388	45	15	3	5	52.568	184.815	11649	122471.8	4404	55	1.222	716.064	266.883	12365.46	4671.275
permutation389	29	11	4	5	49.997	180.028	11267	78347.33	4020	46	1.586	721.201	268.797	11988.39	4289.023
permutation390	58	15	3	5	51.9	182.292	11375	157466.8	3975	85	1.466	726.019	270.593	12101.25	4245.382
permutation391	49	15	4	5	45.711	180.08	11225	126156.3	3883	75	1.531	724.608	270.067	11949.79	4153.038
permutation392	48	13	3	5	56.207	177.065	11077	128625.6	3988	73	1.521	726.614	270.815	11804.01	4259.053
permutation393	60	17	3	5	54.185	183.095	11433	147329.1	4057	72	1.2	713.607	265.967	12146.11	4322.539
permutation394	51	14	3	5	46.832	185.232	11581	142596.8	4072	70	1.373	720.821	268.656	12301.77	4340.494
permutation395	53	15	3	5	47.969	181.21	11320	127625.5	4004	72	1.358	720.714	268.616	12040.26	4272.984
permutation396	55	16	3	5	52.288	182.152	11365	142818.5	4003	87	1.582	724.6	270.064	12089.18	4272.971
permutation397	62	17	3	5	48.881	170.591	10663	153553.1	3894	83	1.339	721.147	268.777	11384.03	4162.712
permutation398	40	17	3	5	53.998	185.14	11571	109580.8	4076	55	1.375	716.199	266.933	12286.78	4343.068
permutation399	46	17	3	5	49.675	185.809	11679	127310.9	4286	69	1.5	723.363	269.603	12401.86	4555.858
permutation400	59	16	3	5	55.634	186.073	11620	161948.2	4068	81	1.373	721.744	269	12341.7	4337.056
permutation401	56	16	3	5	48.937	179.733	11216	141287	3930	83	1.482	720.153	268.407	11935.76	4198.839
permutation402	33	16	3	5	53.323	174.973	11000	89347.62	4201	43	1.303	715.387	266.631	11715.62	4467.892
permutation403	58	18	3	5	51.139	176.853	11042	141058.8	3930	80	1.379	719.835	268.288	11762.07	4198.059
permutation404	54	14	3	5	43.66	187.684	11700	146622.5	4029	79	1.463	725.657	270.458	12425.31	4299.593
permutation405	46	17	3	5	46.072	186.498	11671	118346.4	4131	66	1.435	721.688	268.979	12392.28	4399.619
permutation406	31	12	3	5	35.181	183.154	11367	81416.27	3754	67	2.161	740.428	275.964	12107.09	4029.782
permutation407	64	15	3	5	51.69	186.043	11628	166857.5	4115	83	1.297	720.243	268.44	12348.43	4383.233
permutation408	41	11	4	5	44.428	173.715	10870	105209.4	3921	62	1.512	717.218	267.313	11586.92	4188.621
permutation409	50	13	3	5	55.044	185.849	11657	135413.1	4225	61	1.22	716.765	267.144	12373.98	4491.969
permutation410	53	14	3	5	50.541	182.523	11393	144166.6	4001	91	1.717	732.128	272.87	12125.42	4274.213
permutation411	65	17	3	5	52.071	186.226	11608	163429	4061	125	1.923	740.081	275.834	12348.09	4336.632
permutation412	39	14	3	5	44.489	182.435	11377	96509.85	3939	60	1.538	720.082	268.381	12097.29	4207.343
permutation413	32	12	4	5	57.659	176.816	11033	85012.08	3891	54	1.688	714.315	266.231	11747.52	4156.9
permutation414	61	18	3	5	50.744	181.075	11306	155941.1	3998	93	1.525	723.953	269.823	12029.99	4267.699
permutation415	44	13	3	5	46.218	181.39	11319	112493.5	3966	68	1.545	721.588	268.942	12040.33	4234.676
permutation416	44	14	3	5	41.013	182.999	11519	121911.5	4215	67	1.523	721.006	268.725	12240.32	4483.693
permutation417	56	18	3	5	56.633	174.19	10890	152238.1	3963	75	1.339	716.498	267.045	11606.68	4229.935
permutation418	48	14	4	5	50.227	174.645	10964	120289.6	4044	62	1.292	715.954	266.842	11679.72	4311.283
permutation419	41	17	3	5	44.838	178.177	11157	110677.4	4011	65	1.585	721.85	269.039	11878.54	4280.3
permutation420	57	18	3	5	46.732	177.401	11073	142913.2	3942	118	2.07	741.552	276.382	11815.04	4218.585
permutation421	48	20	3	5	42.832	180.497	11228	124560.1	3841	75	1.562	722.889	269.427	11950.58	4110.079
permutation422	45	13	3	5	49.246	181.316	11350	115416.6	4100	61	1.356	716.96	267.217	12066.6	4367.01
permutation423	48	13	3	5	50.194	184.077	11500	129108.4	4022	69	1.438	726.878	270.913	12226.45	4293.184
permutation424	60	16	3	5	52.346	174.861	10929	150859.7	3977	87	1.45	720.008	268.353	11648.59	4245.527
permutation425	36	9	4	5	48.099	175.996	10986	85479.44	3877	63	1.75	718.219	267.686	11704.16	4144.539
permutation426	52	15	4	5	48.841	180.384	11284	128559.7	4023	74	1.423	722.25	269.188	12006.53	4292.353
permutation427	58	15	3	5	49.213	188.724	11759	160937.9	4045	83	1.431	723.14	269.52	12482.37	4314.416
permutation428	39	13	3	5	33.812	178.149	11166	99928.52	4024	60	1.538	725.956	270.57	11891.46	4295.041
permutation429	30	11	3	5	50.359	183.13	11425	78876.03	3963	47	1.567	721.094	268.758	12145.91	4231.695
permutation430	50	12	3	5	39.876	182.901	11472	132755.2	4133	66	1.32	719.336	268.102	12191.23	4401.037
permutation431	55	18	3	5	47.413	177.457	11078	140460.4	3916	82	1.491	724.356	269.973	11802.8	4186.394
permutation432	51	14	3	5	45.931	188.633	11751	126437.5	4006	76	1.49	726.107	270.626	12476.88	4276.785
permutation433	47	13	4	5	50.797	169.893	10648	122539.3	3942	71	1.511	721.359	268.856	11369.84	4210.655
permutation434	58	15	3	5	49.128	182.511	11375	149122.6	3935	81	1.397	720.278	268.453	12095.13	4203.594
permutation435	50	12	3	5	41.918	181.076	11269	120913	3847	81	1.62	720.183	268.418	11989.31	4115.89
permutation436	34	16	3	5	45.372	173.056	10817	83098.69	3897	51	1.5	714.088	266.146	11531.44	4163.271
permutation437	66	19	3	5	56.83	177.627	11124	179969.4	4099	84	1.273	714.612	266.342	11838.67	4365.126
permutation438	46	13	3	5	46.652	181.306	11328	120678.7	4001	63	1.37	717.537	267.432	12045.05	4268.221
permutation439	44	15	3	5	55.702	180.875	11394	115303.9	4395	56	1.273	722.397	269.243	12116.22	4664.475
permutation440	38	13	3	5	43.078	179.152	11196	100792.4	3975	59	1.553	726.165	270.648	11922.18	4246.146
permutation441	65	16	3	5	53.954	183.959	11507	177333.2	4121	90	1.385	719.064	268.001	12226.17	4388.596
permutation442	48	15	3	5	47.013	182.344	11347	121128.7	3882	81	1.688	726.09	270.62	12073.39	4152.82
permutation443	50	13	3	5	48.891	184.824	11566	137734.6	4107	78	1.56	725.504	270.401	12291.27	4377.108
permutation444	53	14	3	5	53.281	178.591	11127	132760.9	3914	70	1.321	719.743	268.254	11846.74	4181.91

permutation445	55	15	3	5	53.171	185.112	11595	150315.6	4152	77	1.4	719.936	268.326	12314.84	4420.28
permutation446	38	11	4	5	48.101	173.186	10809	92993.79	3899	50	1.316	720.07	268.376	11529.43	4167.213
permutation447	56	16	3	5	43.944	186.648	11686	155720.7	4108	88	1.571	724.483	270.021	12410.95	4378.102
permutation448	46	17	3	5	49.592	183.226	11454	119720.8	4070	64	1.391	723.066	269.493	12177.06	4339.186
permutation449	46	16	3	5	53.425	168.102	10546	116275	3999	60	1.304	718.338	267.73	11264.56	4266.776
permutation450	43	14	3	5	42.482	181.549	11307	112795.7	3883	74	1.721	725.833	270.524	12032.8	4153.904
permutation451	62	16	3	5	49.245	183.342	11473	169904.6	4097	106	1.71	728.829	271.64	12202.02	4368.331
permutation452	44	12	3	5	42.731	179.675	11265	118775.1	4071	66	1.5	725.639	270.451	11990.64	4341.095
permutation453	55	16	3	5	48.834	190.088	11917	149060	4244	80	1.455	727.627	271.193	12644.25	4515.233
permutation454	59	18	3	5	51.705	184.749	11501	152753.9	3951	99	1.678	729.597	271.927	12230.76	4222.881
permutation455	54	15	3	5	48.232	184.438	11555	146145.5	4123	74	1.37	723.268	269.568	12277.98	4392.266
permutation456	41	13	3	5	39.539	184.131	11488	114052.3	3949	72	1.756	726.212	270.665	12214.4	4219.298
permutation457	48	12	3	5	48.176	175.792	11015	130563.3	4004	66	1.375	718.088	267.637	11732.83	4271.288
permutation458	50	16	3	5	49.933	181.064	11280	131832	3908	76	1.52	719.902	268.313	12000.38	4176.314
permutation459	46	13	3	5	52.314	176.082	11045	127138.4	4107	60	1.304	713.415	265.896	11758.31	4372.958
permutation460	51	14	3	5	48.785	183.005	11476	136482.8	4174	64	1.255	713.352	265.872	12189.51	4440.088
permutation461	59	14	3	5	45.848	188.461	11738	162776.2	3992	105	1.78	730.246	272.169	12468.33	4264.224
permutation462	52	16	3	5	54.139	184.883	11564	131219.1	4113	70	1.346	722.48	269.274	12286.63	4382.286
permutation463	56	14	3	5	50.7	193.828	12083	156597.6	4122	84	1.5	726.766	270.872	12810.09	4392.626
permutation464	49	13	3	5	44.128	179.639	11275	132450.1	4085	76	1.551	722.79	269.39	11997.99	4354.355
permutation465	43	18	3	5	41.502	181.125	11295	117183	3910	63	1.465	721.945	269.075	12016.62	4178.588
permutation466	49	17	3	5	44.225	178.061	11144	121099.5	4003	68	1.388	716.294	266.969	11860.74	4269.836
permutation467	40	14	3	5	42.225	183.003	11448	111288.7	4055	63	1.575	721.307	268.837	12169.68	4323.88
permutation468	55	15	3	5	45.811	181.351	11334	142073.6	4042	68	1.236	713.682	265.995	12047.9	4308.317
permutation469	45	14	3	5	47.578	188.755	11746	117609.2	3991	72	1.6	730.918	272.419	12477.4	4263.74
permutation470	48	17	4	5	40.621	179.864	11266	124577.1	4003	76	1.583	725.816	270.518	11991.56	4273.729
permutation471	50	16	3	5	51.53	185.33	11560	137939.4	4001	72	1.44	720.132	268.399	12280.54	4269.519
permutation472	50	17	4	5	55.235	169.719	10655	132049	4007	65	1.3	718.822	267.911	11373.67	4274.644
permutation473	48	14	3	5	48.075	181.542	11340	130927.1	3979	70	1.458	725.002	270.214	12064.7	4249.486
permutation474	51	17	3	5	44.942	184.368	11494	129864.7	3957	102	2	739.254	275.526	12233.42	4232.642
permutation475	44	16	3	5	51.801	179.053	11224	122611.5	4075	61	1.386	720.106	268.389	11944.27	4342.951
permutation476	47	14	3	5	52.264	174.043	10879	114155.5	3947	53	1.128	711.554	265.202	11590.97	4212.661
permutation477	41	15	3	5	42.611	179.095	11211	115161.8	4003	58	1.415	714.735	266.388	11925.86	4268.993
permutation478	55	16	3	5	52.165	187.315	11685	143365.6	4071	70	1.273	718.743	267.882	12404.12	4338.766
permutation479	47	13	3	5	48.115	186.319	11619	128392.8	3992	82	1.745	729.807	272.005	12348.94	4263.572
permutation480	51	17	3	5	37.894	182.286	11376	132252.3	3947	81	1.588	724.11	269.882	12099.92	4217.193
permutation481	46	16	3	5	54.156	175.106	11066	128131.6	4353	55	1.196	708.216	263.958	11774.54	4617.25
permutation482	51	16	3	5	52.251	181.134	11273	127361.8	3884	78	1.529	720.366	268.486	11993.5	4152.703
permutation483	55	15	3	5	43.309	188.543	11802	150684	4116	87	1.582	726.695	270.845	12528.44	4386.486
permutation484	49	15	3	5	45.526	186.612	11661	134163.8	4060	69	1.408	719.131	268.026	12379.94	4327.754
permutation485	63	16	3	5	53.729	178.774	11193	167368.3	4093	83	1.317	718.872	267.929	11912.08	4361.276
permutation486	54	15	3	5	54.992	189.307	11787	135362.9	4025	73	1.352	722.791	269.39	12510.03	4294.158
permutation487	50	16	3	5	49.697	185.983	11648	138478.1	4159	75	1.5	721.67	268.972	12369.54	4427.547
permutation488	47	14	3	5	46.686	181.314	11290	123433.5	3895	73	1.553	720.025	268.359	12010.31	4163.233
permutation489	55	18	3	5	52.7	172.74	10864	149338.5	4100	70	1.273	718.743	267.882	11582.57	4367.934
permutation490	50	15	3	5	45.719	183.787	11467	132592.6	3983	75	1.5	723.962	269.827	12190.74	4253.024
permutation491	47	13	3	5	47.705	180.712	11377	129322.7	4244	64	1.362	717.546	267.435	12094.73	4511.118
permutation492	50	13	3	5	51.134	181.476	11318	136813.1	3955	71	1.42	717.348	267.362	12035.42	4222.051
permutation493	58	15	3	5	46.596	186.751	11685	159205	4107	89	1.534	727.798	271.256	12412.94	4378.102
permutation494	56	18	3	5	49.769	180.073	11225	139728.1	3960	79	1.411	722.405	269.246	11946.98	4229.607
permutation495	56	18	3	5	49.741	183.136	11407	136191	3946	80	1.429	722.864	269.417	12129.82	4214.945
permutation496	53	15	3	5	48.756	191.724	11910	134391.3	3949	71	1.34	718.075	267.633	12628.55	4216.877
permutation497	52	14	3	5	48.643	183.307	11475	142763.1	4083	71	1.365	720.766	268.636	12196.21	4351.603
permutation498	29	13	4	5	58.249	168.792	10582	74290.21	3989	39	1.345	750.764	279.816	11332.95	4268.468
permutation499	54	14	3	5	50.575	184.998	11581	147801.3	4172	72	1.333	722.313	269.212	12303.48	4441.33
permutation500	50	14	4	5	40.294	173.697	10821	124897.7	3767	81	1.62	724.744	270.118	11545.32	4037.264
permutation501	50	14	4	5	47.656	178.197	11156	134054.3	4002	77	1.54	720.413	268.504	11876.02	4270.677
permutation502	51	15	3	5	54.883	181.831	11365	138441.5	4040	74	1.451	720.593	268.571	12086.06	4309.049
permutation503	51	13	3	5	52.569	175.709	10997	136878.4	3989	76	1.49	726.107	270.626	11723.43	4259.166
permutation504	57	15	3	5	53.154	187.894	11761	149892.3	4196	75	1.316	718.067	267.629	12478.69	4463.426
permutation505	36	11	4	5	34.854	179.158	11233	98766.1	3996	63	1.75	724.506	270.029	11957.39	4265.837
permutation506	55	17	3	5	53.008	180.483	11276	135284.9	4031	74	1.345	720.614	268.579	11996.53	4299.984
permutation507	44	16	3	5	44.615	173.524	10841	117958.7	3880	72	1.636	729.152	271.761	11570.07	4151.45
permutation508	50	17	3	5	51.554	181.851	11396	129257.7	4182	65	1.3	714.283	266.219	12109.87	4447.763
permutation509	49	15	3	5	51.8	177.063	11052	125247.2	3925	71	1.449	720.176	268.416	11771.75	4193.619
permutation510	58	18	3	5	48.558	177.265	11114	150969	4078	79	1.362	719.392	268.123	11833.86	4345.672
permutation511	37	14	3	5	44.21	176.905	11042	96666.94	3905	51	1.378	715.37	266.624	11757.1	4171.73
permutation512	57	17	3	5	53.277	182.954	11416	139952	4011	79	1.386	719.868	268.301	12136.27	4279.201
permutation513	48	15	4	5	47.447	171.815	10711	122305.3	3803	65	1.354	719.928	268.323	11430.94	4071.553
permutation514	55	17	3	5	44.652	185.147	11628	152462.9	4202	89	1.618	727.63	271.194	12355.59	4473.102
permutation515	42	15	3	5	43.279	187.141	11692	117212.2	4045	73	1.738	726.018	270.593	12417.67	4315.949
permutation516	57	15	3	5	55.926	182.275	11402	157940	4077	82	1.439	723.23	269.554	12124.75	4346.714
permutation517	50	15	3	5	48.749	177.495	11087	132189	3898	76	1.52	719.902	268.313	11806.45	4166.223
permutation518	40	19	3	5	54.132	174.611	11033	110686.1	4343	50	1.25	715.831	266.796	11748.75	4610.142
permutation519	49	15	3	5	48.054	181.871	11333	126183.9	3919	63	1.286	715.994	266.857	12048.7	4185.508

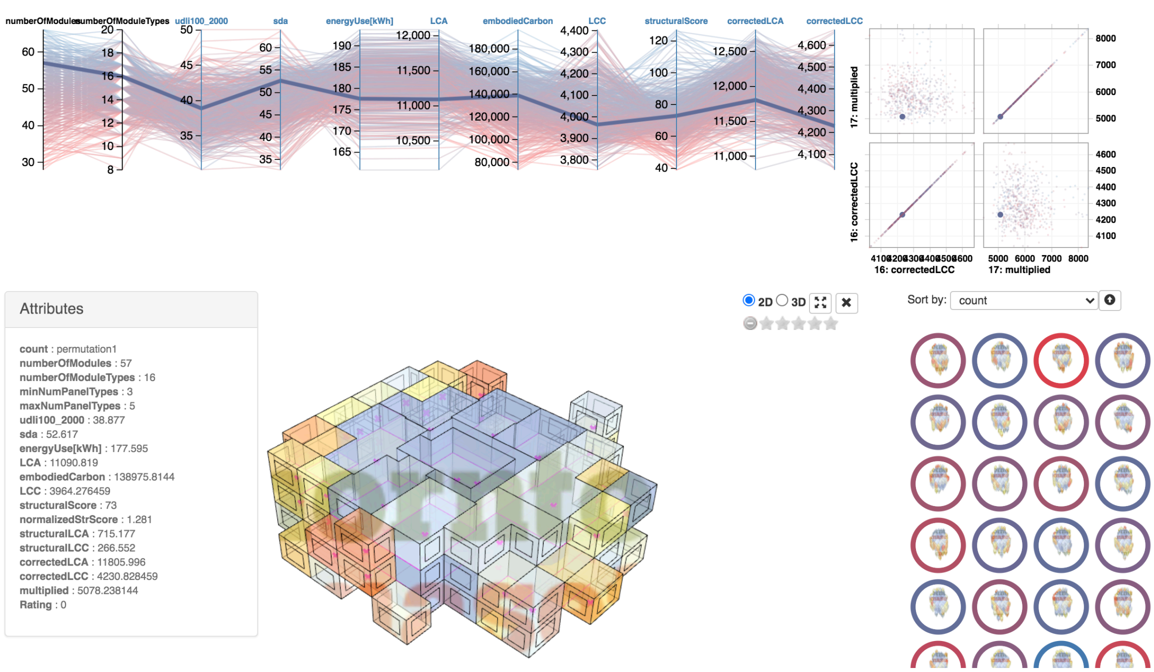
permutation520	66	14	3	5	55.006	183.045	11446	177194.4	4128	123	1.864	736.784	274.605	12182.69	4402.139
permutation521	37	15	3	5	42.954	184.449	11533	97928.09	4060	62	1.676	726.046	270.603	12258.97	4330.822
permutation522	42	13	3	5	46.16	186.083	11708	113163.2	4343	58	1.381	719.596	268.199	12427.32	4611.64
permutation523	47	16	3	5	50.174	169.353	10612	121349	3953	62	1.319	716.457	267.029	11328.88	4219.937
permutation524	53	14	3	5	45.452	184.645	11511	137992.3	3963	87	1.642	723.652	269.711	12234.9	4232.885
permutation525	38	12	3	5	37.073	182.668	11380	104735.2	3871	69	1.816	723.849	269.784	12104.01	4141.251
permutation526	56	13	3	5	50.923	184.35	11506	153630.9	4012	81	1.446	721.276	268.825	12227.27	4280.551
permutation527	59	16	3	5	48.074	190.587	11890	153150.7	4106	78	1.322	720.435	268.512	12610.42	4374.11
permutation528	50	14	3	5	49	189.1	11803	139432.6	4089	77	1.54	722.694	269.354	12525.31	4358.218
permutation529	58	16	3	5	53.188	183.829	11462	142342.8	4005	79	1.362	717.431	267.392	12179.92	4272.248
permutation530	52	14	3	5	44.671	181.67	11314	130767.7	3919	75	1.442	720.542	268.552	12034.63	4187.873
permutation531	48	16	3	5	49.839	182.898	11480	125707.7	4219	63	1.312	718.857	267.924	12198.66	4487.267
permutation532	43	15	3	5	45.61	179.171	11222	116505.5	4029	61	1.419	718.103	267.643	11940.55	4297.102
permutation533	58	16	3	5	52.018	171.308	10727	147572.2	3975	75	1.293	717.622	267.464	11445.09	4242.448
permutation534	51	13	3	5	46.124	180.31	11248	129944.4	3932	76	1.49	719.364	268.113	11967.05	4200.598
permutation535	43	14	3	5	50.702	177.841	11214	117488.6	4274	56	1.302	717.768	267.518	11932.08	4541.785
permutation536	57	14	3	5	49.571	192.112	11963	156856.9	4061	84	1.474	726.159	270.645	12689.21	4331.773
permutation537	62	17	3	5	47.629	181.596	11346	158928.5	4035	83	1.339	723.002	269.469	12068.74	4304.583
permutation538	38	13	3	5	40.008	183.738	11493	102554.3	4049	70	1.842	730.557	272.284	12223.13	4320.849
permutation539	42	13	4	5	40.523	177.997	11106	103534.7	3877	61	1.452	716.023	266.867	11821.93	4144.02
permutation540	57	17	3	5	45.76	181.495	11310	154507	3889	87	1.526	723.469	269.643	12033.32	4159.122
permutation541	45	15	3	5	51.013	178.31	11156	116230.2	4007	62	1.378	720.058	268.372	11876.53	4275.741
permutation542	38	14	3	5	46.507	170.491	10660	96438.01	3901	56	1.474	721.116	268.766	11381.42	4170.232
permutation543	60	17	3	5	46.187	189.872	11835	156558.8	4080	121	2.017	740.378	275.945	12575.65	4356.315
permutation544	49	14	3	5	43.709	182.446	11336	124065.8	3837	78	1.592	726.181	270.654	12062.48	4107.977
permutation545	42	12	3	5	55.163	179.366	11279	110643.5	4222	57	1.357	721.71	268.987	12000.28	4490.875
permutation546	53	16	3	5	49.274	180.273	11247	143825.3	3950	77	1.453	720.978	268.714	11967.59	4218.53
permutation547	57	17	3	5	43.834	179.17	11167	145444.4	3881	82	1.439	721.218	268.804	11888.3	4150.015
permutation548	57	15	3	5	54.16	185.279	11604	155014.6	4136	79	1.386	717.87	267.556	12322.18	4403.312
permutation549	40	16	3	5	46.287	175.261	10977	109963.2	3983	60	1.5	713.759	266.024	11690.69	4248.822
permutation550	60	18	3	5	53.714	172.672	10813	158036	4001	82	1.367	717.874	267.558	11530.81	4268.207
permutation551	41	15	3	5	42.429	180.932	11298	103777.7	3975	62	1.512	719.98	268.342	12017.64	4242.962
permutation552	53	16	3	5	49.171	183.274	11475	134238.6	4111	74	1.396	721.684	268.978	12196.39	4380.369
permutation553	55	16	3	5	46.117	183.705	11433	142677.2	3904	96	1.745	730.904	272.414	12163.6	4176
permutation554	60	17	3	5	49.643	182.632	11401	152953.9	4030	81	1.35	721.252	268.817	12122.56	4298.444
permutation555	36	12	4	5	58.29	170.165	10653	92246.07	4016	48	1.333	717.021	267.24	11370.25	4283.429
permutation556	50	12	3	5	43.07	183.061	11456	135852.1	4031	82	1.64	727.561	271.168	12184.02	4301.707
permutation557	56	16	3	5	44.674	181.103	11275	141987.3	3883	81	1.446	723.324	269.589	11998.31	4153.067
permutation558	49	13	4	5	45.733	178.523	11168	119282.4	4006	69	1.408	721.461	268.895	11889.83	4274.611
permutation559	44	11	4	5	44.656	170.9	10704	113803.1	3926	59	1.341	716.356	266.992	11420.2	4193.163
permutation560	63	17	3	5	48.92	181.224	11378	187916.1	4193	108	1.714	730.907	272.415	12108.76	4465.177
permutation561	43	13	3	5	44.997	184.4	11472	110839.6	3908	67	1.558	724.333	269.965	12196.44	4177.575
permutation562	52	16	3	5	52.158	183.045	11495	145740.6	4218	69	1.327	719.777	268.267	12215.22	4486.381
permutation563	50	15	3	5	47.156	176.77	11031	131390.8	3915	71	1.42	719.62	268.208	11750.61	4183.379
permutation564	55	13	3	5	48.374	180.64	11281	141912.3	3999	70	1.273	718.743	267.882	11999.83	4266.683
permutation565	43	15	3	5	44.701	181.157	11363	121512.2	4130	59	1.372	719.558	268.185	12082.86	4398.479
permutation566	52	13	3	5	48.429	183.997	11518	137829.1	4111	95	1.827	737.139	274.738	12255.52	4385.606
permutation567	55	16	3	5	50.573	182.216	11338	140927.5	3886	75	1.364	721.082	268.753	12059.11	4154.364
permutation568	47	16	3	5	56.022	172.022	10745	113029.2	3904	68	1.447	717.31	267.347	11462.38	4171.78
permutation569	38	14	3	5	37.835	175.836	11035	103391.9	3985	55	1.447	714.486	266.295	11749.66	4250.837
permutation570	55	18	3	5	50.709	179.621	11207	147957.5	3945	79	1.436	720.869	268.674	11928.1	4214.147
permutation571	54	15	3	5	52.898	179.091	11231	144442	4112	68	1.259	718.282	267.709	11949.24	4379.316
permutation572	38	12	3	5	40.688	180.432	11266	99059.96	3954	61	1.605	724.487	270.022	11990.9	4224.235
permutation573	56	15	3	5	41.599	180.947	11316	143541.8	3992	80	1.429	722.864	269.417	12038.42	4261.835
permutation575	51	14	4	5	47.807	179.038	11206	125928.1	4018	74	1.451	720.593	268.571	11926.28	4286.743
permutation576	48	12	3	5	41.524	190.302	11840	131960.5	3948	77	1.604	731.188	272.52	12570.71	4220.276
permutation577	59	17	3	5	55.329	176.785	11060	149119.8	4048	91	1.542	724.154	269.898	11784.17	4317.684
permutation578	45	15	3	5	45.581	187.032	11682	123479.9	4083	61	1.356	722.034	269.108	12403.78	4352.096
permutation579	47	13	3	5	46.887	181.061	11328	118257.5	4068	62	1.319	714.053	266.133	12042.21	4333.927
permutation580	59	15	3	5	53.109	186.928	11646	163510.2	3997	80	1.356	717.439	267.395	12363.85	4264.548
permutation581	47	13	4	5	52.419	163.451	10250	118509.3	3891	64	1.362	719.97	268.339	10969.48	4159.268
permutation582	33	12	3	5	52.189	172.741	10840	90867.35	4067	41	1.242	720.742	268.626	11561.21	4335.593
permutation583	55	15	4	5	45.758	178.461	11173	142740.2	4012	79	1.436	720.869	268.674	11894.14	4280.997
permutation584	48	13	3	5	46.782	179.371	11257	132353.5	4130	60	1.25	712.538	265.569	11969.16	4395.495
permutation585	51	14	3	5	45.232	181.721	11388	141228.8	4092	72	1.412	719.588	268.196	12107.36	4360.301
permutation586	54	15	3	5	47.648	187.691	11674	143792.5	3913	93	1.722	732.345	272.951	12406.83	4185.62
permutation587	54	13	4	5	50.834	171.879	10726	133562.3	3870	73	1.352	722.791	269.39	11449.1	4138.95
permutation588	42	16	3	5	50.566	177.207	11078	115636.7	3953	59	1.405	717.498	267.417	11795.28	4220.589
permutation589	45	13	3	5	49.534	182.247	11372	113111.3	3970	58	1.289	720.316	268.468	12092.43	4238.902
permutation590	46	15	3	5	43.45	184.21	11479	124733.4	3934	78	1.696	723.396	269.615	12202.36	4203.376
permutation591	48	14	3	5	46.15	177.144	11038	122262.6	3860	68	1.417	716.792	267.154	11755.14	4127.334
permutation592	52	17	3	5	47.095	178.724	11211	133893.8	4117	68	1.308	714.914	266.454	11926.3	4383.9
permutation593	53	14	3	5	42.288	174.865	10930	136249	3891	83	1.566	721.723	268.992	11651.34	4159.933
permutation594	53	18	3	5	51.388	181.55	11403	145476.9	4208	62	1.17	711.594	265.217	12114.4	4473.614
permutation595	52	13	3	5	51.275	192.035	11957	133956.2	4051	73	1.404	723.968	269.829	12680.86	4321.307
permutation596	55	17	3	5	51.118	190.187	11914	150625	4242	77	1.4	724.11	269.882	12638.37	4511.634
permutation597	46	16	3	5	41.395	187.041	11659	120158.9	3965	78	1.696	730.909	272.416	12389.42	4237.871
permutation598	54	19	3	5	45.247	180.324	11254	130827.9	3961	75	1.389	721.616	268.952	11975.82	4230.095
permutation599	41	14	3	5	42.887	181.175	11278	103626.5	3882	62	1.512	722.764	269.38	12000.28	4150.975
permutation600	53	16	3	5	50.45	184.683	11586	161008.6	4200	80	1.509	722.429	269.255	12308.74	4469.401

B.1.2 Design Explorer: Visualization Interface

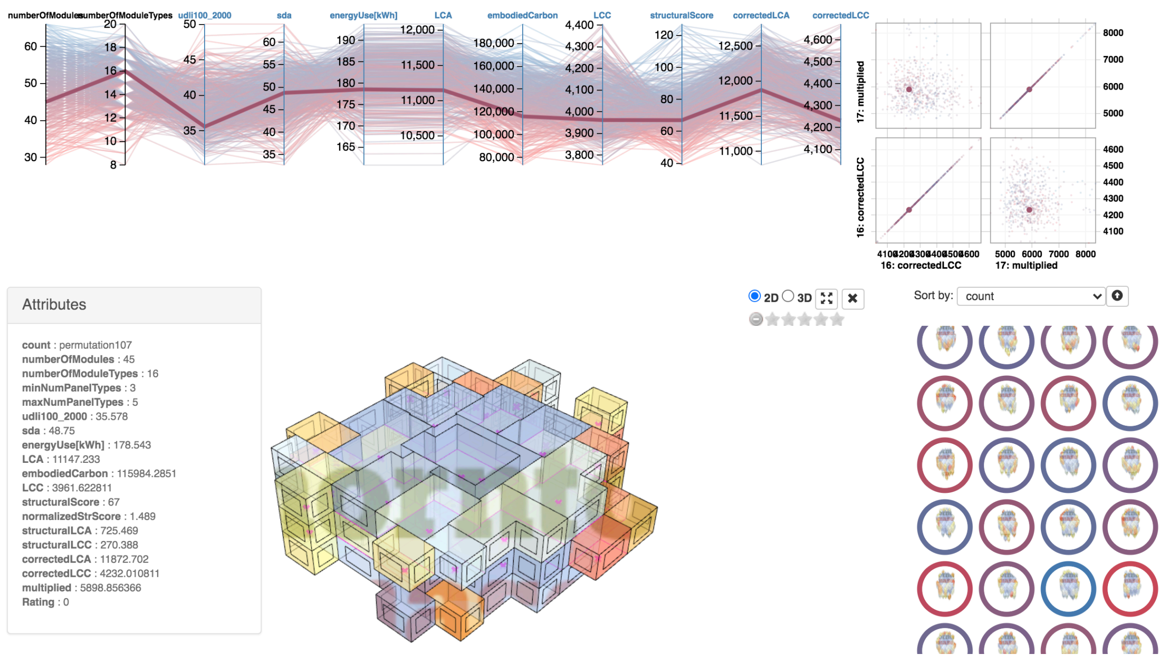
All **600** Permutations:



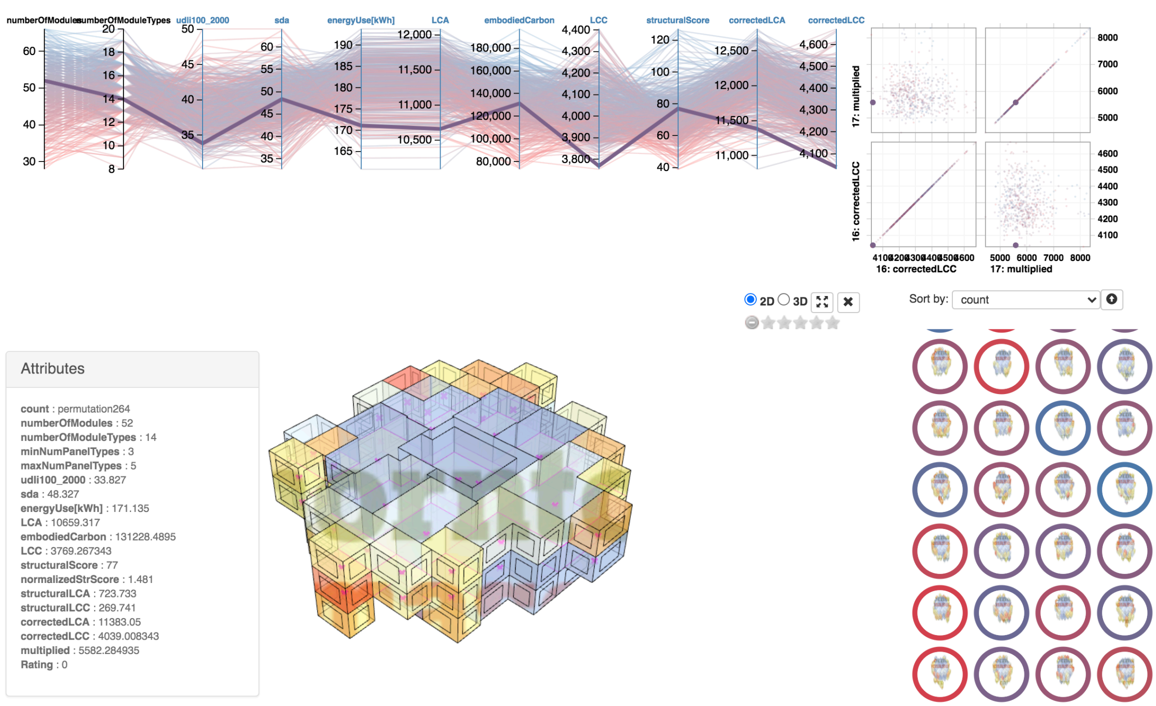
Permutation **1** of **600**:



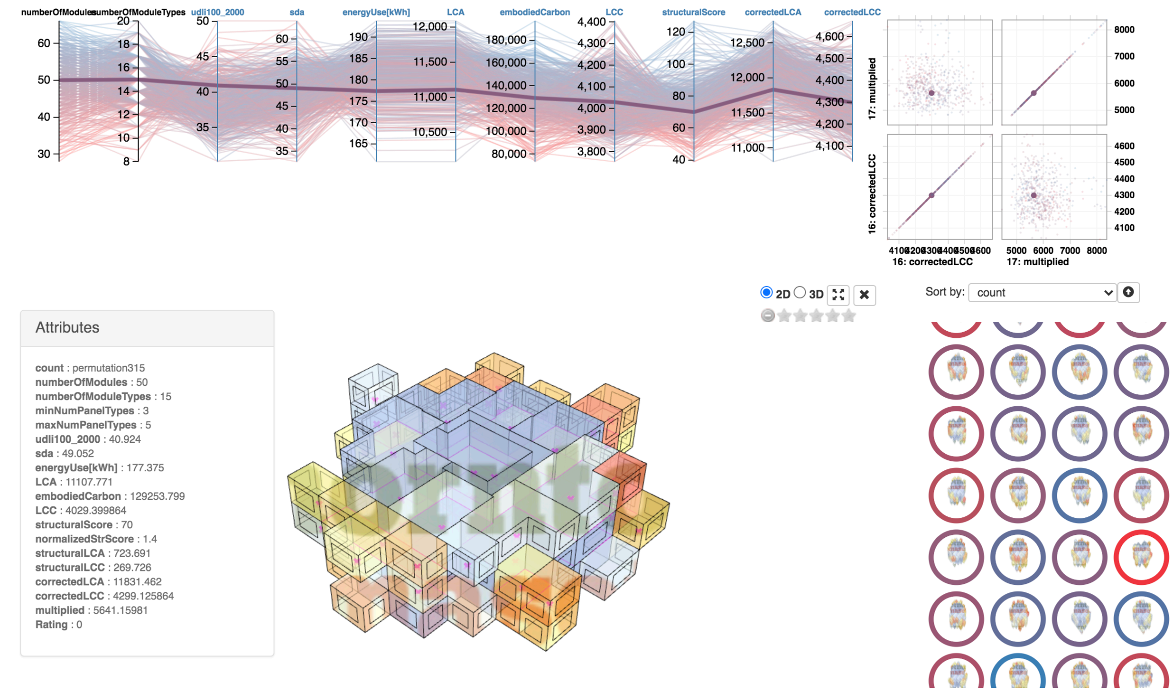
Permutation **107** of **600**:



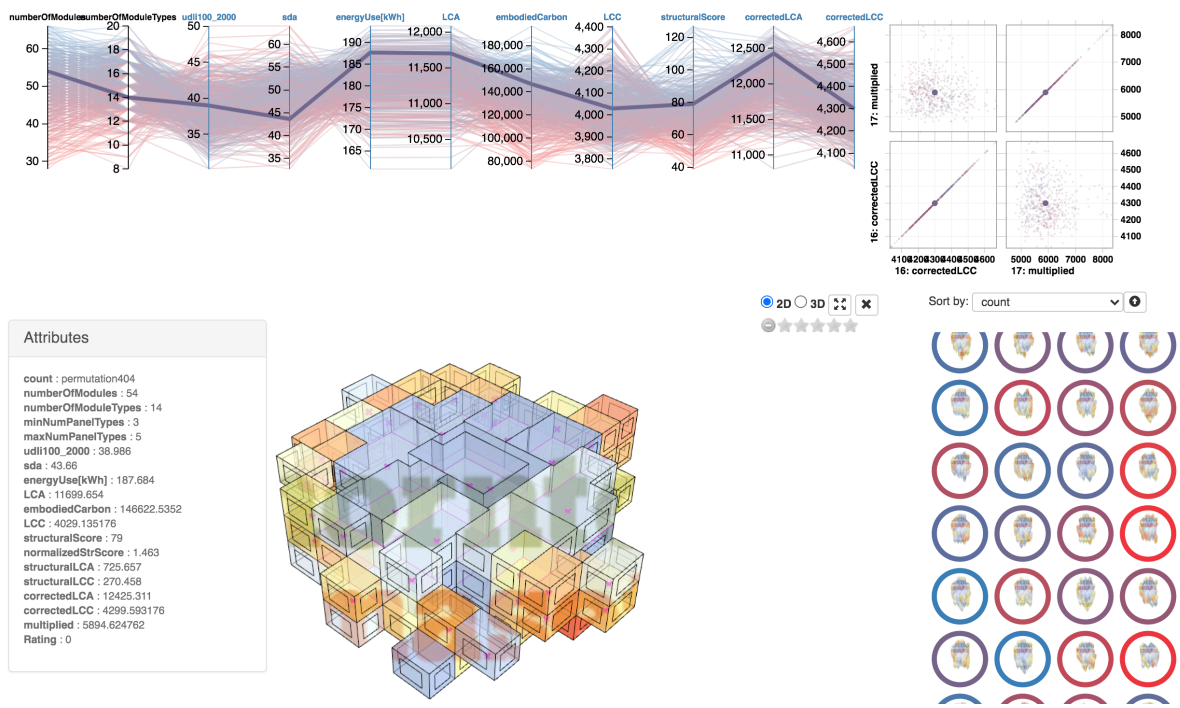
Permutation **264** of **600**:



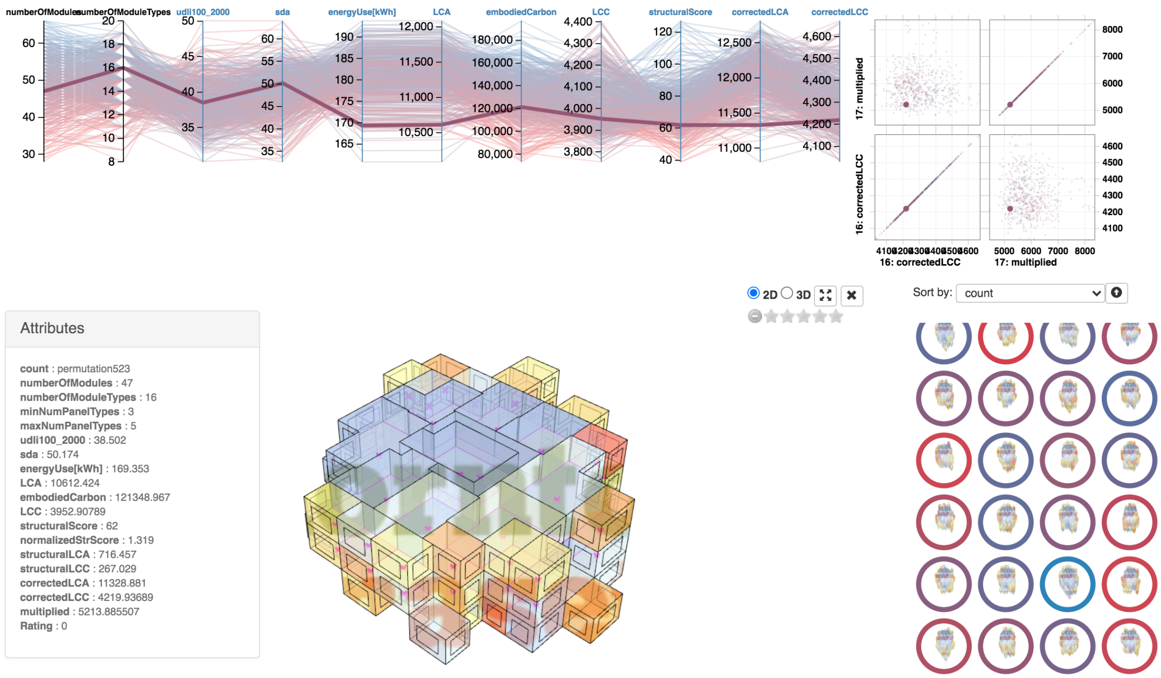
Permutation **315** of **600**:



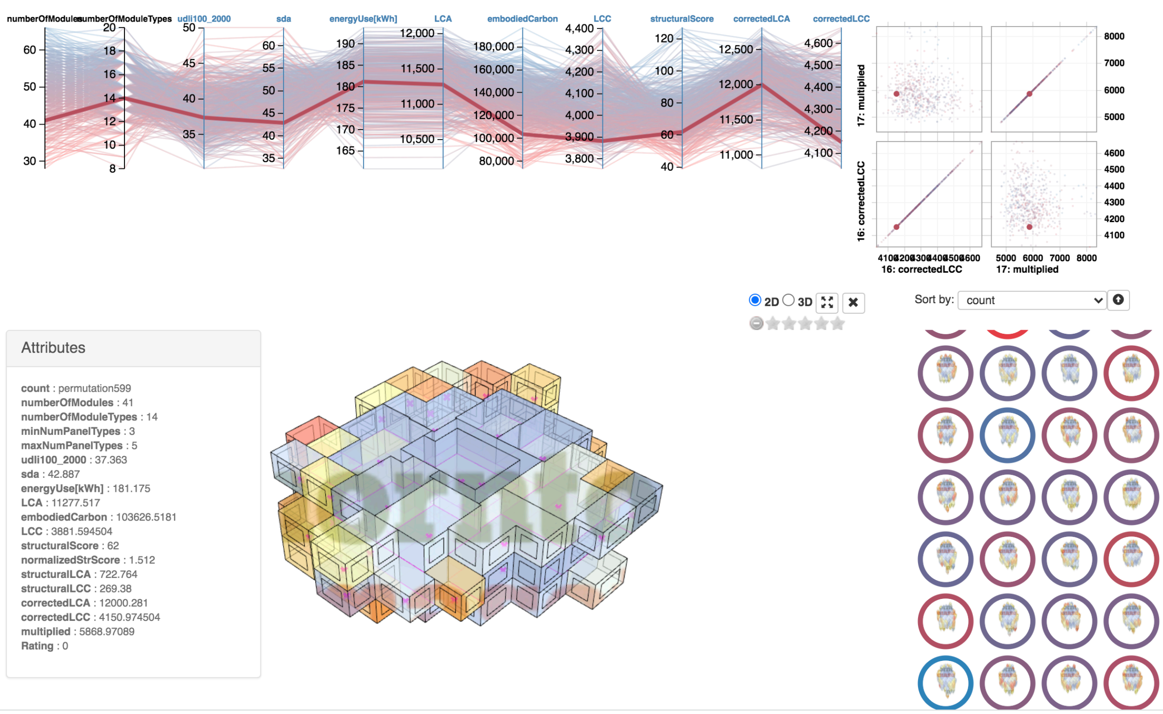
Permutation **404** of **600**:



Permutation **523** of **600**:



Permutation **599** of **600**:



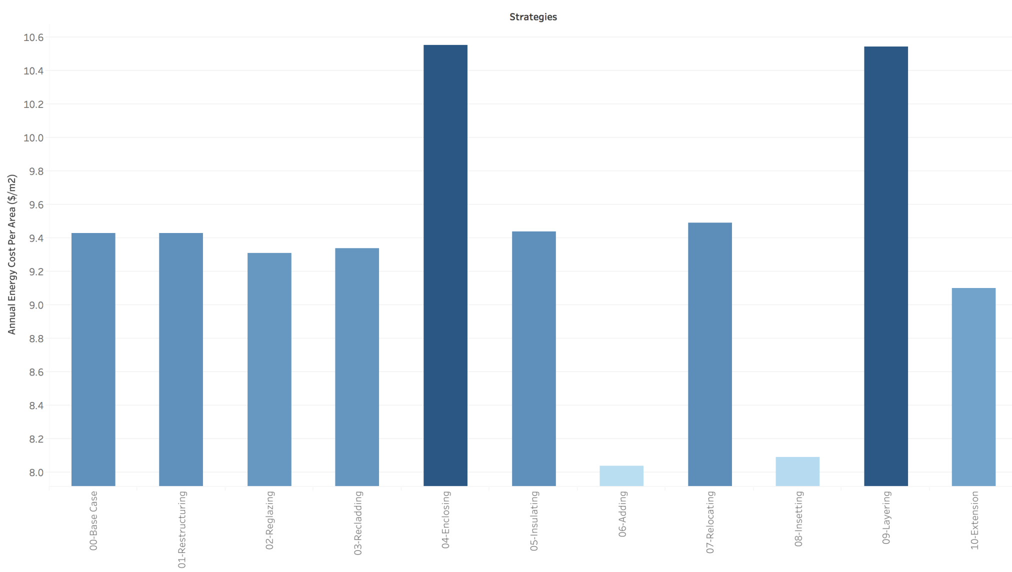
Appendix C: Simulation Results

Table of Contents

C.1: Energy Modeling Results

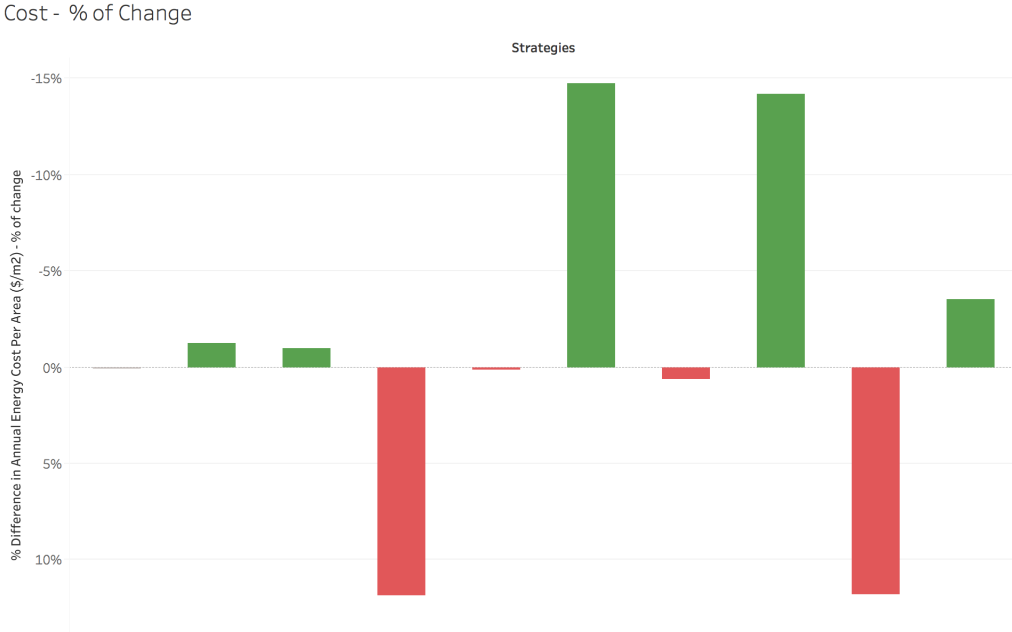
C.1.1 Energy Modeling - Overview of Results

Cost

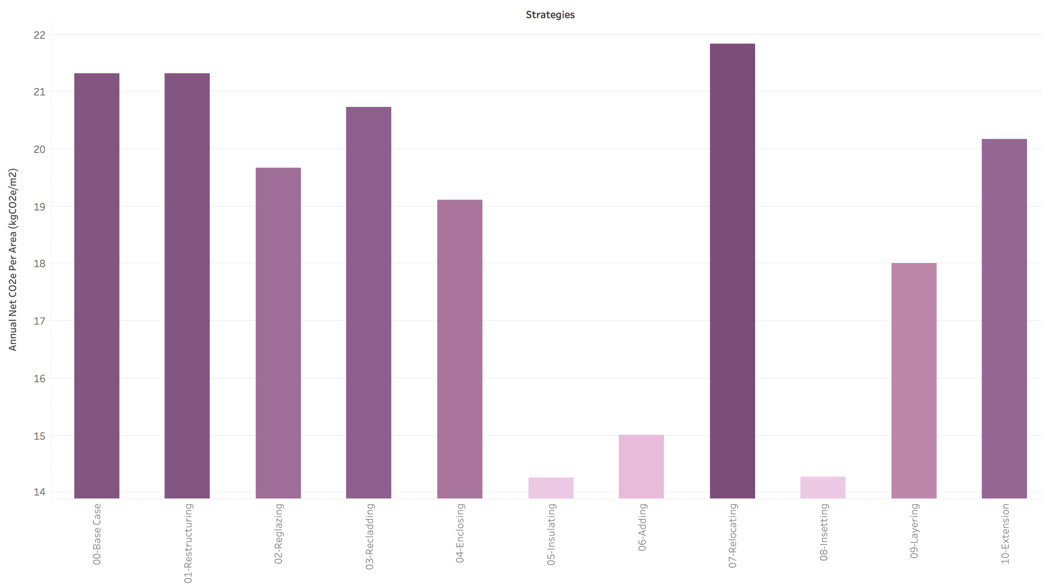


Sum of Annual Energy Cost Per Area ($/m2) for each Strategies. Color shows sum of Annual Energy Cost Per Area ($/m2).

Cost - % of Change



CO2

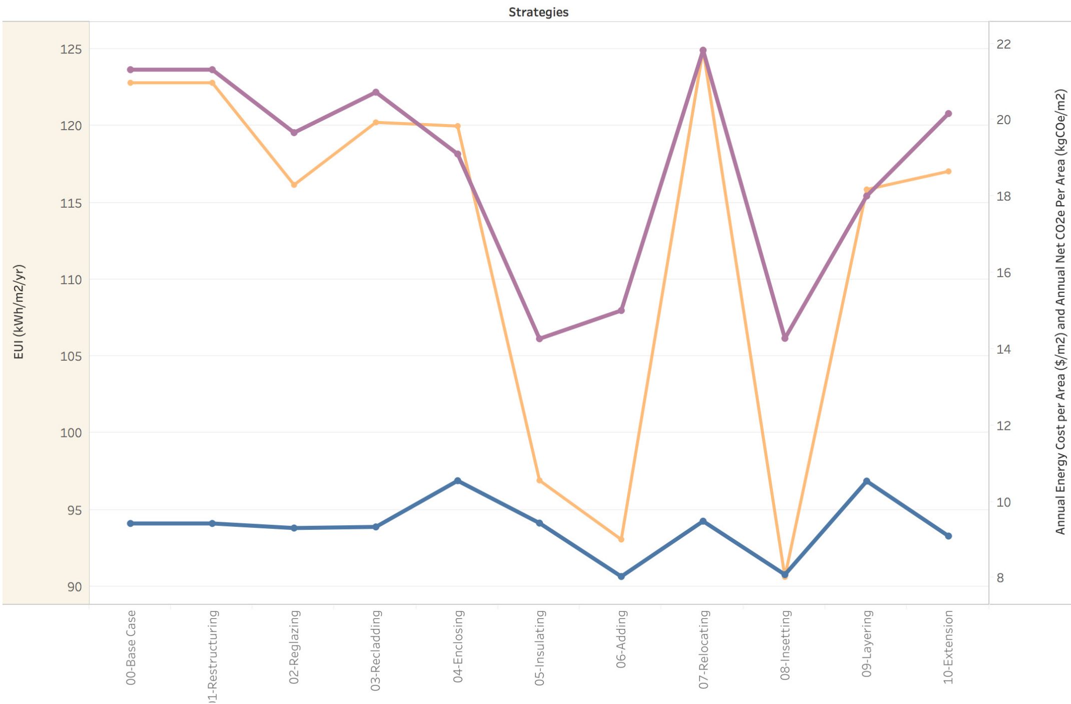


Sum of Annual Net CO2e Per Area (kgCO2e/m2) for each Strategies. Color shows sum of Annual Net CO2e Per Area (kgCO2e/m2).

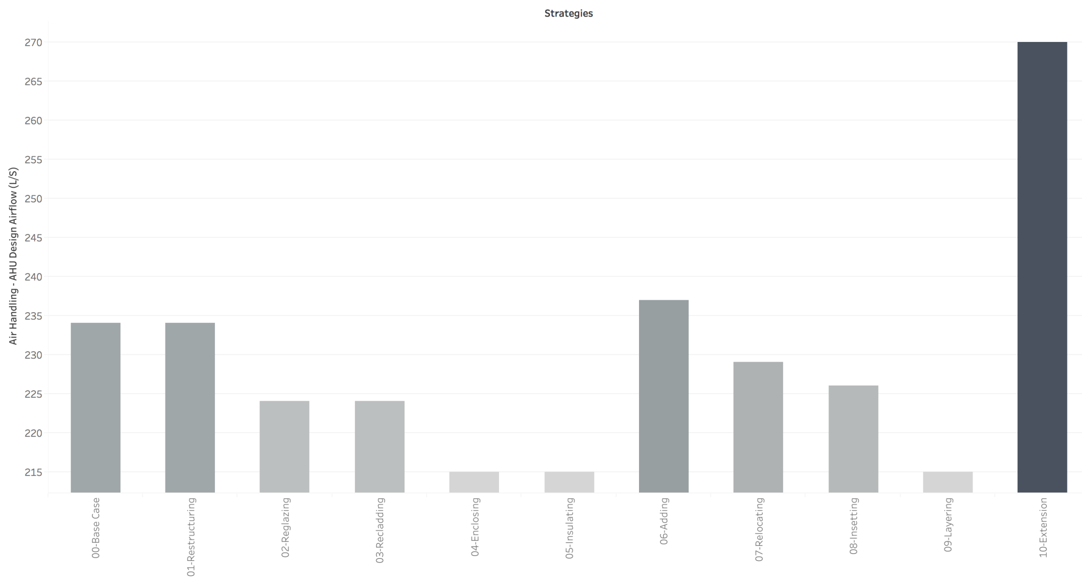
CO2 - % of Change

% Difference in Annual Net CO2e Per Area (kgCO2e/m2) - % of change from the '00-Base Case' along Strategies for each Strategies. Color shows details about Strategies and % Difference in Annual Net CO2e Per Area (kgCO2e/m2) - % of change from the '00-Base Case' along Strategies.

EUI/Cost/CO2

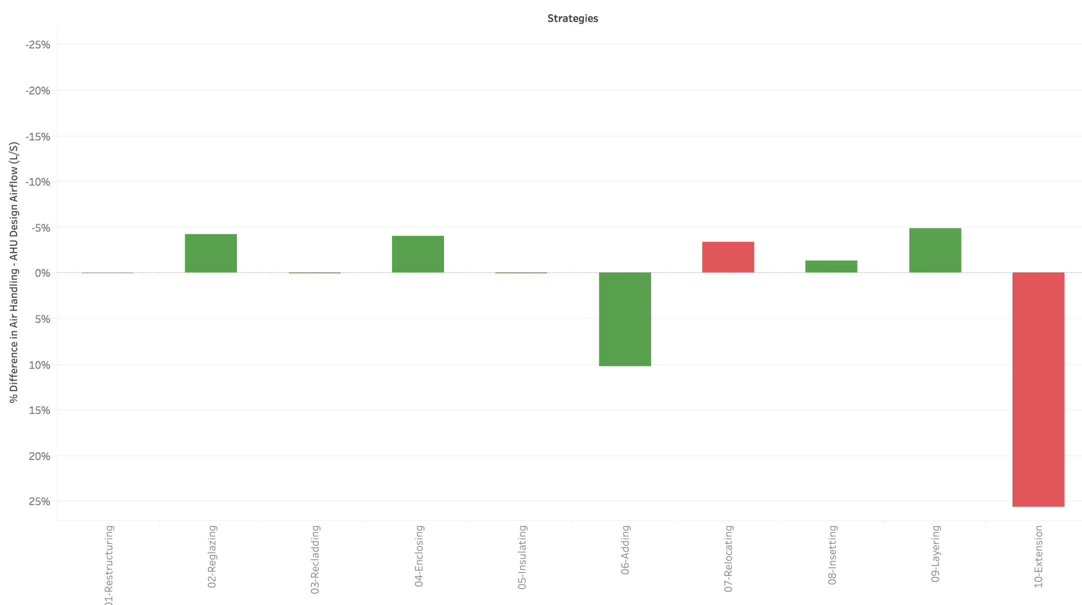

Strategies
EUI (kWh/m2/yr)
125
120
115
110
105
100
95
90
Annual Energy Cost per Area ($/m2) and Annual Net CO2e Per Area (kgCOe/m2)
22
20
18
16
14
12
10
8
00-Base Case
01-Restructuring
02-Reglazing
03-Recladding
04-Enclosing
05-Insulating
06-Adding
07-Relocating
08-Insetting
09-Layering
10-Extension

AHU



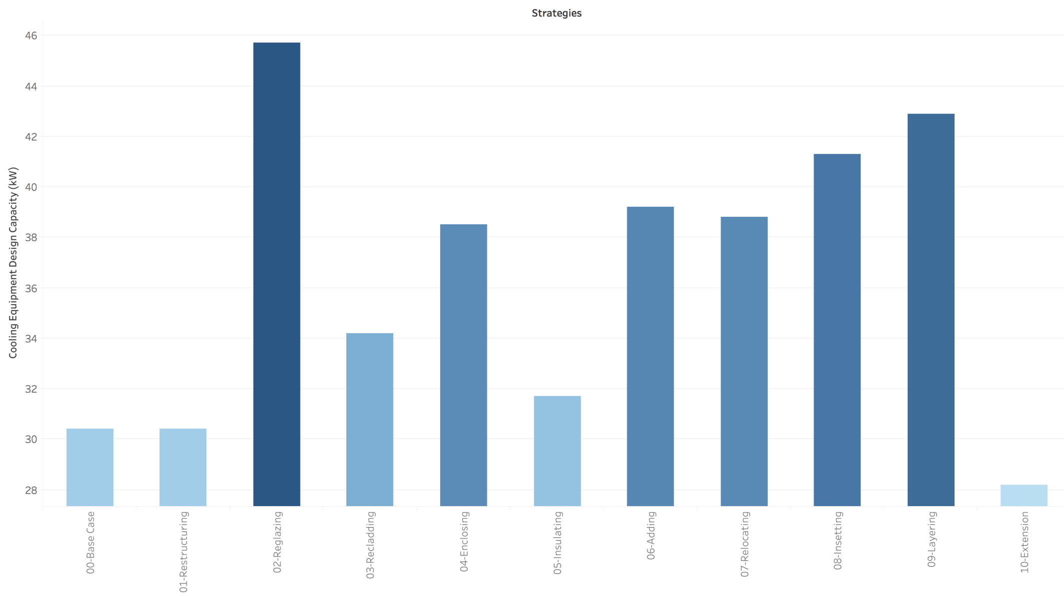
Sum of Air Handling - AHU Design Airflow (L/S) for each Strategies. Color shows sum of Air Handling - AHU Design Airflow (L/S).

AHU - % of Change



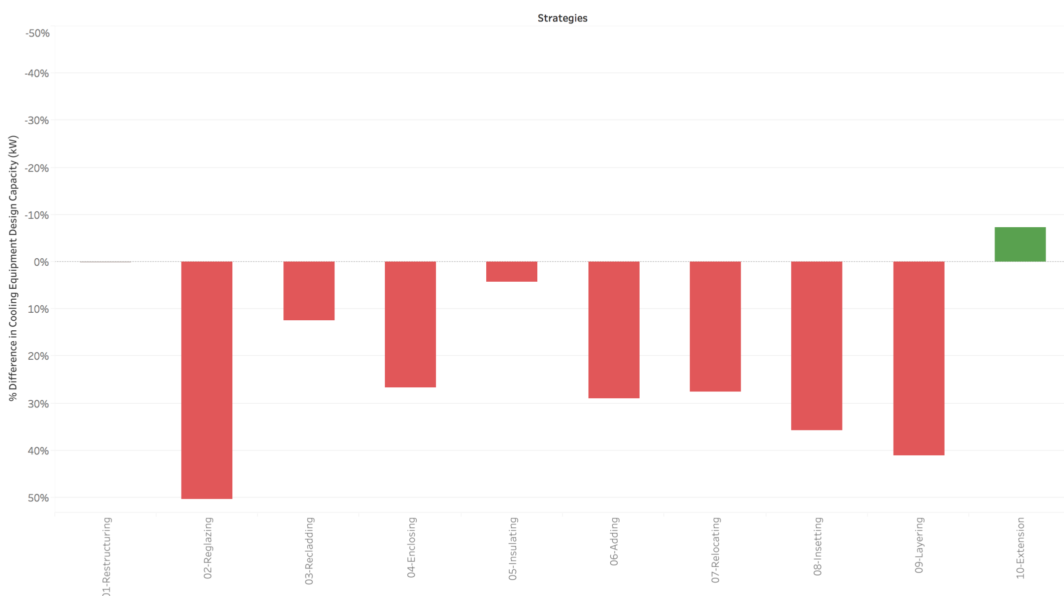
% Difference in Air Handling - AHU Design Airflow (L/S) for each Strategies. Color shows details about Strategies.

Cooling Requirement



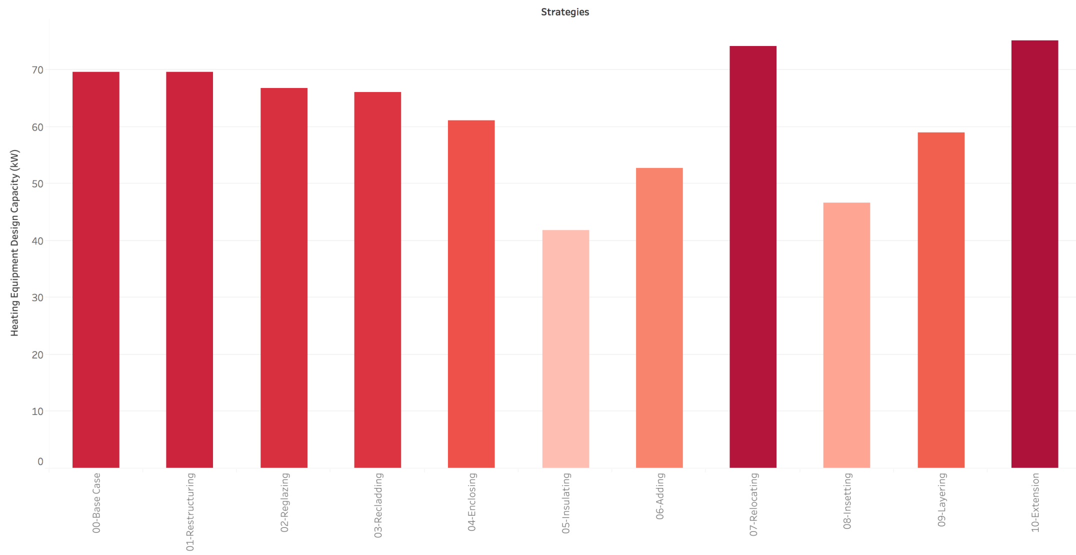
Sum of Cooling Equipment Design Capacity (kW) for each Strategies. Color shows sum of Cooling Equipment Design Capacity (kW).

Cooling Requirement - % of Change



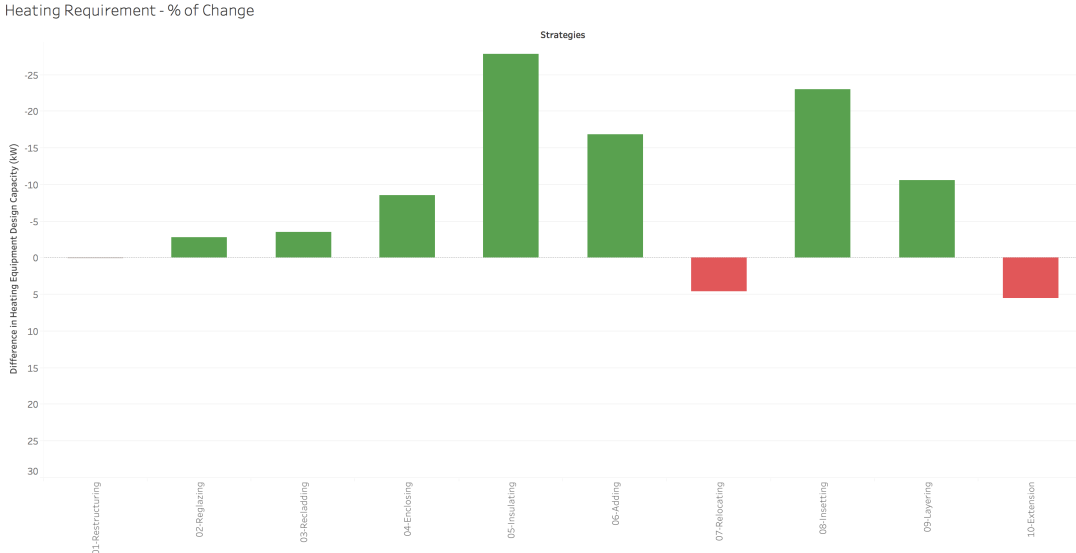
% Difference in Cooling Equipment Design Capacity (kW) for each Strategies. Color shows details about Strategies.

Heating Requirement



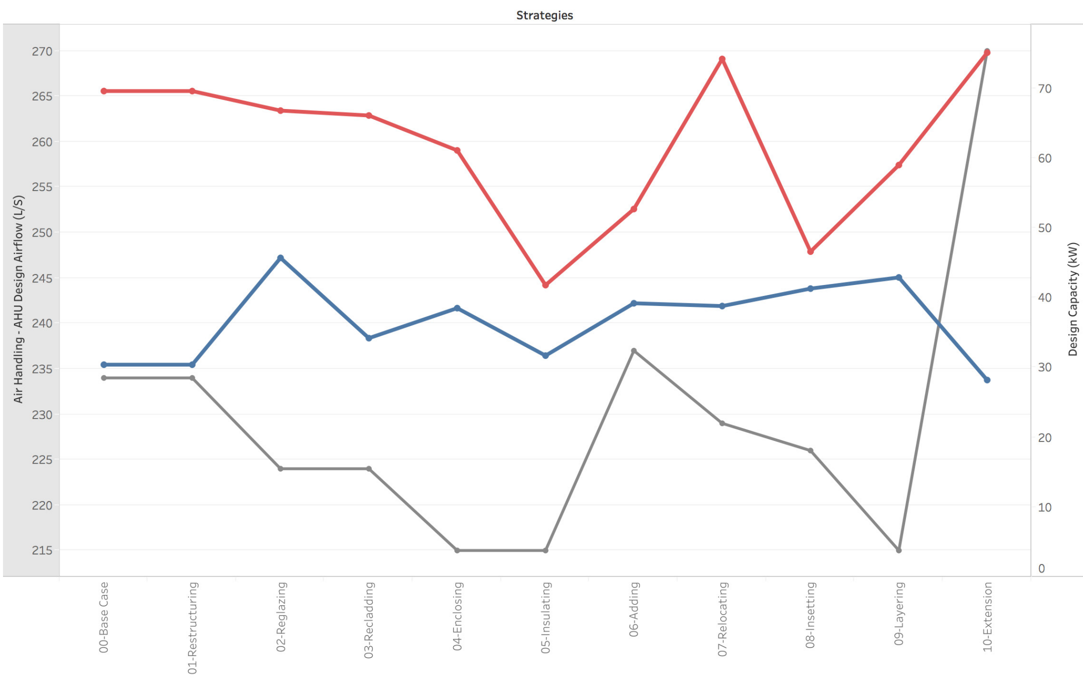
Sum of Heating Equipment Design Capacity (kW) for each Strategies. Color shows sum of Heating Equipment Design Capacity (kW).

Heating Requirement - % of Change



Difference in Heating Equipment Design Capacity (kW) for each Strategies. Color shows details about Strategies.

AHU/HVAC



The trends of sum of Air Handling - AHU Design Airflow (L/S), Cooling Equipment Design Capacity (kW) and Heating Equipment Design Capacity (kW) for Strategies. For pane Measure Values: Color

C.1.2 Energy Modeling Inputs - (pages **1-3** of **23**)

Input Type	Units (SI)		
		00-Base Case	01-Restructuring*
Building	Sefaira ID	183516	183516
Location	-	Toronto, CA	Toronto, CA
Orientation	deg	0	0
Building Area	m2	1170	1170
Conditioned Area	m2	1170	1170
Ignored Zones Area	m2	0	0
Zoning Strategy	-	Basic Perimeter / Core	Basic Perimeter / Core
Perimeter Depth	m	4.572	4.572
Massing	Sefaira ID	893661	893661
Energy Plus version	-	8.6	8.6
Exterior Wall			
Assembly Type	-	Brick	Brick
		U-factor / R-value	U-factor / R-value
North	W/m2K	0.57	0.57
East	W/m2K	0.57	0.57
South	W/m2K	0.57	0.57
West	W/m2K	0.57	0.57
Facade Glazing			
		U-factor	U-factor
North	W/m2K	3.3	3.3
East	W/m2K	3.3	3.3
South	W/m2K	3.3	3.3
West	W/m2K	3.3	3.3
		SHGC	SHGC
North	-	0.4	0.4
East	-	0.4	0.4
South	-	0.4	0.4
West	-	0.4	0.4
Floors			
Assembly Type	-	Carpet	Carpet
U-factor / R-value	W/m2K	0.36	0.36
Roof Glazing			
U-factor	W/m2K	2.4	2.4
SHGC	-	0.6	0.6
Roofs			
Assembly Type	-	Metal Deck	Metal Deck
U-factor / R-value	W/m2K	0.36	0.36
Infiltration			
Air Changes	-	0.2	0.2

Input Type	Units (SI)		
		00-Base Case	01-Restructuring*
Facade Area 50 Pa	m3/m2 h	-	-
Facade Area 75 Pa	m3/m2 h	-	-
Crack Infiltration	L/s m	-	-
Window to Wall Ratio			
North	-	n/a	n/a
East	-	n/a	n/a
South	-	n/a	n/a
West	-	n/a	n/a
Shading			
3D Model Shading			
Analyse Shading Drawn in 3D Model	-	TRUE	TRUE
Software Shading			
		Horizontal Shading Ratio	Horizontal Shading Ratio
North	-	0.55	0.55
East	-	0.55	0.55
South	-	0.55	0.55
West	-	0.55	0.55
		Vertical Shading Ratio	Vertical Shading Ratio
North	-	0	0
East	-	0	0
South	-	0	0
West	-	0	0
Automated Blinds and Shades		FALSE	FALSE
		Shading Type Applied	Shading Type Applied
North	-	n/a	n/a
East	-	n/a	n/a
South	-	n/a	n/a
West	-	n/a	n/a
		Control Basis	Control Basis
North	-	n/a	n/a
East	-	n/a	n/a
South	-	n/a	n/a
West	-	n/a	n/a
		Solar Gain Threshold	Solar Gain Threshold
North	W/m2	n/a	n/a
East	W/m2	n/a	n/a
South	W/m2	n/a	n/a
West	W/m2	n/a	n/a
Active Space Use Template			
Total Area of Zones Affected	m2	1170	1170
Total Area Percentage of Zones Affected	%	100	100
		Design Loads	Design Loads
Occupant Density	m2/person	50	50
Equipment Power Density	W/m2	5	5

Input Type	Units (SI)		
		00-Base Case	01-Restructuring*
Lighting Power Density	W/m2	10	10
		Ventilation and OA	Ventilation and OA
Outside Air Rate / Person	L/s · person	10	10
Outside Air Rate / Unit Area	L/m2 · s	0	0
Outside Air Rate Changes per Hour	1/h	0	0
Total Air Rate Changes per Hour	1/h	0	0
		Temperature Setpoints	Temperature Setpoints
Heating Setpoint	C	20	20
Heating Setback	C	18	18
Cooling Setpoint	C	25	25
Cooling Setback	C	28	28
		HVAC Schedule	HVAC Schedule
Operating Hours Start	hr	6	6
Operating Hours End	hr	22	22
Setback to Setpoint Ramp Up Time	hr	1	1
		Annual Diversity Schedule	Annual Diversity Schedule
0	hr	0.3	0.3
1	hr	0.3	0.3
2	hr	0.3	0.3
3	hr	0.3	0.3
4	hr	0.3	0.3
5	hr	0.3	0.3
6	hr	0.3	0.3
7	hr	0.5	0.5
8	hr	0.5	0.5
9	hr	0.15	0.15
10	hr	0.15	0.15
11	hr	0.15	0.15
12	hr	0.15	0.15
13	hr	0.15	0.15
14	hr	0.15	0.15
15	hr	0.15	0.15
16	hr	0.15	0.15
17	hr	0.4	0.4
18	hr	0.6	0.6
19	hr	0.8	0.8
20	hr	0.8	0.8
21	hr	0.8	0.8
22	hr	0.6	0.6
23	hr	0.3	0.3
		Day Schedules	Day Schedules
Internal Loads Applied	-	5 days per week	5 days per week
HVAC System Operating On	-	5 days per week	5 days per week
HVAC System - Air Side			
System Type		Fan Coil Units/Central Plant	Fan Coil Units/Central Plant

C.1.3 Energy Modeling Results

		Air Handling
Iteration Name	Primary HVAC System	AHU Design Airflow
		L/s
00-Base Case	Fan Coil Units and Central Plant	234
01-Restructuring	*Fan Coil Units and Central Plant*	*234*
02-Reglazing	Fan Coil Units and Central Plant	224
03-Recladding	Fan Coil Units and Central Plant	224
04-Enclosing	Fan Coil Units and Central Plant	215
05-Insulating	Fan Coil Units and Central Plant	215
06-Adding	Fan Coil Units and Central Plant	237
07-Relocating	Fan Coil Units and Central Plant	229
08-Insetting	Fan Coil Units and Central Plant	226
09-Layering	Fan Coil Units and Central Plant	215
10-Extension	Fan Coil Units and Central Plant	270

		Cooling
Iteration Name	AHU Minimum Outside Airflow	Cooling Equipment Design Capacity
	L/s	kW
00-Base Case	234	30.4
01-Restructuring	*234*	*30.4*
02-Reglazing	224	45.7
03-Recladding	224	34.2
04-Enclosing	215	38.5
05-Insulating	215	31.7
06-Adding	237	39.2
07-Relocating	229	38.8
08-Insetting	226	41.3
09-Layering	215	42.9
10-Extension	270	28.2

Iteration Name	Total Peak Cooling Coil Load	All Zones Peak Cooling Coil Load
	kW	kW
00-Base Case	30.4	30.4
01-Restructuring	*30.4*	*30.4*
02-Reglazing	45.7	40.7
03-Recladding	34.2	29.2
04-Enclosing	38.5	33.7
05-Insulating	31.7	26.7
06-Adding	39.2	34.0
07-Relocating	38.8	32.0
08-Insetting	41.3	36.3
09-Layering	42.9	38.1
10-Extension	28.2	28.2

Iteration Name	**Chilled Water Pumps**	**Highest Peak Cooling Load by Zone**
	L/min	**W/m2**
00-Base Case	**100.4**	**64**
01-Restructuring	*100.4*	*64*
02-Reglazing	**145.4**	**112**
03-Recladding	**120.3**	**63**
04-Enclosing	**128.0**	**99**
05-Insulating	**102.4**	**68**
06-Adding	**127.9**	**75**
07-Relocating	**125.9**	**60**
08-Insetting	**135.0**	**92**
09-Layering	**136.2**	**121**
10-Extension	**96.0**	**30**

	Heating	
Iteration Name	**Heating Equipment Design Capacity**	**Total Peak Heating Coil Load**
	kW	**kW**
00-Base Case	**69.6**	**59.2**
01-Restructuring	*69.6*	*59.2*
02-Reglazing	**66.8**	**56.8**
03-Recladding	**66.1**	**56.2**
04-Enclosing	**61.1**	**52.0**
05-Insulating	**41.8**	**35.5**
06-Adding	**52.7**	**44.8**
07-Relocating	**74.2**	**63.1**
08-Insetting	**46.6**	**39.6**
09-Layering	**59.0**	**50.1**
10-Extension	**75.1**	**63.9**

Iteration Name	**All Zones Peak Heating Coil Load**	**Heating Water Pumps**
	kW	**L/min**
00-Base Case	**62.7**	**87.1**
01-Restructuring	*62.7*	*87.1*
02-Reglazing	**53.8**	**78.7**
03-Recladding	**53.2**	**79.0**
04-Enclosing	**49.1**	**74.2**
05-Insulating	**33.1**	**49.9**
06-Adding	**42.4**	**63.3**
07-Relocating	**60.1**	**88.4**
08-Insetting	**37.0**	**55.0**
09-Layering	**47.3**	**68.9**
10-Extension	**68.0**	**94.2**

Sefaira Energy Modeling Results

		Heat Rejection
Iteration Name	Highest Peak Heating Load by Zone	Heat Rejection Design Capacity
	W/m2	kW
00-Base Case	80	45.6
01-Restructuring	*80*	*45.6*
02-Reglazing	81	57.0
03-Recladding	77	48.1
04-Enclosing	75	48.8
05-Insulating	60	42.7
06-Adding	62	50.0
07-Relocating	80	53.9
08-Insetting	62	52.4
09-Layering	75	54.8
10-Extension	138	21.1

		Energy Use
Iteration Name	Condenser Water Pumps	HVAC Energy per Unit Area
	L/min	kWh/m2/yr
00-Base Case	116.3	87.39
01-Restructuring	*116.3*	*87.39*
02-Reglazing	177.9	80.74
03-Recladding	145.3	84.81
04-Enclosing	154.8	72.91
05-Insulating	130.3	49.83
06-Adding	154.2	57.64
07-Relocating	159.9	89.54
08-Insetting	159.5	55.20
09-Layering	167.2	68.78
10-Extension	108.4	81.62

Iteration Name	Annual Cooling Energy per Unit Area	Annual Heating Energy per Unit Area
	kWh/m2/yr	kWh/m2/yr
00-Base Case	1.59	77.94
01-Restructuring	*1.59*	*77.94*
02-Reglazing	2.89	69.43
03-Recladding	1.94	75.07
04-Enclosing	3.04	61.36
05-Insulating	2.91	39.49
06-Adding	2.08	49.18
07-Relocating	1.76	80.46
08-Insetting	2.92	45.03
09-Layering	4.30	55.40
10-Extension	1.30	72.99

Sefaira Energy Modeling Results

Iteration Name	**EUI**	**Annual Electricity Demand**
	kWh/m2/yr	**kWh**
00-Base Case	**122.82**	**52536.1**
01-Restructuring	*122.82*	*52536.1*
02-Reglazing	**116.17**	**52407.0**
03-Recladding	**120.24**	**50649.8**
04-Enclosing	**120.00**	**63051.6**
05-Insulating	**96.92**	**61746.1**
06-Adding	**93.07**	**52023.8**
07-Relocating	**124.97**	**50995.6**
08-Insetting	**90.63**	**51612.2**
09-Layering	**115.87**	**65028.7**
10-Extension	**117.05**	**59522.5**

Iteration Name	**Annual Gas Use**	**Annual Net Electricity Use**
	kWh	**kWh**
00-Base Case	**91149.07**	**52536.1**
01-Restructuring	*91149.07*	*52536.1*
02-Reglazing	**77775.48**	**52407.0**
03-Recladding	**84095.67**	**50649.8**
04-Enclosing	**65873.48**	**63051.6**
05-Insulating	**42383.91**	**61746.1**
06-Adding	**58215.36**	**52023.8**
07-Relocating	**92084.80**	**50995.6**
08-Insetting	**50899.85**	**51612.2**
09-Layering	**59483.35**	**65028.7**
10-Extension	**98523.13**	**59522.5**

	Energy Costs	
Iteration Name	**Annual Energy Cost**	**Annual Electricity Cost**
	$	**$**
00-Base Case	**11030.0**	**7055.6**
01-Restructuring	*11030.0*	*7055.6*
02-Reglazing	**10429.5**	**7038.3**
03-Recladding	**10469.1**	**6802.3**
04-Enclosing	**11340.1**	**8467.8**
05-Insulating	**10140.6**	**8292.5**
06-Adding	**9525.2**	**6986.8**
07-Relocating	**10863.9**	**6848.7**
08-Insetting	**9150.9**	**6931.5**
09-Layering	**11327.0**	**8733.4**
10-Extension	**12289.8**	**7993.9**

Sefaira Energy Modeling Results

Iteration Name	Annual Gas Cost	Annual Energy Cost Per Area
	$	$/m2
00-Base Case	**3974.4**	**9.43**
01-Restructuring	*3974.4*	*9.43*
02-Reglazing	**3391.3**	**9.31**
03-Recladding	**3666.9**	**9.34**
04-Enclosing	**2872.3**	**10.55**
05-Insulating	**1848.1**	**9.44**
06-Adding	**2538.4**	**8.04**
07-Relocating	**4015.2**	**9.49**
08-Insetting	**2219.4**	**8.09**
09-Layering	**2593.7**	**10.54**
10-Extension	**4295.9**	**9.10**

		Co2e Emissions
Iteration Name	Annual Electricity Cost Per Area	Annual Gas Cost Per Area
	$/m2	$/m2
00-Base Case	**6.03**	**3.40**
01-Restructuring	*6.03*	*3.40*
02-Reglazing	**6.28**	**3.03**
03-Recladding	**6.07**	**3.27**
04-Enclosing	**7.88**	**2.67**
05-Insulating	**7.72**	**1.72**
06-Adding	**5.90**	**2.14**
07-Relocating	**5.98**	**3.51**
08-Insetting	**6.13**	**1.96**
09-Layering	**8.13**	**2.41**
10-Extension	**5.92**	**3.18**

		Comfort
Iteration Name	Annual Net CO2e Emissions	Annual Net CO2e Per Area
	kgCO2e/yr	kgCO2e/m2
00-Base Case	**24941.81**	**21.32**
01-Restructuring	*24941.81*	*21.32*
02-Reglazing	**22040.21**	**19.67**
03-Recladding	**23229.65**	**20.73**
04-Enclosing	**20533.83**	**19.11**
05-Insulating	**15329.53**	**14.27**
06-Adding	**17776.90**	**15.01**
07-Relocating	**24989.87**	**21.83**
08-Insetting	**16155.59**	**14.28**
09-Layering	**19351.28**	**18.01**
10-Extension	**27233.24**	**20.17**

Sefaira Energy Modeling Results

C.1.4 Energy Modeling Results: Percentage of Change from Base Case

	Air Handling	Air Handling
Iteration Name	AHU Design Airflow	AHU Minimum Outside Airflow
	L/s	L/s
01-Restructuring	*0%*	*0%*
02-Reglazing	4.27%	4.27%
03-Recladding	4.27%	4.27%
04-Enclosing	8.12%	8.12%
05-Insulating	8.12%	8.12%
06-Adding	-1.28%	-1.28%
07-Relocating	2.14%	2.14%
08-Insetting	3.42%	3.42%
09-Layering	8.12%	8.12%
10-Extension	-15.38%	-15.38%

	Cooling	Cooling
Iteration Name	Cooling Equipment Design Capacity	Total Peak Cooling Coil Load
	kW	kW
01-Restructuring	*0%*	*0%*
02-Reglazing	-50.33%	-50.33%
03-Recladding	-12.50%	-12.50%
04-Enclosing	-26.64%	-26.64%
05-Insulating	-4.28%	-4.28%
06-Adding	-28.95%	-28.95%
07-Relocating	-27.63%	-27.63%
08-Insetting	-35.86%	-35.86%
09-Layering	-41.12%	-41.12%
10-Extension	7.24%	7.24%

	Cooling	Cooling
Iteration Name	All Zones Peak Cooling Coil Load	Chilled Water Pumps
	kW	L/min
01-Restructuring	*0%*	*0%*
02-Reglazing	-33.88%	-44.82%
03-Recladding	3.95%	-19.82%
04-Enclosing	-10.86%	-27.49%
05-Insulating	12.17%	-1.99%
06-Adding	-11.84%	-27.39%
07-Relocating	-5.26%	-25.40%
08-Insetting	-19.41%	-34.46%
09-Layering	-25.33%	-35.66%
10-Extension	7.24%	4.38%

	Cooling	Heating
Iteration Name	Highest Peak Cooling Load by Zone	Heating Equipment Design Capacity
	W/m2	kW
01-Restructuring	0%	0%
02-Reglazing	-75.00%	4.02%
03-Recladding	1.56%	5.03%
04-Enclosing	-54.69%	12.21%
05-Insulating	-6.25%	39.94%
06-Adding	-17.19%	24.28%
07-Relocating	6.25%	-6.61%
08-Insetting	-43.75%	33.05%
09-Layering	-89.06%	15.23%
10-Extension	53.13%	-7.90%

	Heating	Heating
Iteration Name	Total Peak Heating Coil Load	All Zones Peak Heating Coil Load
	kW	kW
01-Restructuring	0%	0%
02-Reglazing	4.05%	14.19%
03-Recladding	5.07%	15.15%
04-Enclosing	12.16%	21.69%
05-Insulating	40.03%	47.21%
06-Adding	24.32%	32.38%
07-Relocating	-6.59%	4.15%
08-Insetting	33.11%	40.99%
09-Layering	15.37%	24.56%
10-Extension	-7.94%	-8.45%

	Heating	Heating
Iteration Name	Heating Water Pumps	Highest Peak Heating Load by Zone
	L/min	W/m2
01-Restructuring	0%	0%
02-Reglazing	9.64%	-1.25%
03-Recladding	9.30%	3.75%
04-Enclosing	14.81%	6.25%
05-Insulating	42.71%	25.00%
06-Adding	27.32%	22.50%
07-Relocating	-1.49%	0.00%
08-Insetting	36.85%	22.50%
09-Layering	20.90%	6.25%
10-Extension	-8.15%	-72.50%

	Heat Rejection	Heat Rejection
Iteration Name	Heat Rejection Design Capacity	Condenser Water Pumps
	kW	L/min
01-Restructuring	0%	0%
02-Reglazing	-25.00%	-52.97%
03-Recladding	-5.48%	-24.94%
04-Enclosing	-7.02%	-33.10%
05-Insulating	6.36%	-12.04%
06-Adding	-9.65%	-32.59%
07-Relocating	-18.20%	-37.49%
08-Insetting	-14.91%	-37.15%
09-Layering	-20.18%	-43.77%
10-Extension	53.73%	6.79%

	Energy Use	Energy Use
Iteration Name	HVAC Energy per Unit Area	Annual Cooling Energy per Unit Area
	kWh/m2/yr	kWh/m2/yr
01-Restructuring	0%	0%
02-Reglazing	7.61%	-81.76%
03-Recladding	2.95%	-22.01%
04-Enclosing	16.57%	-91.19%
05-Insulating	42.98%	-83.02%
06-Adding	34.04%	-30.82%
07-Relocating	-2.46%	-10.69%
08-Insetting	36.83%	-83.65%
09-Layering	21.30%	-170.44%
10-Extension	6.60%	18.24%

	Energy Use	Energy Use
Iteration Name	Annual Heating Energy per Unit Area	EUI
	kWh/m2/yr	kWh/m2/yr
01-Restructuring	0%	0%
02-Reglazing	10.92%	5.41%
03-Recladding	3.68%	2.10%
04-Enclosing	21.27%	2.30%
05-Insulating	49.33%	21.09%
06-Adding	36.90%	24.22%
07-Relocating	-3.23%	-1.75%
08-Insetting	42.22%	26.21%
09-Layering	28.92%	5.66%
10-Extension	6.35%	4.70%

	Energy Use	Energy Use
Iteration Name	Annual Electricity Demand	Annual Gas Use
	kWh	kWh
01-Restructuring	*0%*	*0%*
02-Reglazing	0.25%	14.67%
03-Recladding	3.59%	7.74%
04-Enclosing	-20.02%	27.73%
05-Insulating	-17.53%	53.50%
06-Adding	0.98%	36.13%
07-Relocating	2.93%	-1.03%
08-Insetting	1.76%	44.16%
09-Layering	-23.78%	34.74%
10-Extension	-13.30%	-8.09%

	Energy Use	Energy Costs
Iteration Name	Annual Net Electricity Use	Annual Energy Cost
	kWh	$
01-Restructuring	*0%*	*0%*
02-Reglazing	0.25%	5.44%
03-Recladding	3.59%	5.09%
04-Enclosing	-20.02%	-2.81%
05-Insulating	-17.53%	8.06%
06-Adding	0.98%	13.64%
07-Relocating	2.93%	1.51%
08-Insetting	1.76%	17.04%
09-Layering	-23.78%	-2.69%
10-Extension	-13.30%	-11.42%

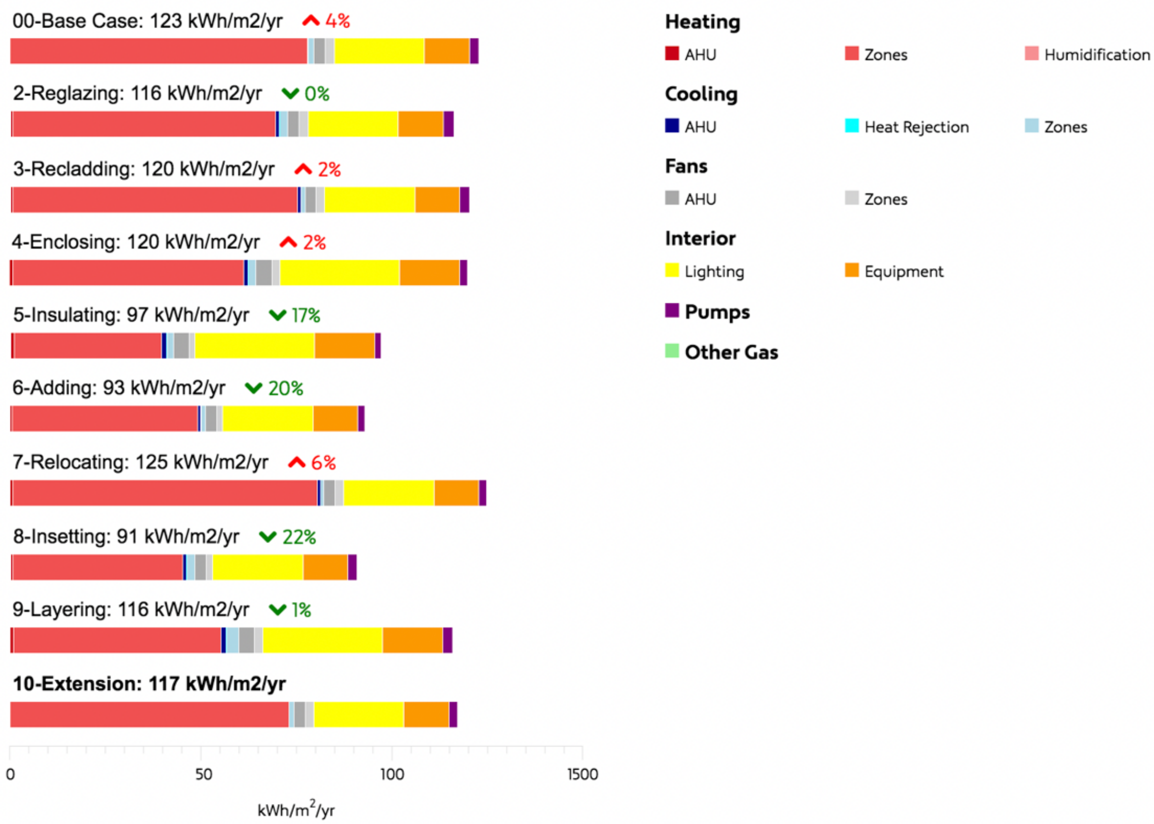
	Energy Costs	Energy Costs
Iteration Name	Annual Electricity Cost	Annual Gas Cost
	$	$
01-Restructuring	*0%*	*0%*
02-Reglazing	0.25%	14.67%
03-Recladding	3.59%	7.74%
04-Enclosing	-20.02%	27.73%
05-Insulating	-17.53%	53.50%
06-Adding	0.98%	36.13%
07-Relocating	2.93%	-1.03%
08-Insetting	1.76%	44.16%
09-Layering	-23.78%	34.74%
10-Extension	-13.30%	-8.09%

	Energy Costs	Energy Costs
Iteration Name	Annual Energy Cost Per Area	Annual Electricity Cost Per Area
	$/m2	$/m2
01-Restructuring	0%	0%
02-Reglazing	1.27%	-4.15%
03-Recladding	0.95%	-0.66%
04-Enclosing	-11.88%	-30.68%
05-Insulating	-0.11%	-28.03%
06-Adding	14.74%	2.16%
07-Relocating	-0.64%	0.83%
08-Insetting	14.21%	-1.66%
09-Layering	-11.77%	-34.83%
10-Extension	3.50%	1.82%

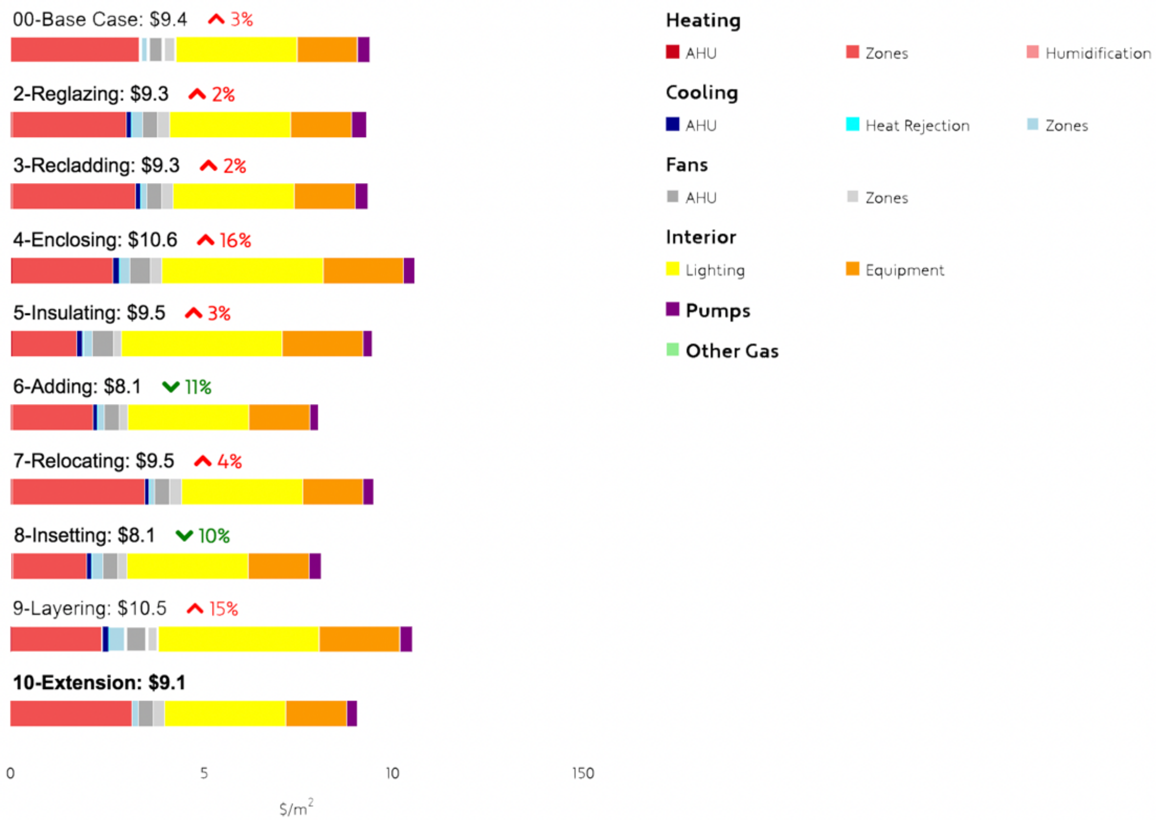
	Co2e Emissions	Co2e Emissions
Iteration Name	Annual Gas Cost Per Area	Annual Net CO2e Emissions
	$/m2	kgCO2e/yr
01-Restructuring	0%	0%
02-Reglazing	10.88%	11.63%
03-Recladding	3.82%	6.86%
04-Enclosing	21.47%	17.67%
05-Insulating	49.41%	38.54%
06-Adding	37.06%	28.73%
07-Relocating	-3.24%	-0.19%
08-Insetting	42.35%	35.23%
09-Layering	29.12%	22.41%
10-Extension	6.47%	-9.19%

	Comfort
Iteration Name	Annual Net CO2e Per Area
	kgCO2e/m2
01-Restructuring	0%
02-Reglazing	7.74%
03-Recladding	2.77%
04-Enclosing	10.37%
05-Insulating	33.07%
06-Adding	29.60%
07-Relocating	-2.39%
08-Insetting	33.02%
09-Layering	15.53%
10-Extension	5.39%

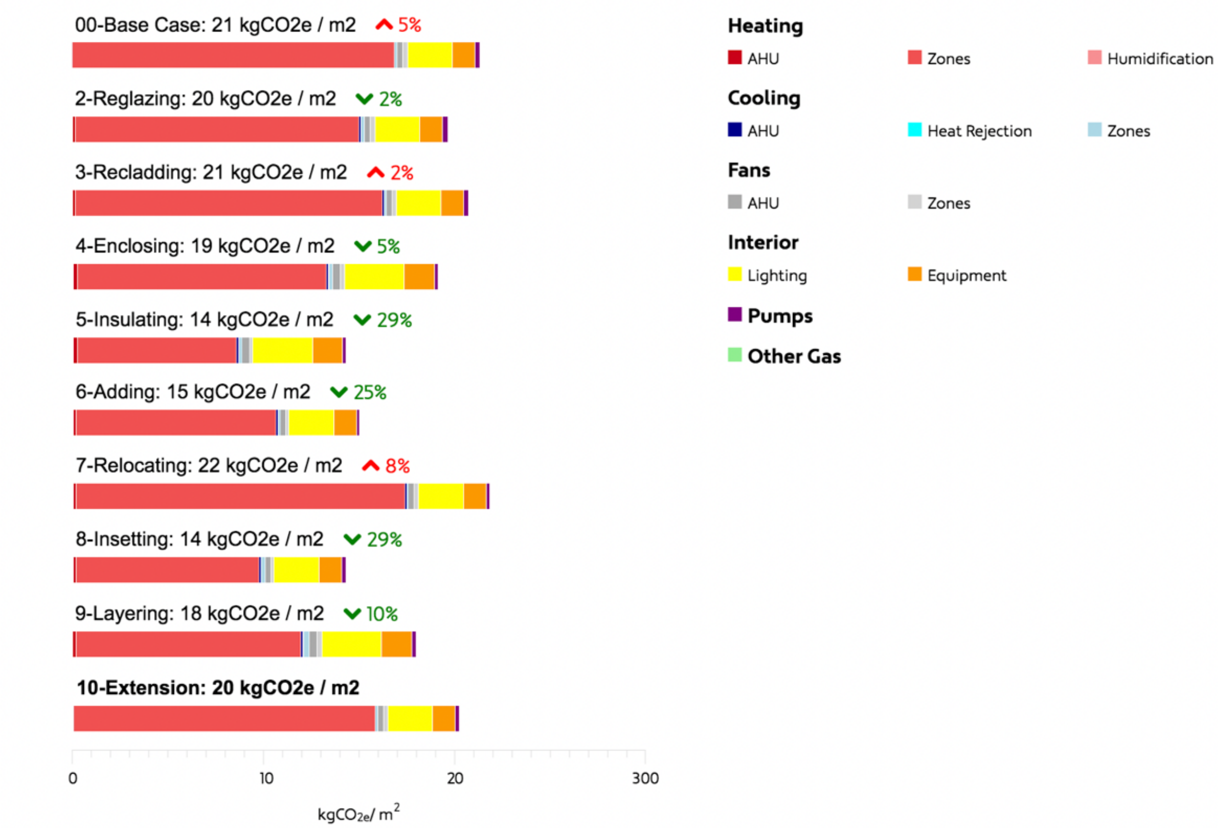
C.1.5 Energy Modeling Results: Annual Energy Use



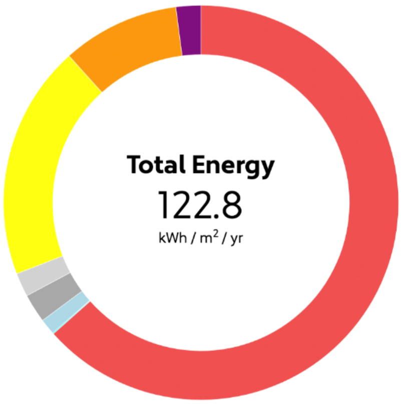
C.1.6 Energy Modeling Results: Annual Energy Cost



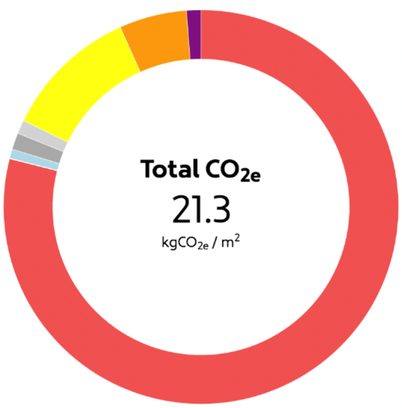
C.1.7 Energy Modeling Results: Annual CO2



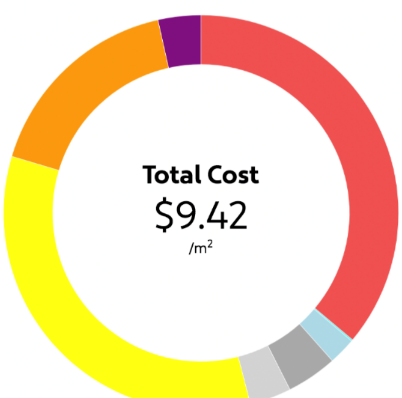
C.1.8 Energy Modeling Results: Visualizations (page **1** of **10**)



Segment	kWh / m^2 / yr	% of total use
Heating	**77.9**	**63 %**
AHU	0.0	0 %
Zones	77.9	63 %
Humidification	0.0	0 %
Cooling	**1.7**	**1 %**
AHU	0.0	0 %
Heat Rejection	0.1	0 %
Zones	1.6	1 %
Fans	**5.3**	**4 %**
AHU	2.9	2 %
Zones	2.4	2 %
Interior	**35.4**	**29 %**
Lighting	23.6	19 %
Equipment	11.8	10 %
Pumps	**2.5**	**2 %**



Segment	$kgCO_{2e}$ / m^2	% of total use
Heating	**16.8**	**79 %**
AHU	0.00	0 %
Zones	16.83	79 %
Humidification	0.00	0 %
Cooling	**0.2**	**1 %**
AHU	0.00	0 %
Heat Rejection	0.01	0 %
Zones	0.16	1 %
Fans	**0.5**	**2 %**
AHU	0.29	1 %
Zones	0.24	1 %
Interior	**3.5**	**16 %**
Lighting	2.36	11 %
Equipment	1.18	6 %
Pumps	**0.25**	**1 %**



Segment	\$ /m^2	% of total use
Heating	**\$3.40**	**36 %**
AHU	\$0.00	0 %
Zones	\$3.40	36 %
Humidification	\$0.00	0 %
Cooling	**\$0.22**	**2 %**
AHU	\$0.00	0 %
Heat Rejection	\$0.01	0 %
Zones	\$0.21	2 %
Fans	**\$0.71**	**8 %**
AHU	\$0.39	4 %
Zones	\$0.32	3 %
Interior	**\$4.76**	**51 %**
Lighting	\$3.17	34 %
Equipment	\$1.59	17 %
Pumps	**\$0.33**	**4 %**

00 – Base Case

C.1.9 Energy Modeling Results: Systems

COOLING		HEATING	
Cooling Equipment Design Capacity	26.0 W/m²	Heating Equipment Design Capacity	59.5 W/m²
Total Peak Coil Load	26.0 W/m²	Total Peak Coil Load	50.6 W/m²
AHU Peak Coil Load	0.0 W/m²	AHU Peak Coil Load	0.3 W/m²
All Zones Peak Coil Load	26.0 W/m²	All Zones Peak Coil Load	53.6 W/m²
Chilled Water Pumps	0.1 L/min·m²	Heating Water Pumps	0.1 L/min·m²
Collapse outputs		Collapse outputs	

AIR HANDLING		HEAT REJECTION	
Design Capacity	0.2 (L/m²·s)	Design Capacity for Heat Rejection System	39.0 W/m²
Min. Outside Air	0.2 (L/m²·s)	Condenser Water Pumps	0.1 L/min·m²

00 – Base Case

COOLING		HEATING	
Cooling Equipment Design Capacity	40.7 W/m²	Heating Equipment Design Capacity	59.6 W/m²
Total Peak Coil Load	40.7 W/m²	Total Peak Coil Load	50.6 W/m²
AHU Peak Coil Load	9.0 W/m²	AHU Peak Coil Load	2.9 W/m²
All Zones Peak Coil Load	36.3 W/m²	All Zones Peak Coil Load	48.0 W/m²
Chilled Water Pumps	0.1 L/min·m²	Heating Water Pumps	0.1 L/min·m²
Collapse outputs		Collapse outputs	

AIR HANDLING		HEAT REJECTION	
Design Capacity	0.2 (L/m²·s)	Design Capacity for Heat Rejection System	50.9 W/m²
Min. Outside Air	0.2 (L/m²·s)	Condenser Water Pumps	0.2 L/min·m²

02 – Reglazing

COOLING

Cooling Equipment Design Capacity	30.5 W/m^2
Total Peak Coil Load	30.5 W/m^2
AHU Peak Coil Load	9.0 W/m^2
All Zones Peak Coil Load	26.0 W/m^2
Chilled Water Pumps	0.1 L/min·m^2

Collapse outputs

HEATING

Heating Equipment Design Capacity	59.0 W/m^2
Total Peak Coil Load	50.1 W/m^2
AHU Peak Coil Load	2.9 W/m^2
All Zones Peak Coil Load	47.5 W/m^2
Heating Water Pumps	0.1 L/min·m^2

Collapse outputs

AIR HANDLING

Design Capacity	0.2 (L/m^2·s)
Min. Outside Air	0.2 (L/m^2·s)

HEAT REJECTION

Design Capacity for Heat Rejection System	42.9 W/m^2
Condenser Water Pumps	0.1 L/min·m^2

03 – Recladding

COOLING

Cooling Equipment Design Capacity	35.8 W/m^2
Total Peak Coil Load	35.8 W/m^2
AHU Peak Coil Load	9.0 W/m^2
All Zones Peak Coil Load	31.4 W/m^2
Chilled Water Pumps	0.1 L/min·m^2

Collapse outputs

HEATING

Heating Equipment Design Capacity	56.9 W/m^2
Total Peak Coil Load	48.4 W/m^2
AHU Peak Coil Load	2.9 W/m^2
All Zones Peak Coil Load	45.7 W/m^2
Heating Water Pumps	0.1 L/min·m^2

Collapse outputs

AIR HANDLING

Design Capacity	0.2 (L/m^2·s)
Min. Outside Air	0.2 (L/m^2·s)

HEAT REJECTION

Design Capacity for Heat Rejection System	45.4 W/m^2
Condenser Water Pumps	0.1 L/min·m^2

04 – Enclosing

COOLING		HEATING	
Cooling Equipment Design Capacity	29.5 W/m^2	Heating Equipment Design Capacity	38.9 W/m^2
Total Peak Coil Load	29.5 W/m^2	Total Peak Coil Load	33.0 W/m^2
AHU Peak Coil Load	9.1 W/m^2	AHU Peak Coil Load	2.9 W/m^2
All Zones Peak Coil Load	24.8 W/m^2	All Zones Peak Coil Load	30.8 W/m^2
Chilled Water Pumps	0.1 L/min·m^2	Heating Water Pumps	0.0 L/min·m^2
Collapse outputs		Collapse outputs	

AIR HANDLING		HEAT REJECTION	
Design Capacity	0.2 (L/m^2·s)	Design Capacity for Heat Rejection System	39.8 W/m^2
Min. Outside Air	0.2 (L/m^2·s)	Condenser Water Pumps	0.1 L/min·m^2

05 – Insulating

COOLING		HEATING	
Cooling Equipment Design Capacity	33.1 W/m^2	Heating Equipment Design Capacity	44.5 W/m^2
Total Peak Coil Load	33.1 W/m^2	Total Peak Coil Load	37.8 W/m^2
AHU Peak Coil Load	9.1 W/m^2	AHU Peak Coil Load	2.9 W/m^2
All Zones Peak Coil Load	28.7 W/m^2	All Zones Peak Coil Load	35.8 W/m^2
Chilled Water Pumps	0.1 L/min·m^2	Heating Water Pumps	0.1 L/min·m^2
Collapse outputs		Collapse outputs	

AIR HANDLING		HEAT REJECTION	
Design Capacity	0.2 (L/m^2·s)	Design Capacity for Heat Rejection System	42.2 W/m^2
Min. Outside Air	0.2 (L/m^2·s)	Condenser Water Pumps	0.1 L/min·m^2

06 – Adding

COOLING

Cooling Equipment Design Capacity	33.9 W/m²
Total Peak Coil Load	33.9 W/m²
AHU Peak Coil Load	9.0 W/m²
All Zones Peak Coil Load	27.9 W/m²
Chilled Water Pumps	0.1 L/min·m²

Collapse outputs

HEATING

Heating Equipment Design Capacity	64.8 W/m²
Total Peak Coil Load	55.1 W/m²
AHU Peak Coil Load	2.9 W/m²
All Zones Peak Coil Load	52.5 W/m²
Heating Water Pumps	0.1 L/min·m²

Collapse outputs

AIR HANDLING

Design Capacity	0.2 (L/m²·s)
Min. Outside Air	0.2 (L/m²·s)

HEAT REJECTION

Design Capacity for Heat Rejection System	47.1 W/m²
Condenser Water Pumps	0.1 L/min·m²

07 – Relocating

COOLING

Cooling Equipment Design Capacity	36.5 W/m²
Total Peak Coil Load	36.5 W/m²
AHU Peak Coil Load	9.1 W/m²
All Zones Peak Coil Load	32.1 W/m²
Chilled Water Pumps	0.1 L/min·m²

Collapse outputs

HEATING

Heating Equipment Design Capacity	41.2 W/m²
Total Peak Coil Load	35.0 W/m²
AHU Peak Coil Load	2.9 W/m²
All Zones Peak Coil Load	32.7 W/m²
Heating Water Pumps	0.0 L/min·m²

Collapse outputs

AIR HANDLING

Design Capacity	0.2 (L/m²·s)
Min. Outside Air	0.2 (L/m²·s)

HEAT REJECTION

Design Capacity for Heat Rejection System	46.3 W/m²
Condenser Water Pumps	0.1 L/min·m²

08 – Insetting

COOLING		HEATING	
Cooling Equipment Design Capacity	39.9 W/m²	Heating Equipment Design Capacity	54.9 W/m²
Total Peak Coil Load	39.9 W/m²	Total Peak Coil Load	46.6 W/m²
AHU Peak Coil Load	9.0 W/m²	AHU Peak Coil Load	2.9 W/m²
All Zones Peak Coil Load	35.5 W/m²	All Zones Peak Coil Load	44.0 W/m²
Chilled Water Pumps	0.1 L/min·m²	Heating Water Pumps	0.1 L/min·m²
Collapse outputs		Collapse outputs	

AIR HANDLING		HEAT REJECTION	
Design Capacity	0.2 (L/m²·s)	Design Capacity for Heat Rejection System	51.0 W/m²
Min. Outside Air	0.2 (L/m²·s)	Condenser Water Pumps	0.2 L/min·m²

09 – Layering

COOLING		HEATING	
Cooling Equipment Design Capacity	20.9 W/m²	Heating Equipment Design Capacity	55.6 W/m²
Total Peak Coil Load	20.9 W/m²	Total Peak Coil Load	47.3 W/m²
AHU Peak Coil Load	0.0 W/m²	AHU Peak Coil Load	0.3 W/m²
All Zones Peak Coil Load	20.9 W/m²	All Zones Peak Coil Load	50.3 W/m²
Chilled Water Pumps	0.1 L/min·m²	Heating Water Pumps	0.1 L/min·m²
Collapse outputs		Collapse outputs	

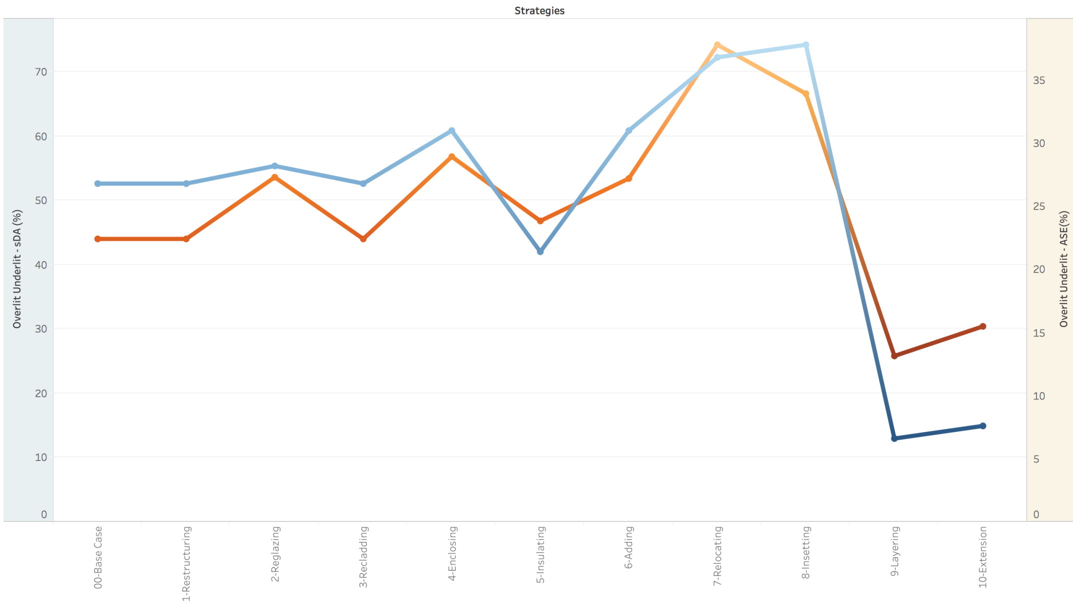
AIR HANDLING		HEAT REJECTION	
Design Capacity	0.2 (L/m²·s)	Design Capacity for Heat Rejection System	15.7 W/m²
Min. Outside Air	0.2 (L/m²·s)	Condenser Water Pumps	0.1 L/min·m²

10 – Extending

C.2: Daylighting Results

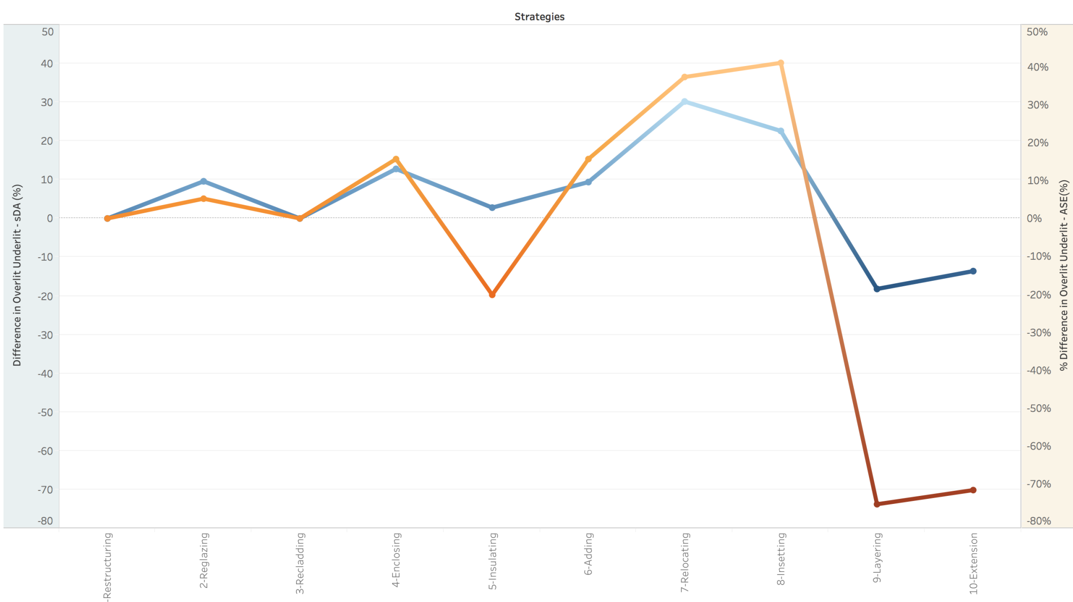
C.2.1 Daylighting - Overview of Results

Overlit Underlit - ASE (%)



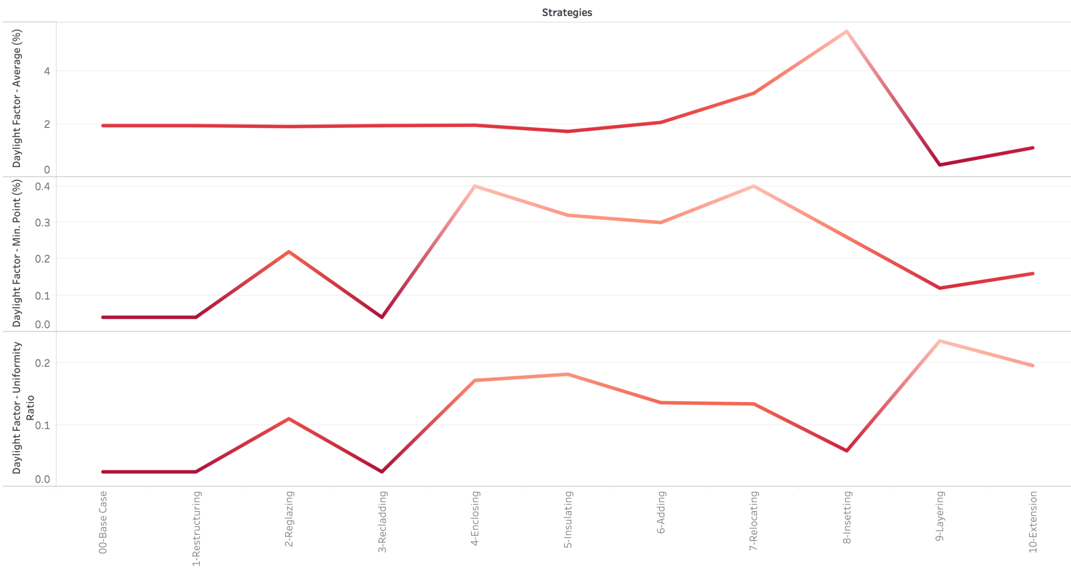
The trends of sum of Overlit Underlit - sDA (%) and sum of Overlit Underlit - ASE(%) for Strategies. For pane Sum of Overlit Underlit - ASE(%): Color shows sum of Overlit Underlit - ASE(%). For pane Sum of Overlit Underlit - sDA (%): Color shows sum of Overlit Underlit - sDA (%).

Overlit Underlit - ASE-sDA - % of Change



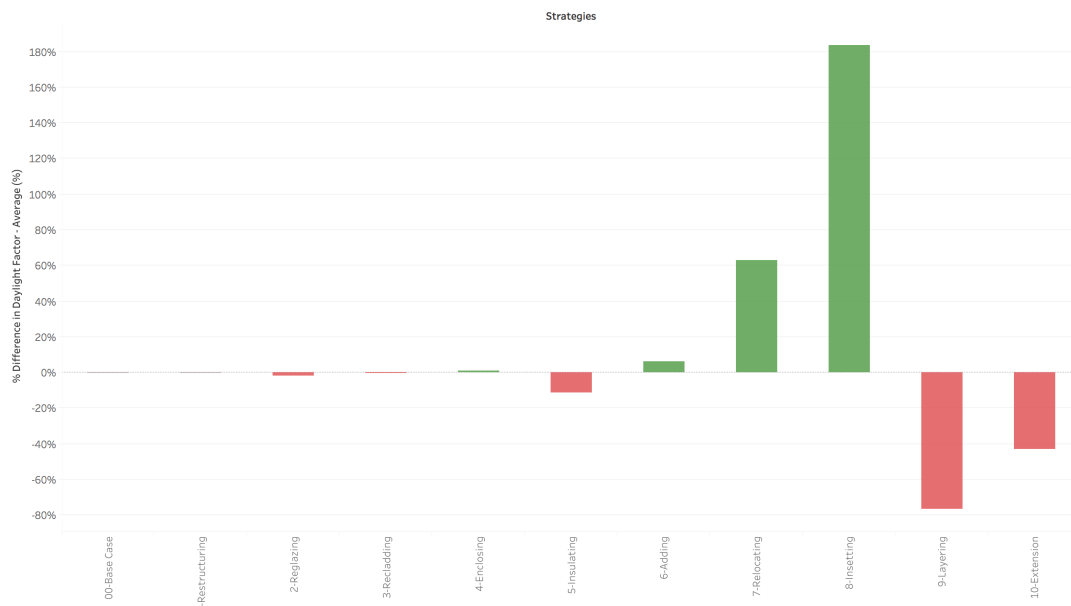
The trends of Difference in Overlit Underlit - sDA (%) and % Difference in Overlit Underlit - ASE(%) for Strategies. For pane % Difference in Overlit Underlit - ASE(%): Color shows sum of Overlit Underlit - ASE(%). For pane Difference in Overlit Underlit - sDA (%): Color shows sum of Overlit Underlit - sDA (%).

Daylight Factor



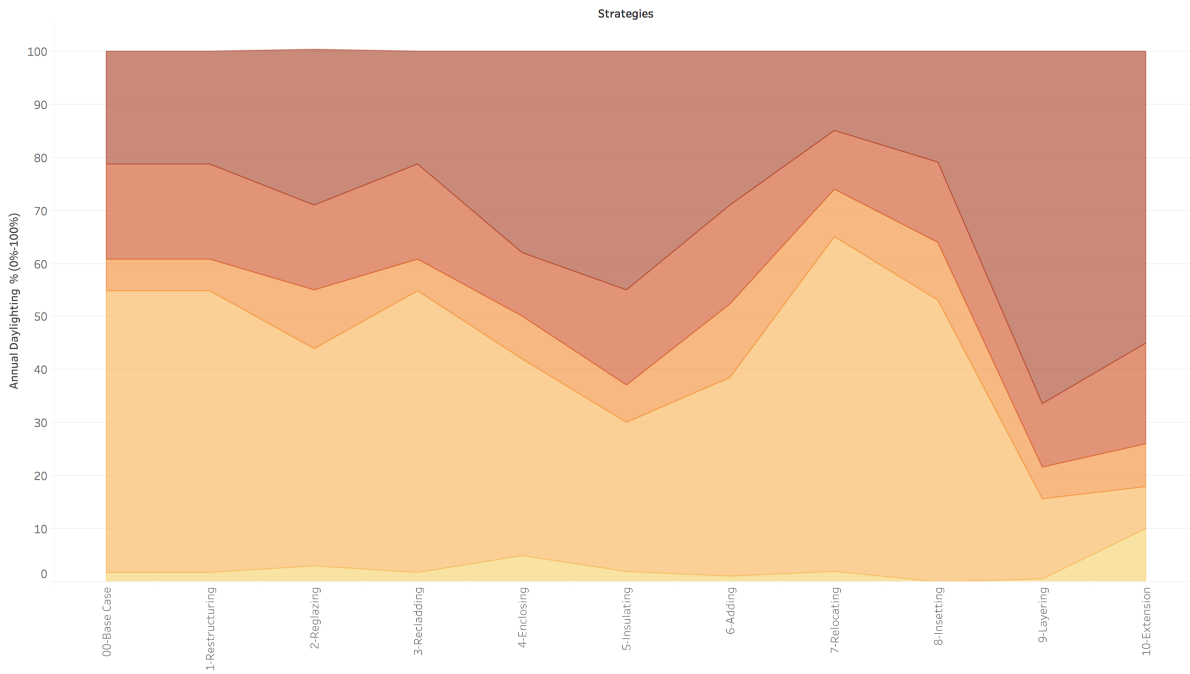
The trends of sum of Daylight Factor - Average (%), sum of Daylight Factor - Min. Point (%) and sum of Daylight Factor - Uniformity Ratio for Strategies. For pane Sum of Daylight Factor - Average (%): Color shows sum of Daylight Factor - Average (%). For pane Sum of Daylight Factor - Min. Point (%): Color shows sum of Daylight Factor - Min. Point (%). For pane Sum of Daylight Factor - Uniformity Ratio: Color shows sum of Daylight Factor - Uniformity Ratio.

Daylight Factor - % of Change



% Difference in Daylight Factor - Average (%) for each Strategies. Color shows details about Strategies.

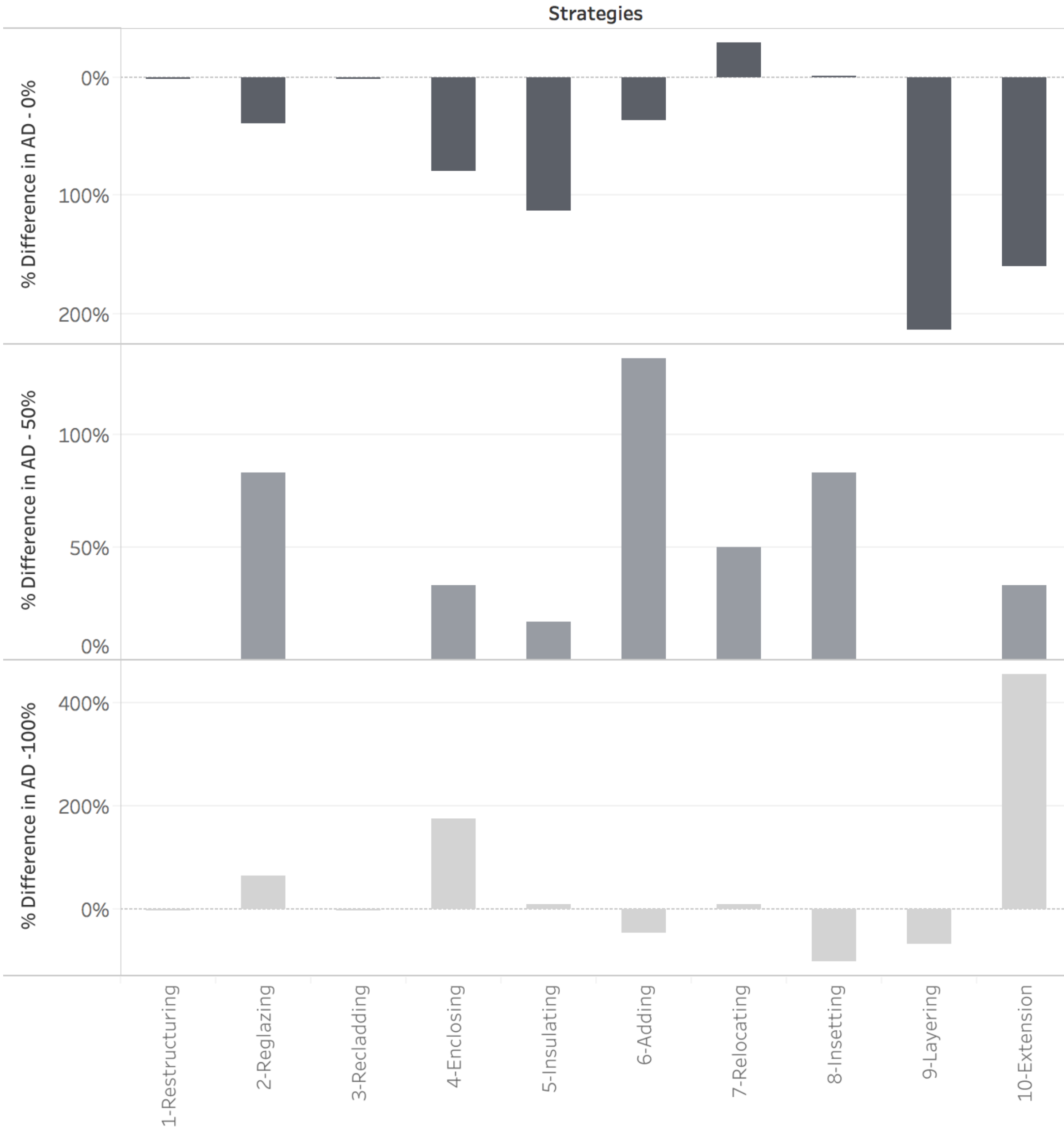
Annual Daylighting Range - Percentage of Area



Annual Daylight - 0%, Annual Daylight - 25%, Annual Daylight - 50%, Annual Daylight - 75% and Annual Daylight -100% for each Strategies. Color shows details about Annual Daylight - 0%, Annual Daylight - 25%, Annual Daylight - 50%, Annual Daylight - 75% and Annual Daylight -100%.

Measure Names
- Annual Daylight - 0%
- Annual Daylight - 25%
- Annual Daylight - 50%

Annual Daylight - % of Change



% Difference in Annual Daylight - 0% from the '00-Base Case' along Strategies, % Difference in Annual Daylight - 50% from the '00-Base Case' along Strategies and % Difference in Annual Daylight -100% from the '00-Base Case' along Strategies for each Strategies. Color shows details about % Difference in Annual Daylight - 0% from the '00-Base Case' along Strategies, % Difference in Annual Daylight - 50% from the '00-Base Case' along Strategies and % Difference in Annual Daylight -100% from the '00-Base Case' along Strategies.

Measure Names

- % Difference in Annual Daylight - 0% from the '00-Base Case' along Strategies
- % Difference in Annual Daylight - 50% from the '00-Base Case' along Strategies
- % Difference in Annual Daylight -100% from the '00-Base Case' along Strategies

C.2.2 Detailed Daylighting Results

	Overlit Underlit	Overlit Underlit	Daylight Factor
Iteration Name	sDA (%)	ASE(%)	Average (%)
1-Restructuring	*0%*	*0%*	*0%*
2-Reglazing	22%	-5%	-2%
3-Recladding	*0%*	*0%*	*0%*
4-Enclosing	29%	-16%	1%
5-Insulating	6%	20%	-11%
6-Adding	18%	-16%	6%
7-Relocating	69%	-37%	63%
8-Insetting	51%	-41%	183%
9-Layering	-41%	75%	-76%
10-Extension	-31%	72%	-43%

	Annual	Annual	Annual
Iteration Name	100%	75%	50%
1-Restructuring	*0%*	*0%*	*0%*
2-Reglazing	44%	-23%	50%
3-Recladding	*0%*	*0%*	*0%*
4-Enclosing	178%	-30%	33%
5-Insulating	11%	-47%	17%
6-Adding	-44%	-29%	133%
7-Relocating	11%	19%	50%
8-Insetting	-100%	0%	83%
9-Layering	-67%	-72%	0%
10-Extension	456%	-85%	33%

	Annual	Annual
Iteration Name	25%	0%
1-Restructuring	*0%*	*0%*
2-Reglazing	22%	-39%
3-Recladding	*0%*	*0%*
4-Enclosing	33%	-79%
5-Insulating	0%	-112%
6-Adding	-3%	-37%
7-Relocating	39%	29%
8-Insetting	17%	1%
9-Layering	33%	-213%
10-Extension	-6%	-159%

C.2.3 Daylighting Results: Percentage of Change

	Overlit Underlit	Overlit Underlit	Daylight Factor
Iteration Name	**sDA (%)**	**ASE(%)**	**Average (%)**
00-Existing	**44**	**26.8**	**1.944**
1-Restructuring	*44*	*26.8*	*1.944*
2-Reglazing	**53.6**	**28.2**	**1.91**
3-Recladding	*44*	*26.8*	*1.944*
4-Enclosing	**56.8**	**31**	**1.96**
5-Insulating	**46.8**	**21.4**	**1.726**
6-Adding	**53.4**	**31**	**2.066**
7-Relocating	**74.2**	**36.8**	**3.17**
8-Insetting	**66.6**	**37.8**	**5.51**
9-Layering	**25.8**	**6.6**	**0.458**
10-Extension	**30.4**	**7.6**	**1.106**

	Annual Daylight	Annual Daylight	Annual Daylight
Iteration Name	**100%**	**75%**	**50%**
00-Existing	**1.8**	**53**	**6**
1-Restructuring	*1.8*	*53*	*6*
2-Reglazing	**2.6**	**41**	**9**
3-Recladding	*1.8*	*53*	*6*
4-Enclosing	**5**	**37**	**8**
5-Insulating	**2**	**28**	**7**
6-Adding	**1**	**37.4**	**14**
7-Relocating	**2**	**63**	**9**
8-Insetting	**0**	**53**	**11**
9-Layering	**0.6**	**15**	**6**
10-Extension	**10**	**8**	**8**

	Annual Daylight	Annual Daylight
Iteration Name	**25%**	**0%**
00-Existing	**18**	**21.2**
1-Restructuring	*18*	*21.2*
2-Reglazing	**14**	**29.4**
3-Recladding	*18*	*21.2*
4-Enclosing	**12**	**38**
5-Insulating	**18**	**45**
6-Adding	**18.6**	**29**
7-Relocating	**11**	**15**
8-Insetting	**15**	**21**
9-Layering	**12**	**66.4**
10-Extension	**19**	**55**

C.2.4 Daylighting Results: Detailed Analysis

Daylight Factor	Zone 1	Zone 2	Zone 3	Zone 4	Zone 5	Average
Average (%)	1.67	2.1	2.1	2.1	1.75	1.944
Min. Point (%)	0.1	0	0	0	0.1	0.04
Uniformity Ratio	0.06	0	0	0	0.06	0.024

Overlit Underlit	Zone 1	Zone 2	Zone 3	Zone 4	Zone 5	Average
sDA (%)	40	46	46	46	42	44
ASE (%)	16	33	33	33	19	26.8

Annual (% at 300 lux min)	Zone 1	Zone 2	Zone 3	Zone 4	Zone 5	Average
100%	0	2	5	2	0	1.8
75%	50	60	50	50	55	53
50%	5	5	10	5	5	6
25%	20	20	15	15	20	18
0%	25	13	20	28	20	21.2

Daylighting Results–00-Existing

Daylight Factor	Zone 1	Zone 2	Zone 3	Zone 4	Zone 5	Average
Average (%)		1.16	1.56	1.93	2.99	1.91
Min. Point (%)	0.2	0.1	0.2	0.3	0.3	0.22
Uniformity Ratio	0.07	0.09	0.13	0.16	0.1	0.11

Overlit Underlit	Zone 1	Zone 2	Zone 3	Zone 4	Zone 5	Average
sDA (%)	66	63	43	33	63	53.6
ASE (%)	38	25	25	19	34	28.2

Annual (% at 300 lux min)	Zone 1	Zone 2	Zone 3	Zone 4	Zone 5	Average
100%	0	5	3	5	0	2.6
75%	60	20	45	20	60	41
50%	10	5	15	5	10	9
25%	20	10	10	10	20	14
0%	10	50	27	50	10	29.4

Daylighting Results–02-Reglazing

Daylight Factor	Zone 1	Zone 2	Zone 3	Zone 4	Zone 5	Average
Average (%)	0.74	3.55	2.93	1.85	0.73	1.96
Min. Point (%)	0.1	1.3	0.3	0.2	0.1	0.4
Uniformity Ratio	0.14	0.37	0.1	0.11	0.14	0.172

Overlit Underlit	Zone 1	Zone 2	Zone 3	Zone 4	Zone 5	Average
sDA (%)	28	100	75	50	31	56.8
ASE (%)	19	50	42	22	22	31

Annual (% at 300 lux min)	Zone 1	Zone 2	Zone 3	Zone 4	Zone 5	Average
100%	0	10	5	10	0	5
75%	40	20	65	20	40	37
50%	5	10	10	10	5	8
25%	10	15	10	15	10	12
0%	45	45	10	45	45	38

Daylighting Results–04-Enclosing

Daylight Factor	Zone 1	Zone 2	Zone 3	Zone 4	Zone 5	Average
Average (%)	0.75	2.83	2.9	1.87	0.28	1.726
Min. Point (%)	0	1	0.3	0.2	0.1	0.32
Uniformity Ratio	0	0.35	0.1	0.11	0.35	0.182

Overlit Underlit	Zone 1	Zone 2	Zone 3	Zone 4	Zone 5	Average
sDA (%)	14	100	67	44	9	46.8
ASE (%)	4	33	42	22	6	21.4

Annual (% at 300 lux min)	Zone 1	Zone 2	Zone 3	Zone 4	Zone 5	Average
100%	0	5	0	5	0	2
75%	10	35	50	35	10	28
50%	5	5	10	5	10	7
25%	10	45	15	10	10	18
0%	75	10	25	45	70	45

Daylighting Results–05-Insulating

Daylight Factor	Zone 1	Zone 2	Zone 3	Zone 4	Zone 5	Average
Average (%)	1.78	2.63	2.79	1.36	1.77	2.066
Min. Point (%)	0.1	0.9	0.2	0.2	0.1	0.3
Uniformity Ratio	0.06	0.34	0.07	0.15	0.06	0.136

Overlit Underlit	Zone 1	Zone 2	Zone 3	Zone 4	Zone 5	Average
sDA (%)	44	83	54	39	47	53.4
ASE (%)	25	50	33	22	25	31

Annual (% at 300 lux min)	Zone 1	Zone 2	Zone 3	Zone 4	Zone 5	Average
100%	0	3	0	2	0	1
75%	40	27	45	35	40	37.4
50%	15	10	15	15	15	14
25%	20	20	20	18	15	18.6
0%	25	40	20	30	30	29

Daylighting Results–06-Adding

Daylight Factor	Zone 1	Zone 2	Zone 3	Zone 4	Zone 5	Average
Average (%)	5.17	2.43	2.04	1.52	4.69	3.17
Min. Point (%)	0.5	0.5	0.2	0.2	0.6	0.4
Uniformity Ratio	0.1	0.21	0.1	0.13	0.13	0.134

Overlit Underlit	Zone 1	Zone 2	Zone 3	Zone 4	Zone 5	Average
sDA (%)	94	100	64	48	65	74.2
ASE (%)	63	25	36	24	36	36.8

Annual (% at 300 lux min)	Zone 1	Zone 2	Zone 3	Zone 4	Zone 5	Average
100%	0	5	0	0	5	2
75%	80	50	50	55	80	63
50%	5	10	10	10	10	9
25%	10	10	15	15	5	11
0%	5	25	25	20	0	15

Daylighting Results–07-Relocating

Daylight Factor	Zone 1	Zone 2	Zone 3	Zone 4	Zone 5	Average
Average (%)	1.79	8.07	7.81	8.07	1.81	5.51
Min. Point (%)	0.1	0.5	0	0.5	0.2	0.26
Uniformity Ratio	0.06	0.06	0	0.06	0.11	0.058

Overlit Underlit	Zone 1	Zone 2	Zone 3	Zone 4	Zone 5	Average
sDA (%)	50	83	67	83	50	66.6
ASE (%)	28	50	33	50	28	37.8

Annual (% at 300 lux min)	Zone 1	Zone 2	Zone 3	Zone 4	Zone 5	Average
100%	0	0	0	0	0	0
75%	50	60	45	60	50	53
50%	10	10	15	10	10	11
25%	15	10	30	10	10	15
0%	25	20	10	20	30	21

Daylighting Results–08-Insetting

Daylight Factor	Zone 1	Zone 2	Zone 3	Zone 4	Zone 5	Average
Average (%)	0.5	0.55	0.48	0.31	0.45	0.458
Min. Point (%)	0.1	0.3	0.1	0	0.1	0.12
Uniformity Ratio	0.2	0.55	0.21	0	0.22	0.236

Overlit Underlit	Zone 1	Zone 2	Zone 3	Zone 4	Zone 5	Average
sDA (%)	25	33	29	17	25	25.8
ASE (%)	6	17	4	0	6	6.6

Annual (% at 300 lux min)	Zone 1	Zone 2	Zone 3	Zone 4	Zone 5	Average
100%	0	3	0	0	0	0.6
75%	25	5	15	10	20	15
50%	5	5	10	5	5	6
25%	10	10	20	10	10	12
0%	60	77	55	75	65	66.4

Daylighting Results–09-Layering

Daylight Factor	Zone 1	Zone 2	Zone 3	Zone 4	Zone 5	Average
Average (%)	1.6	0.83	2.08	0.47	0.55	1.106
Min. Point (%)	0.1	0.4	0.1	0.1	0.1	0.16
Uniformity Ratio	0.06	0.48	0.05	0.21	0.18	0.196

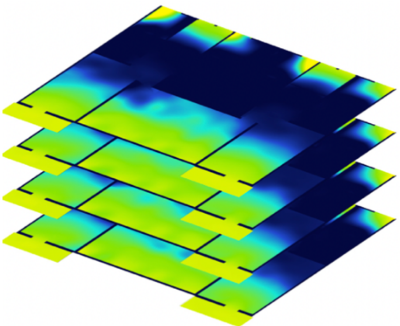
Overlit Underlit	Zone 1	Zone 2	Zone 3	Zone 4	Zone 5	Average
sDA (%)	42	22	50	22	16	30.4
ASE (%)	17	0	21	0	0	7.6

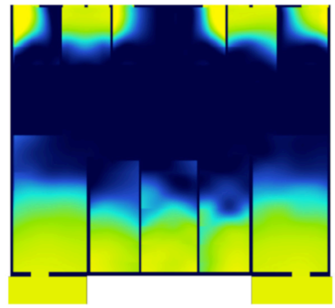
Annual (% at 300 lux min)	Zone 1	Zone 2	Zone 3	Zone 4	Zone 5	Average
100%	10	10	10	10	10	10
75%	10	5	5	10	10	8
50%	10	5	5	10	10	8
25%	20	20	15	20	20	19
0%	50	60	65	50	50	55

Daylighting Results–10-Extending

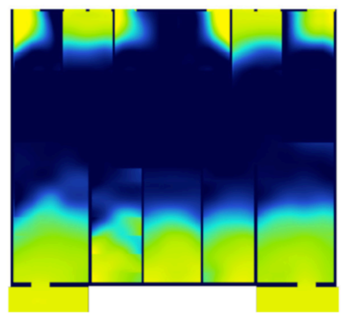
C.2.5 Daylighting Results: Visualizations (Illuminance)

Percentage of occupied hours where illuminance is at least 300 lux, measure at 0.85 meters above the floor plate - (pages **1** of **9**)

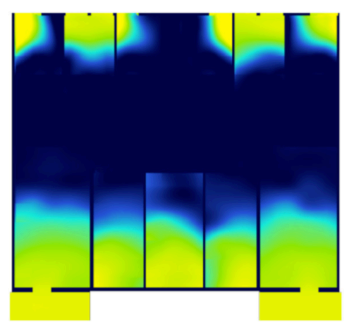




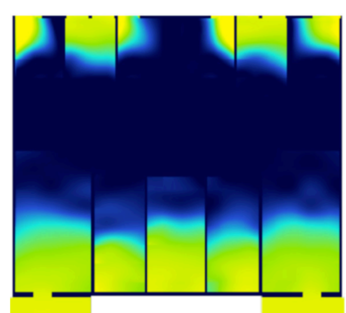
Level 4–Annual Daylight



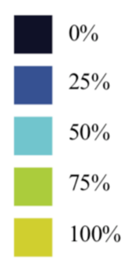
Level 3–Annual Daylight



Level 2–Annual Daylight



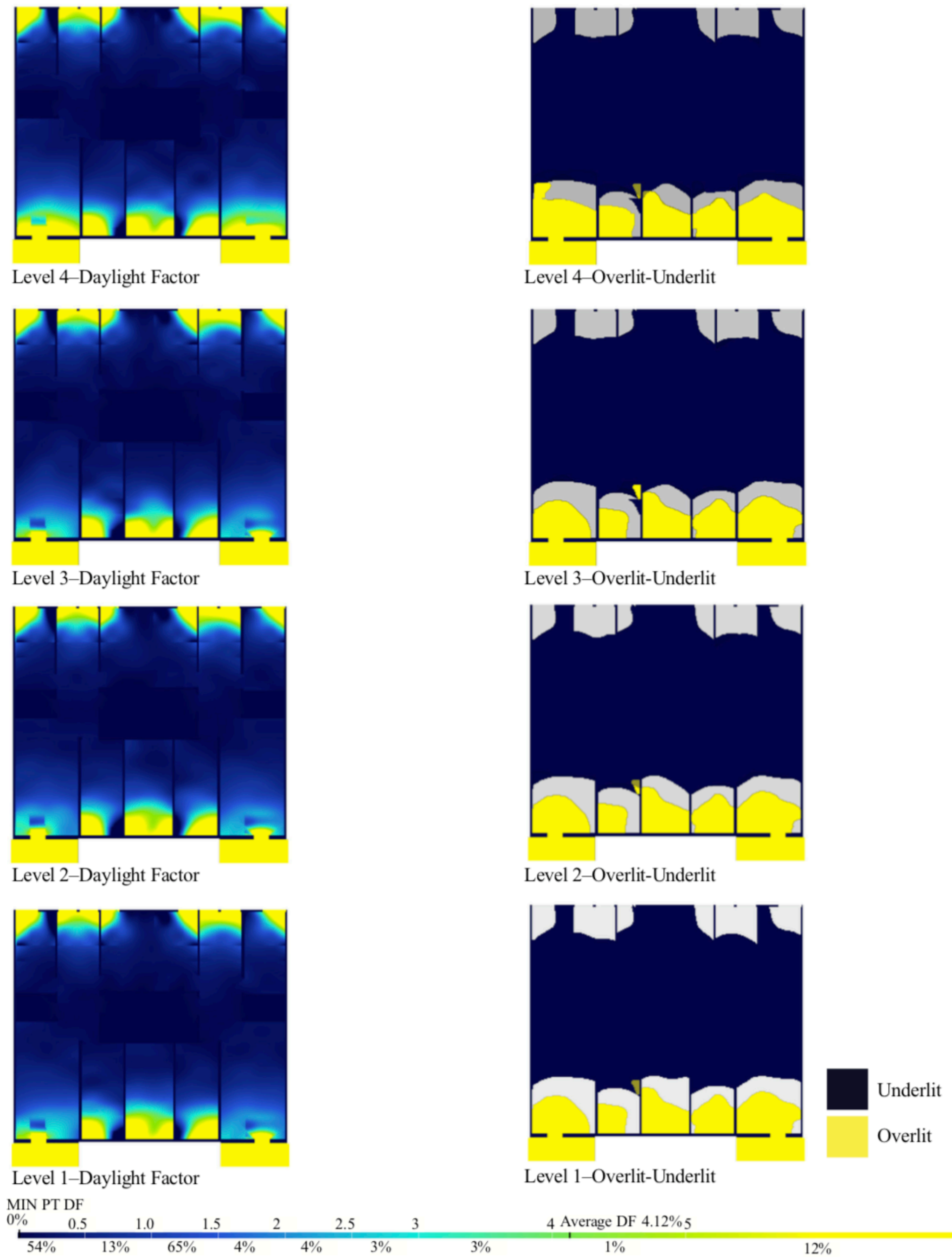
Level 1–Annual Daylight



00 - Existing

C.2.6 Daylighting Results: Visualizations (Daylighting Factor)

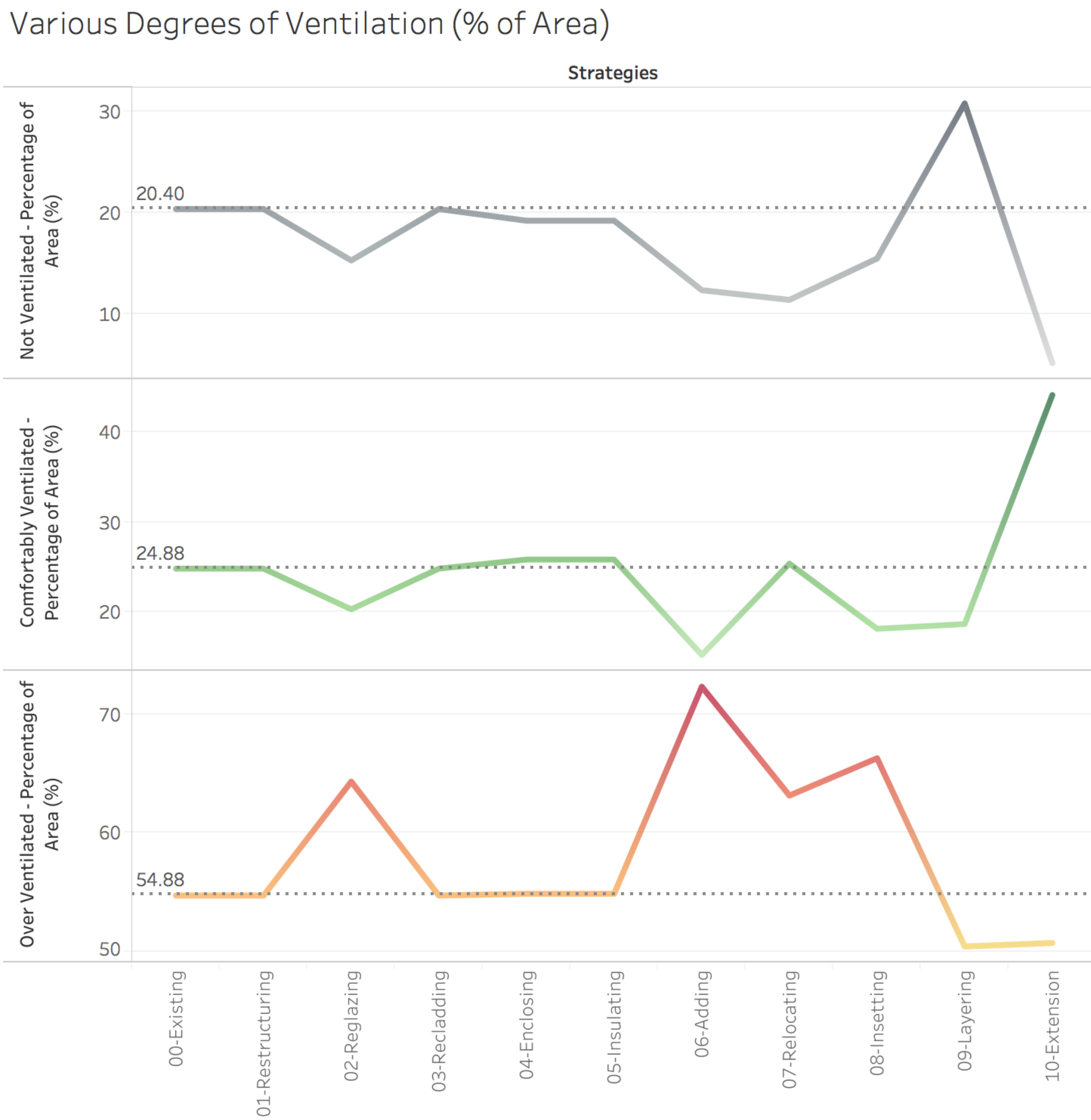
Percentage of Floor Area Where Daylight Factor (DF) is measured at 0.85 meters above the floor plate - (pages **1** of **9**)



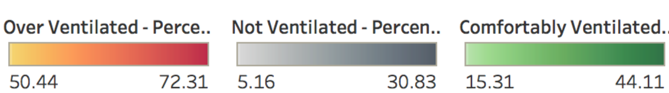
00 - Existing

C.3 Ventilation Results

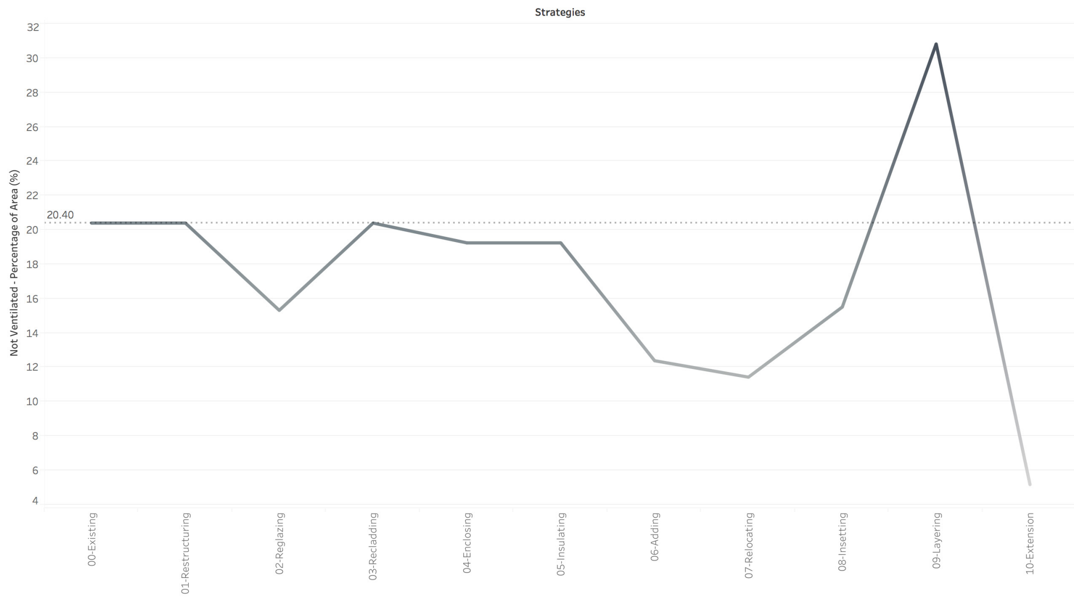
C.3.1 Ventilation – Overview of Results



The trends of sum of Not Ventilated - Percentage of Area (%), sum of Comfortably Ventilated - Percentage of Area (%) and sum of Over Ventilated - Percentage of Area (%) for Strategies. For pane Sum of Not Ventilated - Percentage of Area (%): Color shows sum of Not Ventilated - Percentage of Area (%). For pane Sum of Comfortably Ventilated - Percentage of Area (%): Color shows sum of Comfortably Ventilated - Percentage of Area (%). For pane Sum of Over Ventilated - Percentage of Area (%): Color shows sum of Over Ventilated - Percentage of Area (%).

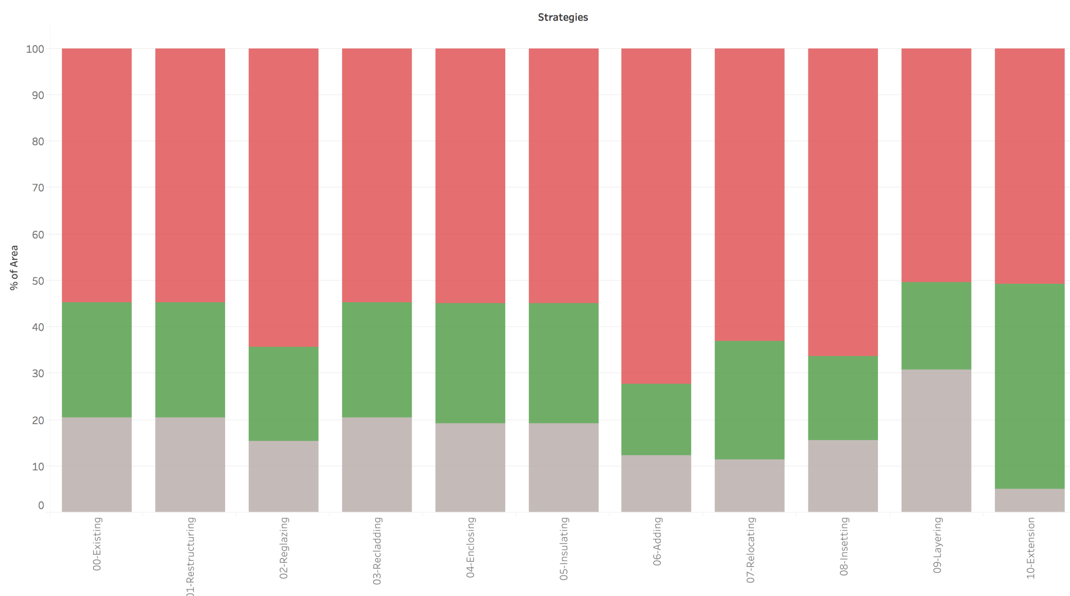


Percentage of Area Not Ventilated



The trend of sum of Not Ventilated - Percentage of Area (%) for Strategies. Color shows sum of Not Ventilated - Percentage of Area (%). The data is filtered on sum of Total Ventilated - Percentage of Area (%), which keeps all values.

Comparison of Ventilation

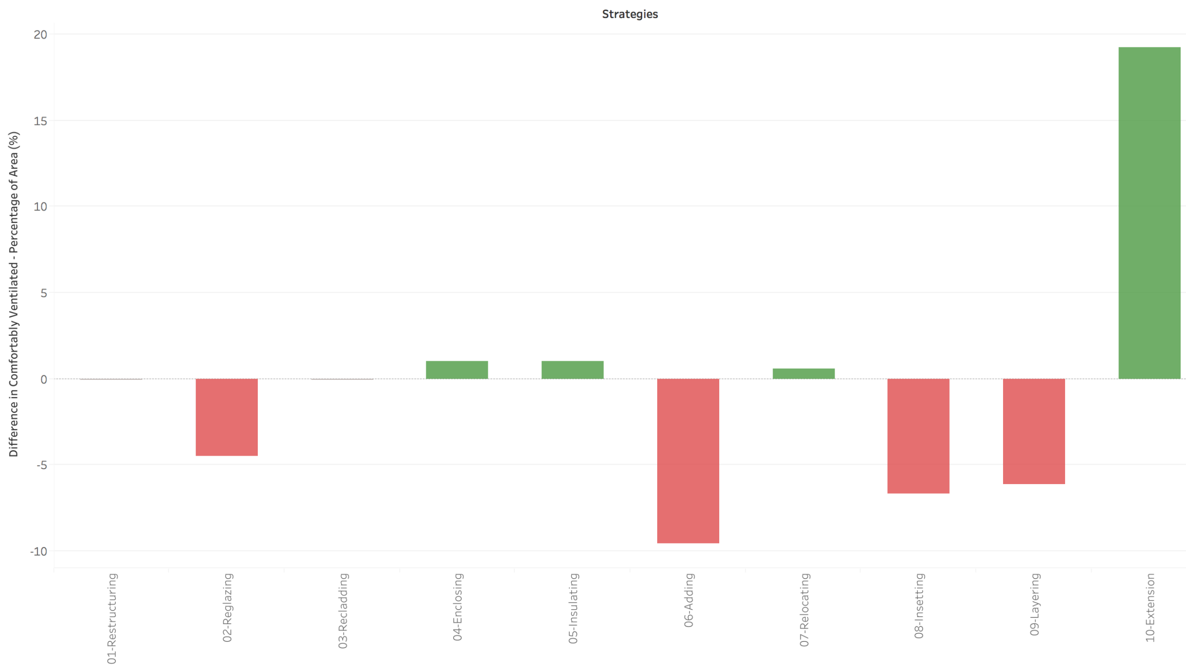


Over Ventilated - Percentage of Area (%), Comfortably Ventilated - Percentage of Area (%) and Not Ventilated - Percentage of Area (%) for each Strategies. Color shows details about Over Ventilated - Percentage of Area (%), Comfortably Ventilated - Percentage of Area (%) and Not Ventilated - Percentage of Area (%).

Measure Names

- Over Ventilated - Percentage of Area (%)
- Comfortably Ventilated - Percentage of Area (%)
- Not Ventilated - Percentage of Area (%)

Comparison - Comfortably Ventilated



Difference in Comfortably Ventilated - Percentage of Area (%) for each Strategies. Color shows details about Strategies. The data is filtered on sum of Total Ventilated - Percentage of Area (%), which keeps all values.

C.3.2 Input and Output Results - (pages **1-7** of **63**)

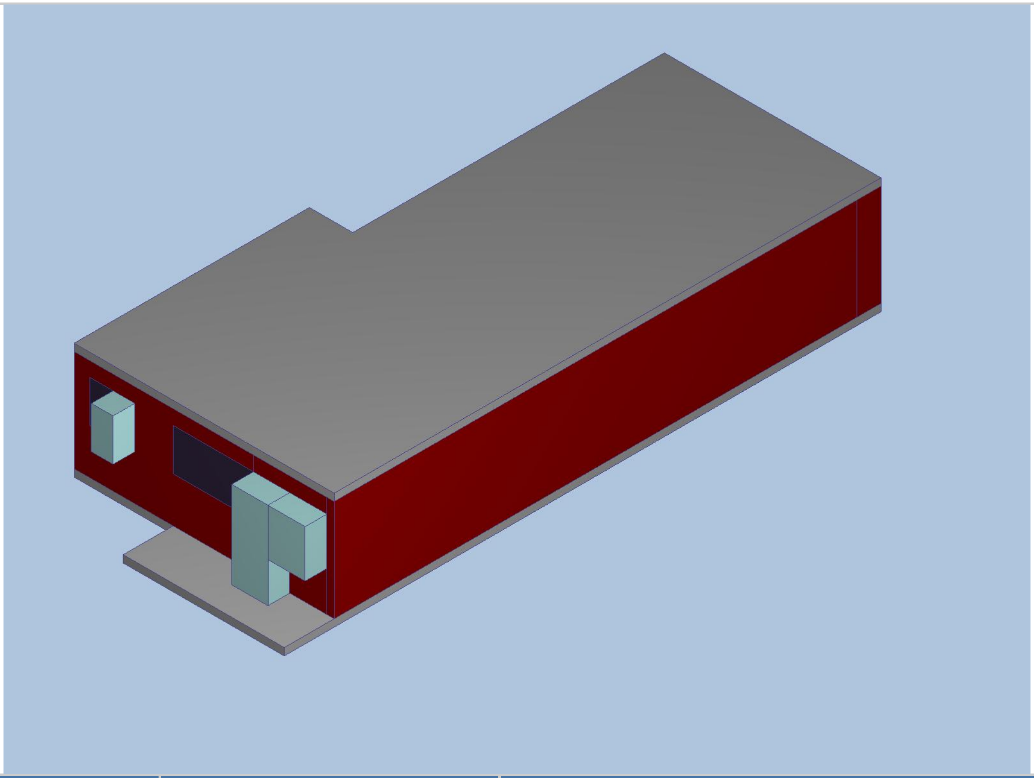
00-Existing.cfdst

00-Existing

Length units	mm
Coordinate system	Cartesian 3D

00-EXISTING

MATERIALS



NAME	ASSIGNED TO	PROPERTIES	
Concrete	Floor Floor	X-Direction	1.1 W/m-K
		Y-Direction	Same as X-dir.
		Z-Direction	Same as X-dir.
		Density	2306.0 kg/m3
		Specific heat	837.0 J/kg-K
		Emissivity	0.92
		Transmissivity	0.0
		Electrical resistivity	0.0 ohm-m
		Wall roughness	0.0 meter

Brick	Walls:Basic:P62-185-16Gb-152Mtl-16Gb Walls:Basic:EWE 34-Brick_90Brck-20Air-90CMU-13Gyp-40Std-13Gyp Walls:Basic:Generic-200mm Walls:Basic:EWE 34-Brick_90Brck-20Air-90CMU-13Gyp-40Std-13Gyp Walls:Basic:EWE 34-Brick_90Brck-20Air-90CMU-13Gyp-40Std-13Gyp Walls:Basic:EWE 34-Brick_90Brck-20Air-90CMU-13Gyp-40Std-13Gyp Walls:Basic:EWE 34-Brick_90Brck-20Air-90CMU-13Gyp-40Std-13Gyp Walls:Basic:EWE 34-Brick_90Brck-20Air-90CMU-13Gyp-40Std-13Gyp Walls:Basic:EWE 34-Brick_90Brck-20Air-90CMU-13Gyp-40Std-13Gyp Walls:Basic:Generic-200mm Walls:Basic:EWE 34-Brick_90Brck-20Air-90CMU-13Gyp-40Std-13Gyp Walls:Basic:EWE 34-Brick_90Brck-20Air-90CMU-13Gyp-40Std-13Gyp Walls:Basic:EWE 34-Brick_90Brck-20Air-90CMU-13Gyp-40Std-13Gyp Walls:Basic:EWE 34-Brick_90Brck-20Air-90CMU-13Gyp-40Std-13Gyp Walls:Basic:Glass Walls:Basic:P42-125-16Gb-92Mtl-16Gb Walls:Basic:P62-185-16Gb-152Mtl-16Gb	X-Direction Y-Direction Z-Direction Density Specific heat Emissivity Transmissivity Electrical resistivity Wall roughness	0.72 W/m-K Same as X-dir. Same as X-dir. 1920.0 kg/m3 835.0 J/kg-K 0.94 0.0 5000.0 ohm-m 0.0 meter
Glass	Walls:Basic:Glass Walls:Basic:Glass Walls:Basic:Glass Walls:Basic:Glass Walls:Basic:Glass	X-Direction Y-Direction Z-Direction Density Specific heat Emissivity Transmissivity Electrical resistivity Wall roughness	0.78 W/m-K Same as X-dir. Same as X-dir. 2700.0 kg/m3 840.0 J/kg-K 0.92 0.0 50000000.0 ohm-m 0.0 meter
Air	Walls:Basic:Glass-air Walls:Basic:Glass-air Walls:Basic:Glass-air Walls:Basic:Glass-air Walls:Basic:Glass-air Walls:Basic:Glass-air Volume	Density Viscosity Conductivity Specific heat Compressibility Emissivity Wall roughness Phase	Equation of State 1.817e-05 Pa-s 0.02563 W/m-K 1004.0 J/kg-K 1.4 1.0 0.0 meter Vapor Pressure

Gypsum-Board	Walls:Basic:P62-185-16Gb-152Mtl-16Gb Walls:Basic:P62-185-16Gb-152Mtl-16Gb Walls:Basic:P62-185-16Gb-152Mtl-16Gb Walls:Basic:P42-125-16Gb-92Mtl-16Gb	X-Direction Y-Direction Z-Direction Density Specific heat Emissivity Transmissivity Electrical resistivity Wall roughness	0.17 W/m-K Same as X-dir. Same as X-dir. 800.0 kg/m3 840.0 J/kg-K 0.8 0.0 1e+13 ohm-m 0.0 meter
Wood (Soft)	Walls:Basic:P62-185-16Gb-152Mtl-16Gb *CAD Volume* *CAD Volume* *CAD Volume* *CAD Volume* *CAD Volume* *CAD Volume* *CAD Volume* *CAD Volume* *CAD Volume* *CAD Volume* *CAD Volume* *CAD Volume*	X-Direction Y-Direction Z-Direction Density Specific heat Emissivity Transmissivity Electrical resistivity Wall roughness	0.12 W/m-K Same as X-dir. Same as X-dir. 510.0 kg/m3 1380.0 J/kg-K 0.8 0.0 3e+20 ohm-m 0.0 meter

BOUNDARY CONDITIONS

TYPE	ASSIGNED TO
Velocity Normal(15 km/h)	Surface:200 Surface:207 Surface:330
Temperature(20 Celsius)	Surface:200 Surface:207 Surface:330
Pressure(0 Pa Gage)	Surface:245 Surface:278 Surface:309

MESH

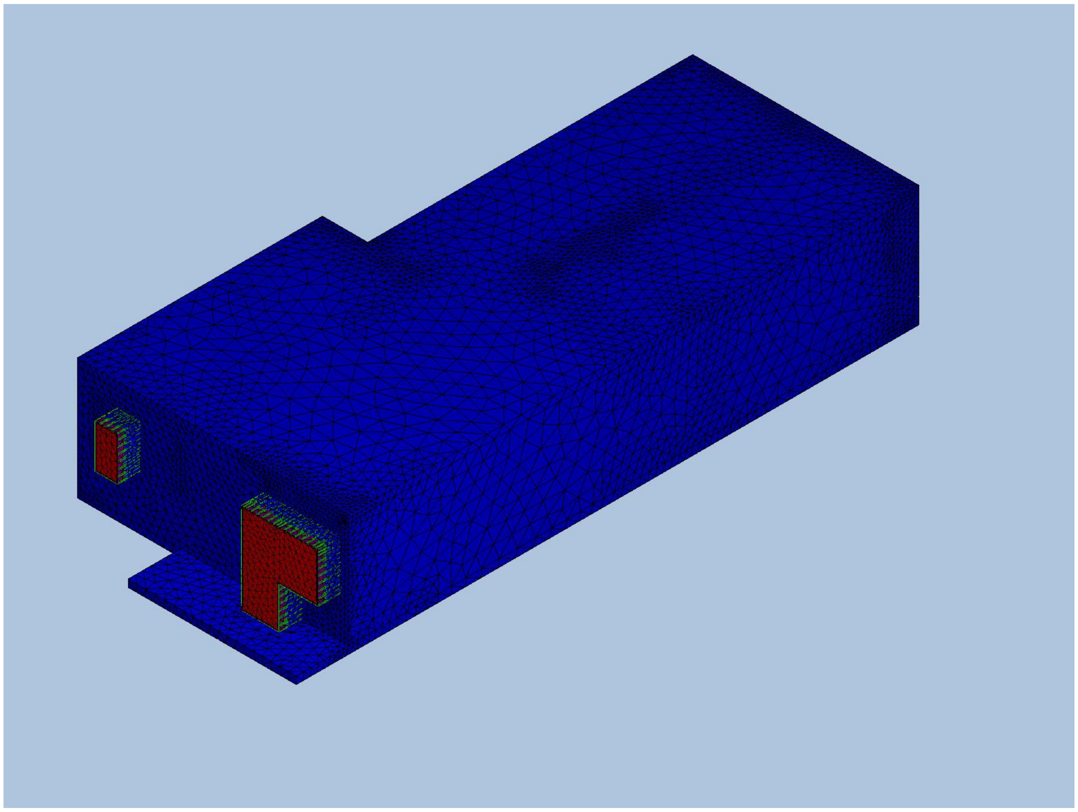
AUTOMATIC MESHING SETTINGS

Surface refinement	0
Gap refinement	0
Resolution factor	1.0
Edge growth rate	1.1
Minimum points on edge	2
Points on longest edge	10
Surface limiting aspect ratio	20

Mesh Enhancement Settings

Mesh enhancement	1
Enhancement blending	0
Number of layers	3
Layer factor	0.45
Layer gradation	1.05

Meshed Model



Number of Nodes	81074
Number of Elements	305698

PHYSICS

Flow	On
Compressibility	Incompressible
Heat Transfer	Off
Auto Forced Convection	Off
Gravity Components	0.0, 0.0, 0.0
Radiation	Off
Scalar	No scalar
Turbulence	On

SOLVER SETTINGS

Solution mode	Steady State
Solver computer	MyComputer
Intelligent solution control	On
Advection scheme	ADV 5
Turbulence model	k-epsilon

CONVERGENCE

Iterations run	1
Solve time	37 seconds
Solver version	19.0.20180307

Energy Balance

Mass Balance

	IN	OUT
Mass flow	21903.31 g/s	-18111.648 g/s
Volume flow	18181090000.0 mm^3/s	-15033726000.0 mm^3/s

RESULTS

Inlets and Outlets

inlet 1	inlet bulk pressure	73.1291 N/m^2
	inlet bulk temperature	20.0 C
	inlet mach number	0.0114027
	mass flow in	18515.0 g/s
	minimum x,y,z of opening	0.0
	node near minimum x,y,z of	15559.0
	reynolds number	527436.0
	surface id	207.0
	volume flow in	15368600000.0 mm^3/s
inlet 2	inlet bulk pressure	366.981 N/m^2
	inlet bulk temperature	20.0 C
	inlet mach number	0.0110267
	mass flow in	3388.31 g/s
	minimum x,y,z of opening	0.0
	node near minimum x,y,z of	366.0
	reynolds number	223906.0
	surface id	330.0
	total mass flow in	21903.4 g/s
	total vol. flow in	18181100000.0 mm^3/s
	volume flow in	2812490000.0 mm^3/s

outlet 1	mass flow out	-429.218 g/s
	minimum x,y,z of opening	0.0
	node near minimum x,y,z of	354.0
	outlet bulk pressure	-0.0 N/m^2
	outlet bulk temperature	20.0 C
	outlet mach number	0.00081221
	reynolds number	25406.2
	surface id	309.0
	volume flow out	-356276000.0 mm^3/s
outlet 2	mass flow out	-8993.56 g/s
	minimum x,y,z of opening	0.0
	node near minimum x,y,z of	333.0
	outlet bulk pressure	-0.0 N/m^2
	outlet bulk temperature	20.0 C
	outlet mach number	0.0198721
	reynolds number	574999.0
	surface id	278.0
	volume flow out	-7465180000.0 mm^3/s
outlet 3	mass flow out	-8688.87 g/s
	minimum x,y,z of opening	0.0
	node near minimum x,y,z of	303.0
	outlet bulk pressure	-0.0 N/m^2
	outlet bulk temperature	20.0 C
	outlet mach number	0.0194099
	reynolds number	555520.0
	surface id	245.0
	total mass flow out	-18111.6 g/s
	total vol. flow out	-15033700000.0 mm^3/s
	volume flow out	-7212270000.0 mm^3/s

Field Variable Results

VARIABLE	MAX	MIN
cond	0.0011 W/mm-K	2.563e-05 W/mm-K
dens	0.0027 g/mm^3	1.20473e-06 g/mm^3
econd	0.002563 W/mm-K	0.0 W/mm-K
emiss	1.0	0.0
evisc	0.00958352 g/mm-s	0.0 g/mm-s
gent	0.0316228 1/s	0.0316228 1/s
press	383.394 N/m^2	0.0 N/m^2
ptotl	421.164 N/m^2	0.0 N/m^2
scal1	0.0	0.0
seebeck	0.0 V/K	0.0 V/K
shgc	0.0	0.0
spech	1.38 J/g-K	0.835 J/g-K
temp	20.0 C	20.0 C
transmiss	0.0	0.0
turbd	408.457 mm^2/s^3	1.0 mm^2/s^3
turbk	21701.4 mm^2/s^2	0.0001 mm^2/s^2

ufactor	0.0	0.0
visc	1.817e-05 g/mm-s	0.0 g/mm-s
vx vel	2311.03 mm/s	-4672.56 mm/s
vy vel	16621.5 mm/s	-345.707 mm/s
vz vel	7045.51 mm/s	-7625.05 mm/s
wrough	0.0 mm	0.0 mm

Component Thermal Summary

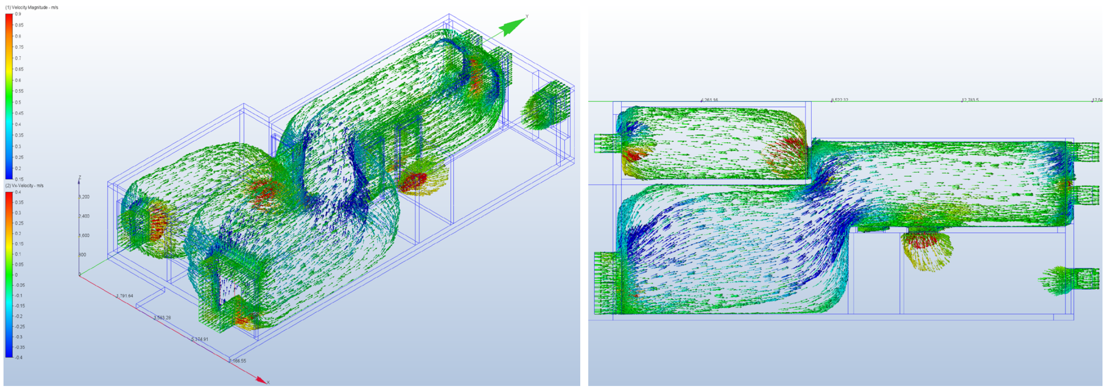
PART	MINIMUM TEMPERATURE	MAXIMUM TEMPERATURE	VOLUME AVERAGED TEMPERATURE
Walls:Basic:P62-185-16Gb-152Mtl-16Gb	20	20	20
CAD Volume	20	20	20
CAD Volume	20	20	20
Walls:Basic:P62-185-16Gb-152Mtl-16Gb	20	20	20
Floor	20	20	20
CAD Volume	20	20	20
CAD Volume	20	20	20
CAD Volume	20	20	20
CAD Volume	20	20	20
Walls:Basic:P62-185-16Gb-152Mtl-16Gb	20	20	20
CAD Volume	20	20	20
CAD Volume	20	20	20
CAD Volume	20	20	20
CAD Volume	20	20	20
CAD Volume	20	20	20
CAD Volume	20	20	20
Walls:Basic:EWE 34-Brick_90Brck-20Air-90CMU-13Gyp-40Std-13Gyp	20	20	20
Walls:Basic:Generic-200mm	20	20	20
Floor	20	20	20
Walls:Basic:Glass-air	20	20	20
Walls:Basic:Glass-air	20	20	20
Walls:Basic:EWE 34-Brick_90Brck-20Air-90CMU-13Gyp-40Std-13Gyp	20	20	20
Walls:Basic:EWE 34-Brick_90Brck-20Air-90CMU-13Gyp-40Std-13Gyp	20	20	20
Walls:Basic:EWE 34-Brick_90Brck-20Air-90CMU-13Gyp-40Std-13Gyp	20	20	20
Walls:Basic:Glass	20	20	20
Walls:Basic:Glass-air	20	20	20
Walls:Basic:EWE 34-Brick_90Brck-20Air-90CMU-13Gyp-40Std-13Gyp	20	20	20
Walls:Basic:EWE 34-Brick_90Brck-20Air-90CMU-13Gyp-40Std-13Gyp	20	20	20
Walls:Basic:Glass	20	20	20
Walls:Basic:Glass-air	20	20	20
Walls:Basic:EWE 34-Brick_90Brck-20Air-90CMU-13Gyp-40Std-13Gyp	20	20	20
Walls:Basic:Generic-200mm	20	20	20
Walls:Basic:Glass	20	20	20
Walls:Basic:Glass-air	20	20	20

Walls:Basic:EWE 34-Brick_90Brck-20Air-90CMU-13Gyp-40Std-13Gyp	20	20	20
Walls:Basic:EWE 34-Brick_90Brck-20Air-90CMU-13Gyp-40Std-13Gyp	20	20	20
Walls:Basic:EWE 34-Brick_90Brck-20Air-90CMU-13Gyp-40Std-13Gyp	20	20	20
Walls:Basic:Glass-air	20	20	20
Walls:Basic:EWE 34-Brick_90Brck-20Air-90CMU-13Gyp-40Std-13Gyp	20	20	20
Walls:Basic:Glass	20	20	20
Walls:Basic:Glass	20	20	20
Walls:Basic:Glass	20	20	20
Walls:Basic:P42-125-16Gb-92Mtl-16Gb	20	20	20
Walls:Basic:P62-185-16Gb-152Mtl-16Gb	20	20	20
Walls:Basic:P62-185-16Gb-152Mtl-16Gb	20	20	20
Walls:Basic:P42-125-16Gb-92Mtl-16Gb	20	20	20
Walls:Basic:P62-185-16Gb-152Mtl-16Gb	20	20	20
Volume	20	20	20

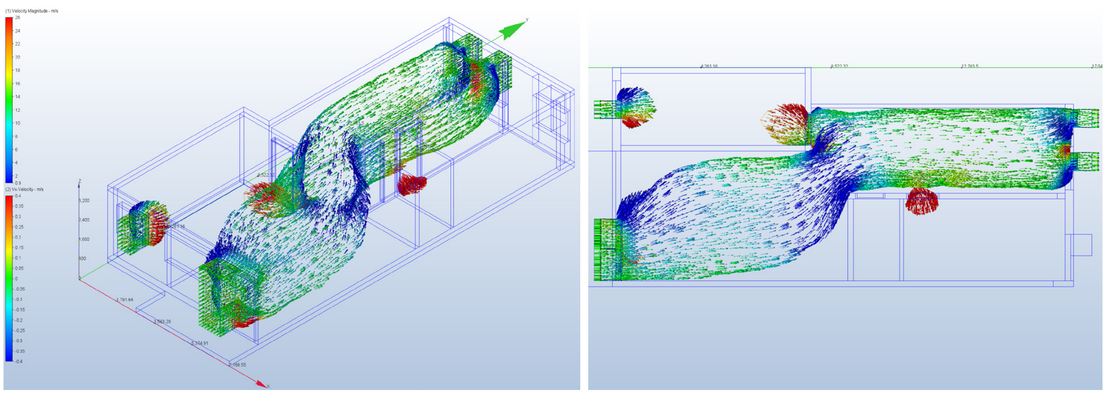
Fluid Forces on Walls

pressx	27451000.0 microNewtons
pressy	264290000.0 microNewtons
pressz	-215410.0 microNewtons
shearx	-1194800.0 microNewtons
sheary	30582000.0 microNewtons
shearz	-148260.0 microNewtons

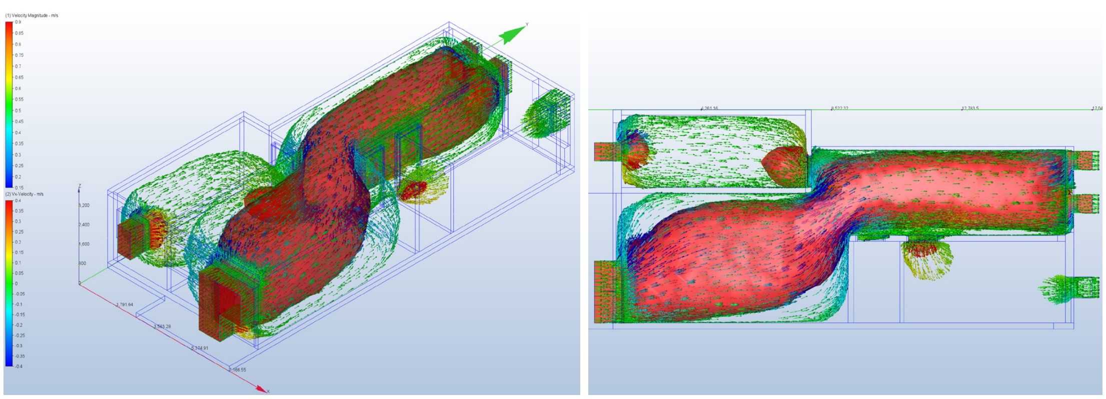
C.3.3 CFD Ventilation Results: Comfortably Ventilated, Over-Ventilated



CFD Ventilation Results–09-Layering–All Ventilated (0.15–0.9 m/s)

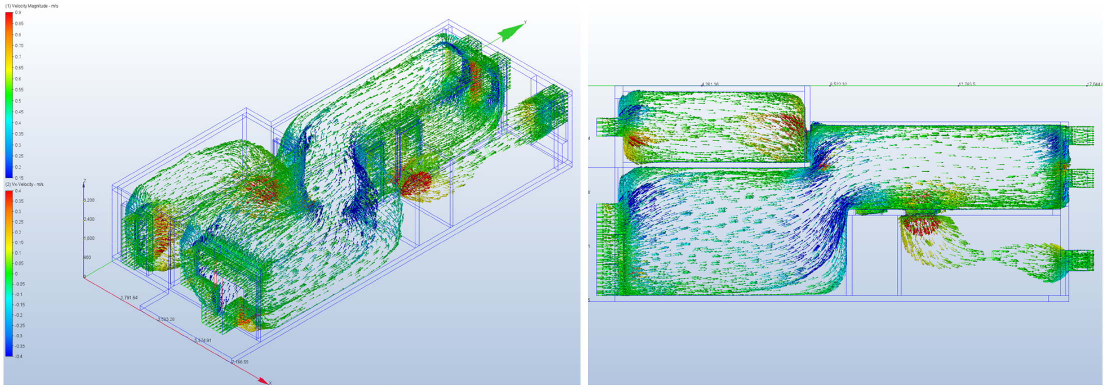


CFD Ventilation Results–09-Layering–Over Ventilated (1.0–26 m/s)

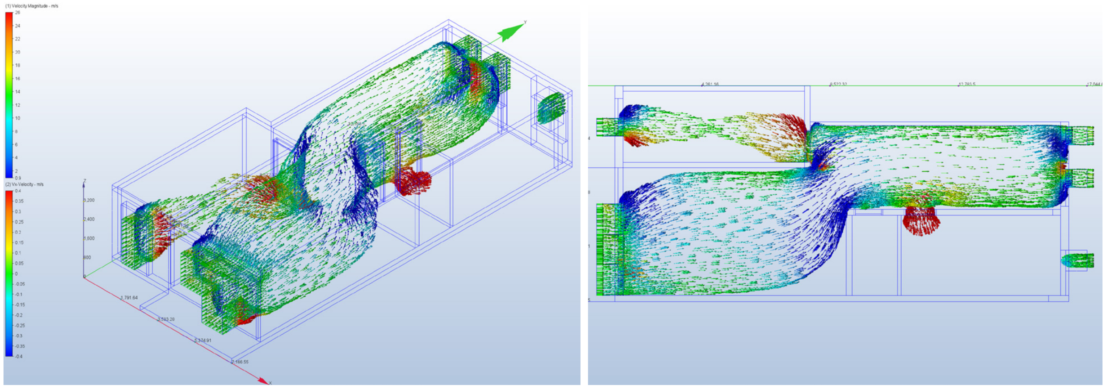


CFD Ventilation Results–09-Layering–Separating Non-Ventilated, Over-Ventilated and Comfortably Ventilated

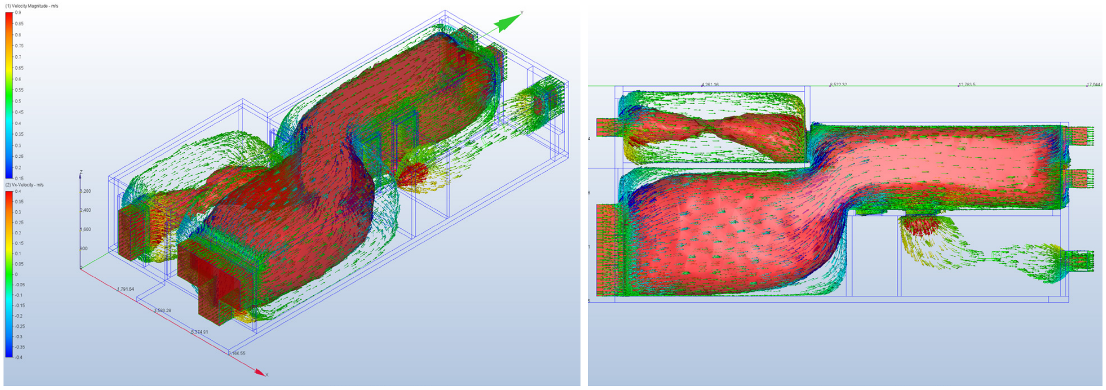
00 - Existing



CFD Ventilation Results–02-Reglazing–All Ventilated (0.15–0.9 m/s)

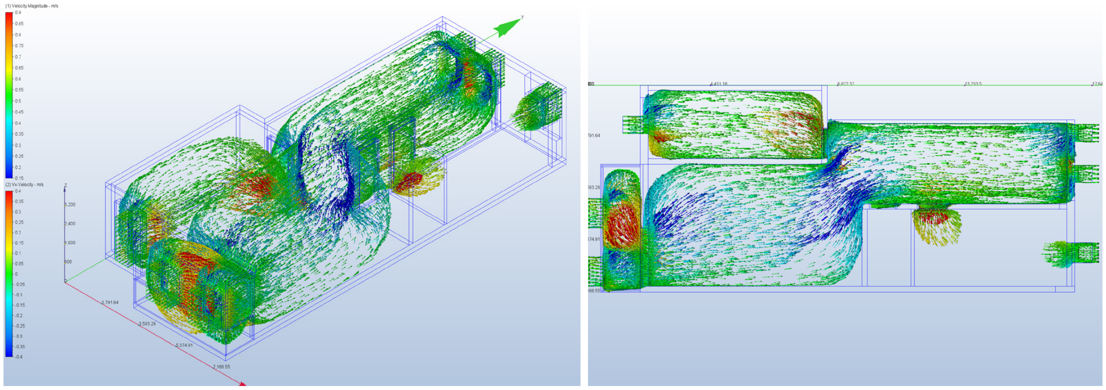


CFD Ventilation Results–02-Reglazing–Over Ventilated (1.0–26 m/s)

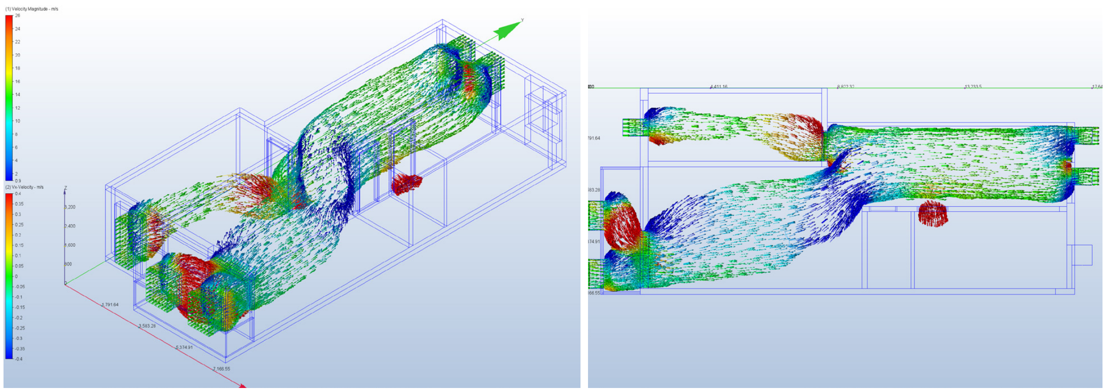


CFD Ventilation Results–02-Reglazing–Separating Non-Ventilated, Over-Ventilated and Comfortably Ventilated

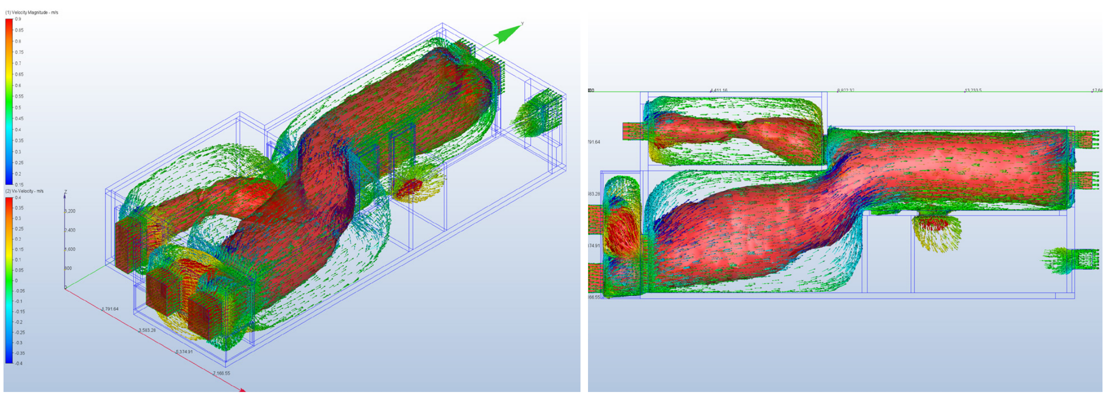
02 – Reglazing



CFD Ventilation Results–04-Enclosing–All Ventilated (0.15–0.9 m/s)

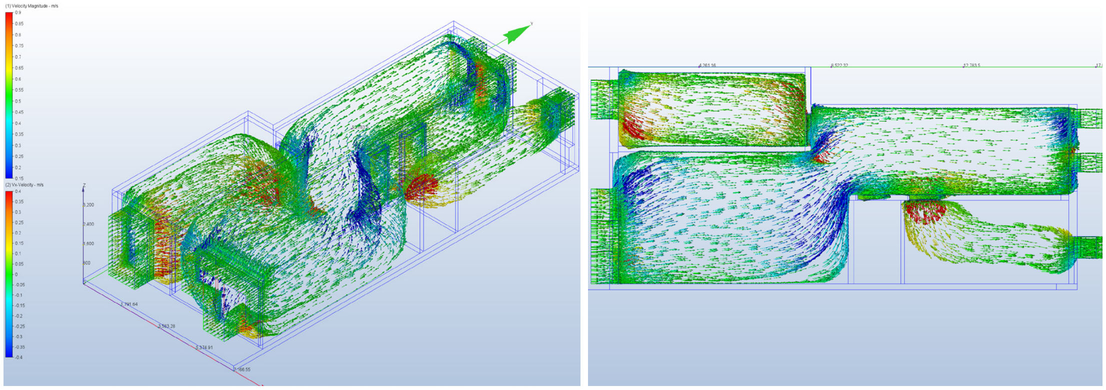


CFD Ventilation Results–04-Enclosing–Over Ventilated (1.0–26 m/s)

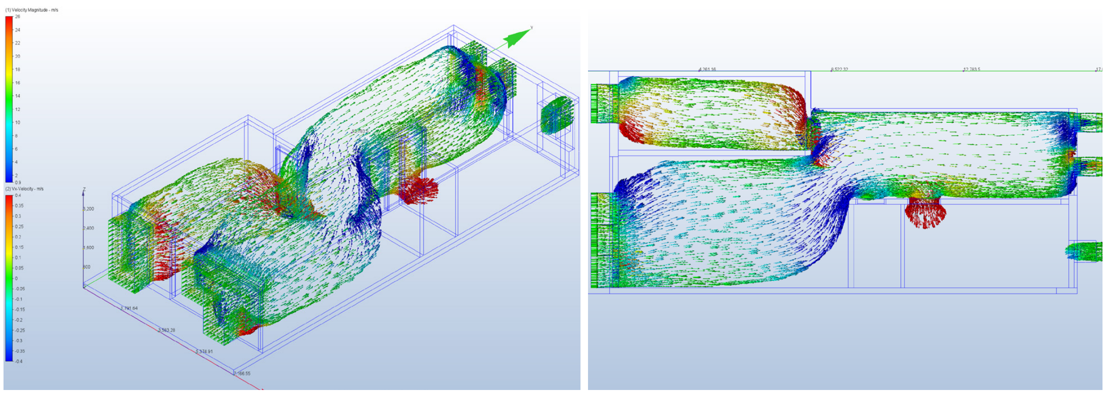


CFD Ventilation Results–04-Enclosing–Separating Non-Ventilated, Over-Ventilated and Comfortably Ventilated

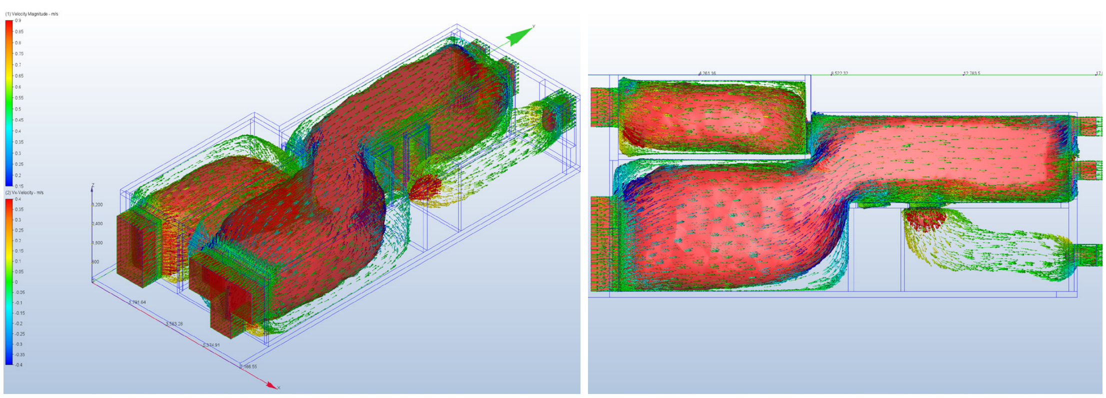
04 – Enclosing



CFD Ventilation Results–06-Adding–All Ventilated (0.15–0.9 m/s)

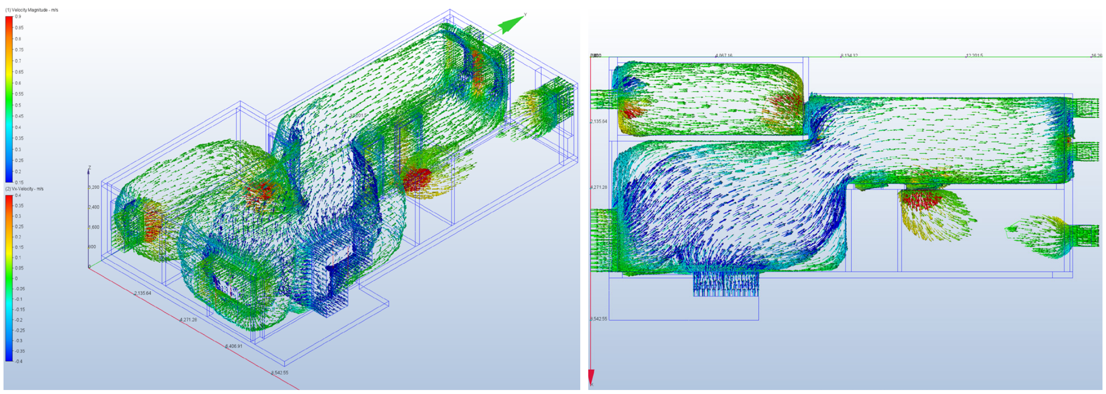


CFD Ventilation Results–06-Adding–Over Ventilated (1.0–26 m/s)

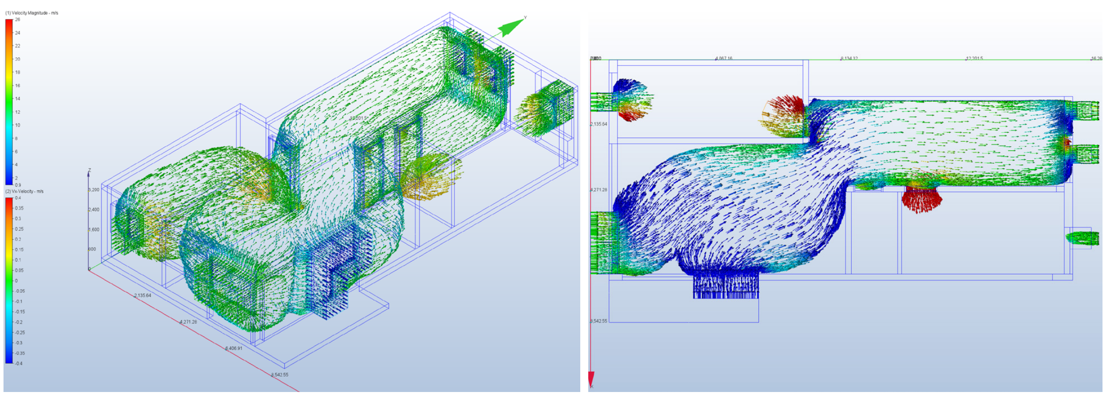


CFD Ventilation Results–06-Adding–Separating Non-Ventilated, Over-Ventilated and Comfortably Ventilated

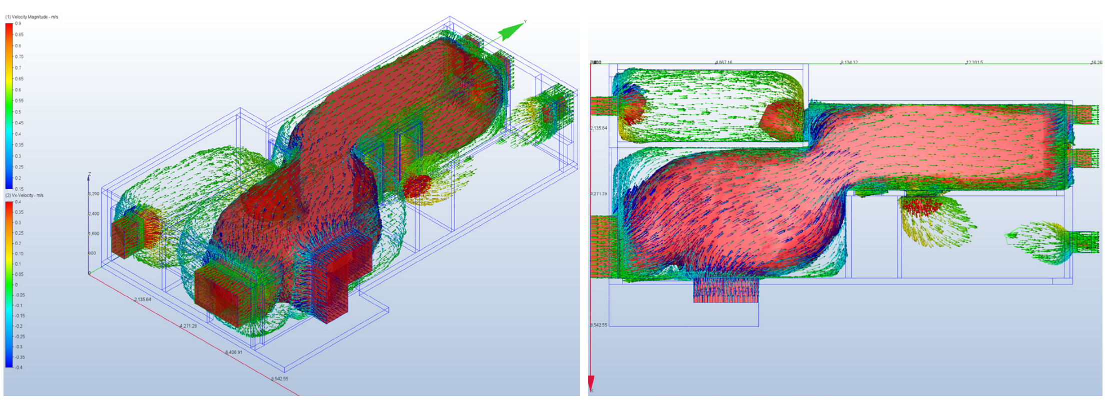
06 – Adding



CFD Ventilation Results–07-Relocating–All Ventilated (0.15–0.9 m/s)

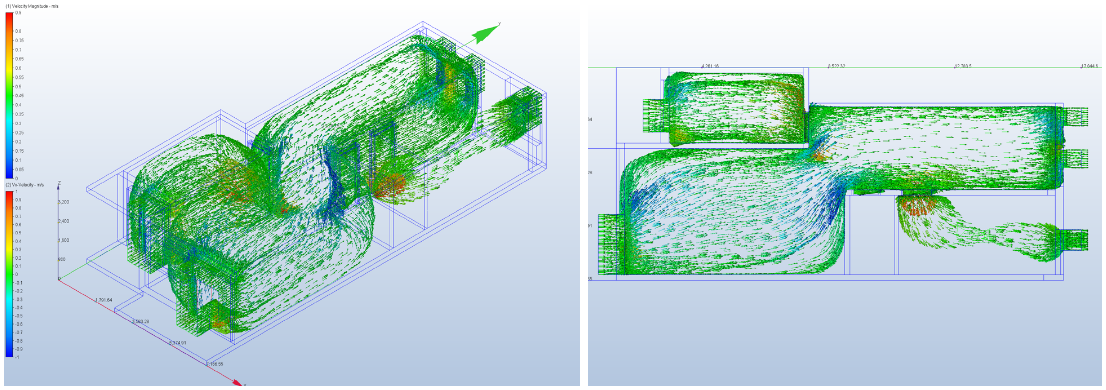


CFD Ventilation Results–07-Relocating–Over Ventilated (1.0–26 m/s)

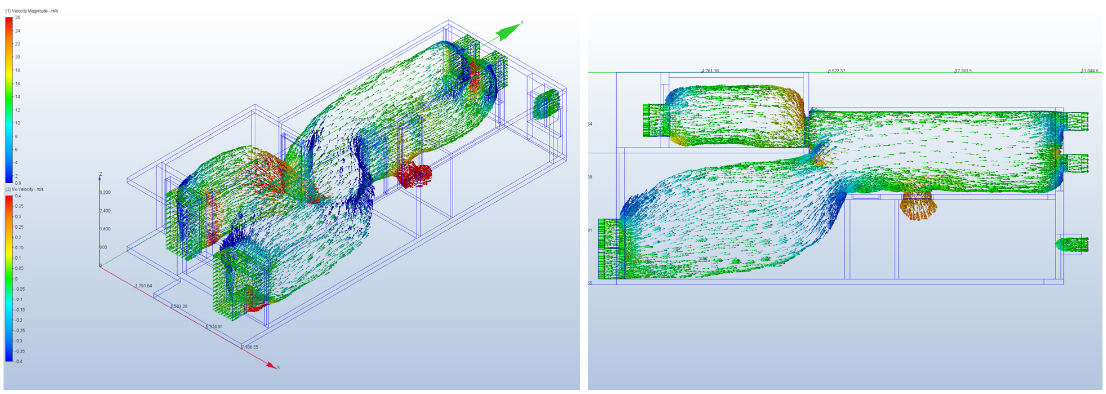


CFD Ventilation Results–07-Relocating–Separating Non-Ventilated, Over-Ventilated and Comfortably Ventilated

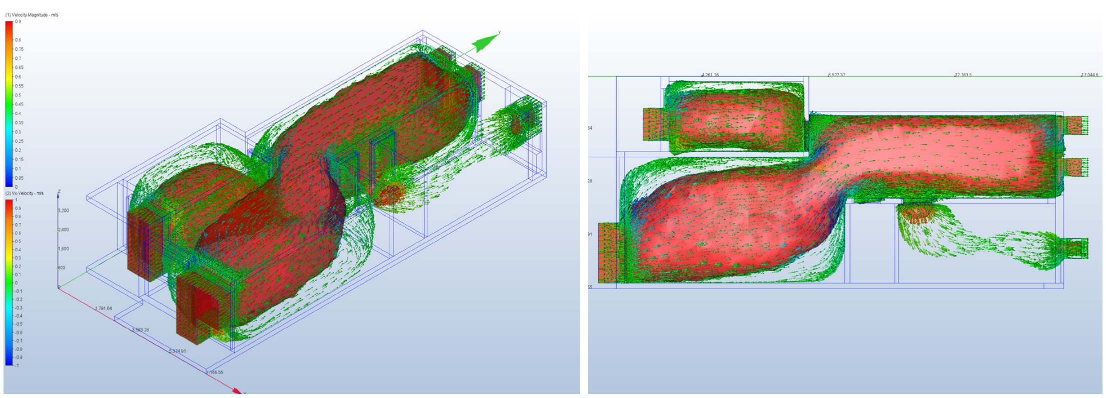
07 – Relocating



CFD Ventilation Results–08-Insetting–All Ventilated (0.15–0.9 m/s)

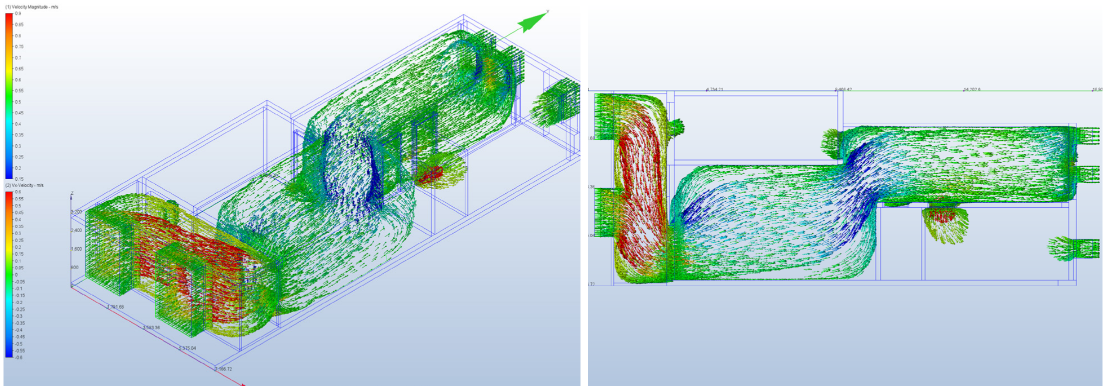


CFD Ventilation Results–08-Insetting–Over Ventilated (1.0–26 m/s)

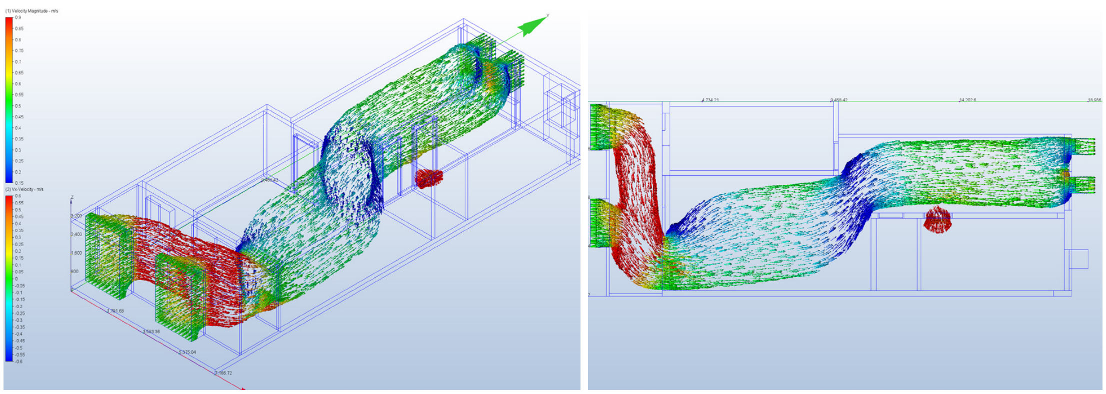


CFD Ventilation Results–08-Insetting–Separating Non-Ventilated, Over-Ventilated and Comfortably Ventilated

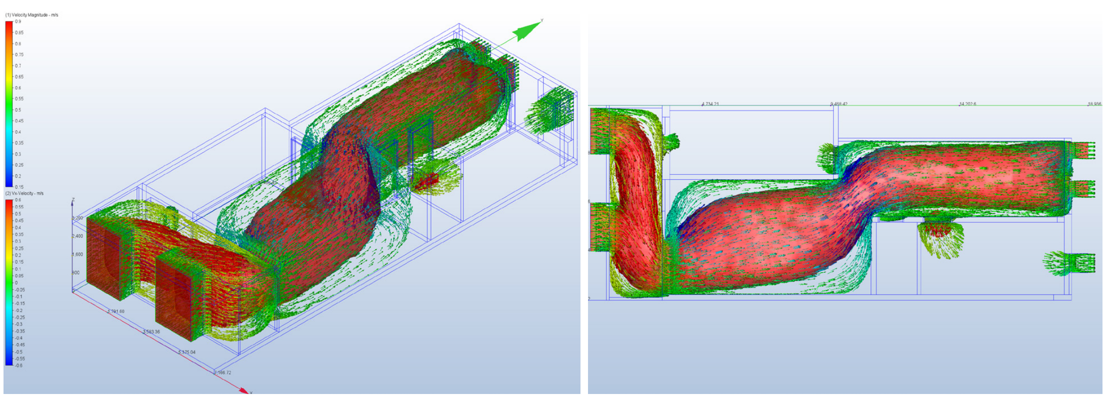
08 – Insetting



CFD Ventilation Results–09-Layering–All Ventilated (0.15–0.9 m/s)

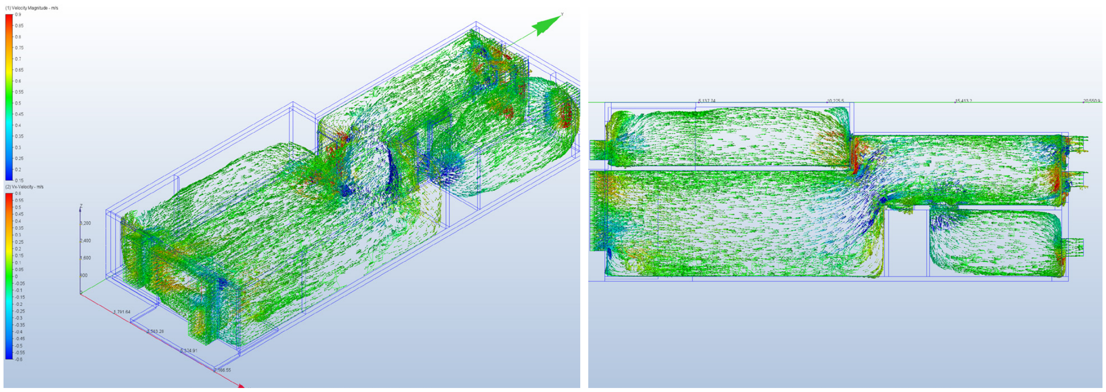


CFD Ventilation Results–09-Layering–Over Ventilated (1.0–26 m/s)

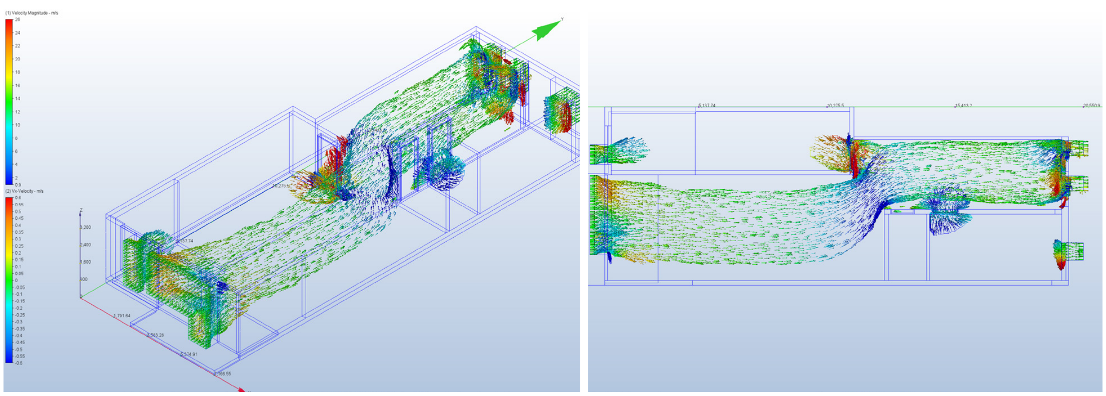


CFD Ventilation Results–09-Layering–Separating Non-Ventilated, Over-Ventilated and Comfortably Ventilated

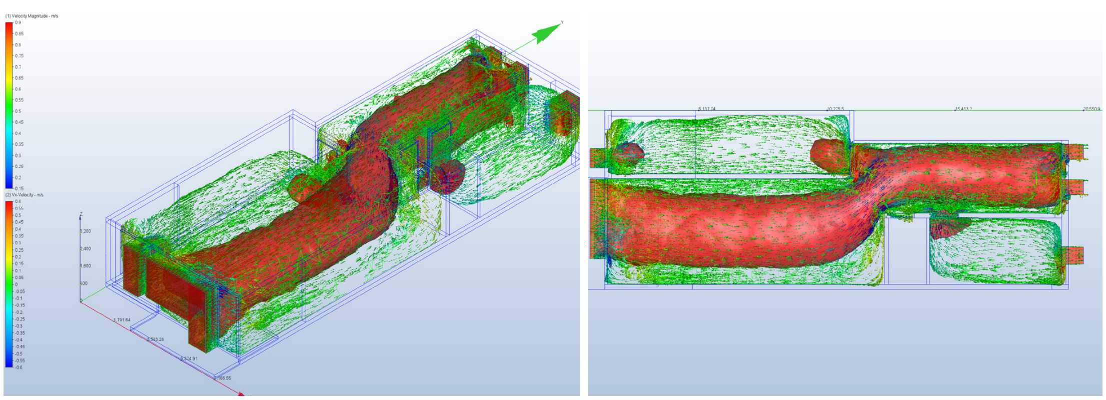
09 – Layering



CFD Ventilation Results–10-Extending–All Ventilated (0.15–0.9 m/s)



CFD Ventilation Results–10-Extending–Over Ventilated (1.0–26 m/s)



CFD Ventilation Results–10-Extending–Separating Non-Ventilated, Over-Ventilated and Comfortably Ventilated

10 – Extending

C.3.4 CFD Ventilation Results: Summary

	Area (sm)	Area (sm)	Area (sm)
	Not Ventilated	Ventilated	Ventilated
Iteration Name	0 m/s	0.15-0.9 m/s	1.0-26 m/s
00-Existing	**17.58**	**21.44**	**47.17**
01-Restructuring	*17.58*	*21.44*	*47.17*
02-Reglazing	**13.29**	**17.68**	**55.83**
03-Recladding	*17.58*	*21.44*	*47.17*
04-Enclosing	**17.74**	**23.86**	**50.59**
05-Insulating	**17.74**	**23.86**	**50.59**
06-Adding	**10.74**	**13.29**	**62.76**
07-Relocating	**9.42**	**20.98**	**52.1**
08-Insetting	**12.86**	**15.1**	**54.98**
09-Layering	**30.73**	**18.67**	**50.27**
10-Extension	**5.65**	**48.31**	**55.56**

	Area (sm)	Area (sm)	Percentage of Area (%)
	Ventilated	Total Area	Not Ventilated
Iteration Name	Total Ventilated		0 m/s
00-Existing	**68.61**	**86.19**	**20.40%**
01-Restructuring	*68.61*	*86.19*	*20.40%*
02-Reglazing	**73.51**	**86.8**	**15.31%**
03-Recladding	*68.61*	*86.19*	*20.40%*
04-Enclosing	**74.45**	**92.19**	**19.24%**
05-Insulating	**74.45**	**92.19**	**19.24%**
06-Adding	**76.05**	**86.79**	**12.37%**
07-Relocating	**73.08**	**82.5**	**11.42%**
08-Insetting	**70.08**	**82.94**	**15.51%**
09-Layering	**68.94**	**99.67**	**30.83%**
10-Extension	**103.87**	**109.52**	**5.16%**

	Percentage of Area (%)	Percentage of Area (%)	Percentage of Area (%)
	Ventilated	Ventilated	Ventilated
Iteration Name	0.15-0.9 m/s	1.0-26 m/s	Total Ventilated
00-Existing	**24.88%**	**54.73%**	**79.60%**
01-Restructuring	*24.88%*	*54.73%*	*79.60%*
02-Reglazing	**20.37%**	**64.32%**	**84.69%**
03-Recladding	*24.88%*	*54.73%*	*79.60%*
04-Enclosing	**25.88%**	**54.88%**	**80.76%**
05-Insulating	**25.88%**	**54.88%**	**80.76%**
06-Adding	**15.31%**	**72.31%**	**87.63%**
07-Relocating	**25.43%**	**63.15%**	**88.58%**
08-Insetting	**18.21%**	**66.29%**	**84.49%**
09-Layering	**18.73%**	**50.44%**	**69.17%**
10-Extension	**44.11%**	**50.73%**	**94.84%**

Autodesk CFD Ventilation Results

C.3.5 CFD Ventilation Results: Percentage of Change

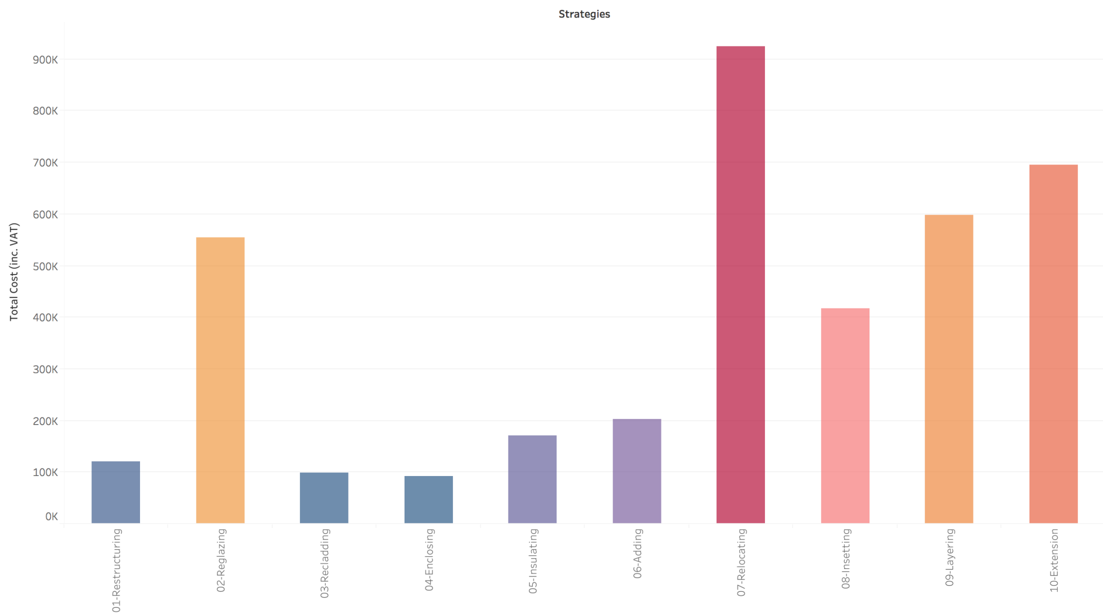
	Percentage of Change (%)	Percentage of Change (%)
	Not Ventilated	Ventilated
Iteration Name	0 m/s	0.15-0.9 m/s
01-Restructuring	*0%*	*0%*
02-Reglazing	24.40%	-17.54%
03-Recladding	*0%*	*0%*
04-Enclosing	-0.91%	11.29%
05-Insulating	-0.91%	11.29%
06-Adding	38.91%	-38.01%
07-Relocating	46.42%	-2.15%
08-Insetting	26.85%	-29.57%
09-Layering	-74.80%	-12.92%
10-Extension	67.86%	125.33%

	Percentage of Change (%)	Percentage of Change (%)
	Ventilated	Ventilated
Iteration Name	1.0-26 m/s	Total Ventilated
01-Restructuring	*0%*	*0%*
02-Reglazing	-18.36%	7.14%
03-Recladding	*0%*	*0%*
04-Enclosing	-7.25%	8.51%
05-Insulating	-7.25%	8.51%
06-Adding	-33.05%	10.84%
07-Relocating	-10.45%	6.52%
08-Insetting	-16.56%	2.14%
09-Layering	-6.57%	0.48%
10-Extension	-17.79%	51.39%

C.4 Costing

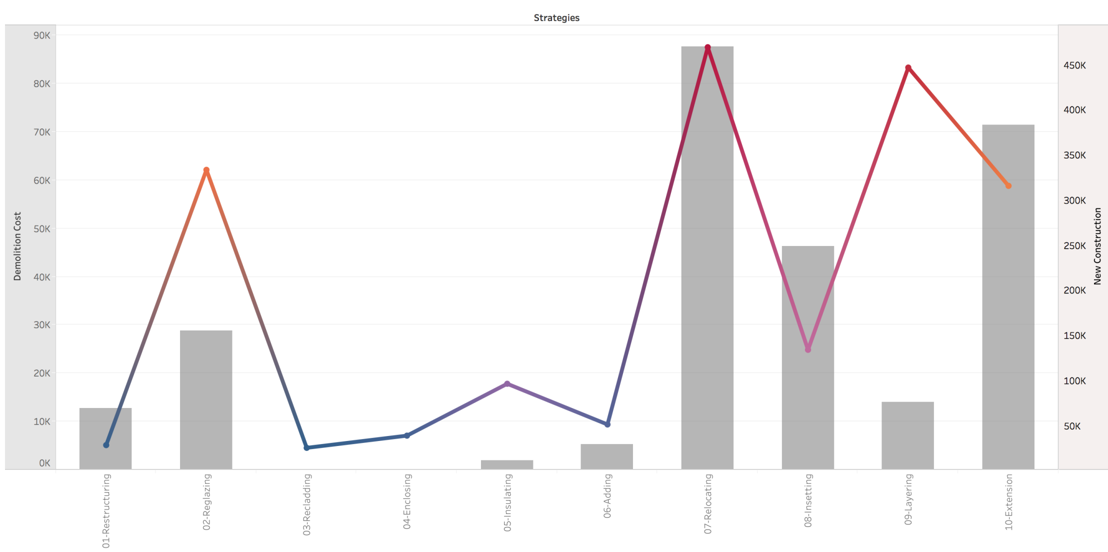
C.4.1 Costing: Overview of Results

Total Cost



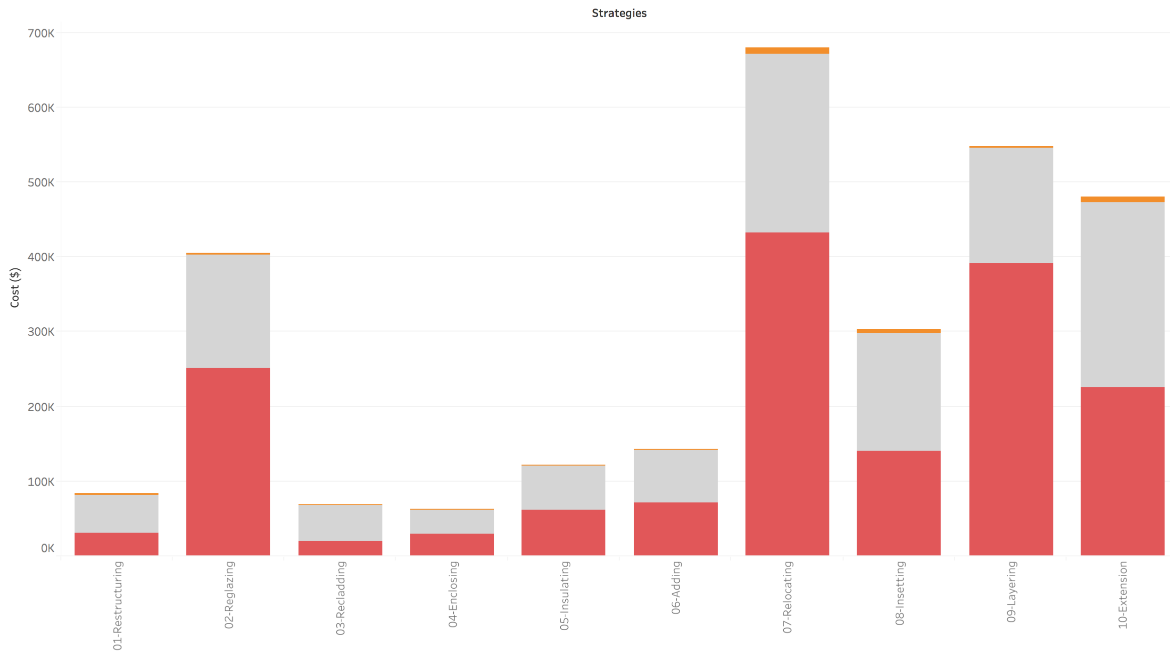
Sum of Total Cost (inc. VAT) for each Strategies. Color shows sum of Total Cost (inc. VAT).

Demolition Cost vs. New Construction Cost



The trends of sum of Demolition Cost and sum of New Construction for Strategies. For pane Sum of New Construction: Color shows sum of New Construction.

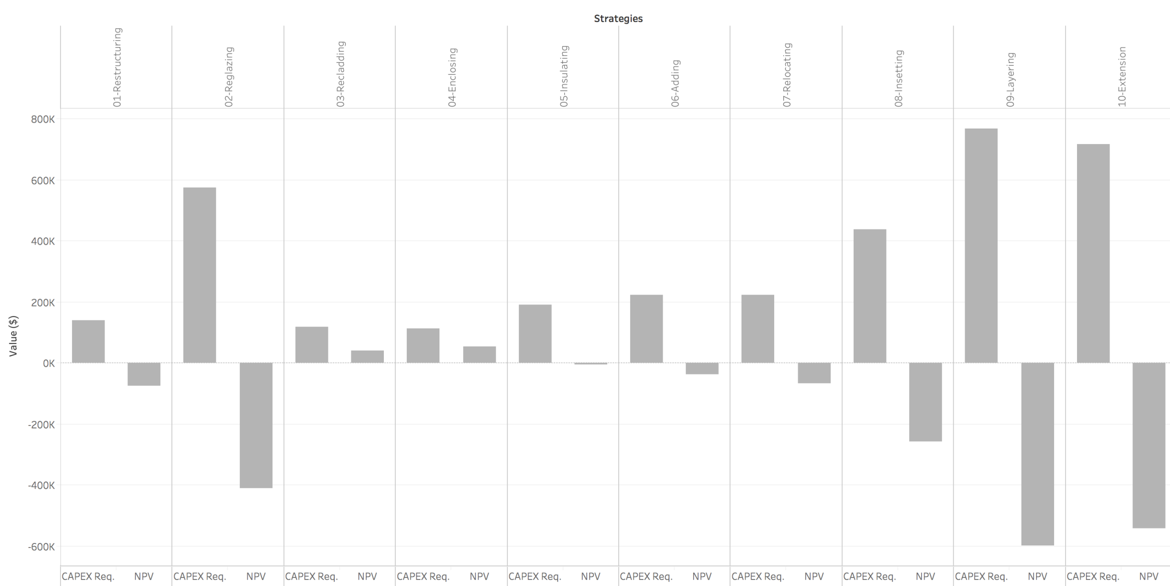
Equipment vs. Labour vs. Material Costs



Equipment, Labour and Materials for each Strategies. Color shows details about Equipment, Labour and Materials.

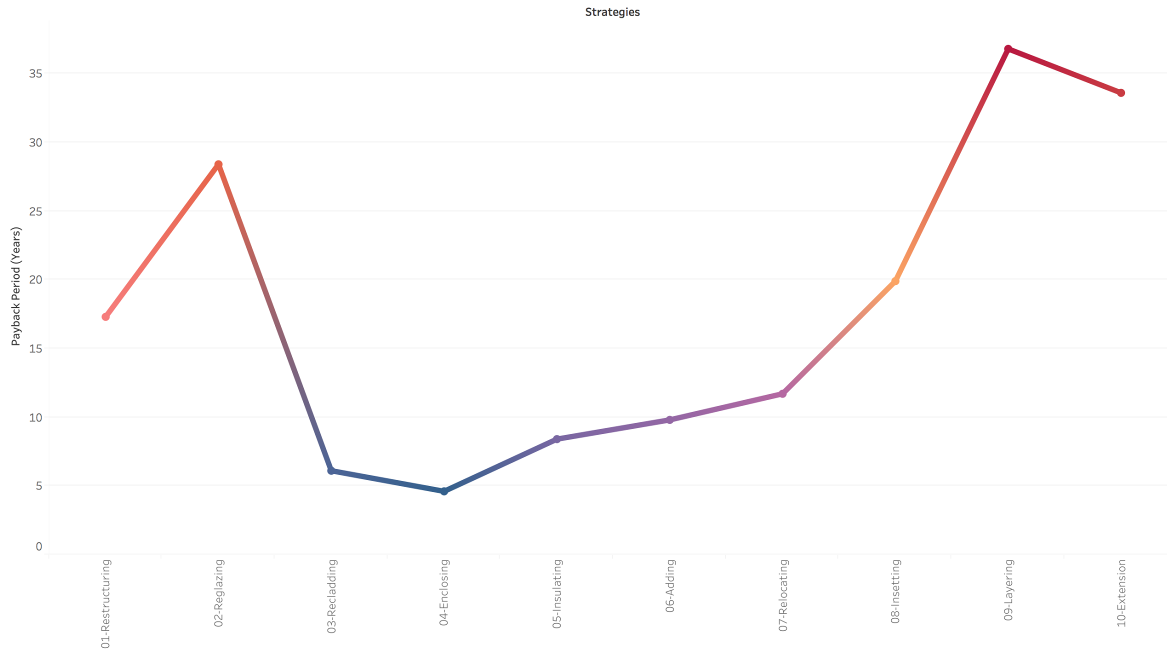
Measure Names
Equipment
Labour
Materials

NPV & CAPEX



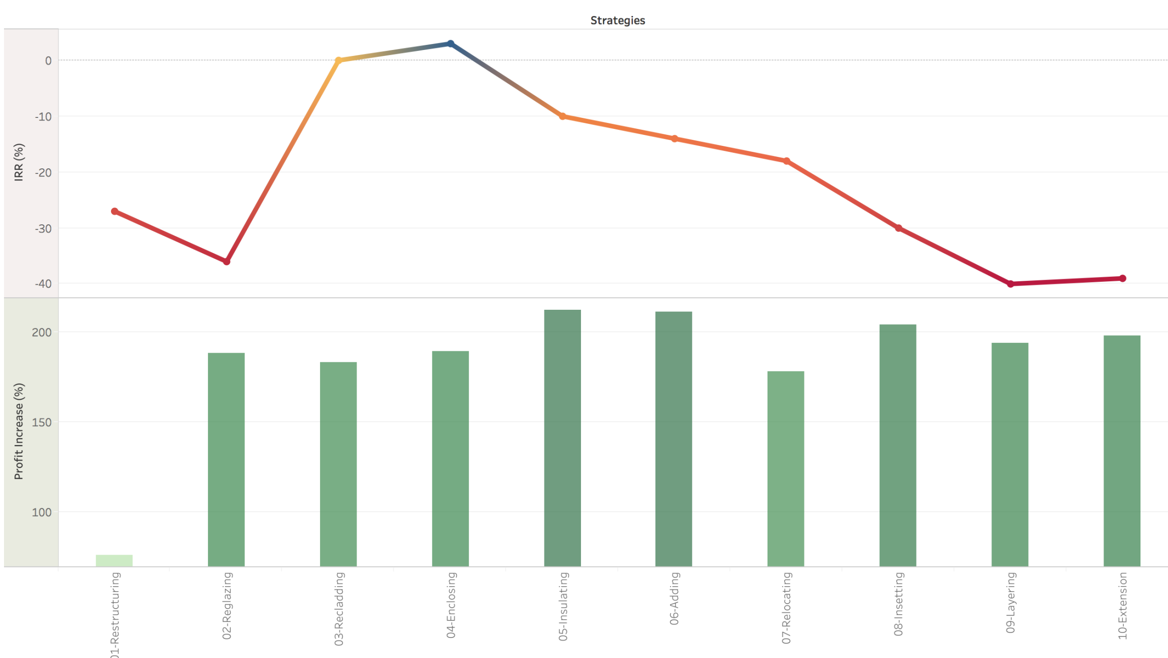
CAPEX Req. and NPV for each Strategies.

Payback Period



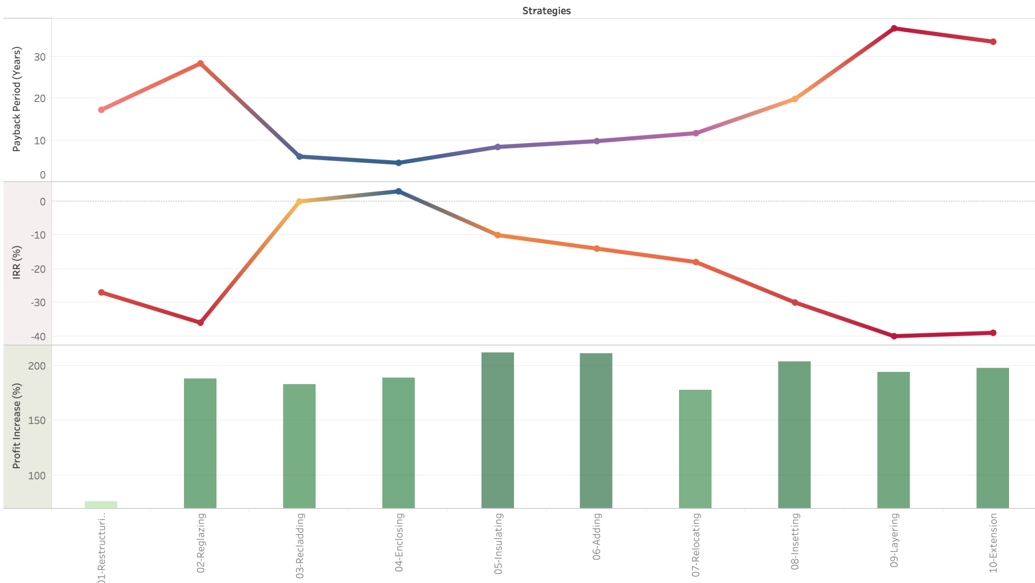
The trend of sum of Payback Period (Years) for Strategies. Color shows sum of Payback Period (Years).

IRR & Profit



The trends of sum of IRR and sum of Profit Increase for Strategies. For pane Sum of IRR: Color shows sum of IRR. For pane Sum of Profit Increase: Color shows sum of Profit Increase.

IRR/Profit/PBP



The trends of sum of Payback Period (Years), sum of IRR and sum of Profit Increase for Strategies. For pane Sum of IRR: Color shows sum of IRR. For pane Sum of Profit Increase: Color shows sum of Profit Increase. For pane Sum of Payback Period (Years): Color shows sum of Payback Period (Years).

C.4.2 Total Cost Breakdown

No.	Text	Unit	Quantity	Total Cost	Sales Price
	Fixed items				
	Railings				
	- Demolished	sum	1	3,010.49	3,010.00
	- New Construction	sum	1	20,825.94	20,826.00
				23,836.43	**23,836.00**
	Floors				
	- Demolished	sum	1	9,676.58	9,677.00
	- New Construction	sum	1	7,659.94	7,660.00
				17,336.51	**17,337.00**
	Construction				
22-01 56 26 50	- Temporary fencing, chain link, 5' high, 11 ga	L.F.	1	499.95	500.00
22-01 58 13 50	- Project signs, sign, high intensity reflectorized, buy, excl. posts	Ea.	1	280.50	281.00
22-01 71 23 13	- Boundary & survey markers, crew for building layout, 2 person crew	Day	1	9,085.26	9,085.00
22-01 74 13 20	- Cleaning up, cleanup of floor area, continuous, per day, during construction	M.S.F.	60	10,682.94	10,683.00
22-01 74 13 20	- Cleaning up, cleanup of floor area, final by GC at end of job	M.S.F.	1	4,588.55	4,589.00
22-01 45 23 50	- Field testing, for concrete building, costing $1,000,000, minimum	Project	1	5,197.50	5,198.00
22-01 31 13 20	- Field personnel, clerk, average	Week	1	4,356.00	4,356.00
22-01 31 13 20	- Field personnel, field engineer, engineer, average	Week	1	13,420.00	13,420.00
				48,110.70	**48,112.00**
	Consultants				
	- Consultant Fees - 8% of Construction Cost		1	7,143.00	7,143.00
				7,143.00	**7,143.00**
	Total amount, excl. VAT			**96,426.64**	**96,428.00**
	VAT (25%)				**24,107.00**
	Total amount, incl. VAT				**120,535.00**

01- Restructuring

Category - text	Unit	Quantity	Price/quantity	Total Cost
Equipment				**2,269.64**
- 50' Air Hoses, 1.5"	Days	9.1703	25.03	229.49
- Air Compressor, 250 cfm	Days	4.5851	184.75	847.08
- Breaker, Pavement, 60 lb.	Days	9.1703	11.83	108.44
- Flatbed Truck, Gas, 1.5 Ton	Days	0.7989	214.72	171.54
- Lattice Boom Crane, 150 Ton	Days	0.2187	2,223.10	486.26
- Level, Electronic	Days	7	49.94	349.58
- Welder, Gas Engine, 300 amp	Days	0.7341	105.22	77.24
Labor				**50,660.02**
- Common Building Laborers	Hours	202.355	62.11	12,568.00
- Common Building Laborers Outside Foreman	Hours	36.6811	65.13	2,389.21
- Equipment Operators, Crane or Shovel	Hours	1.7499	86.23	150.90
- Equipment Operators, Oilers	Hours	1.7499	73.85	129.23
- Field personnel, clerk, average	Week	8	544.50	4,356.00
- Field personnel, field engineer, engineer, average	Week	8	1,677.50	13,420.00
- Glaziers	Hours	126.3015	74.77	9,443.93
- Skilled Workers Average (35 trades)	Hours	56	81.22	4,548.40
- Structural Steel Workers	Hours	28.1181	89.32	2,511.51
- Structural Steel Workers Outside Foreman	Hours	7.6228	92.51	705.19
- Truck Drivers, Light	Hours	6.3913	68.48	437.66
Materials				**31,156.47**
- Cleaning up, cleanup of floor area, continuous, per day, during construction	M.S.F.	3,000	2.57	7,722.00
- Cleaning up, cleanup of floor area, final by GC at end of job	M.S.F.	1,380	2.73	3,764.64
- Precast slab, roof/floor members, grouted, solid, 6" thick, prestressed	S.F.	612.4568	9.46	5,793.84
- Project signs, sign, high intensity reflectorized, buy, excl. posts	Ea.	10	28.05	280.50
- Railing, industrial, welded, steel pipe, 2 rails, 3'-6" high, posts @ 5' OC, 1-1/2" dia x 42" H, shop fabricated	L.F.	187.2	45.10	8,442.72
- Sheet glass, grey, 1/4" thick	S.F.	571.2	8.64	4,932.31
- Temporary fencing, chain link, 5' high, 11 ga	L.F.	111.9652	1.97	220.46
				84,086.13

01- Restructuring

No.	Text	Unit	Quantity	Total Cost	Sales Price
	Fixed items				
	Windows				
	- Demolished	sum	1	7,361.60	7,362.00
				7,361.60	**7,362.00**
	Walls				
	- Demolished	sum	1	15,894.08	15,894.00
	- New Construction	sum	1	147,321.87	147,322.00
				163,215.96	**163,216.00**
	Curtain Panels				
	- Demolished	sum	1	5,515.31	5,515.00
	- New Construction	sum	1	186,285.94	186,286.00
				191,801.25	**191,801.00**
	Construction				
22-01 56 26 50	- Temporary fencing, chain link, 5' high, 11 ga	L.F.	1	499.95	500.00
22-01 58 13 50	- Project signs, sign, high intensity reflectorized, buy, excl. posts	Ea.	1	280.50	281.00
22-01 71 23 13	- Boundary & survey markers, crew for building layout, 2 person crew	Day	1	9,085.26	9,085.00
22-01 74 13 20	- Cleaning up, cleanup of floor area, continuous, per day, during construction	M.S.F.	60	10,682.94	10,683.00
22-01 74 13 20	- Cleaning up, cleanup of floor area, final by GC at end of job	M.S.F.	1	4,588.55	4,589.00
22-01 45 23 50	- Field testing, for concrete building, costing $1,000,000, minimum	Project	1	5,197.50	5,198.00
22-01 31 13 20	- Field personnel, clerk, average	Week	1	4,356.00	4,356.00
22-01 31 13 20	- Field personnel, field engineer, engineer, average	Week	1	13,420.00	13,420.00
				48,110.70	**48,112.00**
	Consultants				
	- Consultant Fees - 8% of Construction Cost		1	32,839.00	32,839.00
				32,839.00	**32,839.00**
	Total amount, excl. VAT			**443,328.50**	**443,330.00**
	VAT (25%)				**110,832.50**
	Total amount, incl. VAT				**554,162.50**

02- Reglazing

Category - text	Unit	Quantity	Price/quantity	Total Cost
Equipment				**3,208.41**
- 50' Air Hoses, 1.5"	Days	20.7958	25.03	520.42
- Air Compressor, 250 cfm	Days	10.3979	184.75	1,920.97
- Breaker, Pavement, 60 lb.	Days	20.7958	11.83	245.91
- Flatbed Truck, Gas, 1.5 Ton	Days	0.7989	214.72	171.54
- Level, Electronic	Days	7	49.94	349.58
Labor				**151,090.90**
- Carpenters	Hours	82.7911	78.15	6,469.83
- Common Building Laborers	Hours	482.2724	62.11	29,953.29
- Common Building Laborers Outside Foreman	Hours	83.1834	65.13	5,418.12
- Field personnel, clerk, average	Week	8	544.50	4,356.00
- Field personnel, field engineer, engineer, average	Week	8	1,677.50	13,420.00
- Glaziers	Hours	1,156.6704	74.77	86,487.60
- Skilled Workers Average (35 trades)	Hours	56	81.22	4,548.40
- Truck Drivers, Light	Hours	6.3913	68.48	437.66
Materials				**250,992.42**
- Cleaning up, cleanup of floor area, continuous, per day, during construction	M.S.F.	3,000	2.57	7,722.00
- Cleaning up, cleanup of floor area, final by GC at end of job	M.S.F.	1,380	2.73	3,764.64
- Exterior shutter, exterior, aluminum, louvered, 16" wide, 6'-8" long	Pr.	62	396.00	24,552.00
- Insulating glass, double glazed, tinted, 3/16" float, for 5/8" thick unit, 15-30	S.F.	5,134.8	15.62	80,205.58
- Moldings, casings, ogee, 11/16" x 2-1/2", pine	L.F.	240	1.56	374.88
- Moldings, window & door, stool caps, stock pine, 11/16" x 3-1/2"	L.F.	75	2.64	198.00
- Project signs, sign, high intensity reflectorized, buy, excl. posts	Ea.	10	28.05	280.50
- Temporary fencing, chain link, 5' high, 11 ga	L.F.	111.9652	1.97	220.46
- Wall framing, window buck, king studs, jack studs, rough sill, cripples, header and accessories, 2" x 4" wall, 3' wide, 8' high	Ea.	15	24.75	371.25
- Window wall, aluminum, stock, including glazing, average	S.F.	1,643.3993	77.55	127,445.61
- Windows, wood, casement, vinyl-clad, premium, double insulated glass, 1'-4" x 4'-0" high, incl. frame, screens and grilles	Ea.	15	390.50	5,857.50
				405,291.73

02- Reglazing

No.	Text	Unit	Quantity	Total Cost	Sales Price
	Fixed items				
	Walls				
	- New Construction	sum	1	25,460.55	25,461.00
				25,460.55	**25,461.00**
	Construction				
22-01 56 26 50	- Temporary fencing, chain link, 5' high, 11 ga	L.F.	1	499.95	500.00
22-01 58 13 50	- Project signs, sign, high intensity reflectorized, buy, excl. posts	Ea.	1	280.50	281.00
22-01 71 23 13	- Boundary & survey markers, crew for building layout, 2 person crew	Day	1	9,085.26	9,085.00
22-01 74 13 20	- Cleaning up, cleanup of floor area, continuous, per day, during construction	M.S.F.	60	10,682.94	10,683.00
22-01 74 13 20	- Cleaning up, cleanup of floor area, final by GC at end of job	M.S.F.	1	4,588.55	4,589.00
22-01 45 23 50	- Field testing, for concrete building, costing $1,000,000, minimum	Project	1	5,197.50	5,198.00
22-01 31 13 20	- Field personnel, clerk, average	Week	1	4,356.00	4,356.00
22-01 31 13 20	- Field personnel, field engineer, engineer, average	Week	1	13,420.00	13,420.00
				48,110.70	**48,112.00**
	Consultants				
	- Consultant Fees - 8% of Construction Cost		1	5,883.00	5,883.00
				5,883.00	**5,883.00**
	Total amount, excl. VAT			**79,454.25**	**79,456.00**
	VAT (25%)				**19,864.00**
	Total amount, incl. VAT				**99,320.00**

03 - Recladding

Category - text	Unit	Quantity	Price/quantity	Total Cost
Equipment				**1,169.43**
- Flatbed Truck, Gas, 1.5 Ton	Days	0.7989	214.72	171.54
- Level, Electronic	Days	7	49.94	349.58
- Mixing Machine, 6 C.F.	Days	4.3544	148.89	648.31
Labor				**47,613.69**
- Carpenters	Hours	69.9055	78.15	5,462.87
- Common Building Laborers	Hours	55.6304	62.11	3,455.13
- Field personnel, clerk, average	Week	8	544.50	4,356.00
- Field personnel, field engineer, engineer, average	Week	8	1,677.50	13,420.00
- Glaziers	Hours	56	74.77	4,187.28
- Plasterer Helpers	Hours	69.6705	61.52	4,286.08
- Plasterers	Hours	104.5058	71.39	7,460.28
- Skilled Workers Average (35 trades)	Hours	56	81.22	4,548.40
- Truck Drivers, Light	Hours	6.3913	68.48	437.66
Materials				**19,590.53**
- Blanket insulation, for walls or ceilings, foil faced fiberglass, 3-1/2" thick, R13,	S.F.	1,698.2189	0.52	877.98
- Cleaning up, cleanup of floor area, continuous, per day, during construction	M.S.F.	3,000	2.57	7,722.00
- Cleaning up, cleanup of floor area, final by GC at end of job	M.S.F.	1,380	2.73	3,764.64
- Polymer based exterior insulation and finish system, field applied, 3" EPS	S.F.	1,698.2189	2.57	4,371.22
- Project signs, sign, high intensity reflectorized, buy, excl. posts	Ea.	10	28.05	280.50
- Sheathing, plywood on walls, CDX, 5/8" thick	S.F.	1,698.2189	0.86	1,457.07
- Temporary fencing, chain link, 5' high, 11 ga	L.F.	111.9652	1.97	220.46
- Wood framing, partitions, standard & better lumber, 2" x 4" studs, 16" OC, 8' high, includes single bottom plate and double top plate, excludes waste	L.F.	212.2774	4.22	896.66
				68,373.65

03 - Recladding

No.	Text	Unit	Quantity	Total Cost	Sales Price
	Fixed items				
	Walls				
	- New Construction	sum	1	37,387.01	37,387.00
				37,387.01	**37,387.00**
	Roof				
	- New Construction	sum	1	1,586.09	1,586.00
				1,586.09	**1,586.00**
	Construction				
22-01 56 26 50	- Temporary fencing, chain link, 5' high, 11 ga	L.F.	1	499.95	500.00
22-01 58 13 50	- Project signs, sign, high intensity reflectorized, buy, excl. posts	Ea.	1	280.50	281.00
22-01 71 23 13	- Boundary & survey markers, crew for building layout, 2 person crew	Day	1	3,893.68	3,894.00
22-01 74 13 20	- Cleaning up, cleanup of floor area, continuous, per day, during construction	M.S.F.	30	5,341.47	5,341.00
22-01 74 13 20	- Cleaning up, cleanup of floor area, final by GC at end of job	M.S.F.	1	4,588.55	4,589.00
22-01 45 23 50	- Field testing, for concrete building, costing $1,000,000, minimum	Project	1	5,197.50	5,198.00
22-01 31 13 20	- Field personnel, clerk, average	Week	1	2,178.00	2,178.00
22-01 31 13 20	- Field personnel, field engineer, engineer, average	Week	1	6,710.00	6,710.00
				28,689.65	**28,691.00**
	Consultants				
	- Consultant Fees - 8% of Construction Cost		1	6,124.00	6,124.00
				6,124.00	**6,124.00**
	Total amount, excl. VAT			**73,786.76**	**73,788.00**
	VAT (25%)				**18,447.00**
	Total amount, incl. VAT				**92,235.00**

04 - Enclosing

Category - text	Unit	Quantity	Price/quantity	Total Cost
Equipment				**254.26**
- Flatbed Truck, Gas, 1.5 Ton	Days	0.4864	214.72	104.44
- Level, Electronic	Days	3	49.94	149.82
Labor				**32,100.47**
- Common Building Laborers	Hours	35.6304	62.11	2,212.96
- Field personnel, clerk, average	Week	4	544.50	2,178.00
- Field personnel, field engineer, engineer, average	Week	4	1,677.50	6,710.00
- Glaziers	Hours	251.2104	74.77	18,783.73
- Skilled Workers Average (35 trades)	Hours	24	81.22	1,949.31
- Truck Drivers, Light	Hours	3.8913	68.48	266.47
Materials				**30,110.60**
- Cleaning up, cleanup of floor area, continuous, per day, during construction	M.S.F.	1,500	2.57	3,861.00
- Cleaning up, cleanup of floor area, final by GC at end of job	M.S.F.	1,380	2.73	3,764.64
- Insulating glass, 2 lites, tinted, 1/8" float, 1/2" thick, under 15 SF	S.F.	1,215.4974	15.95	19,387.18
- Project signs, sign, high intensity reflectorized, buy, excl. posts	Ea.	10	28.05	280.50
- Temporary fencing, chain link, 5' high, 11 ga	L.F.	111.9652	1.97	220.46
- Tube framing, for window walls and storefronts, aluminum, stock, flush tube frame, mill finish, 1/4" glass, 1-3/4" x 4", open sill	L.F.	201.7726	12.87	2,596.81
				62,465.33

04 - Enclosing

No.	Text	Unit	Quantit	Total Cost	Sales Price
	Fixed items				
	Railings				
	- Demolished	sum	1	1,861.52	1,862.00
				1,861.52	**1,862.00**
	Walls				
	- New Construction	sum	1	95,918.65	95,919.00
				95,918.65	**95,919.00**
	Roofs				
	- New Construction	sum	1	562.51	563.00
				562.51	**563.00**
	Construction				
22-01 56 26 50	- Temporary fencing, chain link, 5' high, 11 ga	L.F.	1	499.95	500.00
22-01 58 13 50	- Project signs, sign, high intensity reflectorized, buy, excl. posts	Ea.	1	280.50	281.00
22-01 71 23 13	- Boundary & survey markers, crew for building layout, 2 person crew	Day	1	3,893.68	3,894.00
22-01 74 13 20	- Cleaning up, cleanup of floor area, continuous, per day, during construction	M.S.F.	30	5,341.47	5,341.00
22-01 74 13 20	- Cleaning up, cleanup of floor area, final by GC at end of job	M.S.F.	1	4,588.55	4,589.00
22-01 45 23 50	- Field testing, for concrete building, costing $1,000,000, minimum	Project	1	5,197.50	5,198.00
22-01 31 13 20	- Field personnel, clerk, average	Week	1	2,178.00	2,178.00
22-01 31 13 20	- Field personnel, field engineer, engineer, average	Week	1	6,710.00	6,710.00
				28,689.65	**28,691.00**
	Consultants				
	- Consultant Fees - 8% of Construction Cost		1	10,163.00	10,163.00
				10,163.00	**10,163.00**
	Total amount, excl. VAT			**137,195.32**	**137,198.00**
	VAT (25%)				**34,299.50**
	Total amount, incl. VAT				**171,497.50**

05 - Insulating

Category - text	Unit	Quantity	Price/quantity	Total Cost
Equipment				**638.68**
- Application Equipment	Days	0.0732	199.27	14.58
- Crew Truck	Days	0.0732	169.79	12.43
- Cutting Torch	Days	1.7297	13.75	23.78
- Flatbed Truck, Gas, 1.5 Ton	Days	0.4864	214.72	104.44
- Lattice Boom Crane, 90 Ton	Days	0.0312	1,867.80	58.25
- Level, Electronic	Days	3	49.94	149.82
- Mixing Machine, 6 C.F.	Days	1.7532	148.89	261.03
- Tar Kettle/Pot	Days	0.0732	196.02	14.35
Labor				**59,596.34**
- Bricklayers	Hours	23.96	77.95	1,867.76
- Carpenters	Hours	28.1466	78.15	2,199.56
- Common Building Laborers	Hours	35.6304	62.11	2,212.96
- Equipment Operators, Crane or Shovel	Hours	0.2495	86.23	21.51
- Equipment Operators, Oilers	Hours	0.2495	73.85	18.42
- Field personnel, clerk, average	Week	4	544.50	2,178.00
- Field personnel, field engineer, engineer, average	Week	4	1,677.50	6,710.00
- Glaziers	Hours	478.2854	74.77	35,762.78
- Plasterer Helpers	Hours	28.052	61.52	1,725.74
- Plasterers	Hours	42.0779	71.39	3,003.79
- Roofers, Composition	Hours	2.3419	75.05	175.77
- Roofers, Composition Outside Foreman	Hours	0.5855	78.39	45.89
- Roofers, Helpers (Composition)	Hours	1.1709	56.39	66.03
- Skilled Workers Average (35 trades)	Hours	24	81.22	1,949.31
- Structural Steel Workers	Hours	0.9979	89.32	89.13
- Structural Steel Workers Outside Foreman	Hours	0.2495	92.51	23.08
- Truck Drivers, Light	Hours	3.8913	68.48	266.47
- Welders, Structural Steel Outside Foreman	Hours	13.8378	92.51	1,280.14
Materials				**61,599.70**
- Aluminum, structural shapes, under 1 ton, 1" to 10" members	Lb.	124.7357	4.10	511.79
- Blanket insulation, for walls or ceilings, foil faced fiberglass, 3-1/2" thick, R13, 15" wide	S.F.	683.7666	0.52	353.51
- Built-up roofing systems, asphalt flood coat with gravel/slag surfacing, asphalt base sheet, 4-plies #15 asphalt felt, mopped, excl. insulation, flashing or wood nailers	Sq.	1.4637	159.50	233.46
- Cleaning up, cleanup of floor area, continuous, per day, during construction	M.S.F.	1,500	2.57	3,861.00
- Cleaning up, cleanup of floor area, final by GC at end of job	M.S.F.	1,380	2.73	3,764.64
- Insulating glass, 2 lites, clear, 3/16" float, for 5/8" thick unit, 15-30 SF	S.F.	1,176.7515	15.51	18,251.42

05 - Insulating

- Joint sealants, caulking and sealants, polysulfide compounds, in place, 1 or 2 component, 154 LF per gal, 1/2" x 1/4"	L.F.	862.5589	0.61	521.85
- Polymer based exterior insulation and finish system, field applied, 3" EPS	S.F.	683.7666	2.57	1,760.02
- Project signs, sign, high intensity reflectorized, buy, excl. posts	Ea.	10	28.05	280.50
- Selective demolition, torch cutting, steel, 1" thick plate	L.F.	576	0.97	557.57
- Sheathing, plywood on walls, CDX, 5/8" thick	S.F.	683.7666	0.86	586.67
- Temporary fencing, chain link, 5' high, 11 ga	L.F.	111.9652	1.97	220.46
- Tube framing, for window walls and storefronts, aluminum, stock, flush tube frame, mill finish, 1/4" glass, 1-3/4" x 4", closed back sill	L.F.	391.8583	21.67	8,491.57
- Tube framing, for window walls and storefronts, aluminum, stock, flush tube frame, mill finish, 1/4" glass, 1-3/4" x 4", open header	L.F.	666.0414	15.84	10,550.10
- Tube framing, for window walls and storefronts, aluminum, stock, flush tube frame, mill finish, 1/4" glass, 1-3/4" x 4", open sill	L.F.	195.3408	12.87	2,514.04
- Tube framing, for window walls and storefronts, for joints, 90 degree, clip type, add	Ea.	313.0159	28.05	8,780.10
- Wood framing, partitions, standard & better lumber, 2" x 4" studs, 16" OC, 8' high, includes single bottom plate and double top plate, excludes waste	L.F.	85.4708	4.22	361.03
				121,834.71

05 - Insulating

No.	Text	Unit	Quantity	Total Cost	Sales Price
	Fixed items				
	Windows				
	- Demolished	sum	1	2,301.00	2,301.00
				2,301.00	**2,301.00**
	Walls				
	- Demolished	sum	1	2,994.36	2,994.00
				2,994.36	**2,994.00**
	Floors				
	- New Construction	sum	1	6,992.83	6,993.00
				6,992.83	**6,993.00**
	Railings				
	- New Construction	sum	1	14,345.83	14,346.00
				14,345.83	**14,346.00**
	Curtain Panels				
	- New Construction	sum	1	26,879.73	26,880.00
				26,879.73	**26,880.00**
	Columns				
	- New Construction	sum	1	3,133.92	3,134.00
				3,133.92	**3,134.00**
	Construction				
22-01 56 26 50	- Temporary fencing, chain link, 5' high, 11 ga	L.F.	1	499.95	500.00
22-01 58 13 50	- Project signs, sign, high intensity reflectorized, buy, excl. posts	Ea.	1	280.50	281.00
22-01 71 23 13	- Boundary & survey markers, crew for building layout, 2 person crew	Day	1	9,085.26	9,085.00
22-01 74 13 20	- Cleaning up, cleanup of floor area, continuous, per day, during construction	M.S.F.	120	36,809.88	36,810.00
22-01 74 13 20	- Cleaning up, cleanup of floor area, final by GC at end of job	M.S.F.	1	4,588.55	4,589.00
22-01 45 23 50	- Field testing, for concrete building, costing $1,000,000, minimum	Project	1	5,197.50	5,198.00
22-01 31 13 20	- Field personnel, clerk, average	Week	1	8,712.00	8,712.00
22-01 31 13 20	- Field personnel, field engineer, engineer, average	Week	1	26,840.00	26,840.00
				92,013.64	**92,015.00**
	Consultants				
	- Consultant Fees - 8% of Construction Cost		1	13,791.00	13,791.00
				13,791.00	**13,791.00**
	Total amount, excl. VAT			**162,452.32**	**162,454.00**
	VAT (25%)				**40,613.50**
	Total amount, incl. VAT				**203,067.50**

06 - Adding

Category - text	Unit	Quantity	Price/quantity	Total Cost
Equipment				**1,245.34**
- 50' Air Hoses, 1.5"	Days	3.8275	25.03	95.78
- Air Compressor, 250 cfm	Days	1.9138	184.75	353.56
- Breaker, Pavement, 60 lb.	Days	3.8275	11.83	45.26
- Flatbed Truck, Gas, 1.5 Ton	Days	1.4239	214.72	305.74
- Level, Electronic	Days	7	49.94	349.58
- Welder, Gas Engine, 300 amp	Days	0.9068	105.22	95.41
Labor				**70,240.59**
- Carpenters	Hours	38.9088	78.15	3,040.58
- Carpenters Outside Foreman	Hours	9.7272	81.17	789.58
- Common Building Laborers	Hours	174.6539	62.11	10,847.52
- Common Building Laborers Outside Foreman	Hours	15.3101	65.13	997.22
- Field personnel, clerk, average	Week	16	544.50	8,712.00
- Field personnel, field engineer, engineer, average	Week	16	1,677.50	26,840.00
- Glaziers	Hours	148.0502	74.77	11,070.14
- Skilled Workers Average (35 trades)	Hours	56	81.22	4,548.40
- Structural Steel Workers	Hours	21.7641	89.32	1,943.97
- Structural Steel Workers Outside Foreman	Hours	7.2547	92.51	671.13
- Truck Drivers, Light	Hours	11.3913	68.48	780.05
Materials				**71,977.84**
- C.I.P. concrete forms, elevated slab, flat plate, plywood, to 15' high, 1 use, includes shoring, erecting, bracing, stripping and cleaning	S.F.	571.4727	4.48	2,558.48
- Cleaning up, cleanup of floor area, continuous, per day, during construction	M.S.F.	12,000	2.57	30,888.00
- Cleaning up, cleanup of floor area, final by GC at end of job	M.S.F.	1,380	2.73	3,764.64
- Column, structural, mild steel scrollwork, corner, stock unit, fancy, painted,	V.L.F.	57	36.30	2,069.10
- Doors, glass, swing, tempered, 1/2" thick, 3' x 7' opening, incl. hardware	Opng.	4	2,585.00	10,340.00
- Project signs, sign, high intensity reflectorized, buy, excl. posts	Ea.	10	28.05	280.50
- Railing, industrial, welded, steel pipe, 2 rails, 3'-6" high, posts @ 5' OC, 1-1/2" dia x 42" H, shop fabricated	L.F.	140.4	45.10	6,332.04
- Sheet glass, grey, 1/4" thick	S.F.	357	8.64	3,082.70
- Temporary fencing, chain link, 5' high, 11 ga	L.F.	111.9652	1.97	220.46
- Window wall, aluminum, stock, including glazing, average	S.F.	140.9779	77.55	10,932.83
- Window wall, aluminum, stock, including glazing, minimum	S.F.	26.9	56.10	1,509.09
				143,463.77

06 - Adding

No.	Text	Unit	Quantity	Total Cost	Sales Price
	Fixed items				
	Walls				
	- Demolished	sum	1	42,395.85	42,396.00
	- New Construction	sum	1	184,339.70	184,340.00
				226,735.54	**226,736.00**
	Curtain Panels				
	- Demolished	sum	1	23,100.78	23,101.00
	- New Construction	sum	1	237,161.08	237,161.00
				260,261.87	**260,262.00**
	Windows				
	- Demolished	sum	1	3,032.75	3,033.00
				3,032.75	**3,033.00**
	Railings				
	- Demolished	sum	1	9,467.11	9,467.00
	- New Construction	sum	1	22,155.56	22,156.00
				31,622.67	**31,623.00**
	Floors				
	- Demolished	sum	1	9,721.32	9,721.00
	- New Construction	sum	1	9,297.81	9,298.00
				19,019.13	**19,019.00**
	Doors				
	- New Construction	sum	1	16,580.69	16,581.00
				16,580.69	**16,581.00**
	Construction				
22-01 56 26 50	- Temporary fencing, chain link, 5' high, 11 ga	L.F.	1	499.95	500.00
22-01 58 13 50	- Project signs, sign, high intensity reflectorized, buy, excl. posts	Ea.	1	280.50	281.00
22-01 71 23 13	- Boundary & survey markers, crew for building layout, 2 person crew	Day	1	9,085.26	9,085.00
22-01 74 13 20	- Cleaning up, cleanup of floor area, continuous, per day, during construction	M.S.F.	180	55,214.82	55,215.00
22-01 74 13 20	- Cleaning up, cleanup of floor area, final by GC at end of job	M.S.F.	1	4,588.55	4,589.00
22-01 45 23 50	- Field testing, for concrete building, costing $1,000,000, minimum	Project	1	5,197.50	5,198.00
22-01 31 13 20	- Field personnel, clerk, average	Week	1	13,068.00	13,068.00
22-01 31 13 20	- Field personnel, field engineer, engineer, average	Week	1	40,260.00	40,260.00
				128,194.58	**128,196.00**
	Consultants				
	- Consultant Fees - 8% of Construction Cost		1	54,836.00	54,836.00
				54,836.00	**54,836.00**
	Total amount, excl. VAT			**740,283.23**	**740,286.00**
	VAT (25%)				**185,071.50**
	Total amount, incl. VAT				**925,357.50**

07 - Relocating

Category - text	Unit	Quantity	Price/quantity	Total Cost
Equipment				**9,069.51**
- 50' Air Hoses, 1.5"	Days	63.4029	25.02	1,586.66
- Air Compressor, 250 cfm	Days	31.7015	184.75	5,856.69
- Breaker, Pavement, 60 lb.	Days	63.4029	11.82	749.74
- Flatbed Truck, Gas, 1.5 Ton	Days	2.0489	214.72	439.94
- Level, Electronic	Days	7	49.94	349.58
- Welder, Gas Engine, 300 amp	Days	0.8259	105.22	86.90
Labor				**238,922.69**
- Bricklayer Helpers	Hours	46.2124	61.69	2,850.88
- Bricklayers	Hours	84.6212	77.95	6,596.51
- Carpenters	Hours	83.734	78.15	6,543.51
- Carpenters Outside Foreman	Hours	12.9335	81.17	1,049.84
- Common Building Laborers	Hours	1,387.3061	62.11	86,163.71
- Common Building Laborers Outside Foreman	Hours	253.6118	65.13	16,518.92
- Field personnel, clerk, average	Week	24	544.50	13,068.00
- Field personnel, field engineer, engineer, average	Week	24	1,677.50	40,260.00
- Glaziers	Hours	574.8917	74.77	42,986.32
- Roofers, Composition	Hours	2.2618	75.05	169.75
- Skilled Workers Average (35 trades)	Hours	56	81.22	4,548.40
- Structural Steel Workers	Hours	183.9812	89.32	16,433.20
- Structural Steel Workers Outside Foreman	Hours	6.6071	92.51	611.22
- Truck Drivers, Light	Hours	16.3913	68.48	1,122.44
Materials				**432,257.36**
- Brick walls, face brick, red, running bond, 6.75/SF, 4" thick, includes mortar, 3% brick waste and 25% mortar waste, excludes scaffolding, horizontal	S.F.	409.9485	4.48	1,835.34
- C.I.P. concrete forms, elevated slab, flat plate, plywood, to 15' high, 1 use, includes shoring, erecting, bracing, stripping and cleaning	S.F.	759.8424	4.48	3,401.81
- Cleaning up, cleanup of floor area, continuous, per day, during construction	M.S.F.	18,000	2.57	46,332.00
- Cleaning up, cleanup of floor area, final by GC at end of job	M.S.F.	1,380	2.73	3,764.64
- Concrete block partitions, normal weight blocks, 2000 psi, 6" x 8" x 16", tooled joints both sides, includes mortar, excludes scaffolding, horizontal	S.F.	409.9485	2.73	1,118.34
- Concrete block, insulation inserts, styrofoam, 8" x 16" units, 6" thick, plant installed, add to block prices	S.F.	409.9485	1.34	550.15
- Control joint, PVC, for double wythe 8" minimum wall (Brick/CMU)	L.F.	20.4974	1.86	38.10
- Doors, glass, sliding, aluminum, premium, 5/8" tempered insulated glass, 6'-0" x 6'-8"	Ea.	8	1,760.00	14,080.00
- Joint sealants, caulking and sealants, butyl based, bulk, 1/4" x 1/2"	L.F.	51.2436	0.26	13.53
- Lintel angle, structural, unpainted, under 500 lb., shop fabricated	Lb.	409.9485	1.12	459.96
- Masonry anchors, cavity wall ties, Z-type, galvanized, 6" long x 1/4" diameter	C	1.2298	44.00	54.11
- Pre-formed joint seals, backer rod, polyethylene, 1/4" dia	C.L.F.	0.4099	2.66	1.09

07 - Relocating

- Project signs, sign, high intensity reflectorized, buy, excl. posts	Ea.	10	28.05	280.50
- Railing, industrial, welded, steel pipe, 2 rails, 3'-6" high, posts @ 5' OC, 1-1/2" dia x 42" H, shop fabricated	L.F.	210.6	45.10	9,498.06
- Sheet glass, grey, 1/4" thick	S.F.	571.2	8.64	4,932.31
- Sheet metal flashing, aluminum, flexible, mill finish, .019" thick, including up to 4 bends	S.F.	40.9949	1.56	64.03
- Temporary fencing, chain link, 5' high, 11 ga	L.F.	111.9652	1.97	220.46
- Washing brick, smooth brick, acid wash	S.F.	409.9485	0.06	22.55
- Window wall, aluminum, stock, including glazing, average	S.F.	3,925.164	77.55	304,396.47
- Windows, aluminum, commercial grade, stock units, awning, with screen, 3'-1" x 3'-2" opening, incl. frame and glazing	Ea.	102.6	401.50	41,193.90
				680,249.56

07 - Relocating

No.	Text	Unit	Quantity	Total Cost	Sales Price
	Fixed items				
	Walls				
	- Demolition	sum	1	40,083.67	40,084.00
	- New Construction	sum	1	99,884.01	99,884.00
				139,967.68	**139,968.00**
	Windows				
	- Demolition	sum	1	4,604.00	4,604.00
	- New Construction	sum	1	3,183.18	3,183.00
				7,787.18	**7,787.00**
	Doors				
	- Demolition	sum	1	1,608.59	1,609.00
	- New Construction	sum	1	0.00	0.00
				1,608.59	**1,609.00**
	Curtain Panels				
	- New Construction	sum	1	18,046.53	18,047.00
				18,046.53	**18,047.00**
	Railings				
	- New Construction	sum	1	13,016.21	13,016.00
				13,016.21	**13,016.00**
	Construction				
22-01 56 26 50	- Temporary fencing, chain link, 5' high, 11 ga	L.F.	1	499.95	500.00
22-01 58 13 50	- Project signs, sign, high intensity reflectorized, buy, excl. posts	Ea.	1	280.50	281.00
22-01 71 23 13	- Boundary & survey markers, crew for building layout, 2 person crew	Day	1	9,085.26	9,085.00
22-01 74 13 20	- Cleaning up, cleanup of floor area, continuous, per day, during construction	M.S.F.	180	55,214.82	55,215.00
22-01 74 13 20	- Cleaning up, cleanup of floor area, final by GC at end of job	M.S.F.	1	4,588.55	4,589.00
22-01 45 23 50	- Field testing, for concrete building, costing $1,000,000, minimum	Project	1	5,197.50	5,198.00
22-01 31 13 20	- Field personnel, clerk, average	Week	1	13,068.00	13,068.00
22-01 31 13 20	- Field personnel, field engineer, engineer, average	Week	1	40,260.00	40,260.00
				128,194.58	**128,196.00**
	Consultants				
	- Consultant Fees - 8% of Construction Cost		1	24,689.00	24,689.00
				24,689.00	**24,689.00**
	Total amount, excl. VAT			**333,309.77**	**333,312.00**
	VAT (25%)				**83,328.00**
	Total amount, incl. VAT				**416,640.00**

08 - Insetting

Category - text	Unit	Quantity	Price/quantity	Total Cost
Equipment				**5,162.00**
- 50' Air Hoses, 1.5"	Days	33.4632	25.03	837.42
- Air Compressor, 250 cfm	Days	16.7316	184.75	3,091.08
- Breaker, Pavement, 60 lb.	Days	33.4632	11.83	395.70
- Flatbed Truck, Gas, 1.5 Ton	Days	2.0489	214.72	439.94
- Level, Electronic	Days	7	49.94	349.58
- Welder, Gas Engine, 300 amp	Days	0.4588	105.22	48.28
Labor				**157,411.54**
- Bricklayer Helpers	Hours	135.2761	61.69	8,345.29
- Bricklayers	Hours	247.7092	77.95	19,309.76
- Common Building Laborers	Hours	720.5127	62.11	44,750.07
- Common Building Laborers Outside Foreman	Hours	133.8528	65.13	8,718.46
- Field personnel, clerk, average	Week	24	544.50	13,068.00
- Field personnel, field engineer, engineer, average	Week	24	1,677.50	40,260.00
- Glaziers	Hours	206.8807	74.77	15,469.07
- Roofers, Composition	Hours	6.6209	75.05	496.92
- Skilled Workers Average (35 trades)	Hours	56	81.22	4,548.40
- Structural Steel Workers	Hours	11.0118	89.32	983.57
- Structural Steel Workers Outside Foreman	Hours	3.6706	92.51	339.57
- Truck Drivers, Light	Hours	16.3913	68.48	1,122.44
Materials				**140,849.74**
- Brick walls, face brick, red, running bond, 6.75/SF, 4" thick, includes mortar, 3% brick waste and 25% mortar waste, excludes scaffolding, horizontal	S.F.	1,200.0301	4.48	5,372.53
- Cleaning up, cleanup of floor area, continuous, per day, during construction	M.S.F.	18,000	2.57	46,332.00
- Cleaning up, cleanup of floor area, final by GC at end of job	M.S.F.	1,380	2.73	3,764.64
- Concrete block partitions, normal weight blocks, 2000 psi, 6" x 8" x 16", tooled joints both sides, includes mortar, excludes scaffolding, horizontal	S.F.	1,200.0301	2.73	3,273.68
- Concrete block, insulation inserts, styrofoam, 8" x 16" units, 6" thick, plant installed, add to block prices	S.F.	1,200.0301	1.34	1,610.44
- Control joint, PVC, for double wythe 8" minimum wall (Brick/CMU)	L.F.	60.0015	1.86	111.54
- Doors, glass, swing, tempered, 1/2" thick, 3' x 7' opening, incl. hardware	Opng.	1	2,585.00	2,585.00
- Joint sealants, caulking and sealants, butyl based, bulk, 1/4" x 1/2"	L.F.	150.0038	0.26	39.60
- Lintel angle, structural, unpainted, under 500 lb., shop fabricated	Lb.	1,200.0301	1.12	1,346.43
- Masonry anchors, cavity wall ties, Z-type, galvanized, 6" long x 1/4" diameter	C	3.6001	44.00	158.40
- Pre-formed joint seals, backer rod, polyethylene, 1/4" dia	C.L.F.	1.2	2.66	3.19
- Project signs, sign, high intensity reflectorized, buy, excl. posts	Ea.	10	28.05	280.50
- Railing, industrial, welded, steel pipe, 2 rails, 3'-6" high, posts @ 5' OC, 1-1/2" dia x 42" H, shop fabricated	L.F.	117	45.10	5,276.70
- Sheet glass, grey, 1/4" thick	S.F.	357	8.64	3,082.70
- Sheet metal flashing, aluminum, flexible, mill finish, .019" thick, including up	S.F.	120.003	1.56	187.44
- Temporary fencing, chain link, 5' high, 11 ga	L.F.	111.9652	1.97	220.46
- Washing brick, smooth brick, acid wash	S.F.	1,200.0301	0.06	66.00
- Window wall, aluminum, stock, including glazing, average	S.F.	865.7442	77.55	67,138.46
				303,423.27

08 - Insetting

No.	Text	Unit	Quantity	Total Cost	Sales Price
	Fixed items				
	Railings				
	- Demolished	sum	1	10,969.32	10,969.00
	- New Construction	sum	1	125,312.23	125,312.00
				136,281.54	**136,281.00**
	Floors				
	- Demolished	sum	1	735.28	735.00
	- New Construction	sum	1	25,086.54	25,087.00
				25,821.82	**25,822.00**
	Stairs				
	- Demolished	sum	1	1,912.55	1,913.00
	- New Construction	sum	1	3,485.17	3,485.00
				5,397.72	**5,398.00**
	Walls				
	- Demolished	sum	1	661.38	661.00
	- New Construction	sum	1	214,341.68	214,342.00
				215,003.06	**215,003.00**
	Doors				
	- New Construction	sum	1	62,177.57	62,178.00
				62,177.57	**62,178.00**
	Windows				
	- New Construction	sum	1	3,969.46	3,969.00
				3,969.46	**3,969.00**
	Curtain Panels				
	- New Construction	sum	1	10,978.95	10,979.00
				10,978.95	**10,979.00**
	Roofs				
	- New Construction	sum	1	1,624.18	1,624.00
				1,624.18	**1,624.00**
	Construction				
22-01 56 26 50	- Temporary fencing, chain link, 5' high, 11 ga	L.F.	1	499.95	500.00
22-01 58 13 50	- Project signs, sign, high intensity reflectorized, buy, excl. posts	Ea.	1	280.50	281.00
22-01 71 23 13	- Boundary & survey markers, crew for building layout, 2 person crew	Day	1	9,085.26	9,085.00
22-01 74 13 20	- Cleaning up, cleanup of floor area, continuous, per day, during construction	M.S.F.	120	36,809.88	36,810.00
22-01 74 13 20	- Cleaning up, cleanup of floor area, final by GC at end of job	M.S.F.	1	4,588.55	4,589.00
22-01 45 23 50	- Field testing, for concrete building, costing $1,000,000, minimum	Project	1	5,197.50	5,198.00
22-01 31 13 20	- Field personnel, clerk, average	Week	1	8,712.00	8,712.00
22-01 31 13 20	- Field personnel, field engineer, engineer, average	Week	1	26,840.00	26,840.00
				92,013.64	**92,015.00**
	Consultants				
	- Consultant Fees - 8% of Construction Cost		1	44,261.00	44,261.00
				44,261.00	**44,261.00**
	Total amount, excl. VAT			**597,528.96**	**597,530.00**

09 - Layering

Category - text	Unit	Quantity	Price/quantity	Total Cost
Equipment				**2,928.44**
- 50' Air Hoses, 1.5"	Days	10.3206	25.03	258.27
- Air Compressor, 250 cfm	Days	5.1603	184.75	953.34
- Application Equipment	Days	0.2113	199.27	42.11
- Breaker, Pavement, 60 lb.	Days	10.3206	11.83	122.04
- Crew Truck	Days	0.2113	169.79	35.88
- Flatbed Truck, Gas, 1.5 Ton	Days	1.4239	214.72	305.74
- Level, Electronic	Days	7	49.94	349.58
- Tar Kettle/Pot	Days	0.2113	196.02	41.42
- Welder, Gas Engine, 300 amp	Days	7.7941	105.22	820.06
Labor				**153,119.88**
- Bricklayer Helpers	Hours	3.4537	61.69	213.06
- Bricklayers	Hours	6.3242	77.95	492.99
- Carpenters	Hours	283.0429	78.15	22,118.80
- Carpenters Outside Foreman	Hours	40.7607	81.17	3,308.65
- Common Building Laborers	Hours	447.0228	62.11	27,763.98
- Common Building Laborers Outside Foreman	Hours	41.2824	65.13	2,688.92
- Field personnel, clerk, average	Week	16	544.50	8,712.00
- Field personnel, field engineer, engineer, average	Week	16	1,677.50	26,840.00
- Glaziers	Hours	432.4203	74.77	32,333.32
- Roofers, Composition	Hours	6.931	75.05	520.20
- Roofers, Composition Outside Foreman	Hours	1.6905	78.39	132.51
- Roofers, Helpers (Composition)	Hours	3.381	56.39	190.67
- Skilled Workers Average (35 trades)	Hours	56	81.22	4,548.40
- Structural Steel Workers	Hours	187.0587	89.32	16,708.08
- Structural Steel Workers Outside Foreman	Hours	62.3529	92.51	5,768.27
- Truck Drivers, Light	Hours	11.3913	68.48	780.05
Materials				**392,021.81**
- Brick walls, face brick, red, running bond, 6.75/SF, 4" thick, includes mortar, 3% brick waste and 25% mortar waste, excludes scaffolding, horizontal	S.F.	30.6374	4.48	137.16
- Built-up roofing systems, asphalt flood coat with gravel/slag surfacing, asphalt base sheet, 4-plies #15 asphalt felt, mopped, excl. insulation, flashing or	Sq.	4.2262	159.50	674.08
- C.I.P. concrete forms, elevated slab, flat plate, plywood, to 15' high, 1 use, includes shoring, erecting, bracing, stripping and cleaning	S.F.	2,050.1402	4.48	9,178.48
- C.I.P. concrete forms, stairs, (slant length x width), 1 use, includes shoring, erecting, bracing, stripping and cleaning	S.F.	120.96	6.71	811.64
- Cleaning up, cleanup of floor area, continuous, per day, during construction	M.S.F.	12,000	2.57	30,888.00
- Cleaning up, cleanup of floor area, final by GC at end of job	M.S.F.	1,380	2.73	3,764.64
- Concrete block partitions, normal weight blocks, 2000 psi, 6" x 8" x 16", tooled joints both sides, includes mortar, excludes scaffolding, horizontal	S.F.	30.6374	2.73	83.58

09 - Layering

- Concrete block, insulation inserts, styrofoam, 8" x 16" units, 6" thick, plant installed, add to block prices	S.F.	30.6374	1.34	41.12
- Control joint, PVC, for double wythe 8" minimum wall (Brick/CMU)	L.F.	1.5319	1.86	2.85
- Doors, glass, sliding, aluminum, premium, 5/8" tempered insulated glass, 6'-0" x 6'-8"	Ea.	30	1,760.00	52,800.00
- Joint sealants, caulking and sealants, butyl based, bulk, 1/4" x 1/2"	L.F.	3.8297	0.26	1.01
- Lintel angle, structural, unpainted, under 500 lb., shop fabricated	Lb.	30.6374	1.12	34.38
- Masonry anchors, cavity wall ties, Z-type, galvanized, 6" long x 1/4" diameter	C	0.0919	44.00	4.04
- Pre-formed joint seals, backer rod, polyethylene, 1/4" dia	C.L.F.	0.0306	2.66	0.08
- Project signs, sign, high intensity reflectorized, buy, excl. posts	Ea.	10	28.05	280.50
- Railing, industrial, welded, steel pipe, 2 rails, 3'-6" high, posts @ 5' OC, 1-1/2" dia x 42" H, shop fabricated	L.F.	1,987.4986	45.10	89,636.19
- Sheet glass, grey, 1/4" thick	S.F.	694.008	8.64	5,992.76
- Sheet metal flashing, aluminum, flexible, mill finish, .019" thick, including up to 4 bends	S.F.	3.0637	1.56	4.79
- Temporary fencing, chain link, 5' high, 11 ga	L.F.	111.9652	1.97	220.46
- Washing brick, smooth brick, acid wash	S.F.	30.6374	0.06	1.69
- Window wall, aluminum, stock, including glazing, average	S.F.	2,546.2847	77.55	197,464.38
				548,070.14

09 - Layering

No.	Text	Unit	Quantity	Total Cost	Sales Price
	Fixed items				
	Windows				
	Demolished	sum	1	5,052.88	5,053.00
	New Construction	sum	1	13,484.99	13,485.00
				18,537.87	**18,538.00**
	Walls				
	Demolished	sum	1	51,890.22	51,890.00
	New Construction	sum	1	184,995.91	184,996.00
				236,886.12	**236,886.00**
	Curtain Panels				
	- Demolished	sum	1	4,996.19	4,996.00
	- New Construction	sum	1	47,863.98	47,864.00
				52,860.16	**52,860.00**
	Railings				
	- Demolished	sum	1	9,467.11	9,467.00
	- New Construction	sum	1	22,150.21	22,150.00
				31,617.32	**31,617.00**
	Doors				
	- New Construction	sum	1	16,580.69	16,581.00
				16,580.69	**16,581.00**
	Floors				
	- New Construction	sum	1	28,641.99	28,642.00
				28,641.99	**28,642.00**
	Roofs				
	- New Construction	sum	1	2,134.05	2,134.00
				2,134.05	**2,134.00**
	Construction				
22-01 56 26 50	- Temporary fencing, chain link, 5' high, 11 ga	L.F.	1	499.95	500.00
22-01 58 13 50	- Project signs, sign, high intensity reflectorized, buy, excl. posts	Ea.	1	280.50	281.00
22-01 71 23 13	- Boundary & survey markers, crew for building layout, 2 person crew	Day	1	9,085.26	9,085.00
22-01 74 13 20	- Cleaning up, cleanup of floor area, continuous, per day, during construction	M.S.F.	180	55,214.82	55,215.00
22-01 74 13 20	- Cleaning up, cleanup of floor area, final by GC at end of job	M.S.F.	1	4,588.55	4,589.00
22-01 45 23 50	- Field testing, for concrete building, costing $1,000,000, minimum	Project	1	5,197.50	5,198.00
22-01 31 13 20	- Field personnel, clerk, average	Week	1	13,068.00	13,068.00
22-01 31 13 20	- Field personnel, field engineer, engineer, average	Week	1	40,260.00	40,260.00
				128,194.58	**128,196.00**
	Consultants				

	- Consultant Fees - 8% of Construction Cost		1	41,236.00	41,236.00
				41,236.00	**41,236.00**
	Total amount, excl. VAT			**556,688.79**	**556,690.00**
	VAT (25%)				**139,172.50**
	Total amount, incl. VAT				**695,862.50**

10–Extending–Total Cost Breakdown

Category - text	Unit	Quantity	Price/quantity	Total Cost
Equipment				**7,693.21**
- 50' Air Hoses, 1.5"	Days	51.6129	25.03	1,291.61
- Air Compressor, 250 cfm	Days	25.8065	184.75	4,767.62
- Application Equipment	Days	0.2776	199.27	55.33
- Breaker, Pavement, 60 lb.	Days	51.6129	11.83	610.32
- Crew Truck	Days	0.2776	169.79	47.14
- Flatbed Truck, Gas, 1.5 Ton	Days	2.0489	214.72	439.94
- Level, Electronic	Days	7	49.94	349.58
- Tar Kettle/Pot	Days	0.2776	196.02	54.42
- Welder, Gas Engine, 300 amp	Days	0.7341	105.22	77.24
Labor				**247,159.08**
- Bricklayer Helpers	Hours	289.538	61.69	17,861.83
- Bricklayers	Hours	530.1838	77.95	41,329.61
- Carpenters	Hours	203.8113	78.15	15,927.13
- Carpenters Outside Foreman	Hours	39.8417	81.17	3,234.05
- Common Building Laborers	Hours	1,094.7012	62.11	67,990.42
- Common Building Laborers Outside Foreman	Hours	206.4518	65.13	13,447.17
- Field personnel, clerk, average	Week	24	544.50	13,068.00
- Field personnel, field engineer, engineer, average	Week	24	1,677.50	40,260.00
- Glaziers	Hours	322.2825	74.77	24,097.99
- Roofers, Composition	Hours	23.0556	75.05	1,730.40
- Roofers, Composition Outside Foreman	Hours	2.2212	78.39	174.11
- Roofers, Helpers (Composition)	Hours	4.4423	56.39	250.52
- Skilled Workers Average (35 trades)	Hours	56	81.22	4,548.40
- Structural Steel Workers	Hours	17.6188	89.32	1,573.71
- Structural Steel Workers Outside Foreman	Hours	5.8729	92.51	543.31
- Truck Drivers, Light	Hours	16.3913	68.48	1,122.44

10 - Extending

Materials				255,402.83
- Brick walls, face brick, red, running bond, 6.75/SF, 4" thick, includes mortar, 3% brick waste and 25% mortar waste, excludes scaffolding, horizontal	S.F.	2,568.4819	4.48	11,499.09
- Built-up roofing systems, asphalt flood coat with gravel/slag surfacing, asphalt base sheet, 4-plies #15 asphalt felt, mopped, excl. insulation, flashing or	Sq.	5.5529	159.50	885.69
- C.I.P. concrete forms, elevated slab, flat plate, plywood, to 15' high, 1 use, includes shoring, erecting, bracing, stripping and cleaning	S.F.	2,340.7013	4.48	10,479.32
- Cleaning up, cleanup of floor area, continuous, per day, during construction	M.S.F.	18,000	2.57	46,332.00
- Cleaning up, cleanup of floor area, final by GC at end of job	M.S.F.	1,380	2.73	3,764.64
- Concrete block partitions, normal weight blocks, 2000 psi, 6" x 8" x 16", tooled joints both sides, includes mortar, excludes scaffolding, horizontal	S.F.	2,568.4819	2.73	7,006.82
- Concrete block, insulation inserts, styrofoam, 8" x 16" units, 6" thick, plant installed, add to block prices	S.F.	2,568.4819	1.34	3,446.90
- Control joint, PVC, for double wythe 8" minimum wall (Brick/CMU)	L.F.	128.4241	1.86	238.74
- Doors, glass, sliding, aluminum, premium, 5/8" tempered insulated glass, 6'-0" x 6'-8"	Ea.	8	1,760.00	14,080.00
- Joint sealants, caulking and sealants, butyl based, bulk, 1/4" x 1/2"	L.F.	321.0602	0.26	84.76
- Lintel angle, structural, unpainted, under 500 lb., shop fabricated	Lb.	2,568.4819	1.12	2,881.84
- Masonry anchors, cavity wall ties, Z-type, galvanized, 6" long x 1/4" diameter	C	7.7054	44.00	339.04
- Pre-formed joint seals, backer rod, polyethylene, 1/4" dia	C.L.F.	2.5685	2.66	6.84
- Project signs, sign, high intensity reflectorized, buy, excl. posts	Ea.	10	28.05	280.50
- Railing, industrial, welded, steel pipe, 2 rails, 3'-6" high, posts @ 5' OC, 1-1/2" dia x 42" H, shop fabricated	L.F.	187.2	45.10	8,442.72
- Sheet glass, grey, 1/4" thick	S.F.	645.44	8.64	5,573.37
- Sheet metal flashing, aluminum, flexible, mill finish, .019" thick, including up	S.F.	256.8482	1.56	401.20
- Temporary fencing, chain link, 5' high, 11 ga	L.F.	111.9652	1.97	220.46
- Washing brick, smooth brick, acid wash	S.F.	2,568.4819	0.06	141.27
- Window wall, aluminum, stock, including glazing, average	S.F.	1,634.8824	77.55	126,785.13
- Windows, aluminum, horizontal slider, impact resistant, 5'-5" x 5'-2", incl. frame and glazing	Ea.	7	1,787.50	12,512.50
				510,255.12

10 - Extending

C.4.2 Cost-Benefit Analysis (pages **1-7** of **69**)

OVERVIEW & SUMMARY

This worksheet frames the business case for the project using the elements in a typical Capital Expenditure (CAPEX) Request Form.

See the "Overview worksheet" help video for further guidance.

Big Three Justifications	21st Century Capital Request Form Elements Empty numeric fields are filled in automatically as each associated worksheet is completed.								
Do the Right Thing	**Project description**								
	Strategy 01-Restructuring.								
	Purpose fulfillment *								
	Feasibility of Refurbishment Strategy 01-Restructuring.								
	Progress on ESG goals * Fill in how the project will help the company improve its environmental and social performance, using whatever terminology, framework and indicators the company prefers (e.g., Global Reporting Initiative (GRI) indicators, Sustainable Development Goals (SDGs) goals and indicators, Future-Fit Business Benchmark (FFBB) science-based goals and indicators, impact on Integrated Reporting <IR> capitals, etc.)								
	How the initiative improves company environmental performance	N/A							
	How the initiative improves company social performance	Increases quality of housing by restructuring failing balconies.							
Capture Opportunities	**Revenue**	Gross revenue growth	$2,880	Net revenue growth	$403				
	Operating expenses	Expense savings	$5,760	Expense increases	$0	Net savings	$5,760		
	Employee expenses *	Hiring & attrition savings	$0	Productivity benefit	$4,000				
	Capital expenditure	CAPEX required	$140,535						
	ROI / Financial Analysis	**Payback period**	17.3	**NPV**	-$74,221	**IRR**	-27%	**Profit increase**	76%
	Asset value increase *	Increase in asset value	$125,000						
	Market value increase *	Increase in market value	$125,000						
Mitigate Risks	**Risks of NOT doing project** *	Negative cash flow	$17,373	Missed asset value	$125,000	Missed market value	$125,000		
	Risks of DOING the project	Contingency risks	$332,000						

* In addition to traditional financial analysis / ROI criteria, the workbook includes important factors to consider in the more demanding and risky 21st century business environment, as recommended by leading professional accounting organizations.

REVENUE GROWTH

This worksheet assesses how the project directly or indirectly affects top-line revenue growth.

See the "Revenue worksheet" help video for further guidance.

Current Company Data	
Current revenue	$ 96,000.00
Current profit	$ 13,440.00
Current percent profit	14%

Revenue Opportunities	% Growth	Potential Annual Amount
Revenue growth from improved reputation with customers	3%	$2,880
Revenue growth from rental space	0%	$0
Revenue growth from innovative service and financing offerings	0%	$0
	Gross revenue growth	**$2,880**
	Net revenue contribution to annual cash flow	**$403**

01- Restructuring

OPERATING EXPENSES IMPACT

This worksheet assesses how the project directly or indirectly affects Operating Expenses (OPEX).and Employee-related expenses

See the "Expenses worksheet" help video for further guidance.

Operating Expenses	Current Annual Expense	% Savings	Potential Annual Savings
Energy	$11,030	0%	$0
Carbon	$3,978	0%	$0
Shipping	$0	0%	$0
Business travel	$0	0%	$0
Maintenance	$20,000	10%	$2,000
Materials	$19,200	15%	$2,880
Water	$0	0%	$0
Waste disposal	$9,600	5%	$480
Insurance premiums	$8,000	5%	$400
Litigation	$0	0%	$0
Compliance	$0	0%	$0
(Other lower operating expenses …)	$0	0%	$0
Total annual operating expense savings			**$5,760**

Ongoing Expense Increases	Potential Annual Increases
	$0
	$0
Total ongoing / recurring annual operational expenses	**$0**

Total net annual operational expense savings	**$5,760**

Budget Accounts Impacted

Account Name	Acct #	Impact Amount

01- Restructuring

Employee Expenses	Current Annual Expense	% Savings	Potential Annual Benefit
Hiring expenses	$0	0%	**$0**
Attrition expenses	$0	0%	**$0**
Hiring and attrition savings			**$0**

Higher productivity from employees	Current Annual Expense		
Average employee salary	$50,000		
Number of employees	2		
Total payroll / productivity expense	$100,000		
Productivity gains from more time on the job	% Productivity Gain for Affected Employees	% of Employees Affected	Payroll Savings Equivalent
Gains from less unplanned absenteeism	0%	0%	$0
Gains from more telecommuting	0%	0%	$0
Gains from reduced business travel	0%	0%	$0
Productivity gains while on the job	% Productivity Gain for Affected Employees	% of Employees Affected	Payroll Savings Equivalent
Gains from working in green buildings	5%	80%	$4,000
Gains from improved collaboration	0%	0%	$0
Gains from higher employee engagement	0%	0%	$0
Value of higher productivity from employees			**$4,000**

CAPITAL EXPENDITURE & ROI

This worksheet shows the required capital expenditures for the project and the resulting financial analysis / return on investment calculations (ROI).

See the "SRW 3.0 – Capital and ROI worksheet" help video for further guidance.

Capital expenditures (CAPEX)	
Cost of Construction	$120,535
One-time Capital Cost of Implementation	$20,000
	$0
Total onetime capital expenditure (CAPEX)	**$140,535**

Project funding / capital sources

Source	Amount	Borrowing rate
City of Toronto's High-Rise Retrofit Improvement Support Program (Hi-RIS)	$140,535	4.10%
	$0	0.00%
	$0	0.00%
	$0	0.00%
	$0	0.00%

01- Restructuring

ROI CALCULATIONS

This worksheet does the financial analysis / ROI calculations, using values from the other worksheets.
Adjust the starter set of yearly percentages of the benefits realized (50% - 80% - 100% - 100% - 100%) to reflect your situation.

Totals from other worksheets		Annual Totals	Year 1 % and amount	Year 2 % and amount	Year 3 % and amount	Year 4 % and amount	Year 5 % and amount
Net revenue growth		$403	80%	100%	100%	100%	100%
			$323	$403	$403	$403	$403
Net operational expense savings		$5,760	80%	100%	100%	100%	100%
			$4,608	$5,760	$5,760	$5,760	$5,760
Employee hiring and attrition savings		$0	80%	100%	100%	100%	100%
			$0	$0	$0	$0	$0
Employee productivity benefit		$4,000	80%	100%	100%	100%	100%
			$3,200	$4,000	$4,000	$4,000	$4,000
Net annual cash flow		**$10,163**	**$8,131**	**$10,163**	**$10,163**	**$10,163**	**$10,163**
IRR	**-27%**	-140,535	$8,131	$10,163	$10,163	$10,163	$10,163
Payback period	**17.3**	Cumulative totals	-$132,404	-$122,241	-$112,078	-$101,915	-$91,752
NPV	**-$74,221**	Discount rate used in the NPV calculation	8%	(Don't forget this)			

Year 6 % and amount	Year 7 % and amount	Year 8 % and amount	Year 9 % and amount	Year 10 % and amount	Year 11 % and amount	Year 12 % and amount	Year 13 % and amount	Year 14 % and amount
100%	100%	100%	100%	100%	100%	100%	100%	100%
$403	$403	$403	$403	$403	$403	$403	$403	$403
100%	100%	100%	100%	100%	100%	100%	100%	100%
$5,760	$5,760	$5,760	$5,760	$5,760	$5,760	$5,760	$5,760	$5,760
100%	100%	100%	100%	100%	100%	100%	100%	100%
$0	$0	$0	$0	$0	$0	$0	$0	$0
100%	100%	100%	100%	100%	100%	100%	100%	100%
$4,000	$4,000	$4,000	$4,000	$4,000	$4,000	$4,000	$4,000	$4,000
$10,163	**$10,163**	**$10,163**	**$10,163**	**$10,163**	**$10,163**	**$10,163**	**$10,163**	**$10,163**
$10,163	$10,163	$10,163	$10,163	$10,163	$10,163	$10,163	$10,163	$10,163
-$81,588	-$71,425	-$61,262	-$51,099	-$40,936	-$30,772	-$20,609	-$10,446	-$283

Year 15 % and amount	Year 16 % and amount	Year 17 % and amount	Year 18 % and amount	Year 19 % and amount	Year 20 % and amount	Year 21 % and amount	Year 22 % and amount	Year 23 % and amount
100%	100%	100%	100%	100%	100%	100%	100%	100%
$403	$403	$403	$403	$403	$403	$403	$403	$403
100%	100%	100%	100%	100%	100%	100%	100%	100%
$5,760	$5,760	$5,760	$5,760	$5,760	$5,760	$5,760	$5,760	$5,760
100%	100%	100%	100%	100%	100%	100%	100%	100%
$0	$0	$0	$0	$0	$0	$0	$0	$0
100%	100%	100%	100%	100%	100%	100%	100%	100%
$4,000	$4,000	$4,000	$4,000	$4,000	$4,000	$4,000	$4,000	$4,000
$10,163	**$10,163**	**$10,163**	**$10,163**	**$10,163**	**$10,163**	**$10,163**	**$10,163**	**$10,163**
$10,163	$10,163	$10,163	$10,163	$10,163	$10,163	$10,163	$10,163	$10,163
$9,880	$20,044	$30,207	$40,370	$50,533	$60,696	$70,860	$81,023	$91,186

Year 24 % and amount	Year 25 % and amount	Year 26 % and amount	Year 27 % and amount	Year 28 % and amount	Year 28 % and amount	Year 29 % and amount	Year 30 % and amount
100%	100%	100%	100%	100%	100%	100%	100%
$403	$403	$403	$403	$403	$403	$403	$403
100%	100%	100%	100%	100%	100%	100%	100%
$5,760	$5,760	$5,760	$5,760	$5,760	$5,760	$5,760	$5,760
100%	100%	100%	100%	100%	100%	100%	100%
$0	$0	$0	$0	$0	$0	$0	$0
100%	100%	100%	100%	100%	100%	100%	100%
$4,000	$4,000	$4,000	$4,000	$4,000	$4,000	$4,000	$4,000
$10,163	**$10,163**	**$10,163**	**$10,163**	**$10,163**	**$10,163**	**$10,163**	**$10,163**
$10,163	$10,163	$10,163	$10,163	$10,163	$10,163	$10,163	$10,163
$101,349	$111,512	$121,676	$131,839	$142,002	$152,165	$162,328	$172,492

01- Restructuring

Asset and Market Value risks ... if the project is ***not*** undertaken	% Impact	% Probability within timeframe	Change
Risks of lower asset values			
Risk of lower value of company-owned real estate	5%	50%	$125,000
Risk of lower value of company-owned vehicles	0%	0%	$0
Risk of lower value of company-owned equipment	0%	0%	$0
Risk of lower value of company investment portfolio	0%	0%	$0
Risk of lower value of other company asset (customize)	0%	0%	$0
		Potential decrease in asset values	$125,000
Risk of lower market value	% Impact	% Probability within timeframe	Decrease
Risk of lower market value / capitalization	5%	50%	$125,000

Contingency risks … if the project ***is*** undertaken	Potential Impact	% Probability within timeframe	Potential Risk
Risk to revenue, reputation with customers, and social license to operate	$0	0%	$0
Risk of expense overruns and size of emergency / contingency funds	$600,000	50%	$300,000
Risk of higher attrition and lower employee engagement / productivity	$0	0%	$0
Risk of loss of asset values	$400,000	8%	$32,000
Risk of loss of market value	$0	0%	$0
Risk of other (customize)	$0	0%	$0
		Amount at Risk	**$332,000**

01- Restructuring

ASSET VALUE IMPACTS

This worksheet assesses how the project directly or indirectly affects the value of company assets and its market capitalization.

See the "SRW 3.0 – Asset and Market Values worksheet" help video for further guidance.

Potential increase in asset values	Current value	% Change	Increase
Increase in value of company-owned real estate	$5,000,000	3%	$125,000
Increase in value of company-owned vehicles	$0	0%	$0
Increase in value of company-owned equipment	$0	0%	$0
Increase in value of company investment portfolio	$0	0%	$0
(Increase in value of other company asset ...)	$0	0%	$0
Potential increase in asset values			$125,000

Potential increase in market value / capitalization	Current value	% Change	Increase
Increase in market value / capitalization	$5,000,000	3%	$125,000

RISK ANALYSIS

This worksheet assesses the risks if the project is ***not***, or ***is***, undertaken.

See the "SRW 3.0 – Risk Analysis worksheet" help video for further guidance.

Revenue and Expense Risks ... if the project is ***not*** undertaken	% Impact	% Probability within timeframe	Amount at risk
Risk of lost revenue from poor company reputation with customers	6%	50%	$2,880
Risk of lost revenue from products with outdated, unsustainable features	0%	0%	$0
Risk of missed revenue from potential services and financing offerings	0%	0%	$0
Risk of not Improving existing building	40%	50%	$19,200
Net contribution of revenue loss to profit at risk			$3,091
Risk of higher energy expenses	40%	50%	$2,206
Risk of higher carbon expenses	40%	50%	$796
Risk of higher shipping and transportation expenses	0%	0%	$0
Risk of higher business travel expenses	0%	0%	$0
Risk of higher maintenance expenses	60%	50%	$6,000
Risk of higher materials costs	20%	50%	$1,920
Risk of higher water costs	0%	0%	$0
Risk of higher waste disposal costs	20%	50%	$960
Risk of higher insurance premiums	60%	50%	$2,400
Risk of higher litigation expenses	0%	0%	$0
Risk of higher compliance expenses	0%	0%	$0
(Risk of other higher operating expenses ...)	0%	0%	$0
Risk of higher hiring costs	10%	50%	$0
Risk of higher attrition costs	10%	50%	$0
Risk of lower employee engagement and productivity	0%	0%	$0
% Profit at risk	129%	**Negative annual cash flow**	$17,373

01- Restructuring

PROJECT APPRAISAL

This worksheet provides a structured decision-making approach to appraising a capital expenditure (CAPEX) request.

See the "SRW 3.0 – Project Appraisal worksheet" help video for further guidance.

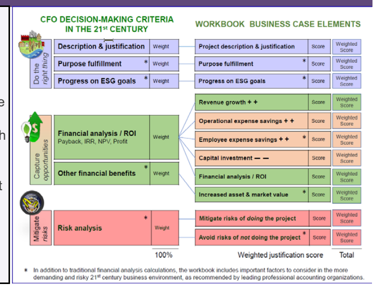
Multi-Criteria Analysis

The tool uses a multi-criteria analysis (MCA) structured decision-making approach to enable CEOs, CFOs, and other executives to make rigorous and transparent decisions about projects that require capital expenditures in the 21st century. A key feature of MCA is its emphasis on the judgement of the decision-making team in determining the relative *weight* or importance of each decision-making criterion, and *scoring* the performance of projects against the criteria. Weights reflect decision-makers' mindsets:

* **Purpose-weighted mindset:** For founder-owned businesses where the founders have strong personal values that are institutionalized throughout the company, the dominant weighting may be on the "Do the right thing" criteria. This may be the most heavily weighted justification for projects in B Corps, cooperatives, social enterprises, and corporations with strong values-based cultures.

* **Opportunity-weighted mindset:** This is usually the dominant mindset of CFOs. Their mandates incline them to approve projects that are cost justified in the short- and/or long-term. In fact, they may be especially driven by an aspect of the "Capture opportunities" cluster of criteria, such as payback period, expense savings, top-line revenue growth, or how the successful project might affect the company's share price.

* **Risk avoidance-weighted mindset:** This is the flip side of the opportunity-weighted mindset. Risk avoidance is a prevalent mindset in mature corporations, where robust enterprise risk management (ERM) processes may be a point of pride and viewed as a sign of prudent governance.



Project Appraisal Tool

Weights and scores are ***starter*** values; replace them with the decision-makers' consensus on what they should be.

Big Three Justifications	Weight for each justification	Weight for each criterion	Performance on each criterion	Score 0-5	Wght'd Score
Do the Right Thing	20%	10%	**Purpose fulfillment** Feasibility of Refurbishment Strategy 01-Restructuring.	3	30
		10%	**Progress on ESG goals** How the initiative improves company environmental performance: N/A How the initiative improves company social performance: Increases quality of housing by restructuring failing balconies.	4	40
		20%			**70**
Capture Opportunities	50%	3%	**Revenue** Gross revenue: $2,880 · Net revenue: $403	4	12
		3%	**Operating expenses** Expense savings: $5,760 · Expense increases: $0 · Net savings: $5,760	5	15
		3%	**Employee expenses** Hiring and attrition savings: $0 · Productivity benefit: $4,000	5	15
		8%	**Capital expenditure (CAPEX)** CAPEX: $140,535	3	24
		30%	**ROI / Financial Analysis** Payback period: 17.3 · IRR: -27% · NPV: -$74,221 · Profit increase: 76%	5	150
		3%	**Asset value and Market value improvement** Asset values: $125,000 · Market value: $125,000	3	9
		50%			**225**
Mitigate Risks	30%	20%	**Avoid risks of NOT doing the project** Negative cash flow: $17,373 · Missed asset value: $125,000 · Missed market value: $125,000	4	80
		10%	**Mitigate risks of DOING the project** Contingency risks: $332,000	3	30
		30%			**110**
	100%		**Weighted Justification Score**		***405***

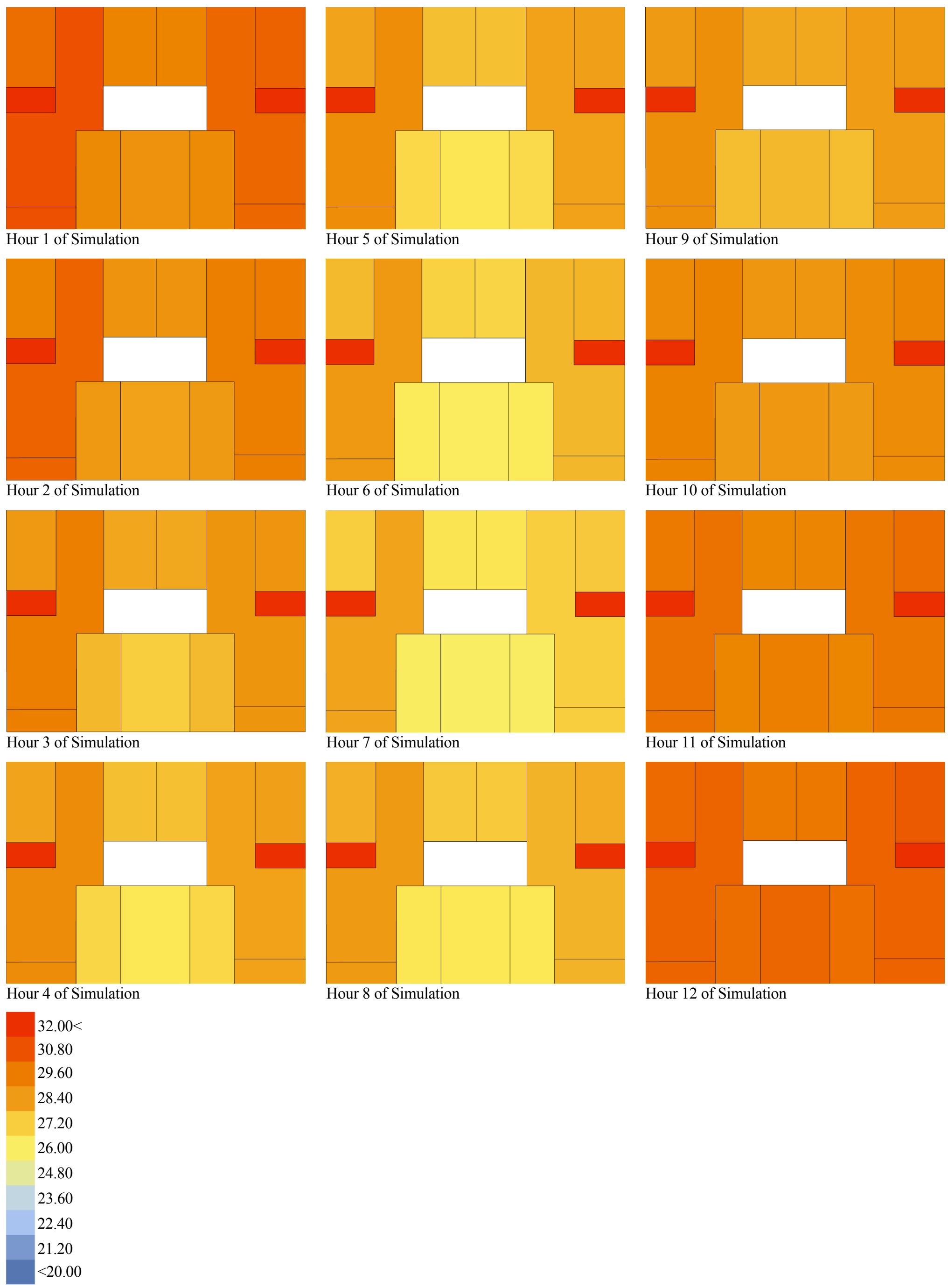
The Weighted Justification Score provides a helpful metric by which to compare multiple projects that are competing for limited capital funds, if they are appraised using similarly weighted justification criteria. Separate workbooks would be used to genertate the scores for each project.

01- Restructuring

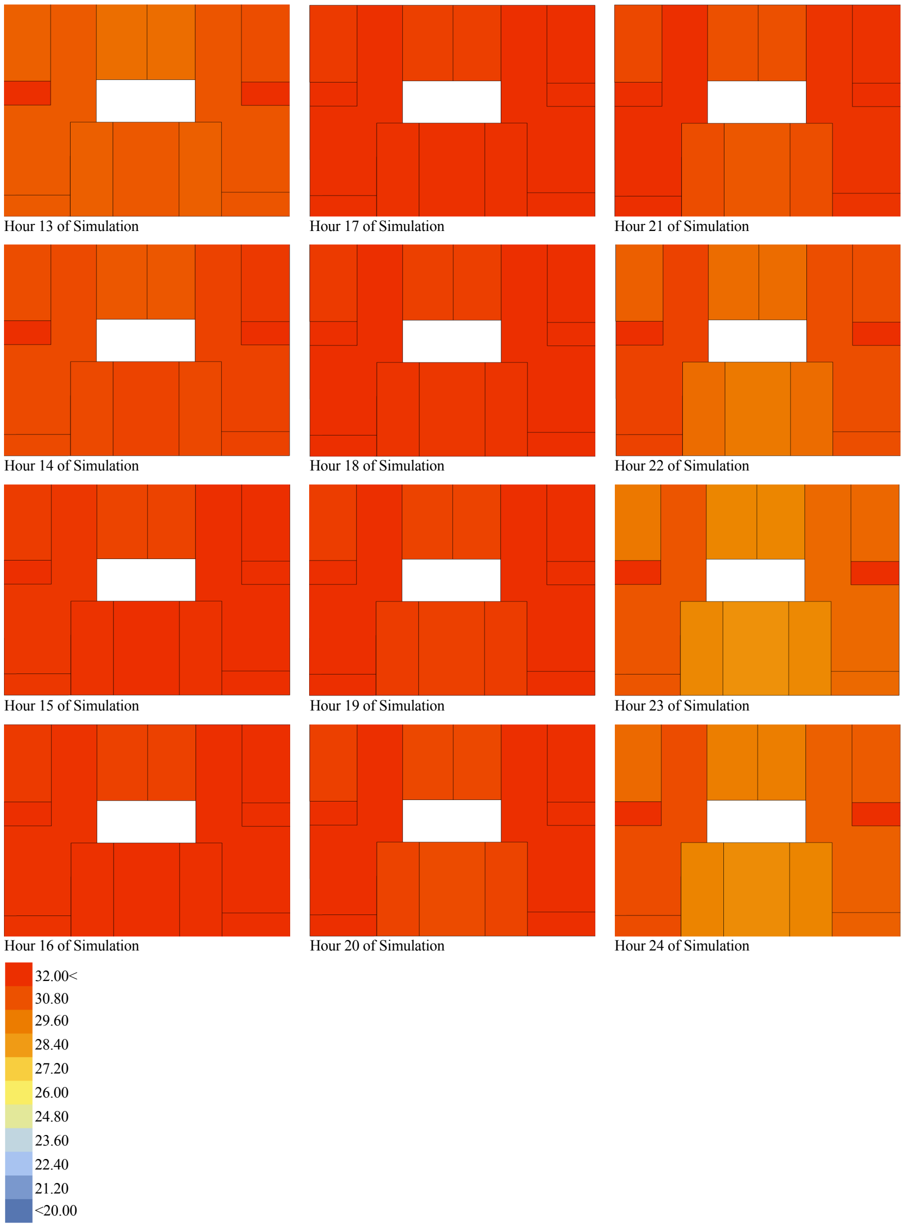
C.5 Thermal Comfort

C.5.1 Average Operative Temperature –Typical Hot Week (°C)

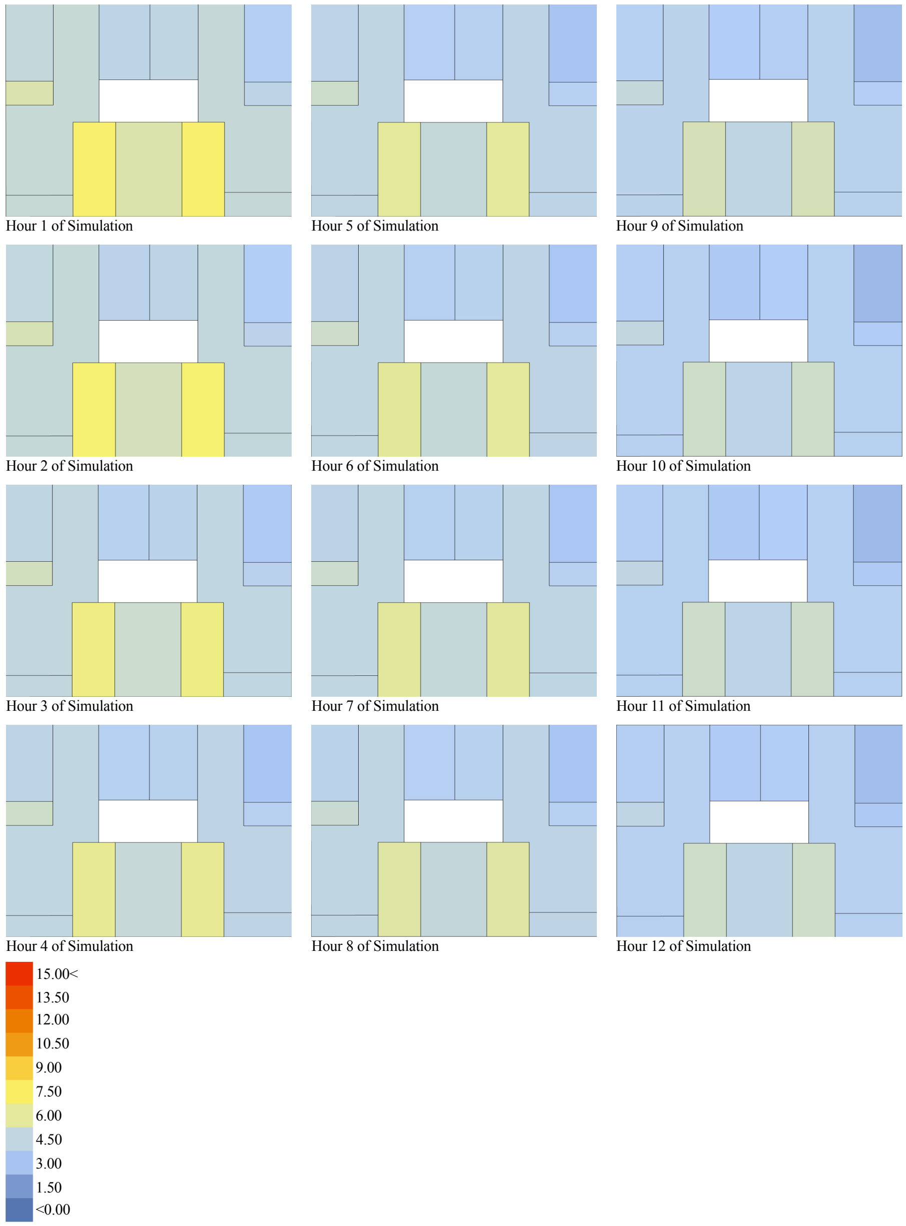
(pages **1-4** of **47**)



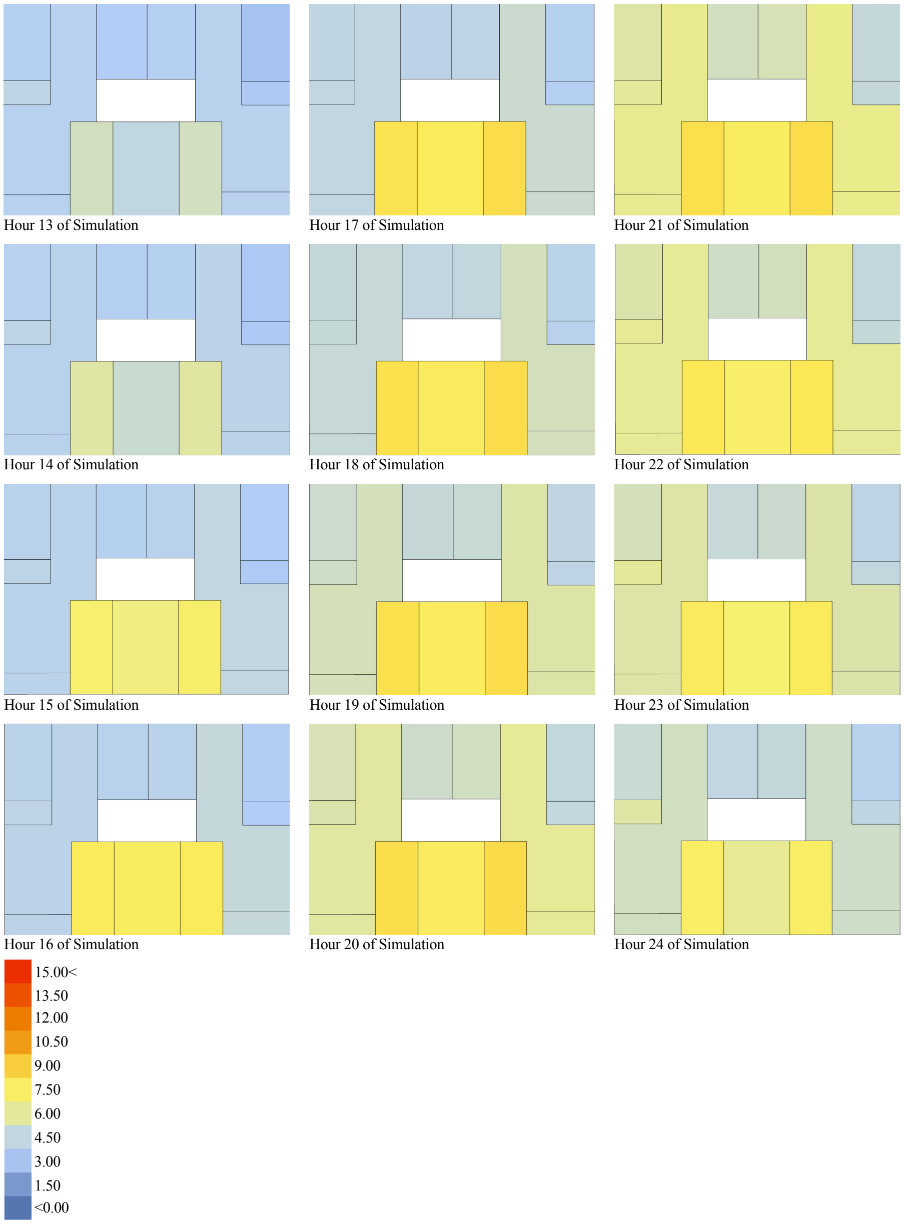
00 - Existing


Hour 13 of Simulation
Hour 17 of Simulation
Hour 21 of Simulation
Hour 14 of Simulation
Hour 18 of Simulation
Hour 22 of Simulation
Hour 15 of Simulation
Hour 19 of Simulation
Hour 23 of Simulation
Hour 16 of Simulation
Hour 20 of Simulation
Hour 24 of Simulation
32.00<
30.80
29.60
28.40
27.20
26.00
24.80
23.60
22.40
21.20
<20.00

00 - Existing


Hour 1 of Simulation
Hour 5 of Simulation
Hour 9 of Simulation
Hour 2 of Simulation
Hour 6 of Simulation
Hour 10 of Simulation
Hour 3 of Simulation
Hour 7 of Simulation
Hour 11 of Simulation
Hour 4 of Simulation
Hour 8 of Simulation
Hour 12 of Simulation
15.00<
13.50
12.00
10.50
9.00
7.50
6.00
4.50
3.00
1.50
<0.00

00 - Existing


Hour 13 of Simulation
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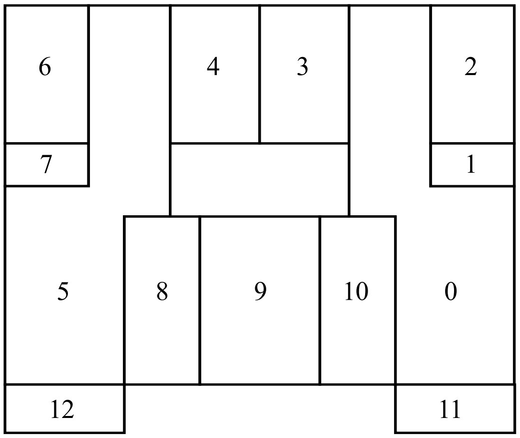
1.50
<0.00

00 - Existing

C.5.2 Percentage of Time Comfortable – Typical Hot Week (°C)



Assigned Zones

	Hot Week (% of time comfortable)						
	Zone 0	Zone 1	Zone 2	Zone 3	Zone 4	Zone 5	Zone 6
00-Existing	60.7	72	56.5	0	75.6	75.6	0
01-Restructuring							
02-Reglazing	72	0	55.4	74.4	76.2	76.8	59.5
03-Recladding	81.5	0	80.4	81.5	81	78	0
04-Enclosing	61.3	75.6	75.6	14.3	75.6	59.5	74.4
05-Insulating	74.4	0	56.5	14.3	65.5	13.1	75.6
06-Adding	58.9	68.5	83.3	75.6	0	56.5	75.6
07-Relocating	76.2	0	56.5	75.6	75.6	63.1	63.1
08-Insetting	59.5	0	56.5	75.6	76.2	53.6	61.3
09-Layering	66.1	0	56.5	75.6	76.2	54.2	61.3
10-Extension	50	0	56.5	75.6	75.6	54.8	61.3

	Zone 7	Zone 8	Zone 9	Zone 10	Zone 11	Zone 12	Average
00-Existing	52.4	61.3	72	73.8	-	-	54.5
01-Restructuring							
02-Reglazing	61.3	0	74.4	59.5	-	-	55.4
03-Recladding	76.2	78	79.2	78.6	-	-	64.9
04-Enclosing	0	13.1	0	56.5	65.5	76.2	49.8
05-Insulating	75.6	59.5	61.3	0	76.2	75.6	49.8
06-Adding	82.1	0	0	0	-	-	45.5
07-Relocating	0	73.2	73.8	72	-	-	57.2
08-Insetting	0	76.2	78.6	76.2	-	-	55.8
09-Layering	0	72	89.9	89.3	-	-	58.3
10-Extension	0	73.2	74.4	0	-	-	47.4

C.5.3 Average Temperatures per Zone – Hot and Cold Week (°C)

(pages **1** of **13**)

Zone	HR 0	HR 1	HR 2	HR 3	HR 4	HR 5	HR 6	HR 7	HR 8	HR 9	HR 10	HR 11	HR 12
0	30.18	29.53	28.68	28.13	28.11	27.65	27.19	27.73	28.38	29.07	29.75	30.28	30.67
1	29.10	28.44	27.58	27.01	26.96	26.47	26.09	26.71	27.52	28.45	29.32	29.97	30.40
2	30.31	29.63	28.73	28.20	28.20	27.72	27.31	27.88	28.58	29.29	29.99	30.54	30.96
3	38.11	37.83	37.53	37.22	36.97	36.85	36.66	36.40	36.05	35.84	35.80	35.87	36.05
4	29.37	28.77	27.96	27.47	27.47	27.08	26.74	27.30	27.96	28.65	29.28	29.71	30.01
5	29.37	28.77	27.98	27.49	27.50	27.11	26.77	27.32	27.97	28.65	29.27	29.70	30.00
6	36.30	36.16	35.99	35.79	35.65	35.62	35.51	35.32	34.97	34.71	34.52	34.37	34.26
7	30.84	30.29	29.53	29.04	29.02	28.57	28.05	28.47	28.93	29.39	29.87	30.25	30.52
8	29.99	29.38	28.53	28.04	28.07	27.59	27.19	27.78	28.46	29.11	29.70	30.10	30.37
9	29.13	28.48	27.62	27.06	27.00	26.51	26.12	26.73	27.54	28.46	29.33	29.99	30.41
10	28.83	28.12	27.23	26.71	26.72	26.24	25.96	26.71	27.63	28.63	29.54	30.20	30.59

Zone	HR 13	HR 14	HR 15	HR 16	HR 17	HR 18	HR 19	HR 20	HR 21	HR 22	HR 23	Average
0	31.35	32.07	32.20	32.25	32.26	32.14	32.06	31.81	30.92	30.11	30.38	30.12
1	31.13	31.89	31.97	31.92	31.82	31.56	31.27	30.93	30.03	29.19	29.33	29.38
2	31.67	32.41	32.54	32.57	32.54	32.37	32.21	31.89	30.97	30.19	30.52	30.30
3	36.30	36.60	36.96	37.42	37.89	38.35	38.75	39.02	39.02	38.81	38.50	37.28
4	30.62	31.28	31.39	31.43	31.44	31.31	31.16	30.87	30.04	29.30	29.55	29.42
5	30.61	31.26	31.37	31.42	31.42	31.29	31.14	30.86	30.04	29.31	29.55	29.42
6	34.21	34.23	34.36	34.68	35.10	35.57	36.05	36.46	36.63	36.61	36.51	35.40
7	31.09	31.73	31.85	31.94	32.04	32.05	32.13	32.06	31.33	30.66	30.99	30.44
8	30.95	31.57	31.62	31.63	31.62	31.51	31.39	31.16	30.38	29.73	30.13	29.83
9	31.12	31.86	31.94	31.90	31.81	31.55	31.28	30.95	30.05	29.21	29.36	29.39
10	31.31	32.03	32.03	31.91	31.75	31.42	31.03	30.61	29.69	28.86	29.07	29.28

00-Existing–Thermal Comfort Results -Typical Hot Week–Average Temperatures (°C)

Zone	HR 0	HR 1	HR 2	HR 3	HR 4	HR 5	HR 6	HR 7	HR 8	HR 9	HR 10	HR 11	HR 12
0	4.86	4.66	4.43	4.24	4.18	4.26	4.30	4.24	3.91	3.70	3.68	3.76	3.88
1	6.96	6.69	6.38	6.13	5.99	5.99	5.95	5.83	5.47	5.23	5.18	5.23	5.37
2	3.55	3.40	3.20	3.05	3.00	3.07	3.10	3.05	2.77	2.63	2.67	2.79	2.94
3	4.16	4.03	3.88	3.75	3.69	3.73	3.74	3.69	3.46	3.29	3.21	3.17	3.16
4	4.38	4.21	4.00	3.84	3.78	3.84	3.86	3.79	3.50	3.32	3.32	3.40	3.53
5	4.19	4.02	3.82	3.66	3.60	3.67	3.70	3.64	3.35	3.18	3.19	3.27	3.40
6	5.65	5.53	5.39	5.24	5.16	5.17	5.14	5.04	4.75	4.54	4.40	4.31	4.25
7	5.01	4.82	4.61	4.43	4.36	4.43	4.44	4.36	4.00	3.77	3.71	3.74	3.81
8	4.75	4.59	4.37	4.20	4.11	4.14	4.12	4.01	3.68	3.49	3.48	3.55	3.66
9	6.94	6.68	6.37	6.12	5.99	5.99	5.95	5.83	5.47	5.23	5.18	5.23	5.36
10	5.69	5.44	5.13	4.90	4.79	4.82	4.80	4.69	4.32	4.10	4.11	4.22	4.42

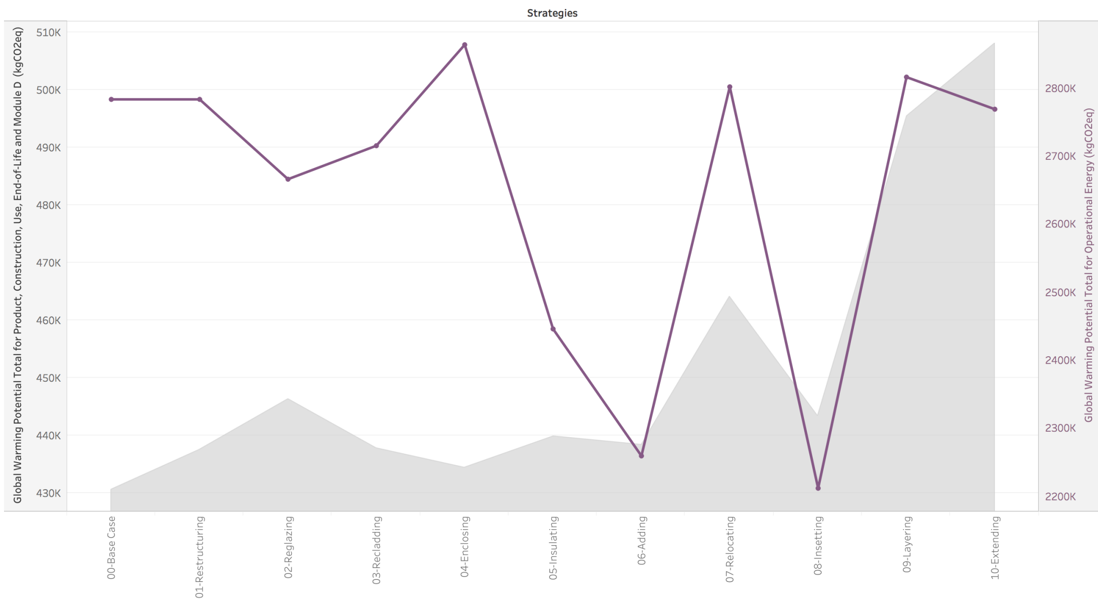
Zone	HR 13	HR 14	HR 15	HR 16	HR 17	HR 18	HR 19	HR 20	HR 21	HR 22	HR 23	Average
0	4.13	4.45	4.76	5.09	5.41	5.77	6.09	6.25	6.09	5.71	5.23	4.71
1	5.86	7.00	8.10	8.62	8.64	8.62	8.66	8.63	8.37	7.92	7.38	6.84
2	3.14	3.28	3.44	3.73	4.04	4.38	4.65	4.76	4.60	4.26	3.84	3.47
3	3.18	3.21	3.31	3.56	3.88	4.25	4.56	4.76	4.76	4.61	4.37	3.81
4	3.70	3.82	3.97	4.26	4.60	4.99	5.32	5.50	5.39	5.08	4.68	4.17
5	3.57	3.70	3.85	4.15	4.50	4.88	5.19	5.35	5.23	4.91	4.49	4.02
6	4.21	4.19	4.25	4.49	4.83	5.27	5.68	6.01	6.10	6.02	5.83	5.06
7	3.92	4.00	4.14	4.49	4.93	5.45	5.90	6.17	6.09	5.78	5.35	4.65
8	3.82	3.93	4.07	4.36	4.71	5.15	5.55	5.79	5.72	5.44	5.04	4.40
9	5.83	6.88	7.95	8.50	8.55	8.55	8.61	8.60	8.34	7.90	7.37	6.81
10	5.07	6.42	7.62	8.09	7.90	7.75	7.72	7.62	7.27	6.74	6.13	5.82

00-Existing–Thermal Comfort Results -Typical Cold Week–Average Temperatures (°C) (Page 1 of 13)

C.6 Life Cycle Analysis

C.6.1 Life Cycle Analysis - Overview of Results

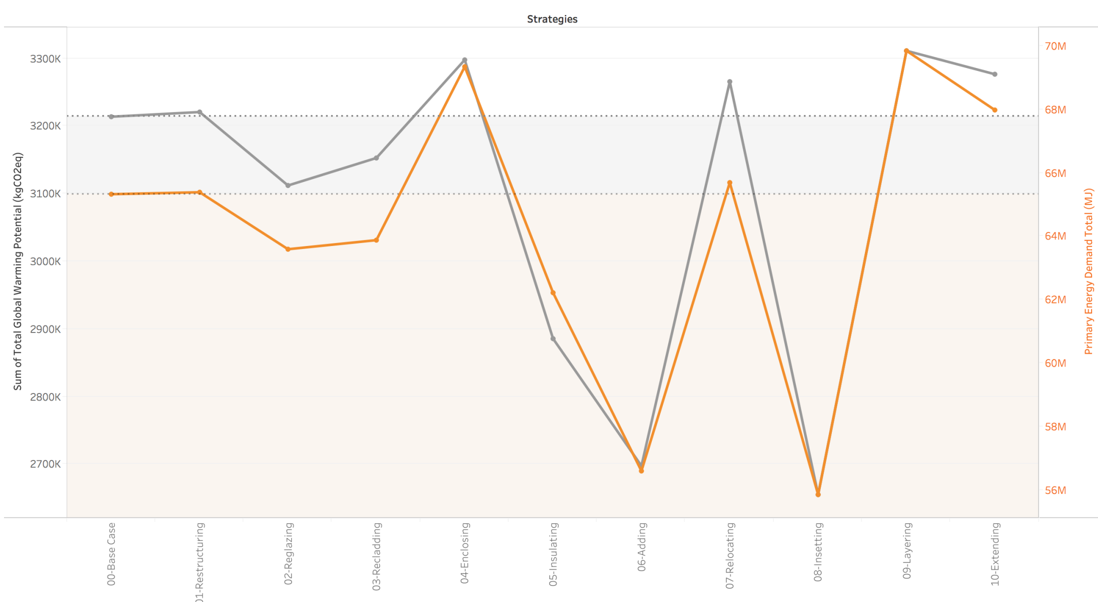
GWP of Product, Construction, Use, EoL, Module D vs. GWP of OE



The trends of Global Warming Potential Total for Product, Construction, Use, End-of-Life and Module D (kgCO2eq) and Global Warming Potential Total for Operational Energy (kgCO2eq) for Strategies. Color shows details about Global Warming Potential Total for Product, Construction, Use, End-of-Life and Module D (kgCO2eq) and Global Warming Potential Total for Operational Energy (kgCO2eq).

Measure Names
- Global Warming Potential Total for Operational Energy (kgCO2eq)
- Global Warming Potential Total for Product, Construction, Use, End-of-Life and Module D (kgCO2eq)

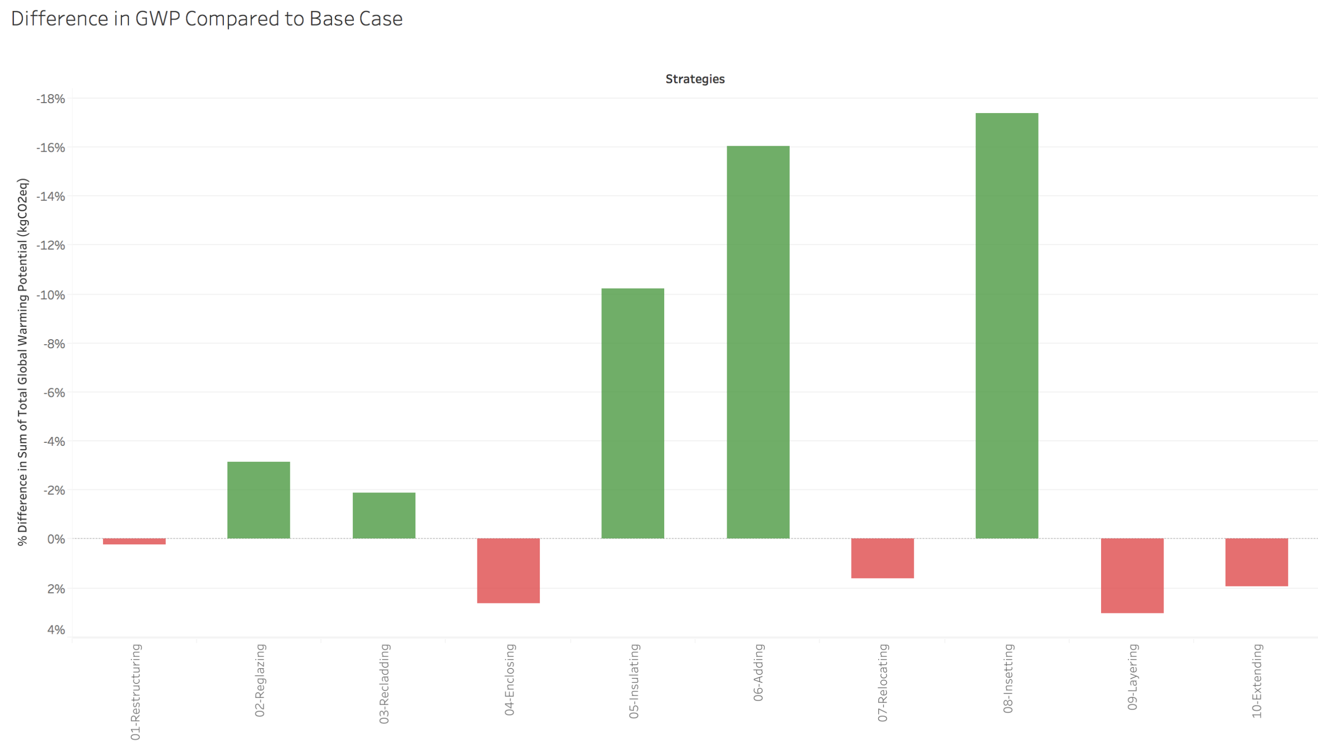
Sum of GWP vs. PED



The trends of sum of Sum of Total Global Warming Potential (kgCO2eq) and Primary Energy Demand Total (MJ) for Strategies. For pane Sum of Primary Energy Demand Total (MJ): Color shows details about Primary Energy Demand Total (MJ).

Measure Names
- Primary Energy Demand Total (MJ)

C.6.2 Life Cycle Analysis – Percentage of Change

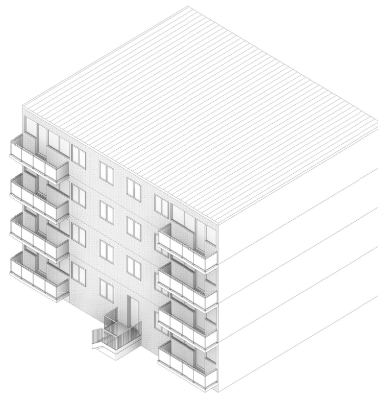


% Difference in Sum of Total Global Warming Potential (kgCO2eq) for each Strategies . Color shows details about Strategies .

C.6.3 Detailed Life Cycle Analysis (pages 1-86 of 184)

Report Summary - 00-Base Case

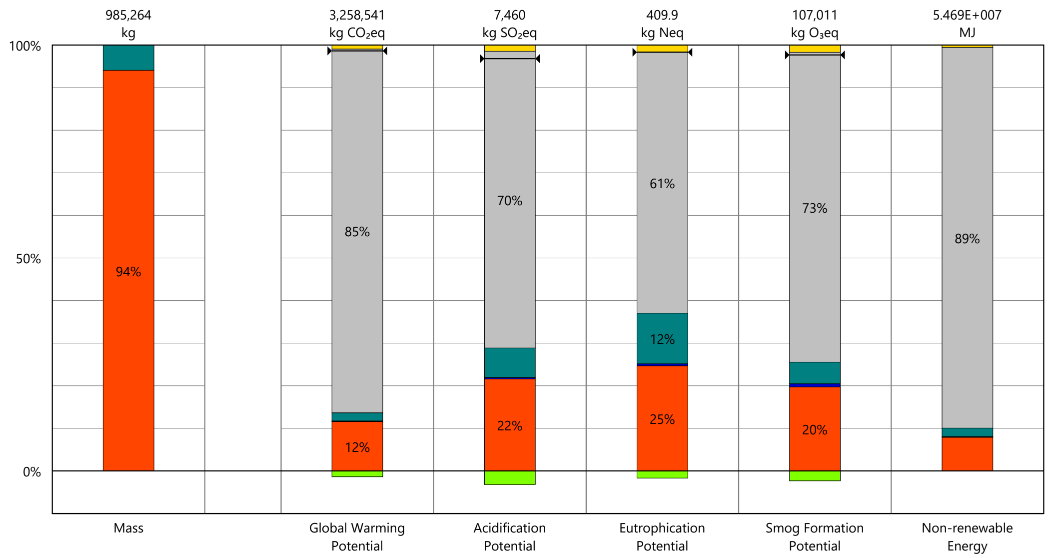
Created with Tally
Non-commercial Version 2018.09.27.01



Location	Toronto, ON
Gross Area	1111 m²
Building Life	60
Boundaries	Cradle to grave, inclusive of biogenic carbon; see appendix for a full list of materials and processes
On-site Construction [A5]	Not included
Operational Energy [B6]	52536.1 kWh annual electricity use 122.82 kWh/m² annual heating energy use

Environmental Impact Totals	**Product Stage [A1-A3]**	**Construction Stage [A4]**	**Use Stage [B2-B6]**	**End of Life Stage [C2-C4]**	**Module D [D]**
Global Warming (kg CO_2eq)	377,329	5,228	2,845,424	30,560	-44,796
Acidification (kg SO_2eq)	1,610	24.22	5,717	109.0	-238
Eutrophication (kg Neq)	101.1	1.972	300.1	6.707	-6.91
Smog Formation (kg O_3eq)	21,105	800.5	83,292	1,814	-2,488
Ozone Depletion (kg CFC-11eq)	0.001426	1.791E-010	0.001606	3.486E-009	5.187E-005
Primary Energy (MJ)	4,931,643	76,026	6.057E+007	322,736	-580,781
Non-renewable Energy (MJ)	4,325,165	74,206	4.999E+007	301,793	-518,638
Renewable Energy (MJ)	609,993	1,838	1.061E+007	21,298	-62,194
Environmental Impacts / Area					
Global Warming (kg CO_2eq/m²)	339.6	4.706	2,561	27.51	-40.3
Acidification (kg SO_2eq/m²)	1.449	0.0218	5.146	0.09809	-0.2141
Eutrophication (kg Neq/m²)	0.09104	0.001775	0.2701	0.006036	-0.006216
Smog Formation (kg O_3eq/m²)	19.00	0.7205	74.97	1.632	-2.24
Ozone Depletion (kg CFC-11eq/m²)	1.283E-006	1.612E-013	1.445E-006	3.138E-012	4.669E-008
Primary Energy (MJ/m²)	4,439	68.43	54,521	290.5	-523
Non-renewable Energy (MJ/m²)	3,893	66.79	44,997	271.6	-467
Renewable Energy (MJ/m²)	549.0	1.655	9,553	19.17	-56.0

Results per Life Cycle Stage

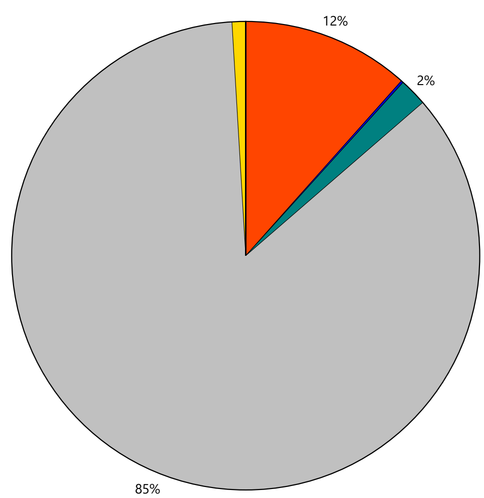


Legend

Net value (impacts + credits)

Life Cycle Stages

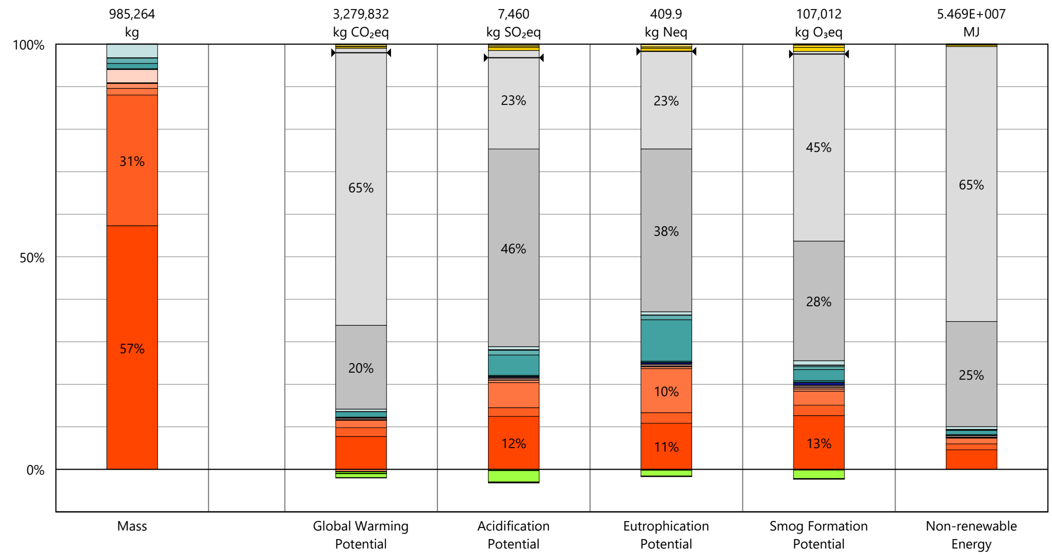
- Product [A1-A3]
- Transportation [A4]
- Maintenance and Replacement [B2-B5]
- Operational Energy [B6]
- End of Life [C2-C4]
- Module D [D]



Global Warming Potential

tally

Results per Life Cycle Stage, itemized by Division



Legend

Net value (impacts + credits)

Product [A1-A3]
- 03 - Concrete
- 04 - Masonry
- 05 - Metals
- 06 - Wood/Plastics/Composites
- 07 - Thermal and Moisture Protection
- 08 - Openings and Glazing
- 09 - Finishes

Transportation [A4]
- 03 - Concrete
- 04 - Masonry
- 05 - Metals
- 06 - Wood/Plastics/Composites
- 07 - Thermal and Moisture Protection
- 08 - Openings and Glazing
- 09 - Finishes

Maintenance and Replacement [B2-B5]
- 03 - Concrete
- 04 - Masonry
- 05 - Metals
- 06 - Wood/Plastics/Composites
- 07 - Thermal and Moisture Protection
- 08 - Openings and Glazing
- 09 - Finishes

Operational Energy [B6]
- Electricity
- Heating

End of Life [C2-C4]
- 03 - Concrete
- 04 - Masonry
- 05 - Metals
- 06 - Wood/Plastics/Composites
- 07 - Thermal and Moisture Protection
- 08 - Openings and Glazing
- 09 - Finishes

Module D [D]
- 03 - Concrete
- 04 - Masonry
- 05 - Metals
- 06 - Wood/Plastics/Composites
- 07 - Thermal and Moisture Protection
- 08 - Openings and Glazing
- 09 - Finishes

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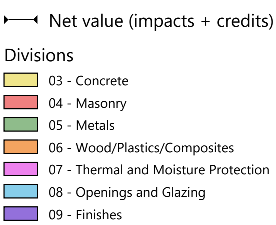
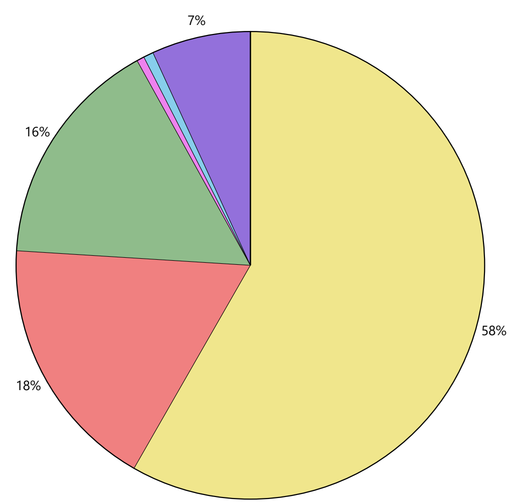
Results per Division

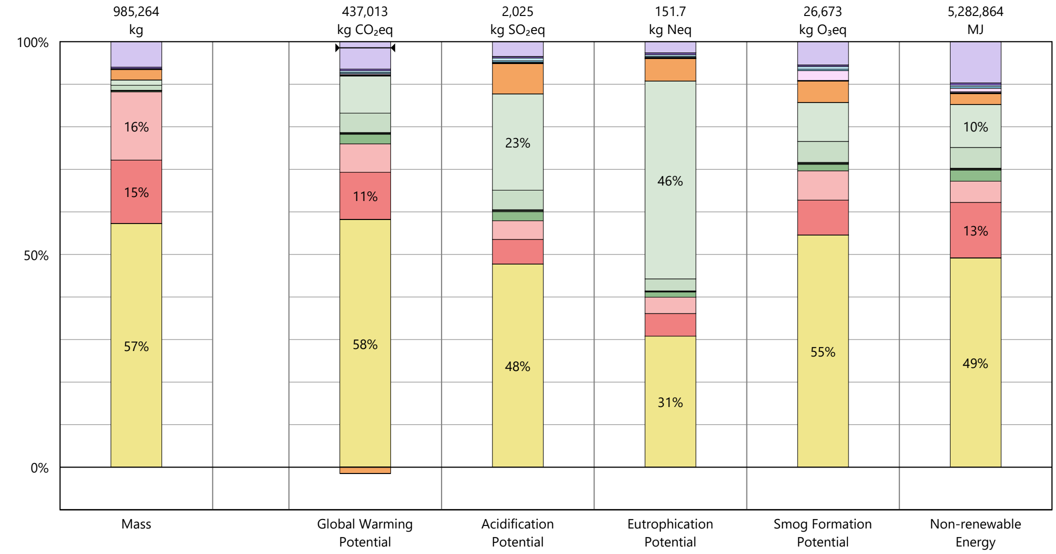
Legend





Global Warming Potential

Results per Division, itemized by Tally Entry



Legend

Net value (impacts + credits)

03 - Concrete

- Cast-in-place concrete, lightweight structural concrete, 2501-3000 psi
- Precast concrete structural panel, hollow core
- Stair, cast-in-place concrete

04 - Masonry

- Brick
- Solid-core CMU

05 - Metals

- Aluminum, sheet
- Stair, laminated glass
- Steel, C-H-stud metal framing
- Steel, C-stud metal framing
- Steel, sheet, carbon steel
- Steel, sheet, stainless
- Zinc sheet

06 - Wood/Plastics/Composites

- Plywood, exterior grade

07 - Thermal and Moisture Protection

- Expanded polystyrene (EPS), board
- Extruded polystyrene (XPS), board
- Glass wool, batt or blown
- Polyethelene sheet vapor barrier (HDPE)
- Self adhering membrane

08 - Openings and Glazing

- Aluminum mullion, inclusive of finish
- Glazing, monolithic sheet

09 - Finishes

- Fiberglass mat gypsum sheathing
- Portland cement stucco
- Wall board, gypsum

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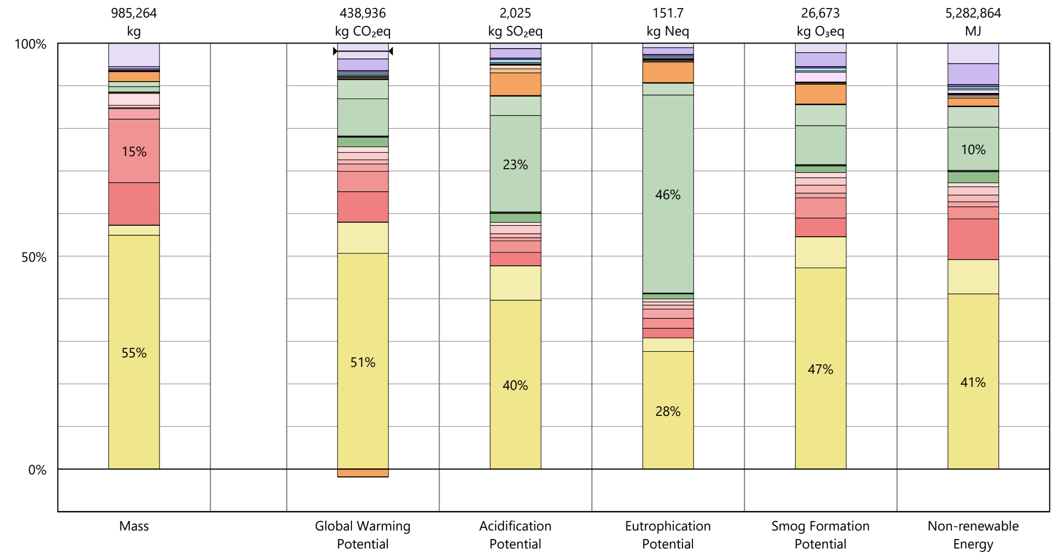
Results per Division, itemized by Material



Legend

Net value (impacts + credits)

03 - Concrete

- Lightweight concrete, 2501-3000 psi, 0-19% fly ash and/or slag
- Steel, reinforcing rod
- Structural concrete, 4001-5000 psi, 0-19% fly ash and/or slag

04 - Masonry

- Brick, generic
- Concrete masonry unit (CMU), solid
- Lime mortar (Mortar type K)
- Paint, exterior acrylic latex
- Steel, reinforcing rod
- Thickset mortar

05 - Metals

- Anodized aluminum, sheet
- Contruction steel, light structural shapes, CMC - EPD
- Glazing, triple, 3 mm, laminated safety glass
- Paint, exterior metal coating, silicone-based
- Stainless steel sheet, Chromium 18/8
- Steel, sheet
- Tin plating, for stainless steel sheet stock
- Un-coated cold-formed steel framing products, ClarkDietrich - EPD
- Zinc sheet

06 - Wood/Plastics/Composites

- Exterior grade plywood, US
- Paint, Brillux, Arylic facade paint - EPD
- Paint, Brillux, Silicone facade paint - EPD

07 - Thermal and Moisture Protection

- Expanded polystyrene (EPS), board
- Fasteners, galvanized steel
- Glass wool kraft faced batt, Knauf, EcoBatt - EPD
- Polyethelene sheet vapor barrier (HDPE)
- Polystyrene board (XPS), Pentane foaming agent
- Self adhering flashing membrane, 40 mil

08 - Openings and Glazing

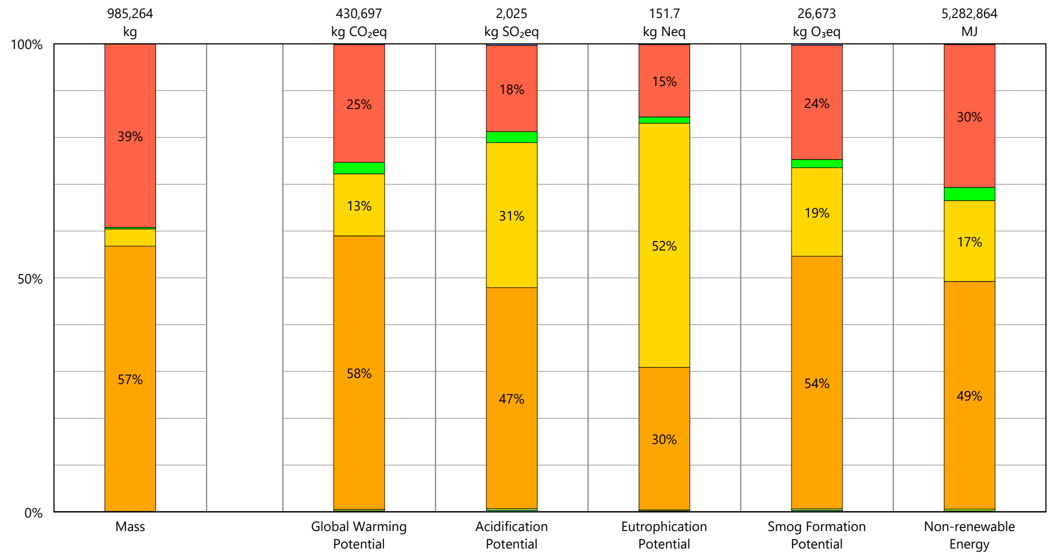
- Aluminum extrusion, anodized, AEC - EPD
- Glazing, monolithic sheet, generic

09 - Finishes

- Fiberglass mat gypsum sheathing board
- Kraft paper
- Metal lath, for plaster
- Paint, exterior acrylic latex
- Paint, interior acrylic latex
- Stucco, portland cement
- Wall board, gypsum, natural

tally

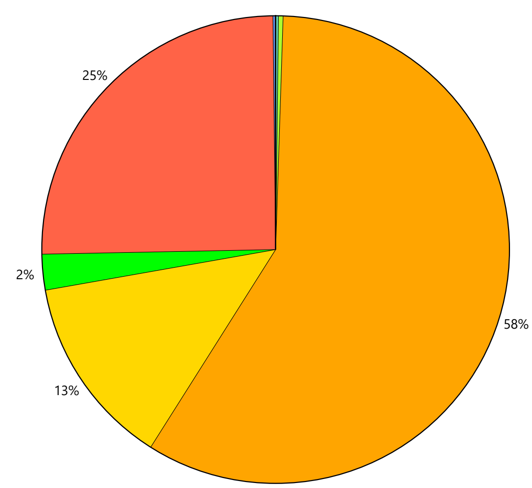
Results per Revit Category



Legend

Revit Categories

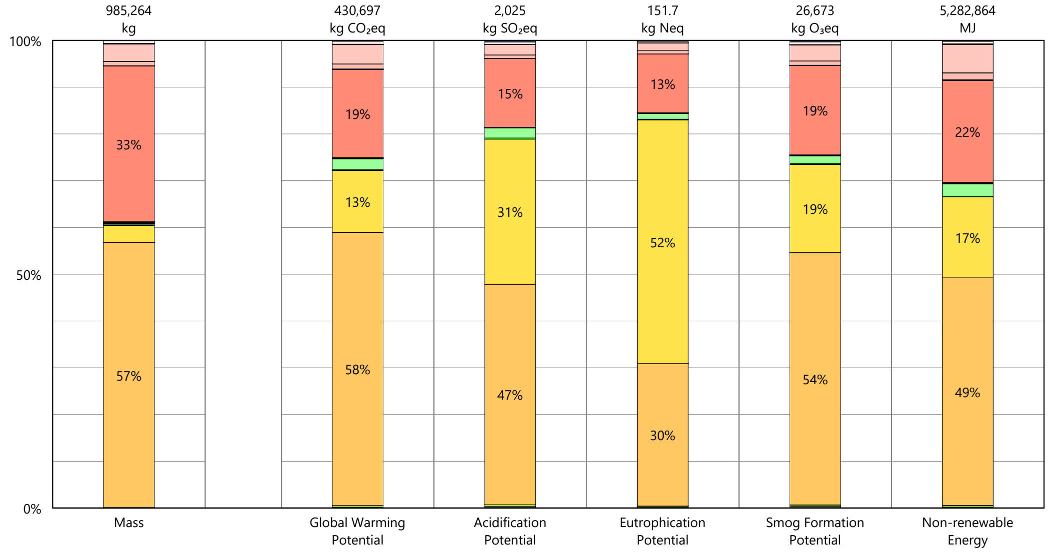
- Curtain Panels
- Curtain Wall Mullions
- Floors
- Roofs
- Stairs and Railings
- Walls
- Windows



Global Warming Potential

tally

Results per Revit Category, itemized by Family



Legend

Curtain Panels

- 08-Glazed Panel
- System Panel

Curtain Wall Mullions

- Rectangular Mullion

Floors

- SF10-Acoustic Jack Slab
- SF1-Concrete Slab on Grade 100mm
- SF2-Concrete Slab on Grade w Insulation
- SF3-Concrete Slab 200mm
- SF4-74Conc-76Met
- SF5-Hollow Core Concrete
- SF6-62Conc-38Met

Roofs

- R1-WP-6Bd-150Ins-AVB
- R2-6Bd-100Ins-16Bd-38Mtl
- R3-Mtl-16Bd-100Ins-16Bd-38Mtl
- R4-Zn-38Mtl
- R5-45Conc-25Air-150Ins-WP
- R6-6Bd-125Ins

Stairs and Railings

- 05-Railing 1070mm-Handrail 915mm-Picket 13mm-Stringer-Square 38mm
- 200mm Max Rise 280mm Tread
- Panel within Slab - Metal Panel

Walls

- CB10-90CMU
- CB20-140CMU
- CB30-190CMU
- CB40-240CMU-180min U904
- CBR20-140CMU-60min
- CBR21-140CMU-120min
- CBR30-190CMU-120min
- CBR31-190CMU-180min
- CBR40-240CMU-180min U904
- EW1-265-90Br-50Air-100Ins
- EW2-170-Zc Corr-25Air-125Ins
- EW31-125-Ins-10Drn
- EW3-170-Zc Pnl-25Air-125Ins
- EW32-100-13Conc-87Ins
- EW33-200-50Stn-25Air-125Ins
- EW4-145-13EIFS-125Ins
- EW5-155-AlumPnlL-25Air-125Ins
- EW6-165-13Conc-25Air-125Ins
- EW7-165-13Wd-25Air-125Ins
- EW8-Kalzip-75Alum-13Therm-19Air-125Ins
- EWE 34-Brick_90Brck-20Air-90CMU-13Gyp-40Std-13Gyp
- F11-55-16Gb-41Mtl
- F2-16-16Gb
- F21-80-16Gb-64Mtl
- F41-110-16Gb-92Mtl
- F61-170-16Gb-152Mtl
- F6-40-16Gb-22Mtl
- F71-15-13Gb
- F72-35-13Gb-22Mtl
- F73-54-13Gb-41Mtl
- F74-54-13Gb-41Mtl+Ins-50Air
- F75-75-13Gb-64Mtl
- F76-105-13Gb-92Mtl
- F77-165-13Gb-152Mtl
- FR10-13Gb-13Gb-41Mtl-80min OBC SB-2
- FR11-13Gb-13Gb-13Gb-41Mtl-120min OBC SB-2
- FR1-13Gb-13Gb-80min OBC SB-2
- FR20-13Gb-13Gb-64Mtl-80min OBC SB-2
- FR21-13Gb-13Gb-13Gb-64Mtl-120min OBC SB-2
- FR2-13Gb-13Gb-13Gb-80min OBC SB-2
- FR40-13Gb-13Gb-92Mtl-80min OBC SB-2
- FR41-13Gb-13Gb-13Gb-92Mtl-120min OBC SB-2
- P12-75-16Gb-41Mtl-16Gb
- P13-75-16Gb-41Mtl+Ins-16Gb
- P22-95-16Gb-64Mtl-16Gb
- P23-95-16Gb-64Mtl+Ins-16Gb
- P42-125-16Gb-92Mtl-16Gb
- P46-140-16Gb-16Gb-92Mtl+Ins-16Gb
- P47-155-16Gb-16Gb-92Mtl+Ins-16Gb-16Gb
- P48-180-16Gb-16Gb-92Mtl+Ins-22mMtl-16Gb-16Gb
- P49A-275-16Gb-16Gb-92Mtl+Ins-25Air-92Mtl+Ins-16Gb-16Gb
- P62-185-16Gb-152Mtl-16Gb
- P64-170-16Gb-140Wd-16Gb
- P71-70-13Gb-41Mtl-13Gb
- P72-70-13Gb-41Mtl+Ins-13Gb
- P73-90-13Gb-64Mtl-13Gb

tally.

Results per Revit Category, itemized by Family (continued)

Legend (continued)

- P74-90-13Gb-64Mtl+Ins-13Gb
- P75-115-13Gb-92Mtl-13Gb
- P76-120-13Gb-92Mtl+Ins-13Gb
- P77-175-13Gb-152Mtl-13Gb
- P78-175-13Gb-152Mtl+Ins-13Gb
- PA1-19Gb-125Ins
- PA2-335-19Gb-125Ins-190CMU
- PR40-125-16Gb-92Mtl-60min ULC W453
- PR41-125-16Gb-92Mtl+Ins-16Gb-60min ULC W453
- PR43-140-16Gb-16Gb-92Mtl+Ins-16Gb-60min ULC W453
- PR44-155-16Gb-16Gb-92Mtl-16Gb-16Gb-120min ULC W453
- PR50-275-16Gb-16Gb-92Mtl+Ins-25Air-92Mtl-16Gb-16Gb-120min ULC W454
- PR61-185-16Gb-92Mtl-16Gb-60min ULC W453
- PR72-130-13Gb-13Gb-92Mtl+Ins-13Gb-60min ULC W453
- ST Conc-200

Windows

- 08-Door-Curtain Wall
- Glass Panel

Calculation Methodology

LIFE CYCLE ASSESSMENT METHODS

The following provides a description of terms and methods associated with the use of Tally to conduct life cycle assessment for construction works and construction products. Tally methodology is consistent with LCA standards ISO 14040-14044, ISO 21930:2017, ISO 21931:2010, EN 15804:2012, and EN 15978:2011. For more information about LCA, please refer to these standards or visit www.choosetally.com.

Studied objects

The life cycle assessment (LCA) results reported represent an analysis of a single building, multiple buildings, or a comparative analysis of two or more building design options. The assessment may represent the complete architectural, structural, and finish systems of the building(s) or a subset of those systems. This may be used to compare the relative environmental impacts associated with building components or for comparative study with one or more reference buildings. Design options may represent a full or partial building across various stages of the design process, or they may represent multiple schemes of a full or partial building that are being compared to one another across a range of evaluation criteria.

Functional unit and reference unit

A functional unit is the quantified performance of a product, building, or system that defines the object of the study. The functional unit of a single building should include the building type (e.g. office, factory), relevant technical and functional requirements (e.g. regulatory requirements, energy performance), pattern of use (e.g. occupancy, usable floor area), and the required service life. For a design option comparison of a partial building, the functional unit is the complete set of building systems or products that perform a given function. It is the responsibility of the modeler to assure that reference buildings or design options are functionally equivalent in terms of scope and relevant performance. The expected life of the building has a default value of 60 years and can be modified by the modeler.

The reference unit is the full collection of processes and materials required to produce a building or portion thereof and is quantified according to the given goal and scope of the assessment over the full life of the building. If construction impacts are included in the assessment, the reference unit also includes the energy, water, and fuel consumed on the building site during construction. If operational energy is included in the assessment, the reference unit includes the electrical and thermal energy consumed on site over the life of the building.

Data source

Tally utilizes a custom designed LCA database that combines material attributes, assembly details, and architectural specifications with environmental impact data resulting from the collaboration between KieranTimberlake and thinkstep. LCA modeling was conducted in GaBi 8.5 using GaBi 2018 databases and in accordance with GaBi databases and modeling principles.

The data used are intended to represent the US and the year 2017. Where representative data were unavailable, proxy data were used. The datasets used, their geographic region, and year of reference are listed for each entry. An effort was made to choose proxy datasets that are technologically consistent with the relevant entry.

Data quality and uncertainty

Uncertainty in results can stem from both the data used and their application. Data quality is judged by: its measured, calculated, or estimated precision; its completeness, such as unreported emissions; its consistency, or degree of uniformity of the methodology applied on a study serving as a data source; and geographical, temporal, and technological representativeness. The GaBi LCI databases have been used in LCA models worldwide in both industrial and scientific applications. These LCI databases have additionally been used both as internal and critically reviewed and published studies. Uncertainty introduced by the use of proxy data is reduced by using technologically, geographically, and/or temporally similar data. It is the responsibility of the modeler to appropriately apply the predefined material entries to the building under study.

System boundaries and delimitations

The analysis accounts for the full cradle to grave life cycle of the design options studied across all life cycle stages, including material manufacturing, maintenance and replacement, and eventual end of life. Optionally, the construction impacts and operational energy of the building can be included within the scope. Product stage impacts are excluded for materials and components indicated as existing or salvaged by the modeler. The modeler defines whether the boundary includes or excludes the flow of biogenic carbon, which is the carbon absorbed and generated by biological sources (e.g. trees, algae) rather than from fossil resources.

Architectural materials and assemblies include all materials required for the product's manufacturing and use including hardware, sealants, adhesives, coatings, and finishing. The materials are included up to a 1% cut-off factor by mass except for known materials that have high environmental impacts at low levels. In these cases, a 1% cut-off was implemented by impact.

LIFE CYCLE STAGES

The following describes the scope and system boudaries used to define each stage of the life cycle of a building or building product, from raw material acquisition to final disposal. For products listed in Tally as Environmental Product Declarations (EPD), the full life cycle impacts are included, even if the published EPD only includes the Product stage [A1-A3].

Product [EN 15978 A1 - A3]

This encompasses the full manufacturing stage, including raw material extraction and processing, intermediate transportation, and final manufacturing and assembly. The product stage scope is listed for each entry, detailing any specific inclusions or exclusions that fall outside of the cradle to gate scope. Infrastructure (buildings and machinery) required for the manufacturing and assembly of building materials are not included and are considered outside the scope of assessment.

Transportation [EN 15978 A4]

This counts transportation from the manufacturer to the building site during the construction stage and can be modified by the modeler.

Construction Installation [EN 15978 A5] (Optional)

This includes the anticipated or measured energy and water consumed on-site during the construction installation process, as specified by the modeler.

Maintenance and Replacement [EN 15978 B2-B5]

This encompasses the replacement of materials in accordance with their expected service life. This includes the end of life treatment of the existing products as well as the cradle to gate manufacturing and transportation to site of the replacement products. The service life is specified separately for each product. Refurbishment of materials marked as existing or salvaged by the modeler is also included.

Operational Energy [EN 15978 B6] (Optional)

This is based on the anticipated or measured energy and natural gas consumed at the building site over the lifetime of the building, as indicated by the modeler.

End of Life [EN 15978 C2-C4]

This includes the relevant material collection rates for recycling, processing requirements for recycled materials, incineration rates, and landfilling rates. The impacts associated with landfilling are based on average material properties, such as plastic waste, biodegradable waste, or inert material. Stage C2 encompasses the transport from the construction site to end-of-life treatment based on national averages. Stages C3-C4 account for waste processing and disposal, i.e., impacts associated with landfilling or incineration.

Module D [EN 15978 D]

This accounts for reuse potentials that fall beyond the system boundary, such as energy recovery and recycling of materials. Along with processing requirements, the recycling of materials is modeled using an avoided burden approach, where the burden of primary material production is allocated to the subsequent life cycle based on the quantity of recovered secondary material. Incineration of materials includes credit for average US energy recovery rates.

PRODUCT	CONSTRUCTION	USE	END-OF-LIFE	MODULE D
A1. Extraction **A2. Transport (to factory)** **A3. Manufacturing**	**A4. Transport (to site)** ***A5. Construction Installation***	B1. Use **B2. Maintenance** **B3. Repair** **B4. Replacement** **B5. Refurbishment** ***B6. Operational energy*** B7. Operational water	C1. Demolition **C2. Transport (to disposal)** **C3. Waste processing** **C4. Disposal**	**D. Benefits and loads beyond the system boundary from:** **1. Reuse** **2. Recycling** **3. Energy recovery**

Life-Cycle Stages as defined by EN 15978. Processes included in Tally modeling scope are shown in bold. Italics indicate optional processes.

ENVIRONMENTAL IMPACT CATEGORIES

A characterization scheme translates all emissions and fuel use associated with the reference flow into quantities of categorized environmental impact. As the degree that the emissions will result in environmental harm depends on regional ecosystem conditions and the location in which they occur, the results are reported as impact potential. Potential impacts are reported in kilograms of equivalent relative contribution (eq) of an emission commonly associated with that form of environmental impact (e.g. kg CO_2eq).

The following list provides a description of environmental impact categories reported according to the TRACI 2.1 characterization scheme, the environmental impact model developed by the US EPA to quantify environmental impact risk associated with emissions to the environment in the United States. TRACI is the standard environmental impact reporting format for LCA in North America. Impacts associated with land use change and fresh water depletion are not included in TRACI 2.1. For more information on TRACI 2.1, reference Bare 2010, EPA 2012, and Guinée 2001. For further description of measurement of environmental impacts in LCA, see Simonen 2014.

Acidification Potential (AP) kg SO_2eq

A measure of emissions that cause acidifying effects to the environment. The acidification potential is a measure of a molecule's capacity to increase the hydrogen ion (H^+) concentration in the presence of water, thus decreasing the pH value. Potential effects include fish mortality, forest decline, and the deterioration of building materials.

Eutrophication Potential (EP) kg Neq

A measure of the impacts of excessively high levels of macronutrients, the most important of which are nitrogen (N) and phosphorus (P). Nutrient enrichment may cause an undesirable shift in species composition and elevated biomass production in both aquatic and terrestrial ecosystems. In aquatic ecosystems, increased biomass production may lead to depressed oxygen levels caused by the additional consumption of oxygen in biomass decomposition.

Global Warming Potential (GWP) kg CO_2eq

A measure of greenhouse gas emissions, such as carbon dioxide and methane. These emissions are causing an increase in the absorption of radiation emitted by the earth, increasing the natural greenhouse effect. This may, in turn, have adverse impacts on ecosystem health, human health, and material welfare.

Ozone Depletion Potential (ODP) kg CFC-11eq

A measure of air emissions that contribute to the depletion of the stratospheric ozone layer. Depletion of the ozone leads to higher levels of UVB ultraviolet rays reaching the earth's surface with detrimental effects on humans and plants. As these impacts tend to be very small, ODP impacts can be difficult to calculate and are prone to a larger margin of error than the other impact categories.

Smog Formation Potential (SFP) kg O_3eq

A measure of ground level ozone, caused by various chemical reactions between nitrogen oxides (NO_x) and volatile organic compounds (VOCs) in sunlight. Human health effects can result in a variety of respiratory issues, including increasing symptoms of bronchitis, asthma, and emphysema. Permanent lung damage may result from prolonged exposure to ozone. Ecological impacts include damage to various ecosystems and crop damage.

Primary Energy Demand (PED) MJ (lower heating value)

A measure of the total amount of primary energy extracted from the earth. PED tracks energy resource use, not the environmental impacts associated with the resource use. PED is expressed in energy demand from non-renewable resources and from renewable resources. Efficiencies in energy conversion (e.g. power, heat, steam, etc.) are taken into account when calculating this result.

Non-Renewable Energy Demand MJ (lower heating value)

A measure of the energy extracted from non-renewable resources (e.g. petroleum, natural gas, etc.) contributing to the PED. Non-renewable resources are those that cannot be regenerated within a human time scale. Efficiencies in energy conversion (e.g. power, heat, steam, etc.) are taken into account when calculating this result.

Renewable Energy Demand MJ (lower heating value)

A measure of the energy extracted from renewable resources (e.g. hydropower, wind energy, solar power, etc.) contributing to the PED. Efficiencies in energy conversion (e.g. power, heat, steam, etc.) are taken into account when calculating this result.

END-OF-LIFE [C2-C4]

A Life Cycle Inventory(LCI) is a compilation and quantification of inputs and outputs for the reference unit.The following LCI provides a summary of all energy, construction, transportation, and material inputs present in the study. Materials are listed in alphabetical order along with a list of all Revit families and Tally entries in which they occur, along with any notes and system boundaries accompanying their database entries.Each entry lists the detailed scope for the LCI data sources used from the GaBi LCI database and identifies the LCI data source.

For LCI data sourced from an Environmental Product Declaration (EPD), the product manufacturer, EPD identification number, and Program Operator are listed. Where the LCI source does not provide data for all life cycle stages, default North American average values are used. This is of particular importance for European EPD sources, as EPD data are generally only provided for the product stage, and North American average values are used for the remaining life cycle stages.

Where specific quantities are associated with a data entry, such as user inputs, energy values, or material mass, the quantity is listed on the same line as the title of the entry.

TRANSPORTATION [A4]

Default transportation values are based on the three-digit material commodity code in the 2012 Commodity Flow Survey by the US Department of Transportation Bureau of Transportation Statistics and the US Department of Commerce where more specific industry-level transportation is not available.

Transportation by Barge
Scope:
The data set represents the transportation of 1 kg of material from the manufacturer location to the building site by barge.

LCI Source:
GLO: Average ship, 1500t payload capacity/ canal ts (2017)
US: Diesel mix at filling station ts (2014)

Transportation by Container Ship
Scope:
The data set represents the transportation of 1 kg of material from the manufacturer location to the building site by container ship.

LCI Source:
GLO: Container ship, 27500 dwt payload capacity, ocean going ts (2017)
US: Heavy fuel oil at refinery (0.3wt.% S) ts (2014)

Transportation by Rail
Scope:
The data set represents the transportation of 1 kg of material from the manufacturer location to the building site by cargo rail.

LCI Source:
GLO: Rail transport cargo - Diesel, average train, gross tonne weight 1000t / 726t payload capacity ts (2017)
US: Diesel mix at filling station ts (2014)

Transportation by Truck
Scope:
The data set represents the transportation of 1 kg of material from the manufacturer location to the building site by diesel truck.

LCI Source:
US: Truck - Trailer, basic enclosed / 45,000 lb payload - 8b ts (2017)
US: Diesel mix at filling station ts (2014)

OPERATIONAL ENERGY [B6]

Each associated dataset includes relevant upstream impacts associated with extraction of energy resources (such as coal or crude oil), including refining, combustion, transmission, losses, and other associated factors.

Operational Electrical Energy **52536.1 kWh**

Description:
Average grid mix - Canadian electricity grid mix

Scope:
The data set represents the average country or region specific electricity supply for final consumers, including electricity own consumption, transmission/distribution losses and electricity imports from neighboring countries. The national energy carrier mixes used for electricity production, the power plant efficiency data, shares on direct to combined heat and power generation (CHP), as well as transmission/distribution losses and own consumption values are taken from official statistics (International Energy Agency, and US-EPA eGRID for USA regions) for the corresponding reference year.

LCI Source:
CA: Electricity grid mix ts (2014)

Operational Heating Energy **122.82 kWh/m²**

Description:
Natural gas - Canadian natural gas

Scope:
The data set represents region-specific natural gas use for heating during building use and operations. Entry includes upstream production of natural gas, transport from refinery to filling station, and on-site combustion.

LCI Source:
CA: Thermal energy from natural gas ts (2014)

END-OF-LIFE [C2-C4]

Specific end-of-life scenarios are detailed for each entry based on the US construction and demolition waste treatment methods and rates in the 2016 WARM Model by the US Environmental Protection Agency except where otherwise specified. Heterogeneous assemblies are modeled using the appropriate methodologies for the component materials.

End-of-Life Landfill

Scope:
Materials for which no recycling or incineration rates are known, no recycling occurs within the US at a commercial scale, or which are unable to be recycled are landfilled. This includes glass, drywall, insulation, and plastics. The solids contents of coatings, sealants, and paints are assumed to go to landfill, while the solvents or water evaporate during installation. Where the landfill contains biodegradable material, the energy recovered from landfill gas utilization is reflected as a credit in Module D.

LCI Source:
US: Glass/inert on landfill ts (2017)
US: Biodegradable waste on landfill, post-consumer ts (2017)
US: Plastic waste on landfill, post-consumer ts (2017)

Concrete End-of-Life

Scope:
Concrete (or other masonry products) are recycled into aggregate or general fill material or they are landfilled. It is assumed that 55% of the concrete is recycled. Module D accounts for both the credit associated with off-setting the production aggregate and the burden of the grinding energy required for processing.

LCI Source:
US: Diesel mix at refinery ts (2014)
GLO: Fork lifter (diesel consumption) ts (2016)
EU - 28 Gravel 2/32 ts (2017)
US: Glass/inert on landfill ts (2017)

Metals End-of-Life

Scope:
Metal products are modeled using the avoided burden approach. The recycling rate at end of life is used to determine how much secondary metal can be recovered after having subtracted any scrap input into manufacturing (net scrap). Net scrap results in an environmental credit in Module D for the corresponding share of the primary burden that can be allocated to the subsequent product system using secondary material as an input. If the value in Module D reflects an environmental burden, then the original product (A1-A3) contains more secondary material than is recovered.

LCI Source:
Aluminum - RNA: Primary Aluminum Ingot AA/ts (2010)
Aluminum - RNA: Secondary Aluminum Ingot AA/ts (2010)
Brass - GLO: Zinc mix ts (2012)
Brass - GLO: Copper (99.99% cathode) ICA (2013)
Brass - EU-28: Brass (CuZn20) ts (2017)
Copper - DE: Recycling potential copper sheet ts (2016)
Steel - GLO: Value of scrap worldsteel (2014)
Zinc - GLO: Special high grade zinc IZA (2012)

Wood End-of-Life

Scope:
End of Life waste treatment methods and rates for wood are based on the 2014 Municipal Solid Waste and Construction Demolition Wood Waste Generation and Recovery in the United States report by Dovetail Partners, Inc. It is assumed that 65.5% of wood is sent to landfill, 17.5% to incineration, and 17.5% to recovery.

LCI Source:
US: Untreated wood in waste incineration plant ts (2017)
US: Wood product (OSB, particle board) waste in waste incineration plant ts (2017)
US: Wood products (OSB, particle board) on landfill, post-consumer ts (2017)
US: Untreated wood on landfill, post-consumer ts (2017)
RNA: Softwood lumber CORRIM (2011)

MODEL ELEMENTS

Revit Categories
- Ceilings
- Curtainwall Mullions
- Curtainwall Panels
- Doors
- Floors
- Roofs
- Stairs and Railings
- Structure
- Walls
- Windows

1810 - LCA - 02 Reglazing
Worksets
- A-Architecture

Phases
- Existing
- New Construction
- Render
- Schedules

PRODUCT [A1-A3]

Materials and components are listed in alphabetical order along with a list of all Revit families and Tally entries in which they occur. The masses given here refer to the quantity of each material used over the building's life-cycle, which includes both Product [A1-A3] and Use [B2-B5] stages.

Additional provided data describing scope boundaries for each life cycle stage may be useful for interpretation of the impacts associated with the specific material or component. Each material or component is listed with its service life, or period of time after installation it is expected to meet the service requirements prior to replacement or repair. This value is indicated in parentheses next to the mass of the material associated with the listed Revit family. Values for transportation distance or service life shown with an asterisk (*) indicate user-defined changes to default values. Values for service life shown with a dagger (†) indicate materials identified by the modeler as existing or salvaged.

Aluminum extrusion, anodized, AEC - EPD **321.0 kg**

Used in the following Revit families:
Rectangular Mullion 321.0 kg (60 yrs)

Used in the following Tally entries:
Aluminum mullion, inclusive of finish

Description:
Extruded and anodized aluminum part. Data based on industry-wide EPD from the Aluminum Extruders Council.

Life Cycle Inventory:
See EPD

Product Scope:
Cradle to gate

Transportation Distance:
By truck: 663 km

End-of-Life Scope:
95% Recovered
5% Landfilled (inert material)

Module D Scope:
Product has 34.5% scrap input while remainder is processed and credited as avoided burden

LCI Source:
RNA: Aluminum extrusion, anodized - AEC (A1-A3) ts-EPD (2015)
RNA: Primary Aluminum Ingot AA/ts (2010)
RNA: Secondary Aluminum Ingot AA/ts (2010)

EPD Source:
11240237.101.1

EPD Designation Holder:
Aluminum Extruders Council (AEC)

EPD Program Operator:
UL Environment

EPD Expiration:
2021-10-04

Anodized aluminum, sheet **2,165.6 kg**

Used in the following Revit families:
Panel within Slab - Metal Panel 2,165.6 kg (60 yrs)

Used in the following Tally entries:
Aluminum, sheet

Description:
Anodized aluminum sheet, formed and cut. Data based on industry-wide EPD for anodized aluminum from the Aluminum Extruders Council (EPD ID 11240237.101.1).

Life Cycle Inventory:
100% Anodized aluminum

Product Scope:
Cradle to gate

Transportation Distance:
By truck: 663 km

End-of-Life Scope:
95% Recovered
5% Landfilled (inert material)

Module D Scope:
Product has 65% scrap input while remainder is processed and credited as avoided burden

LCI Source:
RNA: Cold Rolled Aluminium ts/AA (2010) [EPD]
GLO: Steel sheet stamping and bending (5% loss) ts (2017)
RNA: Anodization of aluminum extrusion AEC/ts (2015) [EPD]
US: Electricity grid mix ts (2014)
US: Lubricants at refinery ts (2014)
GLO: Compressed air 7 bar (medium power consumption) ts (2014)
RNA: Primary Aluminum Ingot AA/ts (2010) [EPD]
RNA: Secondary Aluminum Ingot AA/ts (2010) [EPD]

Brick, generic **98,176.7 kg**

Used in the following Revit families:

EW1-265-90Br-50Air-100Ins	166.3 kg (60 yrs)
EWE 34-Brick_90Brck-20Air-90CMU-13Gyp-40Std-13Gyp	98,010.4 kg (60 yrs)

Used in the following Tally entries:
Brick

Description:
Common extruded brick, excludes mortar.

Life Cycle Inventory:
100% Fired brick

Product Scope:
Cradle to gate
excludes mortar
anchors, ties, and metal accessories outside of scope (<1% mass)

Transportation Distance:
By truck: 172 km

End-of-Life Scope:
55% Recycled into coarse aggregate
45% Landfilled (inert material)

Module D Scope:
Avoided burden credit for coarse aggregate, includes grinding energy

LCI Source:
DE: Stoneware tiles, unglazed (EN15804 A1-A3) ts (2017)

Concrete masonry unit (CMU), solid **146,893.0 kg**

Used in the following Revit families:

CB10-90CMU	217.9 kg (60 yrs)
CB20-140CMU	339.0 kg (60 yrs)
CB30-190CMU	460.0 kg (60 yrs)
CB40-240CMU-180min U904	581.1 kg (60 yrs)
CBR20-140CMU-60min	339.0 kg (60 yrs)
CBR21-140CMU-120min	339.0 kg (60 yrs)
CBR30-190CMU-120min	460.0 kg (60 yrs)
CBR31-190CMU-180min	460.0 kg (60 yrs)
CBR40-240CMU-180min U904	581.1 kg (60 yrs)
EWE 34-Brick_90Brck-20Air-90CMU-13Gyp-40Std-13Gyp	142,656.0 kg (60 yrs)
PA2-335-19Gb-125Ins-190CMU	460.0 kg (60 yrs)

Used in the following Tally entries:
Solid-core CMU

Description:
Solid Concrete Masonry Unit (CMU), excludes mortar

Life Cycle Inventory:
100% Concrete masonry units

Product Scope:
Cradle to gate, excludes mortar
Anchors, ties, and metal accessories outside of scope (<1% mass)

Transportation Distance:
By truck: 172 km

End-of-Life Scope:
55% Recycled into coarse aggregate
45% Landfilled (inert material)

Module D Scope:
Avoided burden credit for coarse aggregate, includes grinding energy

LCI Source:
DE: Concrete bricks (EN15804 A1-A3) ts (2017)

Contruction steel, light structural shapes, CMC - EPD **799.4 kg**

Used in the following Revit families:

F11-55-16Gb-41Mtl	0.6 kg (60 yrs)
F21-80-16Gb-64Mtl	0.6 kg (60 yrs)
F41-110-16Gb-92Mtl	0.6 kg (60 yrs)
F61-170-16Gb-152Mtl	0.6 kg (60 yrs)
F6-40-16Gb-22Mtl	0.6 kg (60 yrs)
FR10-13Gb-13Gb-41Mtl-80min OBC SB-2	0.6 kg (60 yrs)
FR11-13Gb-13Gb-13Gb-41Mtl-120min OBC SB-2	0.6 kg (60 yrs)
FR20-13Gb-13Gb-64Mtl-80min OBC SB-2	0.6 kg (60 yrs)
FR21-13Gb-13Gb-13Gb-64Mtl-120min OBC SB-2	0.6 kg (60 yrs)
FR40-13Gb-13Gb-92Mtl-80min OBC SB-2	0.6 kg (60 yrs)
FR41-13Gb-13Gb-13Gb-92Mtl-120min OBC SB-2	0.6 kg (60 yrs)
P12-75-16Gb-41Mtl-16Gb	0.6 kg (60 yrs)
P22-95-16Gb-64Mtl-16Gb	0.6 kg (60 yrs)
P42-125-16Gb-92Mtl-16Gb	198.3 kg (60 yrs)
P62-185-16Gb-152Mtl-16Gb	592.2 kg (60 yrs)
PR40-125-16Gb-92Mtl-60min ULC W453	0.6 kg (60 yrs)
PR44-155-16Gb-16Gb-92Mtl-16Gb-16Gb-120min ULC W453	0.6 kg (60 yrs)
PR50-275-16Gb-16Gb-92Mtl+Ins-25Air-92Mtl-16Gb-16Gb-120min ULC W454	0.6 kg (60 yrs)

Used in the following Tally entries:
Steel, C-H-stud metal framing

Description:
Light structural steel shapes by Commercial Metals Company. Appropriate for use in a structural capacity. EPD representative of conditions in the US.

Life Cycle Inventory:
See EPD

Product Scope:
Cradle-to-gate

Transportation Distance:
By truck: 431 km

End-of-Life Scope:
98% Recovered
2% Landfilled (inert material)

Module D Scope:
Product has 100% scrap input, burden reflects difference between recovered material and scrap input. Credit given for the avoided burden associated with recovered material.

LCI Source:
EPD (US), Commercial Metals Company (2015)

EPD Source:
EPD-015

EPD Designation Holder:
Commercial Metals Company (CMC)

EPD Program Operator:
ASTM International

EPD Expiration:
2020-09-01

Expanded polystyrene (EPS), board **55.2 kg**

Used in the following Revit families:

EW1-265-90Br-50Air-100Ins	7.3 kg (50 yrs)
EW2-170-Zc Corr-25Air-125Ins	7.3 kg (50 yrs)
EW3-170-Zc Pnl-25Air-125Ins	7.3 kg (50 yrs)
EW5-155-AlumPnlL-25Air-125Ins	7.3 kg (50 yrs)
EW6-165-13Conc-25Air-125Ins	7.3 kg (50 yrs)
EW7-165-13Wd-25Air-125Ins	7.3 kg (50 yrs)
EW8-Kalzip-75Alum-13Therm-19Air-125Ins	7.3 kg (50 yrs)
R1-WP-6Bd-150Ins-AVB	1.0 kg (50 yrs)
R2-6Bd-100Ins-16Bd-38Mtl	1.0 kg (50 yrs)
R5-45Conc-25Air-150Ins-WP	1.0 kg (50 yrs)
R6-6Bd-125Ins	1.0 kg (50 yrs)

Used in the following Tally entries:
Expanded polystyrene (EPS), board

Description:
EPS foam insulation board

Life Cycle Inventory:
100% Expanded polystyrene board

Product Scope:
Cradle to gate

Transportation Distance:
By truck: 1299 km

End-of-Life Scope:
100% Landfilled (plastic waste)

LCI Source:
US: EPS-Foam (expanded polystyrene foam (PS 12)) incl. flame retardant (estimation) ts (2017)

Exterior grade plywood, US **22,421.7 kg**
Used in the following Revit families:
EWE 34-Brick_90Brck-20Air-90CMU-13Gyp-40Std-13Gyp 11,581.5 kg (30 yrs)
R3-Mtl-16Bd-100Ins-16Bd-38Mtl 10,840.2 kg (30 yrs)

Used in the following Tally entries:
Plywood, exterior grade

Description:
Plywood, unfinished

Life Cycle Inventory:
Proxied by interior grade plywood

Product Scope:
Cradle to gate, uncoated

Transportation Distance:
By truck: 468 km

End-of-Life Scope:
14.5% Recovered
22% Incinerated with energy recovery
63.5% Landfilled (wood product waste)

Module D Scope:
Recovered wood products credited as avoided burden.

LCI Source:
RNA: Softwood plywood CORRIM (2011)

Fasteners, galvanized steel **88.0 kg**
Used in the following Revit families:
EW1-265-90Br-50Air-100Ins 0.4 kg (40 yrs)
EW2-170-Zc Corr-25Air-125Ins 0.4 kg (40 yrs)
EW3-170-Zc Pnl-25Air-125Ins 0.4 kg (40 yrs)
EW4-145-13EIFS-125Ins 0.4 kg (40 yrs)
EW5-155-AlumPnlL-25Air-125Ins 0.4 kg (40 yrs)
EW6-165-13Conc-25Air-125Ins 0.4 kg (40 yrs)
EW7-165-13Wd-25Air-125Ins 0.4 kg (40 yrs)
EW8-Kalzip-75Alum-13Therm-19Air-125Ins 0.4 kg (40 yrs)
PA1-19Gb-125Ins 0.4 kg (40 yrs)
PA2-335-19Gb-125Ins-190CMU 0.4 kg (40 yrs)
R1-WP-6Bd-150Ins-AVB 0.1 kg (40 yrs)
R2-6Bd-100Ins-16Bd-38Mtl 0.1 kg (40 yrs)
R3-Mtl-16Bd-100Ins-16Bd-38Mtl 84.3 kg (40 yrs)

Used in the following Tally entries:
Polyethelene sheet vapor barrier (HDPE)

Description:
Galvanized steel part, appropriate for use as fasteners and specialized hardware (bolts, rails, clips, etc.).

Life Cycle Inventory:
100% Galvanized steel

Product Scope:
Cradle to gate

Transportation Distance:
By truck: 1001 km

End-of-Life Scope:
70% Recovered
30% Landfilled (inert material)

Module D Scope:
Product has 16% scrap input while remainder is processed and credited as avoided burden

LCI Source:
GLO: Steel wire rod worldsteel (2014)
GLO: Steel turning ts (2017)
GLO: Electrolytic galvanisation (1 m² steel sheet part, electrolytic) ts (2017)
GLO: Value of scrap worldsteel (2014)

Fiberglass mat gypsum sheathing board **3,211.4 kg**
Used in the following Revit families:
P42-125-16Gb-92Mtl-16Gb 3,211.4 kg (60 yrs)

Used in the following Tally entries:
Fiberglass mat gypsum sheathing

Description:
Fiberglass treated gypsum sheathing product appropriate for use in high-moisture environments.

Life Cycle Inventory:
92% Gypsum
8% Fiberglass mat

Product Scope:
Cradle to gate

Transportation Distance:
By truck: 172 km

End-of-Life Scope:
100% Landfilled (inert waste)

LCI Source:
DE: Gypsum plaster board (Moisture resistant) (EN15804 A1-A3) ts (2017)
US: Fiberglass Duct Board NAIMA (2007)

Glass wool kraft faced batt, Knauf, EcoBatt - EPD **181.4 kg**
Used in the following Revit families:
R3-Mtl-16Bd-100Ins-16Bd-38Mtl 181.4 kg (60 yrs)

Used in the following Tally entries:
Glass wool, batt or blown

Description:
Knauf Insulation's batts and rolls are glasswool thermal and acoustical products that have very high post-consumer glass content and a bio-based a thermosetting resin that gives the product shape. Available with kraft, foil, or flame-rated FSK-25 foil facings, and in sizes R-11 to R-49. EPD is representative of products manufactured in the US and for sale in North America (NA).

Life Cycle Inventory:
See EPD

Product Scope:
Cradle to gate, including packaging disposal

Transportation Distance:
By truck: 172 km

End-of-Life Scope:
100% Landfilled

LCI Source:
EPD (NA), Knauf Insulation (2013)

EPD Source:
4786058564.101.1

EPD Designation Holder:
Knauf Insulation

EPD Program Operator:
UL Environment

Glazing, monolithic sheet, generic **1,371.2 kg**
Used in the following Revit families:
08-Door-Curtain Wall 377.8 kg (40 yrs)
08-Glazed Panel 221.6 kg (40 yrs)
Glass Panel 290.9 kg (40 yrs)
System Panel 480.8 kg (40 yrs)

Used in the following Tally entries:
Glazing, monolithic sheet

Description:
Standard float glass, uncoated. Note: this entry is appropriate for clear or tinted glass. Default thickness is 3 mm.

Life Cycle Inventory:
Glazing

Product Scope:
Cradle to gate

Transportation Distance:
By truck: 940 km

End-of-Life Scope:
100% Landfilled (inert waste)

LCI Source:
DE: Window glass simple (EN15804 A1-A3) ts (2017)

Glazing, triple, 3 mm, laminated safety glass **394.1 kg**
Used in the following Revit families:
05-Railing 1070mm-Handrail 915mm-Picket 13mm-Stringer-Square 38394.1 kg (35 yrs)

Used in the following Tally entries:
Stair, laminated glass

Description:
Laminated glass, 3 lites 3 mm thick, inclusive of polyvinyl butyral, and sealant

Life Cycle Inventory:
2% PVB film (30% adipic acid
70% PVB)
98% Glass

Product Scope:
Cradle to gate, excluding sealant

Transportation Distance:
By truck: 940 km

End-of-Life Scope:
100% Landfilled (inert waste)

LCI Source:
DE: Window glass simple (EN15804 A1-A3) ts (2017)
DE: Adipic acid from cyclohexane ts (2017)
DE: Polyvinyl Butyral Granulate (PVB) ts (2017)
GLO: Plastic film (PE, PP, PVC) ts (2017)
US: Electricity grid mix ts (2014)
US: Thermal energy from natural gas ts (2014)
US: Lubricants at refinery ts (2014)

Kraft paper **0.5 kg**

Used in the following Revit families:

EW4-145-13EIFS-125Ins	0.5 kg (20 yrs)

Used in the following Tally entries:
Portland cement stucco

Description:
Water vapor permeable paper backing

Life Cycle Inventory:
100% Kraft paper

Product Scope:
Cradle to gate, excludes adhesives, backings, or any additional coatings

Transportation Distance:
By truck: 641 km

End-of-Life Scope:
100% Landfilled (biodegradable material)

Module D Scope:
Accounts for recovered energy from landfill gas utilization

LCI Source:
EU-28: Kraft paper agg (2017)

Lightweight concrete, 2501-3000 psi, 0-19% fly ash and/or slag **541,064.4 kg**

Used in the following Revit families:

EW32-100-13Conc-87Ins	45.3 kg (60 yrs)
SF10-Acoustic Jack Slab	39.1 kg (60 yrs)
SF1-Concrete Slab on Grade 100mm	58.6 kg (60 yrs)
SF2-Concrete Slab on Grade w Insulation	39.1 kg (60 yrs)
SF3-Concrete Slab 200mm	535,864.1 kg (60 yrs)
SF4-74Conc-76Met	58.6 kg (60 yrs)
SF6-62Conc-38Met	39.1 kg (60 yrs)
ST Conc-200	4,920.7 kg (60 yrs)

Used in the following Tally entries:
Cast-in-place concrete, lightweight structural concrete, 2501-3000 psi

Description:
Lightweight concrete, 2501-3000 psi, 0-19% fly ash and/or slag. Mix design matches National Ready-Mix Concrete Association (NRMCA) Industry-wide EPD.

Life Cycle Inventory:
17% Cement
9% Batch water
29% Coarse aggregate
45% Fine aggregate

Product Scope:
Cradle to gate, excludes mortar
Anchors, ties, and metal accessories outside of scope (<1% mass)

Transportation Distance:
By truck: 24 km

End-of-Life Scope:
55% Recycled into coarse aggregate
45% Landfilled (inert material)

Module D Scope:
Avoided burden credit for coarse aggregate, includes grinding energy

LCI Source:
US: Portland cement PCA/ts (2014)
DE: Pumice gravel (grain size 4/16) (EN15804 A1-A3) ts (2017)
DE: Gravel (Grain size 2/32) (EN15804 A1-A3) ts (2017)
DE: Fly ash (EN15804 A1-A3) ts (2017)
DE: Slag-tap granulate (EN15804 A1-A3) ts (2017)
DE: Expanded clay (EN15804 A1-A3) ts (2017)
DE: Calcium nitrate ts (2017)
DE: Sodium ligninsulfonate ts (2017)
DE: Sodium naphtalene sulfonate [estimated] ts (2017)
US: Sodium hydroxide (caustic soda) mix (100%) ts (2017)
US: Colophony (rosin, refined) from CN pine gum rosin ts (2017)
US: Tap water from groundwater ts (2017)
US: Electricity grid mix ts (2014)
US: Natural gas mix ts (2014)
US: Diesel mix at filling station (100% fossil) ts (2014)
US: Liquefied Petroleum Gas (LPG) (70% propane
30% butane) ts (2014)
US: Light fuel oil at refinery ts (2014)

Lime mortar (Mortar type K) **24,400.2 kg**

Used in the following Revit families:

CB10-90CMU	11.0 kg (60 yrs)
CB20-140CMU	17.0 kg (60 yrs)
CB30-190CMU	23.1 kg (60 yrs)
CB40-240CMU-180min U904	29.2 kg (60 yrs)
CBR20-140CMU-60min	17.0 kg (60 yrs)
CBR21-140CMU-120min	17.0 kg (60 yrs)
CBR30-190CMU-120min	23.1 kg (60 yrs)
CBR31-190CMU-180min	23.1 kg (60 yrs)
CBR40-240CMU-180min U904	29.2 kg (60 yrs)
EW1-265-90Br-50Air-100Ins	28.8 kg (60 yrs)
EWE 34-Brick_90Brck-20Air-90CMU-13Gyp-40Std-13Gyp	24,158.4 kg (60 yrs)
PA2-335-19Gb-125Ins-190CMU	23.1 kg (60 yrs)

Used in the following Tally entries:
Brick
Solid-core CMU

Description:
Lime mortar, traditionally used for historic masonry.

Life Cycle Inventory:
20-65% Sand
40-70% Limestone
5-15% Hydrated lime
7-15% Cement

Product Scope:
Cradle to gate

Transportation Distance:
By truck: 172 km

End-of-Life Scope:
55% Recycled into coarse aggregate
45% Landfilled (inert material)

Module D Scope:
Avoided burden credit for coarse aggregate, includes grinding energy

LCI Source:
DE: Light plaster (lime-cement) ts (2017)

Metal lath, for plaster **1.7 kg**

Used in the following Revit families:

EW4-145-13EIFS-125Ins	1.7 kg (60 yrs)

Used in the following Tally entries:
Portland cement stucco

Description:
Hot dip galvanized steel lath used as reinforcement of interior or exterior plaster (stucco).

Life Cycle Inventory:
100% Steel, hot dip galvanized

Product Scope:
Cradle to gate of panel only, excludes suspended grid system and installation hardware

Transportation Distance:
By truck: 431 km

End-of-Life Scope:
98% Recovered
2% Landfilled (inert material)

Module D Scope:
Product has 5% scrap input while remainder is processed and credited as avoided burden

LCI Source:
GLO: Steel Electrogalvanized worldsteel (2014)
GLO: Steel sheet stamping and bending (5% loss) ts (2017)
US: Electricity grid mix ts (2014)
US: Lubricants at refinery ts (2014)
GLO: Compressed air 7 bar (medium power consumption) ts (2014)
GLO: Value of scrap worldsteel (2014)
GLO: Punching steel sheet small part ts (2011)

Paint, Brillux, Arylic facade paint - EPD **538.5 kg**

Used in the following Revit families:
R3-Mtl-16Bd-100Ins-16Bd-38Mtl 538.5 kg (15 yrs)

Used in the following Tally entries:
Plywood, exterior grade

Description:
Acrylic facade paint by Brillux GmbH & Co. Appropriate for use as coating and bonding agent for mineral and organic substrates as well as on wood and metal surfaces for outdoor use. EPD representative of German (DE) conditions.

Life Cycle Inventory:
See EPD

Product Scope:
Cradle to gate

Transportation Distance:
By truck: 642 km

End-of-Life Scope:
Includes disposal to landfill

LCI Source:
DE: Primers and facade paints, Acryl-Fassadenfarbe - Brillux (A1-A3) ts-EPD (2010)

EPD Source:
EPD-BRX-2012411-D

EPD Designation Holder:
Brillux GmbH & Co. KG

EPD Program Operator:
Institut Bauen und Umwelt (IBU)

EPD Expiration:
2017-11-17

Paint, Brillux, Silicone facade paint - EPD **690.4 kg**

Used in the following Revit families:
EWE 34-Brick_90Brck-20Air-90CMU-13Gyp-40Std-13Gyp 690.4 kg (15 yrs)

Used in the following Tally entries:
Plywood, exterior grade

Description:
Silicone facade paints by Brillux GmbH & Co. KG. Appropriate for use as coating and bonding agent for mineral and organic substrates as well as on wood and metal surfaces for outdoor use. EPD representative of German (DE) conditions.

Life Cycle Inventory:
See EPD

Product Scope:
Cradle to gate

Transportation Distance:
By truck: 642 km

End-of-Life Scope:
Includes disposal to landfill

LCI Source:
DE: Primers and facade paints, Silicon-Fassadenfarbe- Brillux (A1-A3) ts-EPD (2010)

EPD Source:
EPD-BRX-2012411-D

EPD Designation Holder:
Brillux GmbH & Co. KG

EPD Program Operator:
Institut Bauen und Umwelt (IBU)

EPD Expiration:
2017-11-17

Paint, exterior acrylic latex **2,092.4 kg**

Used in the following Revit families:

CB10-90CMU	1.8 kg (10 yrs)
CB20-140CMU	1.8 kg (10 yrs)
CB30-190CMU	1.8 kg (10 yrs)
CB40-240CMU-180min U904	1.8 kg (10 yrs)
CBR20-140CMU-60min	1.8 kg (10 yrs)
CBR21-140CMU-120min	1.8 kg (10 yrs)
CBR30-190CMU-120min	1.8 kg (10 yrs)
CBR31-190CMU-180min	1.8 kg (10 yrs)
CBR40-240CMU-180min U904	1.8 kg (10 yrs)
EW1-265-90Br-50Air-100Ins	1.8 kg (10 yrs)
EW4-145-13EIFS-125Ins	1.8 kg (10 yrs)
EWE 34-Brick_90Brck-20Air-90CMU-13Gyp-40Std-13Gyp	2,071.3 kg (10 yrs)
PA2-335-19Gb-125Ins-190CMU	1.8 kg (10 yrs)

Used in the following Tally entries:
Brick
Portland cement stucco
Solid-core CMU

Description:
Acrylic-based latex paint for exterior applications. Associated reference table includes primer.

Life Cycle Inventory:
20.5% Binding agent
35% Pigments and fillers
40% Water
4.5% Organic solvents

Product Scope:
Cradle to gate, including emissions during application

Transportation Distance:
By truck: 642 km

End-of-Life Scope:
100% to landfill (plastic waste)

LCI Source:
DE: Application paint emulsion (building, exterior, white) ts (2017)

Paint, exterior metal coating, silicone-based **62.5 kg**

Used in the following Revit families:

Panel within Slab - Metal Panel	10.0 kg (30 yrs)
R2-6Bd-100Ins-16Bd-38Mtl	0.0 kg (30 yrs)
R3-Mtl-16Bd-100Ins-16Bd-38Mtl	52.4 kg (30 yrs)
R4-Zn-38Mtl	0.0 kg (30 yrs)

Used in the following Tally entries:
Aluminum, sheet
Steel, sheet, carbon steel

Description:
Silicone-based metal paint, with a default coating thickness of 100 microns

Life Cycle Inventory:
23% Binding agent
35% Pigments and fillers
40% Water
1.5% Organic solvents

Product Scope:
Cradle to gate, including emissions during application

Transportation Distance:
By truck: 642 km

End-of-Life Scope:
100% to landfill (plastic waste)

LCI Source:
DE: Application coating silicone (building, exterior, white) ts (2017)

Paint, interior acrylic latex **4,765.2 kg**

Used in the following Revit families:

EWE 34-Brick_90Brck-20Air-90CMU-13Gyp-40Std-13Gyp	1,242.8 kg (7 yrs)
F11-55-16Gb-41Mtl	2.1 kg (7 yrs)
F2-16-16Gb	2.1 kg (7 yrs)
F21-80-16Gb-64Mtl	2.1 kg (7 yrs)
F41-110-16Gb-92Mtl	2.1 kg (7 yrs)
F61-170-16Gb-152Mtl	2.1 kg (7 yrs)
F6-40-16Gb-22Mtl	2.1 kg (7 yrs)
F71-15-13Gb	2.1 kg (7 yrs)
F72-35-13Gb-22Mtl	2.1 kg (7 yrs)
F73-54-13Gb-41Mtl	2.1 kg (7 yrs)
F74-54-13Gb-41Mtl+Ins-50Air	2.1 kg (7 yrs)
F75-75-13Gb-64Mtl	2.1 kg (7 yrs)

F76-105-13Gb-92Mtl	2.1 kg (7 yrs)
F77-165-13Gb-152Mtl	2.1 kg (7 yrs)
FR10-13Gb-13Gb-41Mtl-80min OBC SB-2	4.2 kg (7 yrs)
FR11-13Gb-13Gb-13Gb-41Mtl-120min OBC SB-2	6.3 kg (7 yrs)
FR1-13Gb-13Gb-80min OBC SB-2	4.2 kg (7 yrs)
FR20-13Gb-13Gb-64Mtl-80min OBC SB-2	4.2 kg (7 yrs)
FR21-13Gb-13Gb-13Gb-64Mtl-120min OBC SB-2	6.3 kg (7 yrs)
FR2-13Gb-13Gb-13Gb-80min OBC SB-2	6.3 kg (7 yrs)
FR40-13Gb-13Gb-92Mtl-80min OBC SB-2	4.2 kg (7 yrs)
FR41-13Gb-13Gb-13Gb-92Mtl-120min OBC SB-2	6.3 kg (7 yrs)
P12-75-16Gb-41Mtl-16Gb	4.2 kg (7 yrs)
P13-75-16Gb-41Mtl+Ins-16Gb	4.2 kg (7 yrs)
P22-95-16Gb-64Mtl-16Gb	4.2 kg (7 yrs)
P23-95-16Gb-64Mtl+Ins-16Gb	4.2 kg (7 yrs)
P42-125-16Gb-92Mtl-16Gb	441.0 kg (7 yrs)
P46-140-16Gb-16Gb-92Mtl+Ins-16Gb	6.3 kg (7 yrs)
P47-155-16Gb-16Gb-92Mtl+Ins-16Gb-16Gb	8.4 kg (7 yrs)
P48-180-16Gb-16Gb-92Mtl+Ins-22mMtl-16Gb-16Gb	8.4 kg (7 yrs)
P49A-275-16Gb-16Gb-92Mtl+Ins-25Air-92Mtl+Ins-16Gb-16Gb	8.4 kg (7 yrs)
P62-185-16Gb-152Mtl-16Gb	2,900.0 kg (7 yrs)
P64-170-16Gb-140Wd-16Gb	4.2 kg (7 yrs)
P71-70-13Gb-41Mtl-13Gb	4.2 kg (7 yrs)
P72-70-13Gb-41Mtl+Ins-13Gb	4.2 kg (7 yrs)
P73-90-13Gb-64Mtl-13Gb	4.2 kg (7 yrs)
P74-90-13Gb-64Mtl+Ins-13Gb	4.2 kg (7 yrs)
P75-115-13Gb-92Mtl-13Gb	4.2 kg (7 yrs)
P76-120-13Gb-92Mtl+Ins-13Gb	4.2 kg (7 yrs)
P77-175-13Gb-152Mtl-13Gb	4.2 kg (7 yrs)
P78-175-13Gb-152Mtl+Ins-13Gb	4.2 kg (7 yrs)
PR40-125-16Gb-92Mtl-60min ULC W453	4.2 kg (7 yrs)
PR41-125-16Gb-92Mtl+Ins-16Gb-60min ULC W453	4.2 kg (7 yrs)
PR43-140-16Gb-16Gb-92Mtl+Ins-16Gb-60min ULC W453	4.2 kg (7 yrs)
PR61-185-16Gb-92Mtl-16Gb-60min ULC W453	4.2 kg (7 yrs)
PR72-130-13Gb-13Gb-92Mtl+Ins-13Gb-60min ULC W453	8.4 kg (7 yrs)

Used in the following Tally entries:
Wall board, gypsum

Description:
Acrylic-based paint for interior applications

Life Cycle Inventory:
21% Binding agent
35% Pigments and fillers
42% Water
2% Organic solvents

Product Scope:
Cradle to gate, including emissions during application

Transportation Distance:
By truck: 642 km

End-of-Life Scope:
100% to landfill (plastic waste)

LCI Source:
DE: Application paint emulsion (building, interior, white, wear resistant) ts (2017)

Polyethelene sheet vapor barrier (HDPE) **81.3 kg**

Used in the following Revit families:

EW1-265-90Br-50Air-100Ins	0.3 kg (60 yrs)
EW2-170-Zc Corr-25Air-125Ins	0.3 kg (60 yrs)
EW3-170-Zc Pnl-25Air-125Ins	0.3 kg (60 yrs)
EW4-145-13EIFS-125Ins	0.3 kg (60 yrs)
EW5-155-AlumPnlL-25Air-125Ins	0.3 kg (60 yrs)
EW6-165-13Conc-25Air-125Ins	0.3 kg (60 yrs)
EW7-165-13Wd-25Air-125Ins	0.3 kg (60 yrs)
EW8-Kalzip-75Alum-13Therm-19Air-125Ins	0.3 kg (60 yrs)
PA1-19Gb-125Ins	0.3 kg (60 yrs)
PA2-335-19Gb-125Ins-190CMU	0.3 kg (60 yrs)
R1-WP-6Bd-150Ins-AVB	0.0 kg (60 yrs)
R2-6Bd-100Ins-16Bd-38Mtl	0.0 kg (60 yrs)
R3-Mtl-16Bd-100Ins-16Bd-38Mtl	77.8 kg (60 yrs)

Used in the following Tally entries:
Polyethelene sheet vapor barrier (HDPE)

Description:
Polyethelene sheet vapor barrier (HDPE) membrane entry exclusive of adhesive or other co-products

Life Cycle Inventory:
100% Polyethylene film

Product Scope:
Cradle to gate

Transportation Distance:
By truck: 1299 km

End-of-Life Scope:
10.5% Recycled into HDPE
89.5% Landfilled (plastic waste)

Module D Scope:
Avoided burden credit includes processing

LCI Source:
US: Polyethylene High Density Granulate (PE-HD) ts (2017)
GLO: Plastic Film (PE, PP, PVC) ts (2017)
US: Electricity grid mix ts (2014)
US: Thermal energy from natural gas ts (2014)
US: Lubricants at refinery ts (2014)

Polystyrene board (XPS), Pentane foaming agent **54.5 kg**

Used in the following Revit families:

EW31-125-Ins-10Drn	9.6 kg (50 yrs)
EW32-100-13Conc-87Ins	6.5 kg (50 yrs)
EW33-200-50Stn-25Air-125Ins	9.6 kg (50 yrs)
EW4-145-13EIFS-125Ins	9.6 kg (50 yrs)
PA1-19Gb-125Ins	9.6 kg (50 yrs)
PA2-335-19Gb-125Ins-190CMU	9.6 kg (50 yrs)

Used in the following Tally entries:
Extruded polystyrene (XPS), board

Description:
XPS board insulation, inclusive of pentane foaming agent

Life Cycle Inventory:
100% Extruded polystyrol rigid foam (XPS)

Product Scope:
Cradle to gate

Transportation Distance:
By truck: 1299 km

End-of-Life Scope:
100% Landfilled (plastic waste)

LCI Source:
DE: Extruded polystyrene (XPS) (EN15804 A1-A3) ts (2017)

Self adhering flashing membrane, 40 mil **562.5 kg**

Used in the following Revit families:

R3-Mtl-16Bd-100Ins-16Bd-38Mtl	562.5 kg (40 yrs)

Used in the following Tally entries:
Self adhering membrane

Description:
40 mil (1 mm) Asphalt rubber sheet inclusive of polyethelyne backing

Life Cycle Inventory:
82% Rubberized asphalt (25% SBS)
18% Polyethylene HD

Product Scope:
Cradle to gate for materials only, neglects manufacturing requirements

Transportation Distance:
By truck: 172 km

End-of-Life Scope:
100% Landfilled (plastic waste)

LCI Source:
US: Styrene-butadiene rubber (SBR) ts (2017)
DE: Bitumen cold adhesive (EN15804 A1-A3) ts (2017)
US: Polyethylene High Density Granulate (PE-HD) ts (2017)
GLO: Plastic Film (PE, PP, PVC) ts (2017)
US: Electricity grid mix ts (2014)
US: Thermal energy from natural gas ts (2014)
US: Lubricants at refinery ts (2014)

Stainless steel sheet, Chromium 18/8 **12,256.4 kg**

Used in the following Revit families:

R3-Mtl-16Bd-100Ins-16Bd-38Mtl	12,256.4 kg (45 yrs)

Used in the following Tally entries:
Steel, sheet, stainless

Description:
Stainless steel sheet, Type 304 (Chromium 18/8)

Life Cycle Inventory:
100% Stainless steel plate

Product Scope:
Cradle to gate

Transportation Distance:
By truck: 418 km

End-of-Life Scope:
98% Recovered
2% Landfilled (inert material)

Module D Scope:
Product has 52% scrap input while remainder is processed and credited as avoided burden

LCI Source:
RER: Stainless steel cold rolled coil (304) Eurofer (2010)
GLO: Steel sheet stamping and bending (5% loss) ts (2017)
US: Electricity grid mix ts (2014)
US: Lubricants at refinery ts (2014)
GLO: Compressed air 7 bar (medium power consumption) ts (2014)
RER: Stainless steel flat product (304) - value of scrap Eurofer (2010)

Steel, reinforcing rod **28,216.0 kg**

Used in the following Revit families:

200mm Max Rise 280mm Tread	20.6 kg (60 yrs)
CB10-90CMU	4.6 kg (60 yrs)
CB20-140CMU	4.6 kg (60 yrs)
CB30-190CMU	4.6 kg (60 yrs)
CB40-240CMU-180min U904	4.6 kg (60 yrs)
CBR20-140CMU-60min	4.6 kg (60 yrs)
CBR21-140CMU-120min	4.6 kg (60 yrs)
CBR30-190CMU-120min	4.6 kg (60 yrs)
CBR31-190CMU-180min	4.6 kg (60 yrs)
CBR40-240CMU-180min U904	4.6 kg (60 yrs)
EW1-265-90Br-50Air-100Ins	4.6 kg (60 yrs)
EW32-100-13Conc-87Ins	1.9 kg (60 yrs)
EWE 34-Brick_90Brck-20Air-90CMU-13Gyp-40Std-13Gyp	5,399.1 kg (60 yrs)
PA2-335-19Gb-125Ins-190CMU	4.6 kg (60 yrs)
SF10-Acoustic Jack Slab	1.6 kg (60 yrs)
SF1-Concrete Slab on Grade 100mm	2.4 kg (60 yrs)
SF2-Concrete Slab on Grade w Insulation	1.6 kg (60 yrs)
SF3-Concrete Slab 200mm	22,291.2 kg (60 yrs)
SF4-74Conc-76Met	2.4 kg (60 yrs)
SF5-Hollow Core Concrete	1.1 kg (60 yrs)
SF6-62Conc-38Met	1.6 kg (60 yrs)
ST Conc-200	442.0 kg (60 yrs)

Used in the following Tally entries:
Brick
Cast-in-place concrete, lightweight structural concrete, 2501-3000 psi
Precast concrete structural panel, hollow core
Solid-core CMU
Stair, cast-in-place concrete

Description:
Common unfinished tempered steel rod suitable for structural reinforcement (rebar)

Life Cycle Inventory:
100% Steel rebar

Product Scope:
Cradle to gate

Transportation Distance:
By truck: 431 km

End-of-Life Scope:
70% Recovered
30% Landfilled (inert material)

Module D Scope:
Product has a 16.4% scrap input while remainder is processed and credited as avoided burden.

LCI Source:
GLO: Steel rebar worldsteel (2014)

Steel, sheet **11,515.9 kg**

Used in the following Revit families:

R2-6Bd-100Ins-16Bd-38Mtl	6.9 kg (45 yrs)
R3-Mtl-16Bd-100Ins-16Bd-38Mtl	11,502.0 kg (45 yrs)
R4-Zn-38Mtl	6.9 kg (45 yrs)

Used in the following Tally entries:
Steel, sheet, carbon steel

Description:
Steel sheet

Life Cycle Inventory:
100% Steel sheet

Product Scope:
Cradle to gate

Transportation Distance:
By truck: 418 km

End-of-Life Scope:
98% Recovered
2% Landfilled (inert material)

Module D Scope:
Product has 16% scrap input while remainder is processed and credited as avoided burden

LCI Source:
RNA: Steel finished cold rolled coil worldsteel (2007)
GLO: Steel sheet stamping and bending (5% loss) ts (2017)
US: Electricity grid mix ts (2014)
US: Lubricants at refinery ts (2014)
GLO: Compressed air 7 bar (medium power consumption) ts (2014)
GLO: Value of scrap worldsteel (2014)

Structural concrete, 4001-5000 psi, 0-19% fly ash and/or slag **718.9 kg**

Used in the following Revit families:

200mm Max Rise 280mm Tread	643.3 kg (60 yrs)
SF5-Hollow Core Concrete	75.6 kg (60 yrs)

Used in the following Tally entries:
Precast concrete structural panel, hollow core
Stair, cast-in-place concrete

Description:
Structural concrete, 4001-5000 psi, 0-19% fly ash and/or slag. Mix design matches National Ready-Mix Concrete Association (NRMCA) Industry-wide EPD.

Life Cycle Inventory:
20% Cement
7% Batch water
40% Coarse aggregate
33% Fine aggregate

Product Scope:
Cradle to gate, excludes mortar
Anchors, ties, and metal accessories outside of scope (<1% mass)

Transportation Distance:
By truck: 24 km

End-of-Life Scope:
55% Recycled into coarse aggregate
45% Landfilled (inert material)

Module D Scope:
Avoided burden credit for coarse aggregate, includes grinding energy

LCI Source:
US: Portland cement PCA/ts (2014)
DE: Pumice gravel (grain size 4/16) (EN15804 A1-A3) ts (2017)
DE: Gravel (Grain size 2/32) (EN15804 A1-A3) ts (2017)
DE: Fly ash (EN15804 A1-A3) ts (2017)
DE: Slag-tap granulate (EN15804 A1-A3) ts (2017)
DE: Expanded clay (EN15804 A1-A3) ts (2017)
DE: Calcium nitrate ts (2017)
DE: Sodium ligninsulfonate ts (2017)
DE: Sodium naphtalene sulfonate [estimated] ts (2017)
US: Sodium hydroxide (caustic soda) mix (100%) ts (2017)
US: Colophony (rosin, refined) from CN pine gum rosin ts (2017)
US: Tap water from groundwater ts (2017)
US: Electricity grid mix ts (2014)
US: Natural gas mix ts (2014)
US: Diesel mix at filling station (100% fossil) ts (2014)
US: Liquefied Petroleum Gas (LPG) (70% propane 30% butane) ts (2014)
US: Light fuel oil at refinery ts (2014)

Stucco, portland cement **34.7 kg**

Used in the following Revit families:

EW4-145-13EIFS-125Ins	34.7 kg (60 yrs)

Used in the following Tally entries:
Portland cement stucco

Description:
Portland cement plastering (stucco), 7/8" (22.25 mm) nominal thickness is typical

Life Cycle Inventory:
100% Light plaster (Silica sand, Portland cement, Calcinated lime)

Product Scope:
Cradle to gate

Transportation Distance:
By truck: 172 km

End-of-Life Scope:
100% Landfilled (inert waste)

LCI Source:
US: Silica sand (Excavation and processing) ts (2017)
US: Portland cement PCA/ts (2015)
US: Lime (CaO) calcination ts (2017)

Thickset mortar **27,562.4 kg**

Used in the following Revit families:

EW1-265-90Br-50Air-100Ins	46.7 kg (60 yrs)
EWE 34-Brick_90Brck-20Air-90CMU-13Gyp-40Std-13Gyp	27,515.7 kg (60 yrs)

Used in the following Tally entries:
Brick

Description:
Grout, for masonry

Life Cycle Inventory:
15% Cement
50% Sand
21% Gravel
14% Water

Product Scope:
Cradle to gate, excludes mortar
Anchors, ties, and metal accessories outside of scope (<1% mass)

Transportation Distance:
By truck: 172 km

End-of-Life Scope:
55% Recycled into coarse aggregate
45% Landfilled (inert material)

Module D Scope:
Avoided burden credit for coarse aggregate, includes grinding energy

LCI Source:
US: Portland cement PCA/ts (2014)
US: Tap water from groundwater ts (2017)
EU-28: Gravel 2/32 ts (2017)
US: Silica sand (Excavation and processing) ts (2017)

Tin plating, for stainless steel sheet stock **16.8 kg**

Used in the following Revit families:

R3-Mtl-16Bd-100Ins-16Bd-38Mtl	16.8 kg (60 yrs)

Used in the following Tally entries:
Steel, sheet, stainless

Description:
Tin plating for stainless steel sheets

Life Cycle Inventory:
100% Tin coating

Product Scope:
Cradle to gate for coating process, excludes metal

Transportation Distance:
By truck: 431 km

End-of-Life Scope:
100% Landfilled (inert waste)

LCI Source:
GLO: Steel tinplated worldsteel (2014)
GLO: Steel plate worldsteel (2014)

Un-coated cold-formed steel framing products, ClarkDietrich - EPD **303.1 kg**

Used in the following Revit families:

EWE 34-Brick_90Brck-20Air-90CMU-13Gyp-40Std-13Gyp	303.1 kg (60 yrs)

Used in the following Tally entries:
Steel, C-stud metal framing

Description:
Bare steel framing products by ClarkDietrich. Thicknesses in the range of 0.0120 inches to 0.1180 inches. Appropriate for use as interior framing, interior finishing trims and accessories, exterior framing, floor framing, clips/connectors, expanded metal lath, plaster trim and accessories. EPD representative of conditions in the US.

Life Cycle Inventory:
See EPD

Product Scope:
Cradle-to-gate

Transportation Distance:
By truck: 431 km

End-of-Life Scope:
98% Recovered
2% Landfilled (inert material)

Module D Scope:
Credit given for the avoided burden associated with recovered material

LCI Source:
EPD (US), ClarkDietrich Building Systems (2016)

EPD Source:
EPD10056

EPD Designation Holder:
ClarkDietrich Building Systems

EPD Program Operator:
NSF International

EPD Expiration:
2020-06-30

Wall board, gypsum, natural **54,221.6 kg**

Used in the following Revit families:

EWE 34-Brick_90Brck-20Air-90CMU-13Gyp-40Std-13Gyp	14,141.1 kg (30 yrs)
F11-55-16Gb-41Mtl	24.0 kg (30 yrs)
F2-16-16Gb	24.0 kg (30 yrs)
F21-80-16Gb-64Mtl	24.0 kg (30 yrs)
F41-110-16Gb-92Mtl	24.0 kg (30 yrs)
F61-170-16Gb-152Mtl	24.0 kg (30 yrs)
F6-40-16Gb-22Mtl	24.0 kg (30 yrs)
F71-15-13Gb	24.0 kg (30 yrs)
F72-35-13Gb-22Mtl	24.0 kg (30 yrs)
F73-54-13Gb-41Mtl	24.0 kg (30 yrs)
F74-54-13Gb-41Mtl+Ins-50Air	24.0 kg (30 yrs)
F75-75-13Gb-64Mtl	24.0 kg (30 yrs)
F76-105-13Gb-92Mtl	24.0 kg (30 yrs)
F77-165-13Gb-152Mtl	24.0 kg (30 yrs)
FR10-13Gb-13Gb-41Mtl-80min OBC SB-2	48.0 kg (30 yrs)
FR11-13Gb-13Gb-13Gb-41Mtl-120min OBC SB-2	72.0 kg (30 yrs)
FR1-13Gb-13Gb-80min OBC SB-2	48.0 kg (30 yrs)
FR20-13Gb-13Gb-64Mtl-80min OBC SB-2	48.0 kg (30 yrs)
FR21-13Gb-13Gb-13Gb-64Mtl-120min OBC SB-2	72.0 kg (30 yrs)
FR2-13Gb-13Gb-13Gb-80min OBC SB-2	72.0 kg (30 yrs)
FR40-13Gb-13Gb-92Mtl-80min OBC SB-2	48.0 kg (30 yrs)
FR41-13Gb-13Gb-13Gb-92Mtl-120min OBC SB-2	72.0 kg (30 yrs)
P12-75-16Gb-41Mtl-16Gb	48.0 kg (30 yrs)
P13-75-16Gb-41Mtl+Ins-16Gb	48.0 kg (30 yrs)
P22-95-16Gb-64Mtl-16Gb	48.0 kg (30 yrs)
P23-95-16Gb-64Mtl+Ins-16Gb	48.0 kg (30 yrs)
P42-125-16Gb-92Mtl-16Gb	5,017.8 kg (30 yrs)
P46-140-16Gb-16Gb-92Mtl+Ins-16Gb	72.0 kg (30 yrs)
P47-155-16Gb-16Gb-92Mtl+Ins-16Gb-16Gb	96.0 kg (30 yrs)
P48-180-16Gb-16Gb-92Mtl+Ins-22mMtl-16Gb-16Gb	96.0 kg (30 yrs)
P49A-275-16Gb-16Gb-92Mtl+Ins-25Air-92Mtl+Ins-16Gb-16Gb	96.0 kg (30 yrs)
P62-185-16Gb-152Mtl-16Gb	32,998.7 kg (30 yrs)
P64-170-16Gb-140Wd-16Gb	48.0 kg (30 yrs)
P71-70-13Gb-41Mtl-13Gb	48.0 kg (30 yrs)
P72-70-13Gb-41Mtl+Ins-13Gb	48.0 kg (30 yrs)
P73-90-13Gb-64Mtl-13Gb	48.0 kg (30 yrs)
P74-90-13Gb-64Mtl+Ins-13Gb	48.0 kg (30 yrs)
P75-115-13Gb-92Mtl-13Gb	48.0 kg (30 yrs)
P76-120-13Gb-92Mtl+Ins-13Gb	48.0 kg (30 yrs)
P77-175-13Gb-152Mtl-13Gb	48.0 kg (30 yrs)
P78-175-13Gb-152Mtl+Ins-13Gb	48.0 kg (30 yrs)
PR40-125-16Gb-92Mtl-60min ULC W453	48.0 kg (30 yrs)
PR41-125-16Gb-92Mtl+Ins-16Gb-60min ULC W453	48.0 kg (30 yrs)
PR43-140-16Gb-16Gb-92Mtl+Ins-16Gb-60min ULC W453	48.0 kg (30 yrs)
PR61-185-16Gb-92Mtl-16Gb-60min ULC W453	48.0 kg (30 yrs)
PR72-130-13Gb-13Gb-92Mtl+Ins-13Gb-60min ULC W453	96.0 kg (30 yrs)

Used in the following Tally entries:
Wall board, gypsum

Description:
Natural gypsum board

Life Cycle Inventory:
100% Gypsum wallboard (Gypsum, Boric acid, Cement, Glass fibres, Ferrochrome-lignine sulfonate, Silane, Polyglucose, Perlite, Paper, Casein glue)

Product Scope:
Cradle to gate

Transportation Distance:
By truck: 172 km

End-of-Life Scope:
100% Landfilled (inert waste)

LCI Source:
DE: Gypsum wallboard (EN15804 A1-A3) ts (2017)

Zinc sheet	**25.7 kg**
Used in the following Revit families:	
EW2-170-Zc Corr-25Air-125Ins	12.8 kg (60 yrs)
EW3-170-Zc Pnl-25Air-125Ins	12.8 kg (60 yrs)

Used in the following Tally entries:
Zinc sheet

Description:
Zinc sheet, formed and cut

Life Cycle Inventory:
100% Zinc

Product Scope:
Cradle to gate

Transportation Distance:
By truck: 663 km

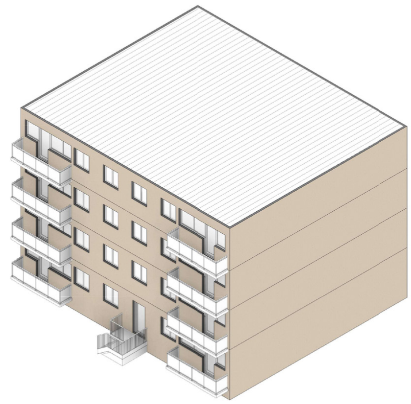
End-of-Life Scope:
90% Recovered
10% Landfilled (inert material)

Module D Scope:
Product has 2% scrap input while remainder is processed and credited as avoided burden

LCI Source:
GLO: Special high grade zinc IZA (2012)
EU-28: Aluminium sheet ts (2017)
GLO: Steel sheet stamping and bending (5% loss) ts (2017)
US: Electricity grid mix ts (2014)
US: Lubricants at refinery ts (2014)
GLO: Compressed air 7 bar (medium power consumption) ts (2014)

Report Summary - 03-Recladding

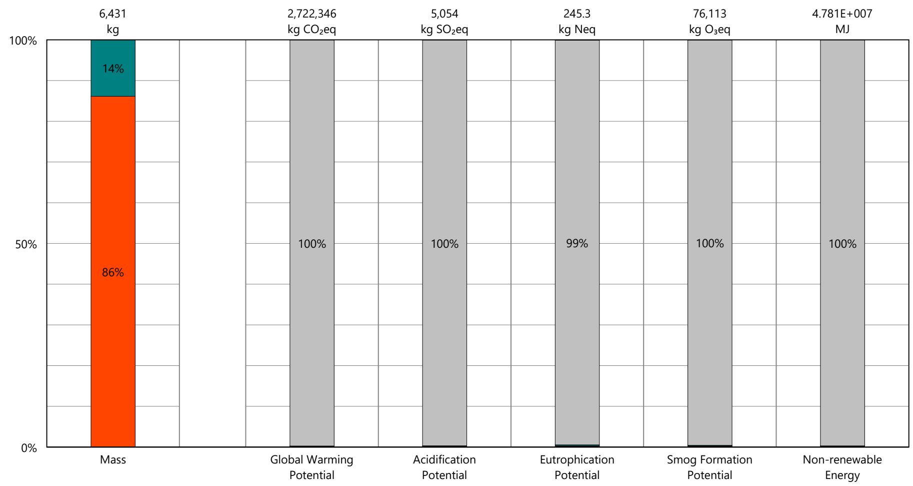
Created with Tally
Non-commercial Version 2018.09.27.01



Location	Toronto
Gross Area	1111 m²
Building Life	60
Boundaries	Cradle to grave, inclusive of biogenic carbon; see appendix for a full list of materials and processes
On-site Construction [A5]	Not included
Operational Energy [B6]	50649.8 kWh annual electricity use 120.24 kWh/m² annual heating energy use

Environmental Impact Totals	Product Stage [A1-A3]	Construction Stage [A4]	Use Stage [B2-B6]	End of Life Stage [C2-C4]	Module D [D]
Global Warming (kg CO_2eq)	4,766	99.36	2,717,238	242.8	-298
Acidification (kg SO_2eq)	9.682	0.4604	5,042	1.494	-0.5823
Eutrophication (kg Neq)	0.6234	0.03749	244.3	0.2739	-0.02338
Smog Formation (kg O_3eq)	185.2	15.21	75,890	22.70	-8.36
Ozone Depletion (kg CFC-11eq)	1.372E-005	3.403E-012	2.734E-006	4.283E-011	2.069E-006
Primary Energy (MJ)	82,651	1,445	5.770E+007	3,992	-2,769
Non-renewable Energy (MJ)	78,245	1,410	4.772E+007	3,732	-2,965
Renewable Energy (MJ)	4,419	34.94	1.001E+007	263.1	187.9
Environmental Impacts / Area					
Global Warming (kg CO_2eq/m²)	4.290	0.08944	2,446	0.2185	-0.2687
Acidification (kg SO_2eq/m²)	0.008715	4.144E-004	4.539	0.001345	-5.241E-004
Eutrophication (kg Neq/m²)	5.611E-004	3.374E-005	0.2199	2.466E-004	-2.104E-005
Smog Formation (kg O_3eq/m²)	0.1667	0.01369	68.31	0.02043	-0.007527
Ozone Depletion (kg CFC-11eq/m²)	1.235E-008	3.063E-015	2.461E-009	3.855E-014	1.862E-009
Primary Energy (MJ/m²)	74.39	1.301	51,932	3.593	-2.49
Non-renewable Energy (MJ/m²)	70.43	1.269	42,956	3.360	-2.67
Renewable Energy (MJ/m²)	3.978	0.03145	9,006	0.2368	0.1691

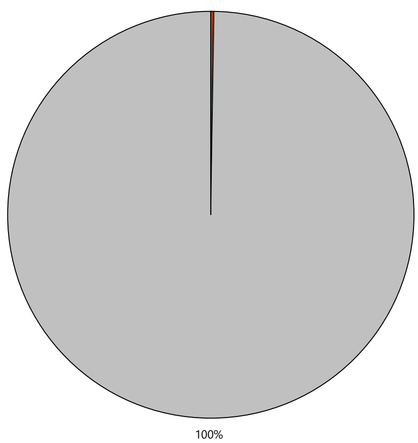
Results per Life Cycle Stage



Legend

Life Cycle Stages

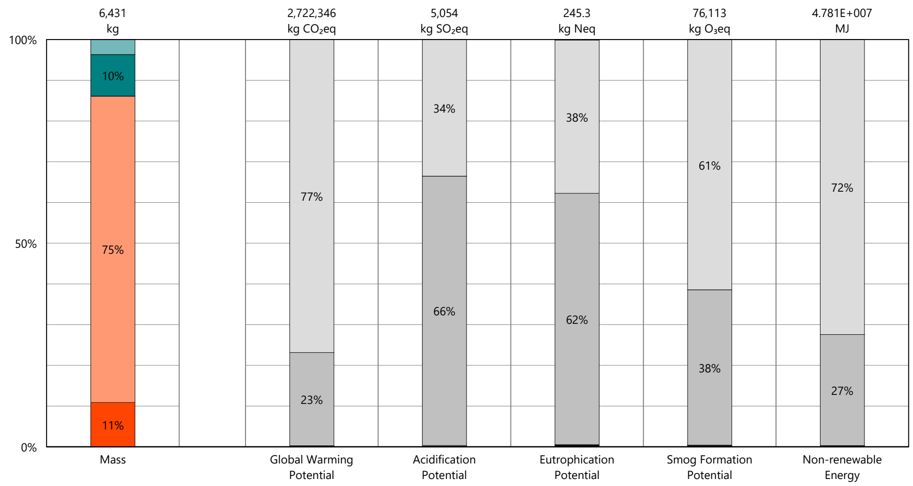
- Product [A1-A3]
- Transportation [A4]
- Maintenance and Replacement [B2-B5]
- Operational Energy [B6]
- End of Life [C2-C4]
- Module D [D]



Global Warming Potential

03-Recladding

Results per Life Cycle Stage, itemized by Division



Legend

Product [A1-A3]
- 07 - Thermal and Moisture Protection
- 09 - Finishes

Transportation [A4]
- 07 - Thermal and Moisture Protection
- 09 - Finishes

Maintenance and Replacement [B2-B5]
- 07 - Thermal and Moisture Protection
- 09 - Finishes

Operational Energy [B6]
- Electricity
- Heating

End of Life [C2-C4]
- 07 - Thermal and Moisture Protection
- 09 - Finishes

Module D [D]
- 07 - Thermal and Moisture Protection
- 09 - Finishes

03-Recladding

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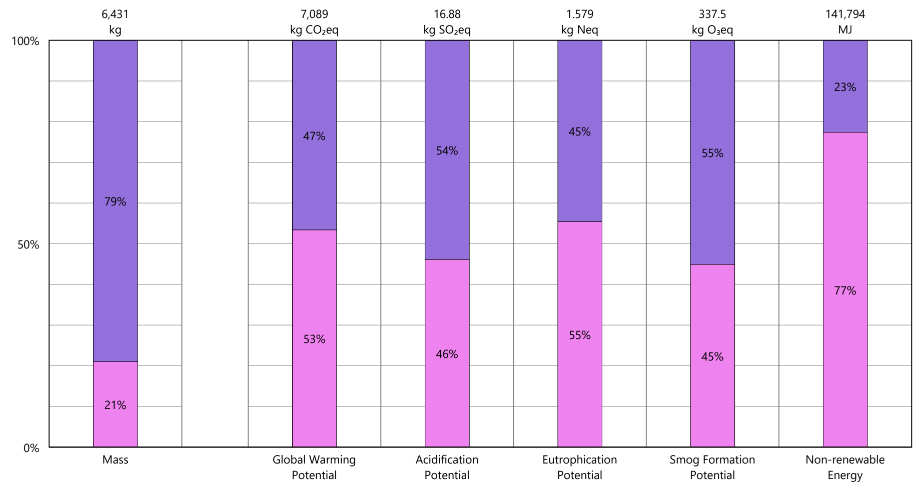
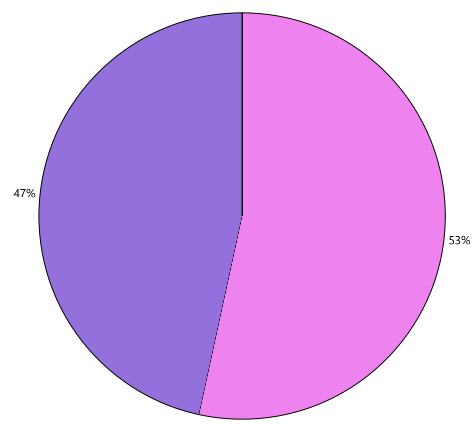
Results per Division



Legend

Divisions

- 07 - Thermal and Moisture Protection
- 09 - Finishes

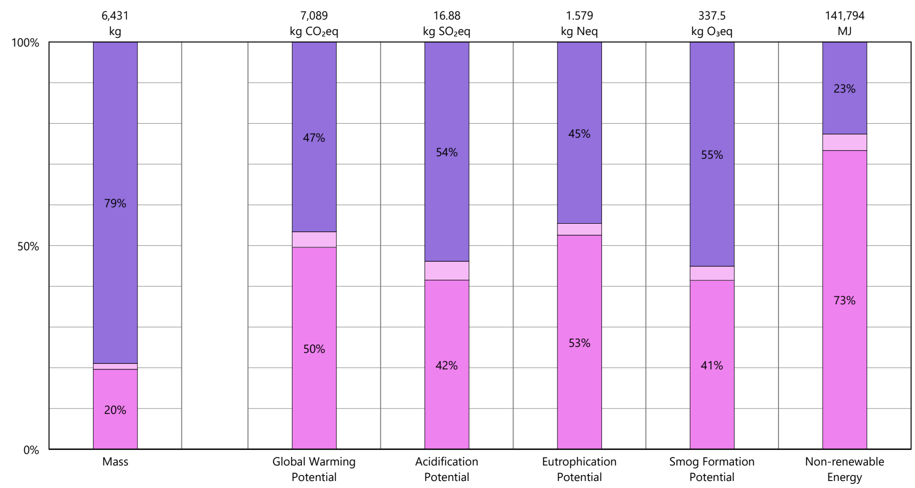


Global Warming Potential

03-Recladding

tally.

Results per Division, itemized by Tally Entry



Legend

07 - Thermal and Moisture Protection

- Extruded polystyrene (XPS), board
- Polyethelene sheet vapor barrier (HDPE)

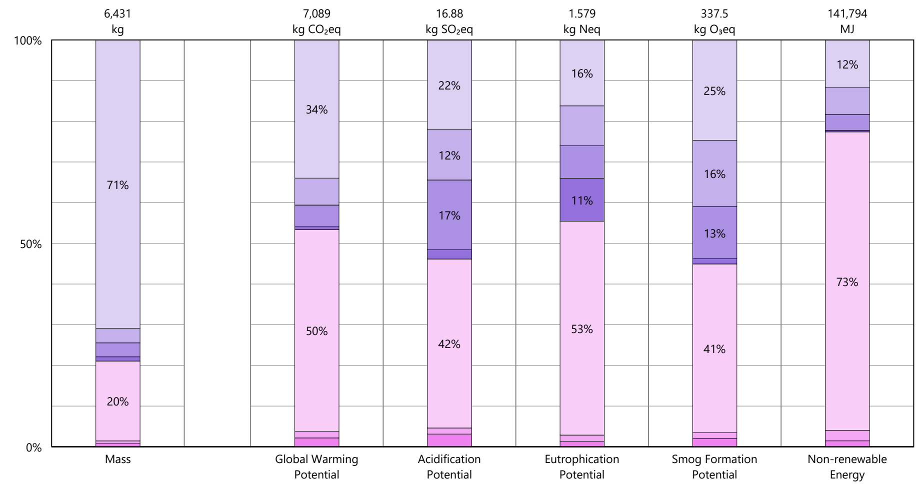
09 - Finishes

- Portland cement stucco

03-Recladding

tally

Results per Division, itemized by Material



Legend

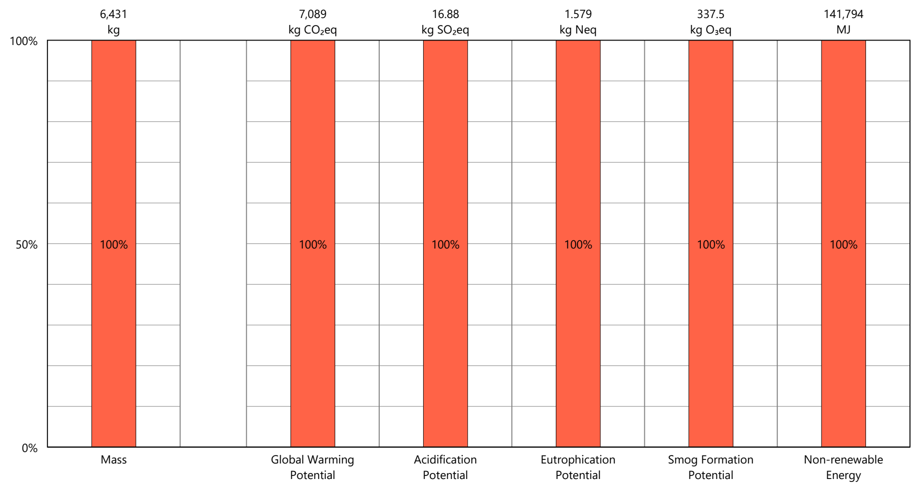
07 - Thermal and Moisture Protection

- Fasteners, galvanized steel
- Polyethelene sheet vapor barrier (HDPE)
- Polystyrene board (XPS), Pentane foaming agent

09 - Finishes

- Kraft paper
- Metal lath, for plaster
- Paint, exterior acrylic latex
- Stucco, portland cement

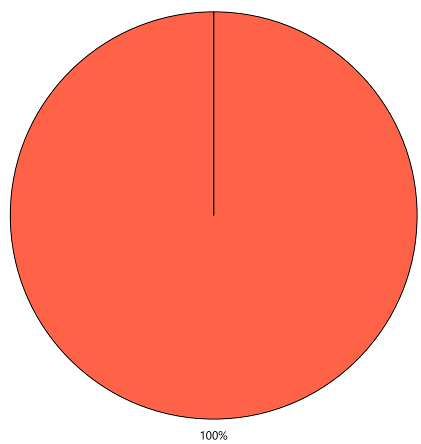
Results per Revit Category



Legend

Revit Categories

Walls

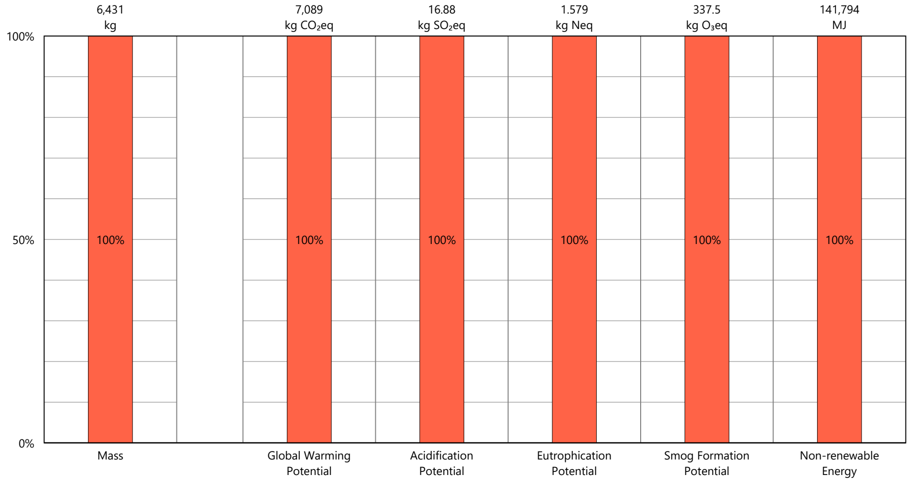


Global Warming Potential

03-Recladding

tally

Results per Revit Category, itemized by Family



Legend

Walls

EW4-145-13EIFS-125Ins

03-Recladding

tally.

Report Summary - 04-Enclosing

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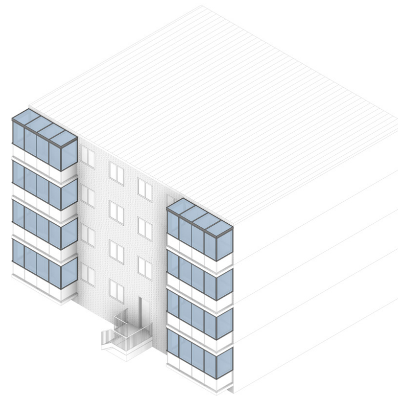
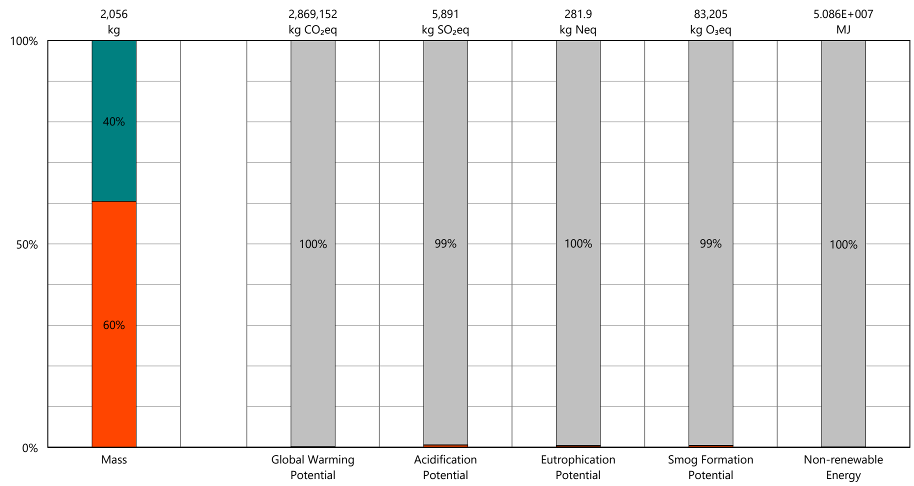


Gross Area	1111 m²
Building Life	60
Boundaries	Cradle to grave, inclusive of biogenic carbon; see appendix for a full list of materials and processes
On-site Construction [A5]	Not included
Operational Energy [B6]	63051.6 kWh annual electricity use 120 kWh/m² annual heating energy use

Environmental Impact Totals	**Product Stage [A1-A3]**	**Construction Stage [A4]**	**Use Stage [B2-B6]**	**End of Life Stage [C2-C4]**	**Module D [D]**
Global Warming (kg CO_2eq)	4,761	57.29	2,864,297	36.71	-2,060
Acidification (kg SO_2eq)	30.72	0.2654	5,860	0.1694	-13.5
Eutrophication (kg Neq)	0.9896	0.02161	280.9	0.008593	-0.2176
Smog Formation (kg O_3eq)	312.6	8.771	82,881	3.362	-105
Ozone Depletion (kg CFC-11eq)	5.079E-007	1.962E-012	3.897E-006	6.750E-012	-9.291E-008
Primary Energy (MJ)	72,086	833.1	6.321E+007	629.1	-31,658
Non-renewable Energy (MJ)	56,811	813.1	5.080E+007	588.2	-19,442
Renewable Energy (MJ)	15,448	20.14	1.244E+007	41.47	-12,173
Environmental Impacts / Area					
Global Warming (kg CO_2eq/m²)	4.285	0.05156	2,578	0.03304	-1.85
Acidification (kg SO_2eq/m²)	0.02765	2.389E-004	5.274	1.525E-004	-0.0122
Eutrophication (kg Neq/m²)	8.908E-004	1.945E-005	0.2528	7.735E-006	-1.959E-004
Smog Formation (kg O_3eq/m²)	0.2813	0.007895	74.60	0.003026	-0.09447
Ozone Depletion (kg CFC-11eq/m²)	4.572E-010	1.766E-015	3.508E-009	6.075E-015	-8.363E-011
Primary Energy (MJ/m²)	64.88	0.7498	56,893	0.5662	-28.5
Non-renewable Energy (MJ/m²)	51.14	0.7319	45,723	0.5294	-17.5
Renewable Energy (MJ/m²)	13.90	0.01813	11,199	0.03732	-11.0

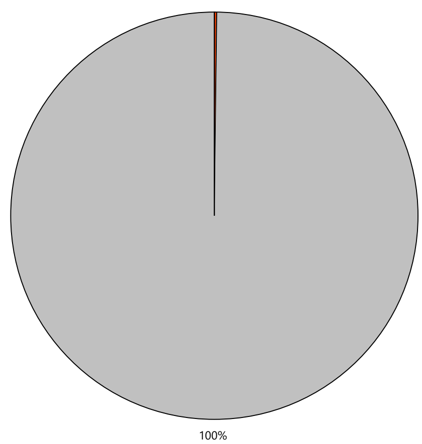
Results per Life Cycle Stage



Legend

Life Cycle Stages

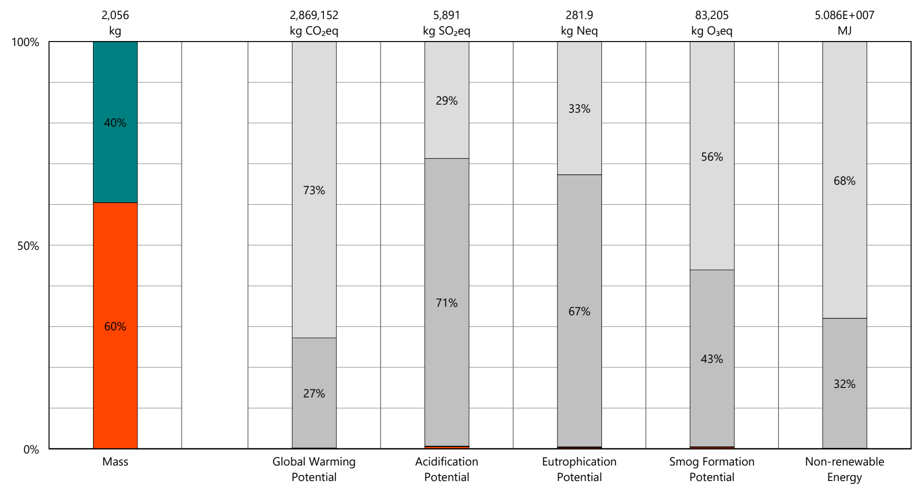
- Product [A1-A3]
- Transportation [A4]
- Maintenance and Replacement [B2-B5]
- Operational Energy [B6]
- End of Life [C2-C4]
- Module D [D]



Global Warming Potential

04-Enclosing

Results per Life Cycle Stage, itemized by Division



Legend

Product [A1-A3]
- 08 - Openings and Glazing

Transportation [A4]
- 08 - Openings and Glazing

Maintenance and Replacement [B2-B5]
- 08 - Openings and Glazing

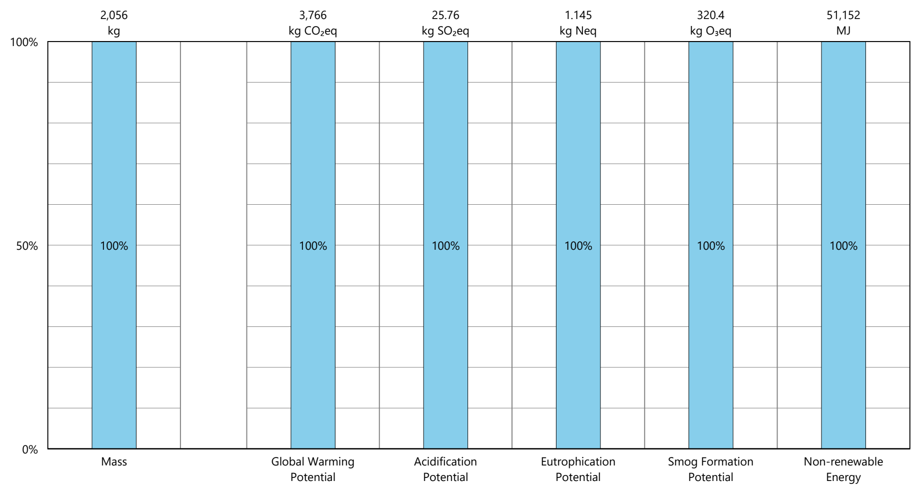
Operational Energy [B6]
- Electricity
- Heating

End of Life [C2-C4]
- 08 - Openings and Glazing

Module D [D]
- 08 - Openings and Glazing

04-Enclosing

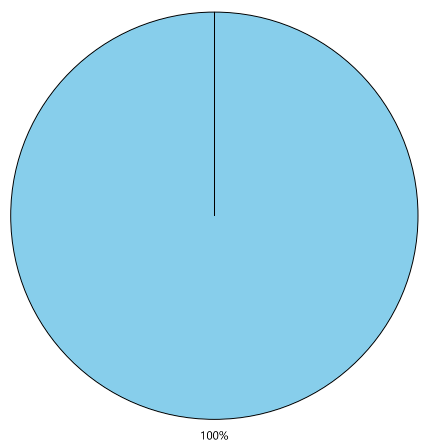
Results per Division



Legend

Divisions

08 - Openings and Glazing

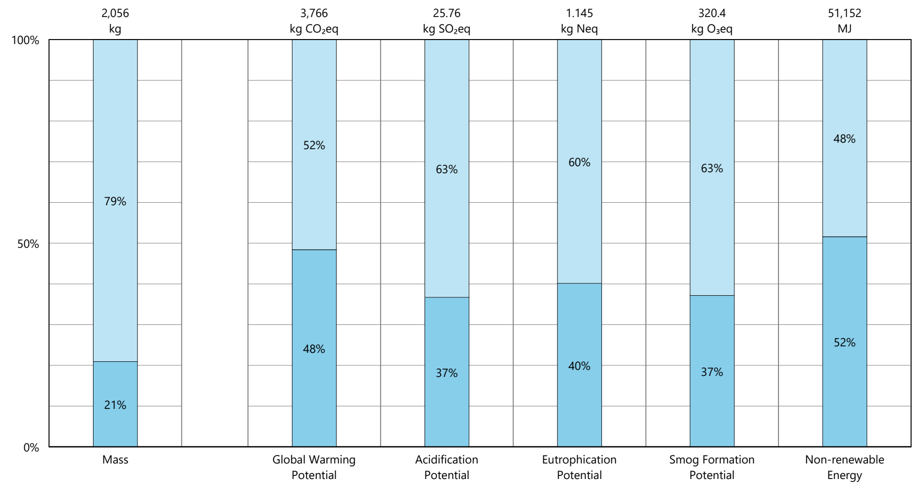


Global Warming Potential

04-Enclosing

tally.

Results per Division, itemized by Tally Entry

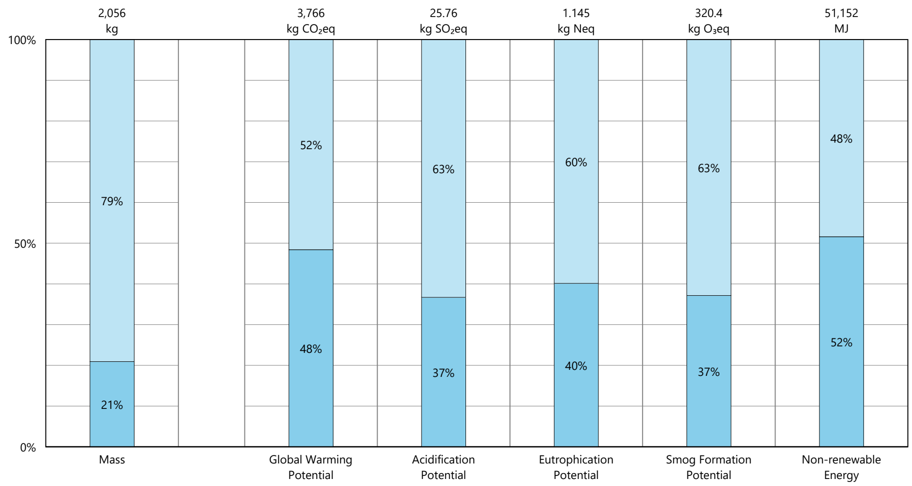


Legend

08 - Openings and Glazing

- Aluminum mullion, inclusive of finish
- Glazing, monolithic sheet

Results per Division, itemized by Material

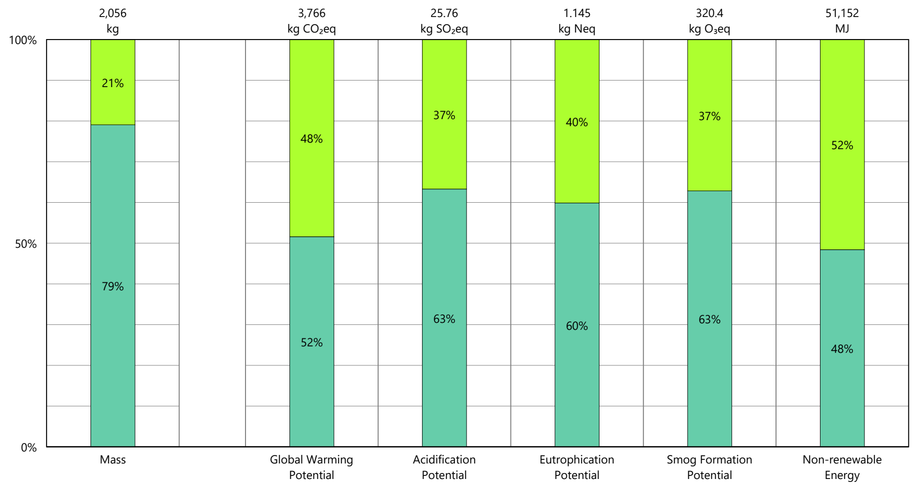


Legend

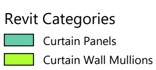
08 - Openings and Glazing

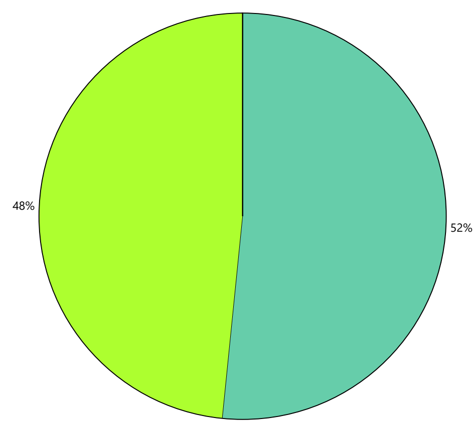
- Aluminum extrusion, anodized, AEC - EPD
- Glazing, monolithic sheet, generic

Results per Revit Category



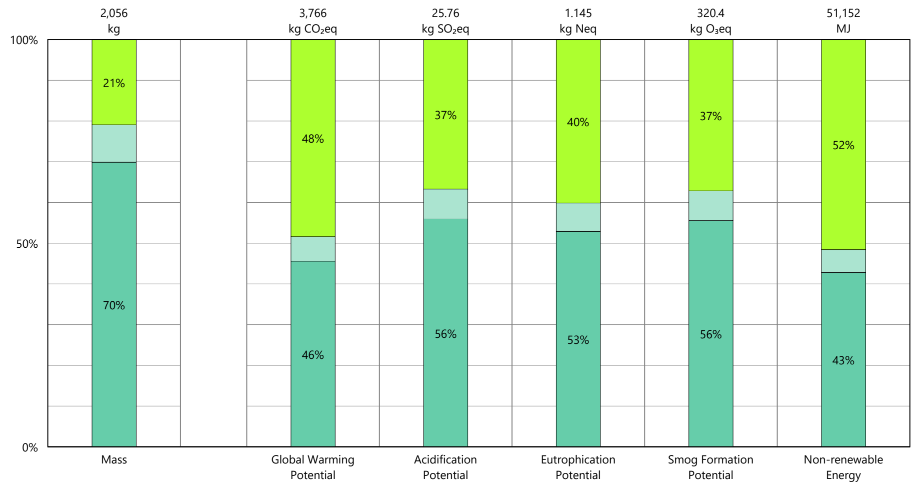
Legend





Global Warming Potential

Results per Revit Category, itemized by Family



Legend

Curtain Panels

- 08-Glazed Panel
- System Panel

Curtain Wall Mullions

- Rectangular Mullion

04-Enclosing

tally.

Report Summary - 05-Insulating

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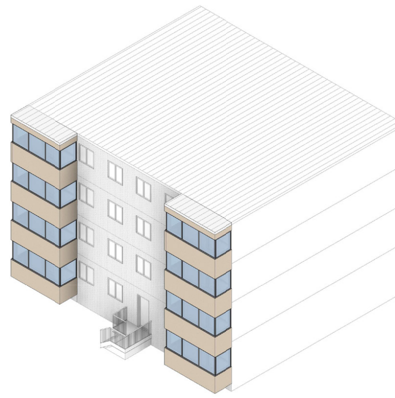
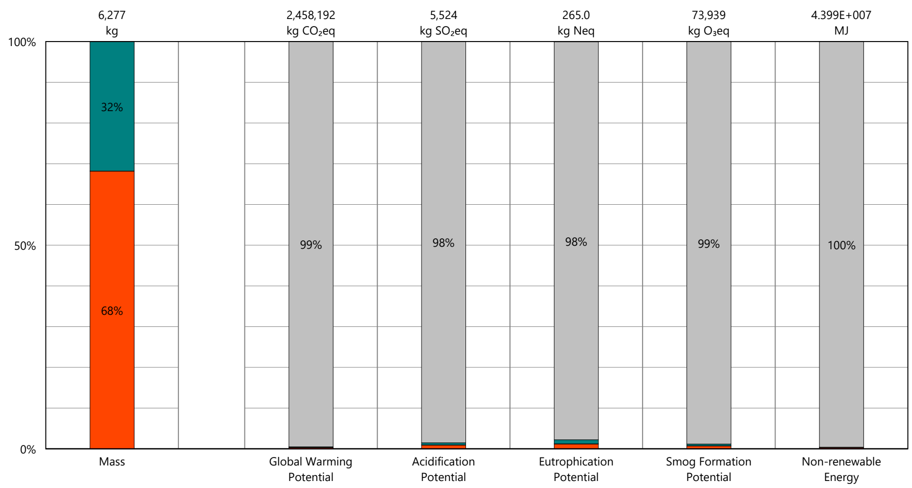
Non-commercial Version 2018.09.27.01



Location	Toronto
Gross Area	1111 m²
Building Life	60
Boundaries	Cradle to grave, inclusive of biogenic carbon; see appendix for a full list of materials and processes
On-site Construction [A5]	Not included
Operational Energy [B6]	61746.1 kWh annual electricity use 96.92 kWh/m² annual heating energy use

Environmental Impact Totals	Product Stage [A1-A3]	Construction Stage [A4]	Use Stage [B2-B6]	End of Life Stage [C2-C4]	Module D [D]
Global Warming (kg CO_2eq)	8,140	114.5	2,449,517	421.3	-3,275
Acidification (kg SO_2eq)	51.68	0.5305	5,470	1.327	-21.2
Eutrophication (kg Neq)	3.195	0.0432	261.6	0.1733	-0.4673
Smog Formation (kg O_3eq)	535.1	17.53	73,371	15.22	-196
Ozone Depletion (kg CFC-11eq)	8.376E-005	3.921E-012	8.160E-005	2.608E-011	-1.928E-006
Primary Energy (MJ)	137,687	1,665	5.603E+007	2,384	-47,129
Non-renewable Energy (MJ)	115,125	1,625	4.387E+007	2,230	-34,750
Renewable Energy (MJ)	22,714	40.26	1.219E+007	156.7	-12,345
Environmental Impacts / Area					
Global Warming (kg CO_2eq/m²)	7.326	0.1031	2,205	0.3792	-2.95
Acidification (kg SO_2eq/m²)	0.04652	4.775E-004	4.923	0.001194	-0.01912
Eutrophication (kg Neq/m²)	0.002876	3.888E-005	0.2354	1.559E-004	-4.207E-004
Smog Formation (kg O_3eq/m²)	0.4817	0.01578	66.04	0.0137	-0.1766
Ozone Depletion (kg CFC-11eq/m²)	7.539E-008	3.529E-015	7.344E-008	2.347E-014	-1.736E-009
Primary Energy (MJ/m²)	123.9	1.499	50,432	2.146	-42.4
Non-renewable Energy (MJ/m²)	103.6	1.463	39,487	2.007	-31.3
Renewable Energy (MJ/m²)	20.44	0.03624	10,969	0.141	-11.1

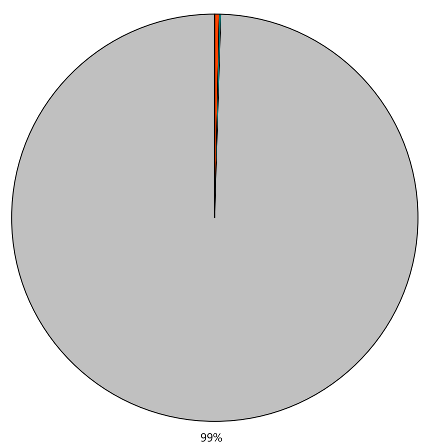
Results per Life Cycle Stage



Legend

Life Cycle Stages

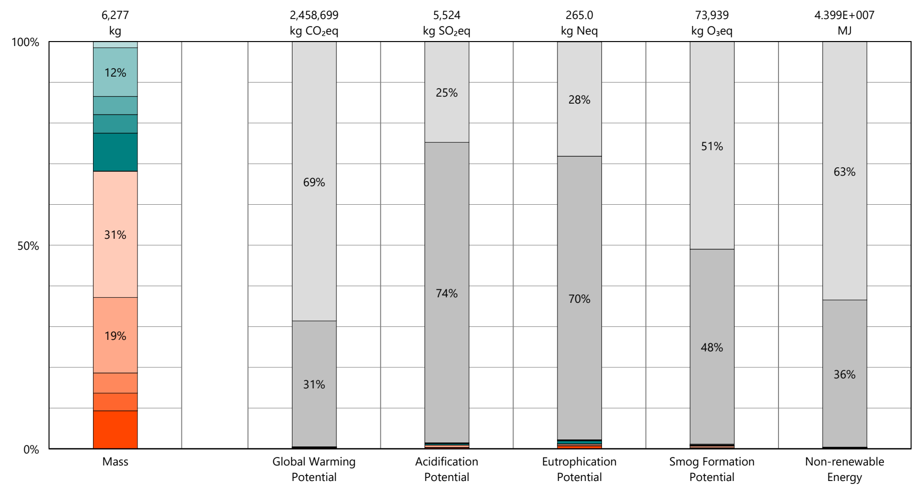
- Product [A1-A3]
- Transportation [A4]
- Maintenance and Replacement [B2-B5]
- Operational Energy [B6]
- End of Life [C2-C4]
- Module D [D]



Global Warming Potential

05-Insulating

Results per Life Cycle Stage, itemized by Division



Legend

Product [A1-A3]
- 05 - Metals
- 06 - Wood/Plastics/Composites
- 07 - Thermal and Moisture Protection
- 08 - Openings and Glazing
- 09 - Finishes

Transportation [A4]
- 05 - Metals
- 06 - Wood/Plastics/Composites
- 07 - Thermal and Moisture Protection
- 08 - Openings and Glazing
- 09 - Finishes

Maintenance and Replacement [B2-B5]
- 05 - Metals
- 06 - Wood/Plastics/Composites
- 07 - Thermal and Moisture Protection
- 08 - Openings and Glazing
- 09 - Finishes

Operational Energy [B6]
- Electricity
- Heating

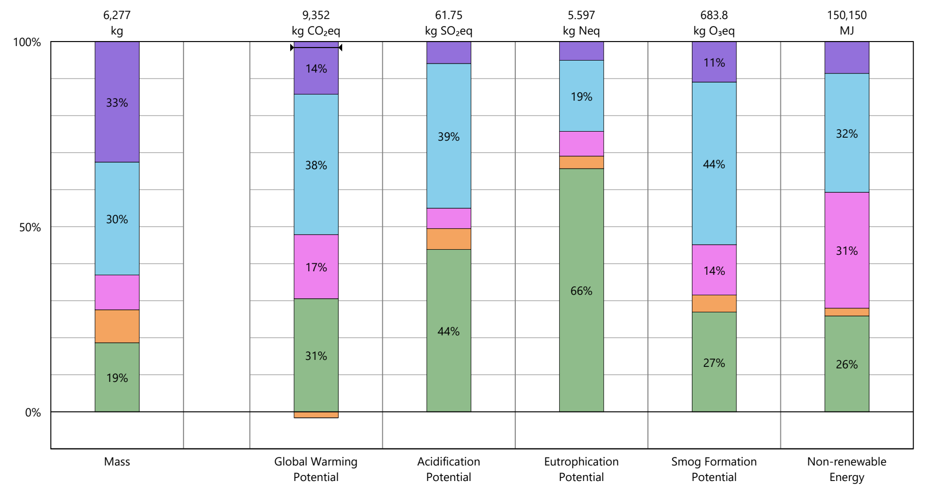
End of Life [C2-C4]
- 05 - Metals
- 06 - Wood/Plastics/Composites
- 07 - Thermal and Moisture Protection
- 08 - Openings and Glazing
- 09 - Finishes

Module D [D]
- 05 - Metals
- 06 - Wood/Plastics/Composites
- 07 - Thermal and Moisture Protection
- 08 - Openings and Glazing
- 09 - Finishes

05-Insulating

tally

Results per Division

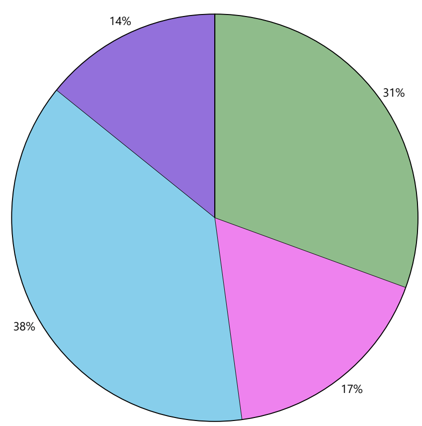


Legend

Net value (impacts + credits)

Divisions

- 05 - Metals
- 06 - Wood/Plastics/Composites
- 07 - Thermal and Moisture Protection
- 08 - Openings and Glazing
- 09 - Finishes

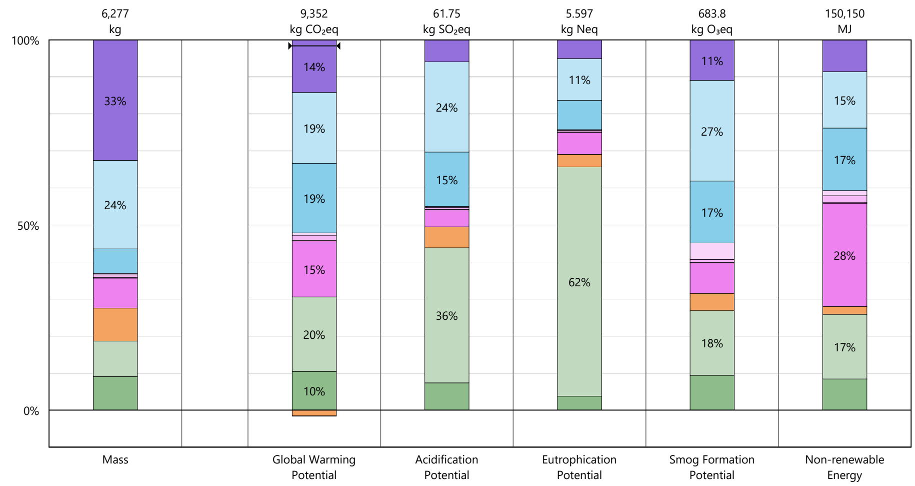


Global Warming Potential

05-Insulating

tally

Results per Division, itemized by Tally Entry



Legend

Net value (impacts + credits)

05 - Metals

- Steel, sheet, carbon steel
- Steel, sheet, stainless

06 - Wood/Plastics/Composites

- Plywood, exterior grade

07 - Thermal and Moisture Protection

- Extruded polystyrene (XPS), board
- Glass wool, batt or blown
- Polyethelene sheet vapor barrier (HDPE)
- Self adhering membrane

08 - Openings and Glazing

- Aluminum mullion, inclusive of finish
- Glazing, monolithic sheet

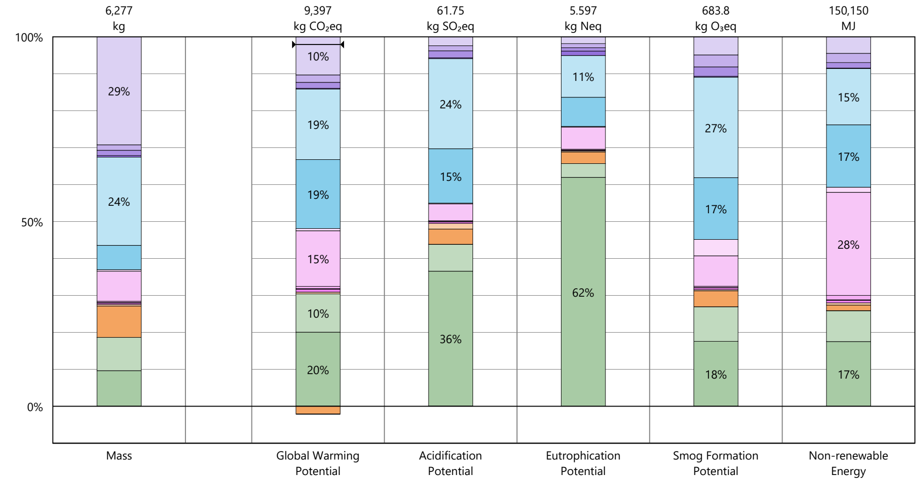
09 - Finishes

- Portland cement stucco

05-Insulating

tally

Results per Division, itemized by Material



Legend

Net value (impacts + credits)

05 - Metals

- Paint, exterior metal coating, silicone-based
- Stainless steel sheet, Chromium 18/8
- Steel, sheet
- Tin plating, for stainless steel sheet stock

06 - Wood/Plastics/Composites

- Exterior grade plywood, US
- Paint, Brillux, Arylic facade paint - EPD

07 - Thermal and Moisture Protection

- Fasteners, galvanized steel
- Glass wool kraft faced batt, Knauf, EcoBatt - EPD
- Polyethelene sheet vapor barrier (HDPE)
- Polystyrene board (XPS), Pentane foaming agent
- Self adhering flashing membrane, 40 mil

08 - Openings and Glazing

- Aluminum extrusion, anodized, AEC - EPD
- Glazing, monolithic sheet, generic

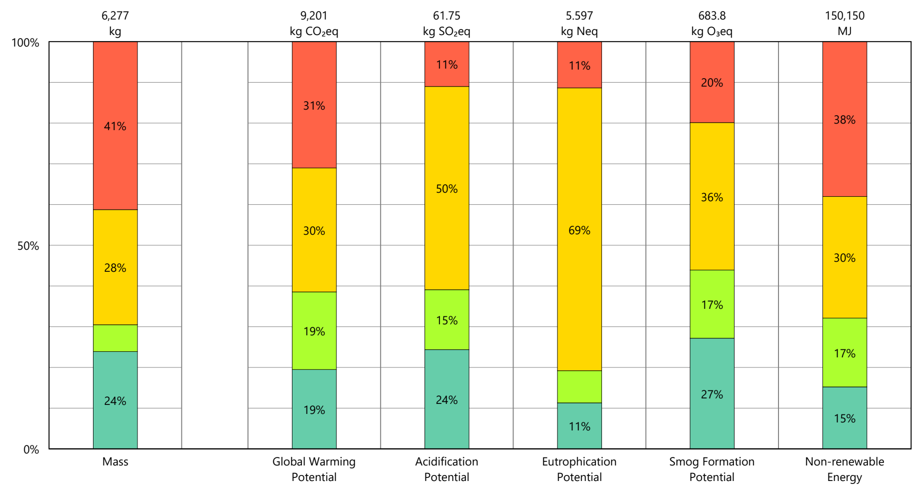
09 - Finishes

- Kraft paper
- Metal lath, for plaster
- Paint, exterior acrylic latex
- Stucco, portland cement

05-Insulating

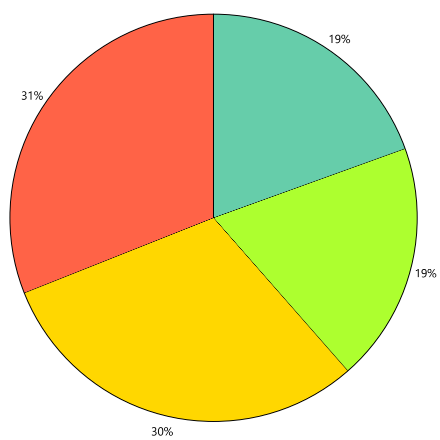
tally

Results per Revit Category



Legend

Revit Categories
- Curtain Panels
- Curtain Wall Mullions
- Roofs
- Walls

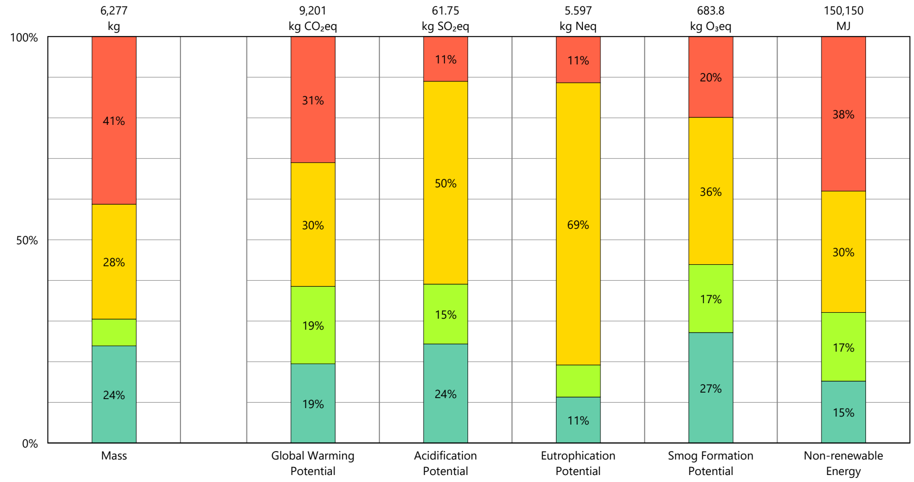


Global Warming Potential

05-Insulating

tally.

Results per Revit Category, itemized by Family



Legend

Curtain Panels

- 08-Glazed Panel

Curtain Wall Mullions

- Rectangular Mullion

Roofs

- R3-Mtl-16Bd-100Ins-16Bd-38Mtl

Walls

- EW4-145-13EIFS-125Ins

Report Summary - 06-Adding

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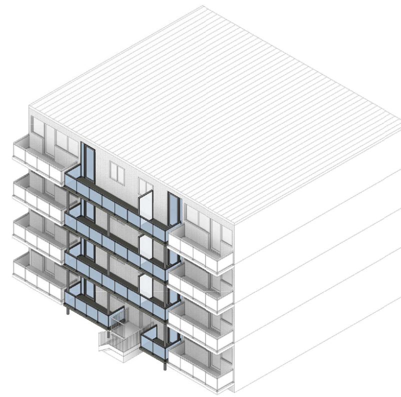
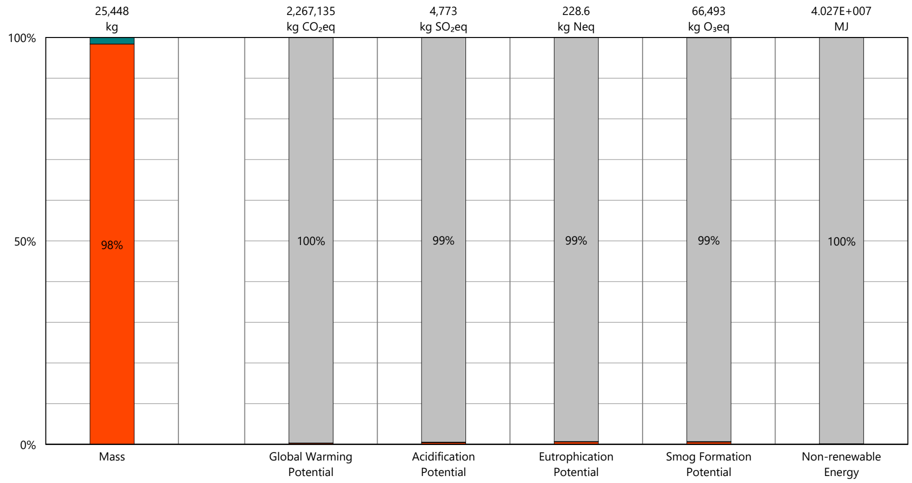


Location	Toronto
Gross Area	1111 m²
Building Life	60
Boundaries	Cradle to grave, inclusive of biogenic carbon; see appendix for a full list of materials and processes
On-site Construction [A5]	Not included
Operational Energy [B6]	52023.8 kWh annual electricity use 93.07 kWh/m² annual heating energy use

Environmental Impact Totals	Product Stage [A1-A3]	Construction Stage [A4]	Use Stage [B2-B6]	End of Life Stage [C2-C4]	Module D [D]
Global Warming (kg CO_2eq)	6,902	62.04	2,259,668	502.8	-323
Acidification (kg SO_2eq)	21.62	0.2875	4,749	2.323	-1.25
Eutrophication (kg Neq)	1.395	0.02341	227.1	0.1178	-0.02254
Smog Formation (kg O_3eq)	393.7	9.499	66,044	46.21	-6.68
Ozone Depletion (kg CFC-11eq)	-2.976E-006	2.125E-012	3.215E-006	9.243E-011	1.300E-006
Primary Energy (MJ)	62,179	902.2	5.044E+007	8,608	-3,881
Non-renewable Energy (MJ)	57,028	880.6	4.020E+007	8,049	-2,974
Renewable Energy (MJ)	5,180	21.82	1.026E+007	568.7	-905
Environmental Impacts / Area					
Global Warming (kg CO_2eq/m²)	6.213	0.05584	2,034	0.4525	-0.2908
Acidification (kg SO_2eq/m²)	0.01946	2.587E-004	4.274	0.002091	-0.001125
Eutrophication (kg Neq/m²)	0.001256	2.107E-005	0.2044	1.060E-004	-2.029E-005
Smog Formation (kg O_3eq/m²)	0.3544	0.00855	59.45	0.04159	-0.006011
Ozone Depletion (kg CFC-11eq/m²)	-2.679E-009	1.912E-015	2.894E-009	8.319E-014	1.170E-009
Primary Energy (MJ/m²)	55.97	0.812	45,399	7.748	-3.49
Non-renewable Energy (MJ/m²)	51.33	0.7926	36,183	7.245	-2.68
Renewable Energy (MJ/m²)	4.662	0.01964	9,238	0.5119	-0.8144

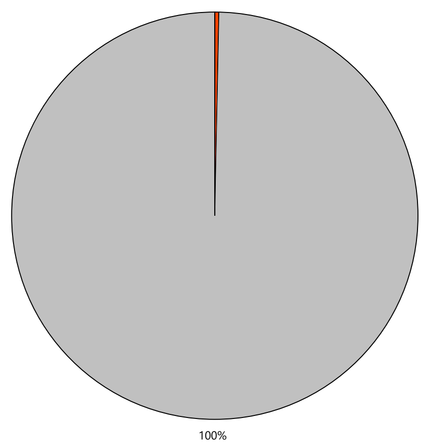
Results per Life Cycle Stage



Legend

Life Cycle Stages

- Product [A1-A3]
- Transportation [A4]
- Maintenance and Replacement [B2-B5]
- Operational Energy [B6]
- End of Life [C2-C4]
- Module D [D]

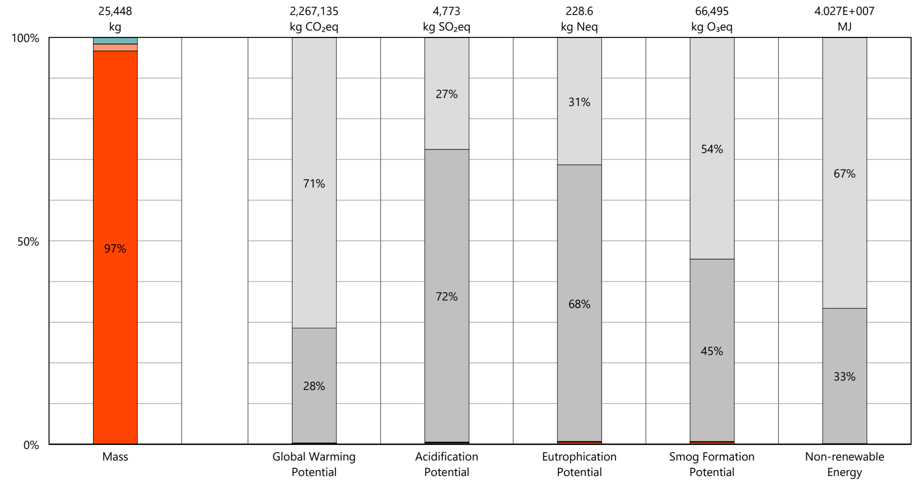


Global Warming Potential

06-Adding

tally

Results per Life Cycle Stage, itemized by Division



Legend

Product [A1-A3]
- 03 - Concrete
- 08 - Openings and Glazing

Transportation [A4]
- 03 - Concrete
- 08 - Openings and Glazing

Maintenance and Replacement [B2-B5]
- 03 - Concrete
- 08 - Openings and Glazing

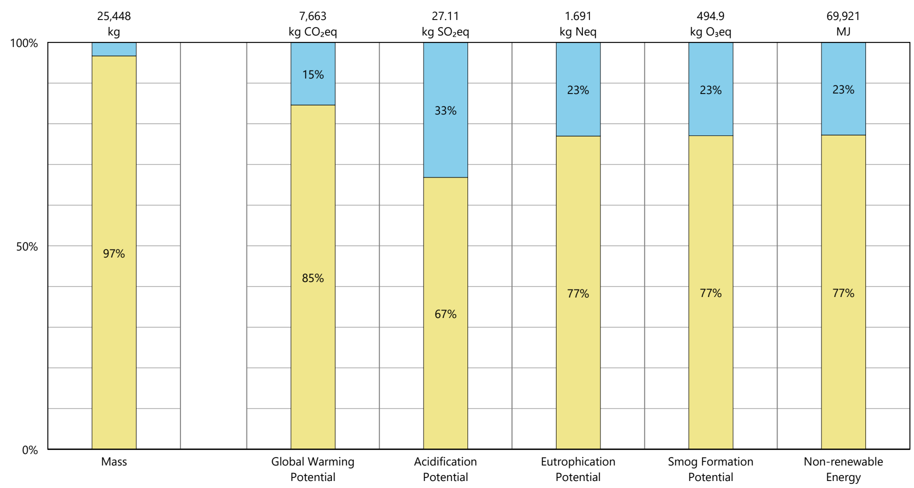
Operational Energy [B6]
- Electricity
- Heating

End of Life [C2-C4]
- 03 - Concrete
- 08 - Openings and Glazing

Module D [D]
- 03 - Concrete
- 08 - Openings and Glazing

06-Adding

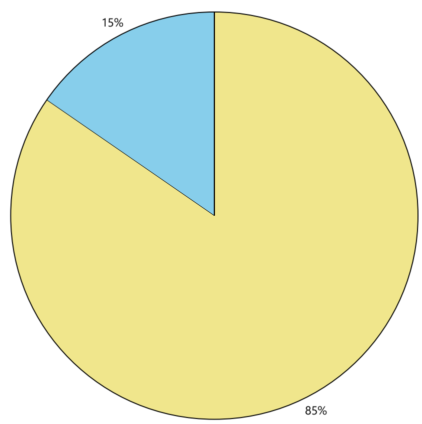
Results per Division



Legend

Divisions

- 03 - Concrete
- 08 - Openings and Glazing

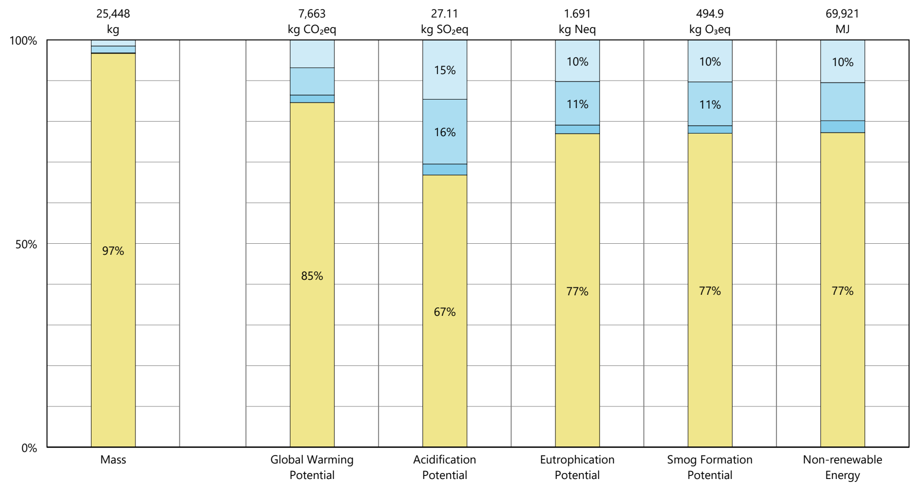


Global Warming Potential

06-Adding

tally

Results per Division, itemized by Tally Entry



Legend

03 - Concrete

- Precast concrete structural panel, hollow core

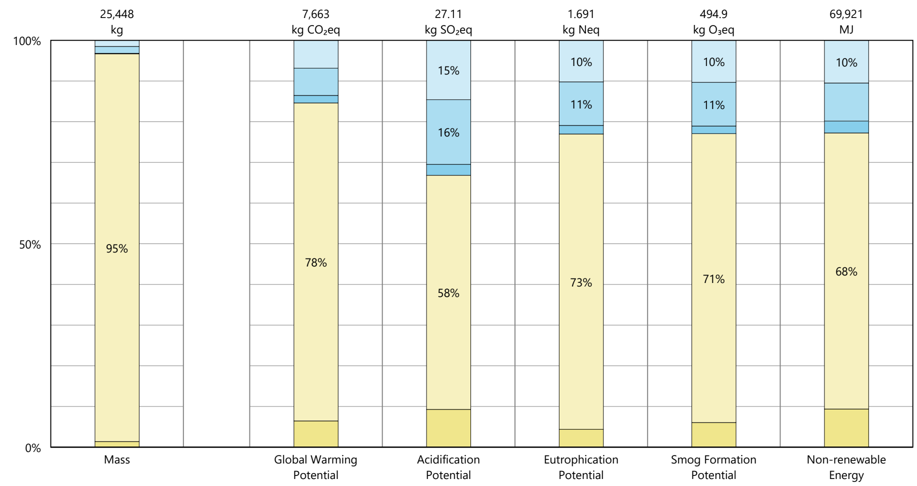
08 - Openings and Glazing

- Aluminum mullion, inclusive of finish
- Glazing, monolithic sheet
- Glazing, triple pane IGU

06-Adding

tally

Results per Division, itemized by Material



Legend

03 - Concrete

- Steel, reinforcing rod
- Structural concrete, 4001-5000 psi, 0-19% fly ash and/or slag

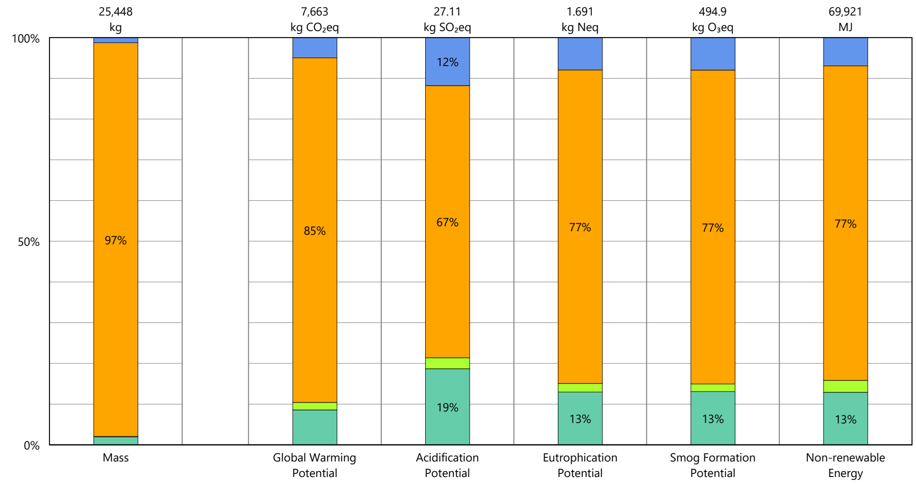
08 - Openings and Glazing

- Aluminum extrusion, anodized, AEC - EPD
- Glazing, monolithic sheet, generic
- Glazing, triple, insulated (air)

06-Adding

tally

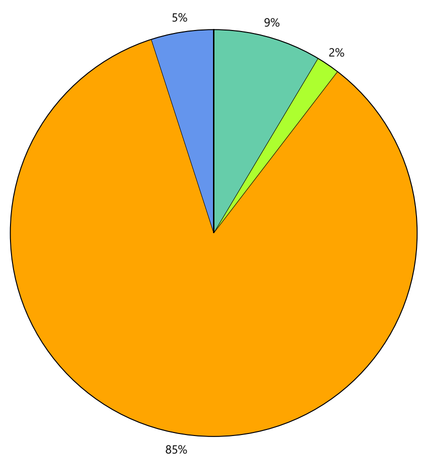
Results per Revit Category



Legend

Revit Categories

- Curtain Panels
- Curtain Wall Mullions
- Floors
- Windows

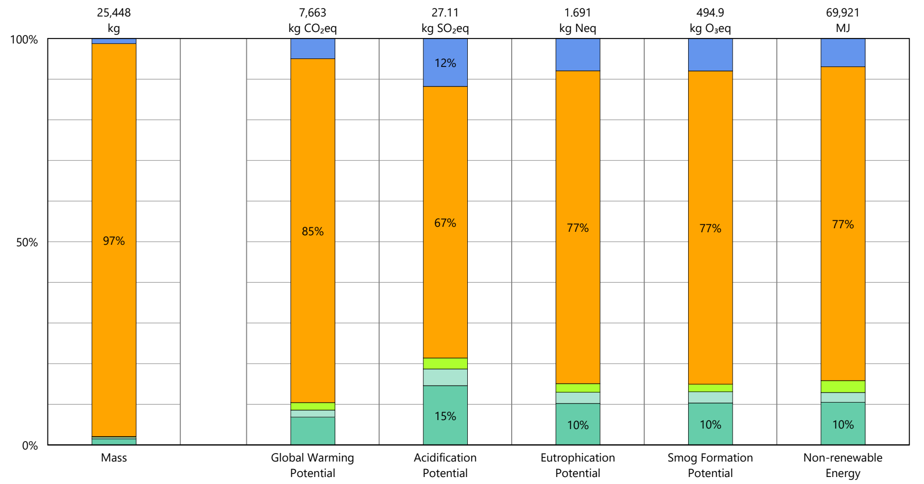


Global Warming Potential

06-Adding

tally.

Results per Revit Category, itemized by Family



Legend

Curtain Panels

- 08-Glass-WW Glazed Panel
- 08-Glazed Panel

Curtain Wall Mullions

- Rectangular Mullion

Floors

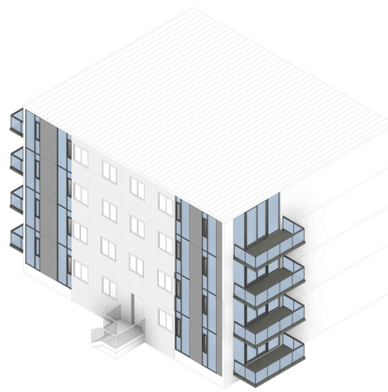
- SF5-Hollow Core Concrete

Windows

- 08-Door-Curtain Wall

Report Summary - 07-Relocating

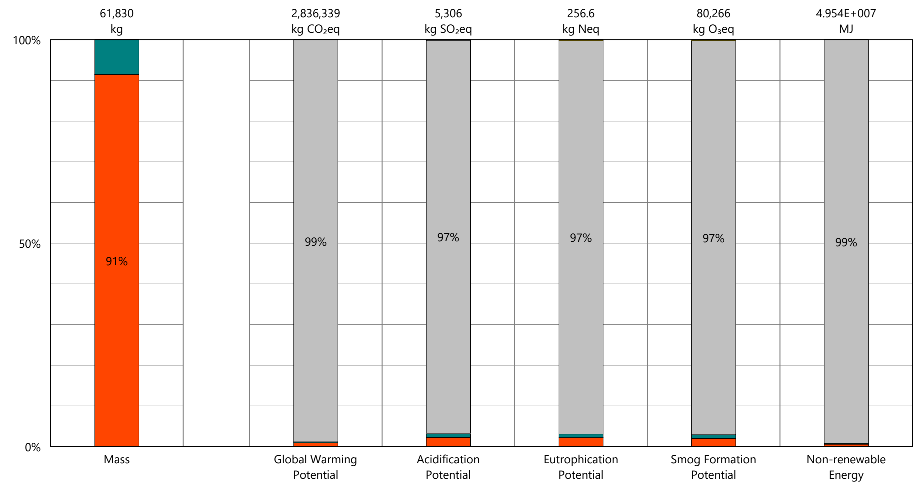
Created with Tally
Non-commercial Version 2018.09.27.01



Location	Toronto
Gross Area	1111 m^2
Building Life	60
Boundaries	Cradle to grave, inclusive of biogenic carbon; see appendix for a full list of materials and processes
On-site Construction [A5]	Not included
Operational Energy [B6]	50995.6 kWh annual electricity use 124.97 kWh/m^2 annual heating energy use

Environmental Impact Totals	**Product Stage [A1-A3]**	**Construction Stage [A4]**	**Use Stage [B2-B6]**	**End of Life Stage [C2-C4]**	**Module D [D]**
Global Warming (kg CO_2eq)	26,319	489.2	2,807,988	1,544	-1,406
Acidification (kg SO_2eq)	121.3	2.267	5,176	6.235	-5.86
Eutrophication (kg Neq)	5.497	0.1846	250.6	0.3503	-0.1262
Smog Formation (kg O_3eq)	1,618	74.90	78,460	114.0	-46.0
Ozone Depletion (kg CFC-11eq)	-1.381E-005	1.675E-011	4.007E-006	2.242E-010	5.782E-006
Primary Energy (MJ)	331,810	7,114	5.926E+007	20,833	-18,483
Non-renewable Energy (MJ)	299,286	6,943	4.921E+007	19,481	-14,275
Renewable Energy (MJ)	32,887	172.0	1.008E+007	1,375	-4,195
Environmental Impacts / Area					
Global Warming (kg CO_2eq/m^2)	23.69	0.4403	2,527	1.390	-1.27
Acidification (kg SO_2eq/m^2)	0.1092	0.00204	4.659	0.005612	-0.00527
Eutrophication (kg Neq/m^2)	0.004948	1.661E-004	0.2256	3.153E-004	-1.135E-004
Smog Formation (kg O_3eq/m^2)	1.456	0.06742	70.62	0.1027	-0.04143
Ozone Depletion (kg CFC-11eq/m^2)	-1.243E-008	1.508E-014	3.607E-009	2.018E-013	5.204E-009
Primary Energy (MJ/m^2)	298.7	6.403	53,336	18.75	-16.6
Non-renewable Energy (MJ/m^2)	269.4	6.250	44,294	17.53	-12.8
Renewable Energy (MJ/m^2)	29.60	0.1548	9,072	1.238	-3.78

Results per Life Cycle Stage



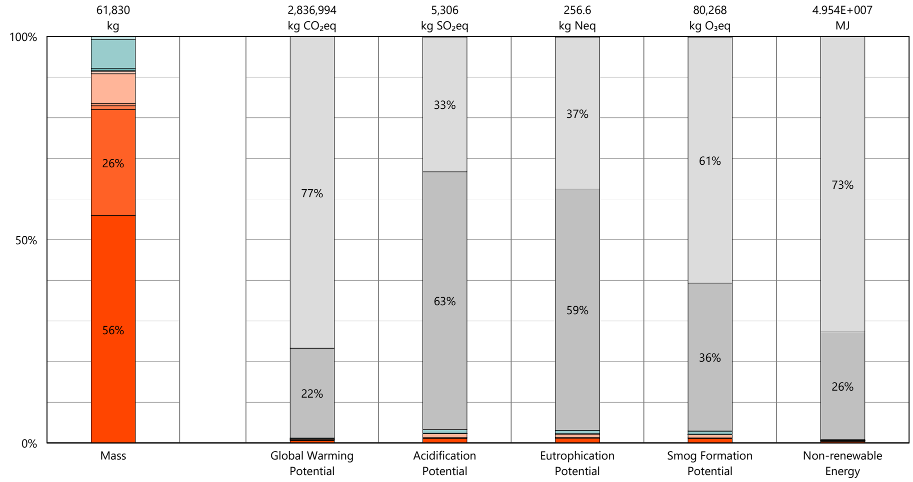
Legend

Life Cycle Stages

- Product [A1-A3]
- Transportation [A4]
- Maintenance and Replacement [B2-B5]
- Operational Energy [B6]
- End of Life [C2-C4]
- Module D [D]

Global Warming Potential

Results per Life Cycle Stage, itemized by Division



Legend

Product [A1-A3]
- 03 - Concrete
- 04 - Masonry
- 05 - Metals
- 06 - Wood/Plastics/Composites
- 08 - Openings and Glazing
- 09 - Finishes

Transportation [A4]
- 03 - Concrete
- 04 - Masonry
- 05 - Metals
- 06 - Wood/Plastics/Composites
- 08 - Openings and Glazing
- 09 - Finishes

Maintenance and Replacement [B2-B5]
- 03 - Concrete
- 04 - Masonry
- 05 - Metals
- 06 - Wood/Plastics/Composites
- 08 - Openings and Glazing
- 09 - Finishes

Operational Energy [B6]
- Electricity
- Heating

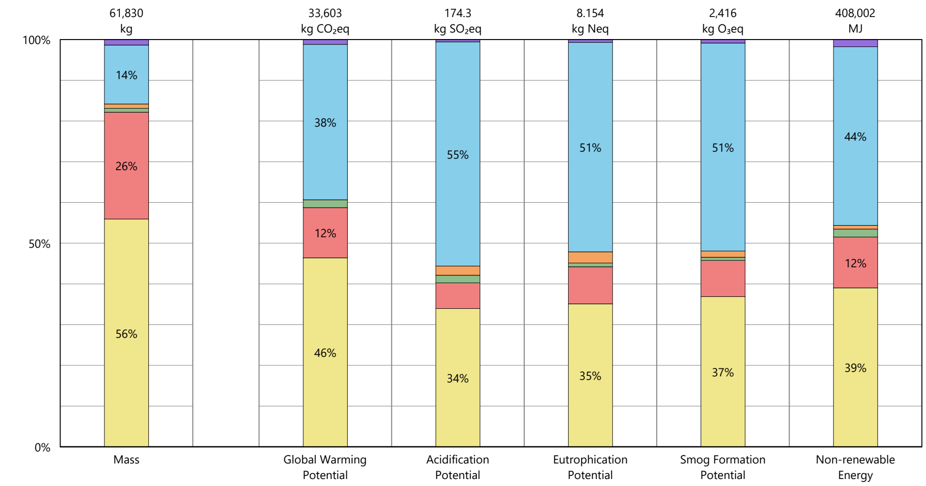
End of Life [C2-C4]
- 03 - Concrete
- 04 - Masonry
- 05 - Metals
- 06 - Wood/Plastics/Composites
- 08 - Openings and Glazing
- 09 - Finishes

Module D [D]
- 03 - Concrete
- 04 - Masonry
- 05 - Metals
- 06 - Wood/Plastics/Composites
- 08 - Openings and Glazing
- 09 - Finishes

07-Relocating

tally

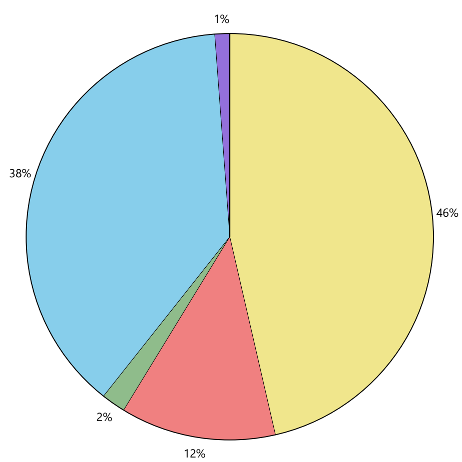
Results per Division



Legend

Divisions

- 03 - Concrete
- 04 - Masonry
- 05 - Metals
- 06 - Wood/Plastics/Composites
- 08 - Openings and Glazing
- 09 - Finishes

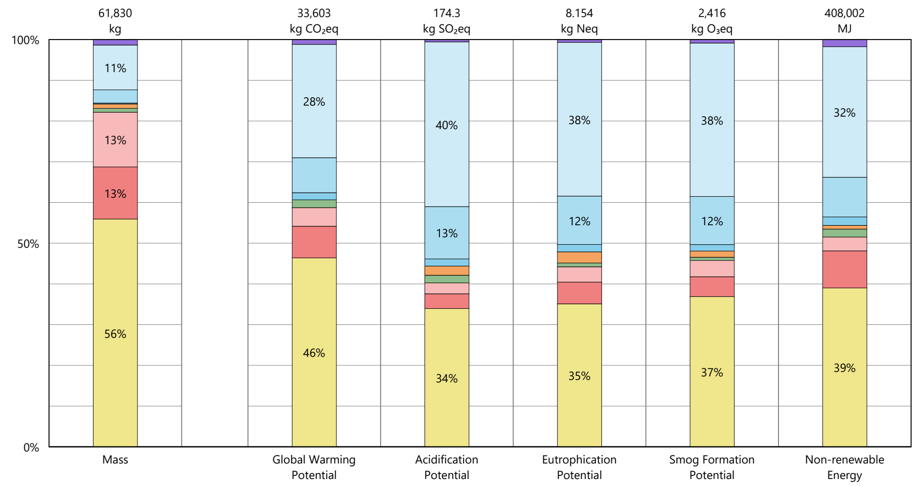


Global Warming Potential

07-Relocating

tally

Results per Division, itemized by Tally Entry



Legend

03 - Concrete

- Cast-in-place concrete, lightweight structural concrete, 2501-3000 psi

04 - Masonry

- Brick
- Solid-core CMU

05 - Metals

- Steel, C channel

06 - Wood/Plastics/Composites

- Plywood, exterior grade

08 - Openings and Glazing

- Aluminum mullion, inclusive of finish
- Glazing, double pane IGU
- Glazing, triple pane IGU

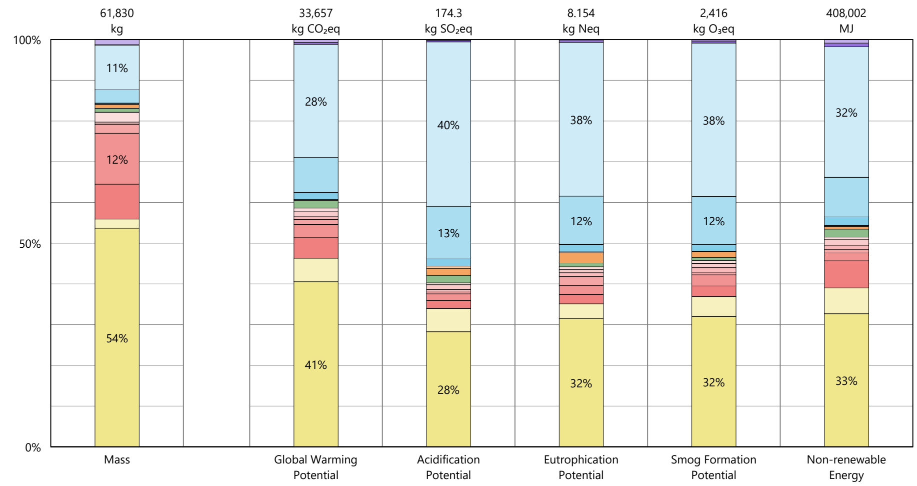
09 - Finishes

- Wall board, gypsum

07-Relocating

tally

Results per Division, itemized by Material



Legend

03 - Concrete

- Lightweight concrete, 2501-3000 psi, 0-19% fly ash and/or slag
- Steel, reinforcing rod

04 - Masonry

- Brick, generic
- Concrete masonry unit (CMU), solid
- Lime mortar (Mortar type K)
- Paint, exterior acrylic latex
- Steel, reinforcing rod
- Thickset mortar

05 - Metals

- Hot rolled structural steel, AISC - EPD

06 - Wood/Plastics/Composites

- Exterior grade plywood, US
- Paint, Brillux, Silicone facade paint - EPD

08 - Openings and Glazing

- Aluminum extrusion, anodized, AEC - EPD
- Glazing, double, insulated (air)
- Glazing, triple, insulated (air)

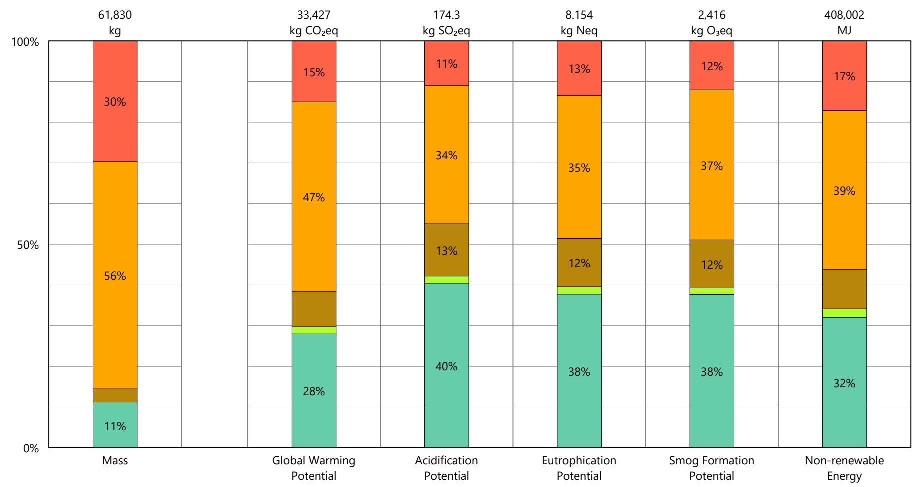
09 - Finishes

- Paint, interior acrylic latex
- Wall board, gypsum, natural

07-Relocating

tally

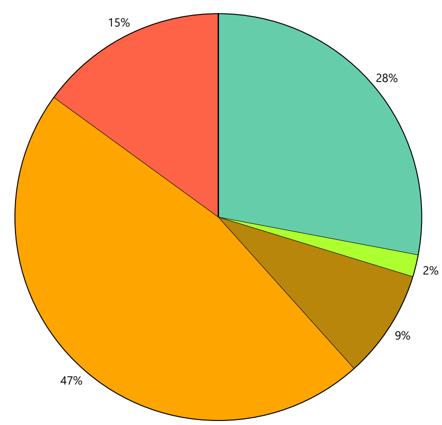
Results per Revit Category



Legend

Revit Categories

- Curtain Panels
- Curtain Wall Mullions
- Doors
- Floors
- Walls

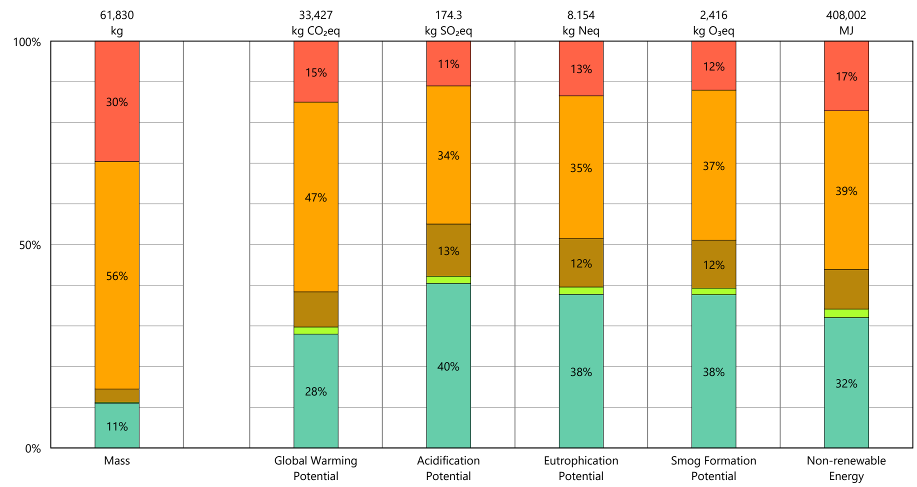


Global Warming Potential

07-Relocating

tally.

Results per Revit Category, itemized by Family



Legend

Curtain Panels
- 08-Glass-WW Glazed Panel

Curtain Wall Mullions
- Rectangular Mullion

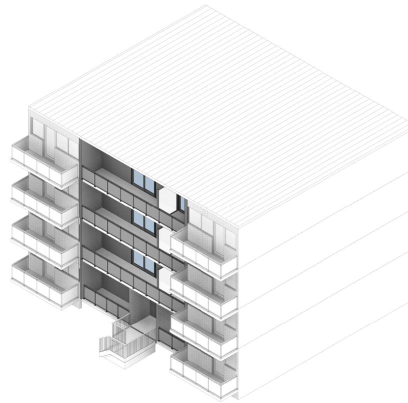
Doors
- 08-Door-Curtain Wall

Floors
- SF3-Concrete Slab 200mm

Walls
- EWE 34-Brick_90Brck-20Air-90CMU-13Gyp-40Std-13Gyp

Report Summary - 08-Insetting

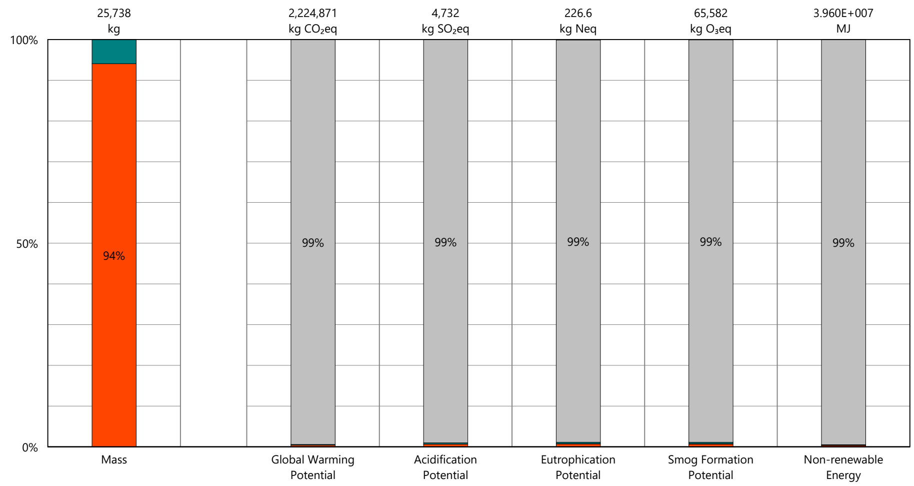
Created with Tally
Non-commercial Version 2018.09.27.01



Gross Area	1111 m^2
Building Life	60
Boundaries	Cradle to grave, inclusive of biogenic carbon; see appendix for a full list of materials and processes
On-site Construction [A5]	Not included
Operational Energy [B6]	51612.2 kWh annual electricity use 90.63 kWh/m^2 annual heating energy use

Environmental Impact Totals	Product Stage [A1-A3]	Construction Stage [A4]	Use Stage [B2-B6]	End of Life Stage [C2-C4]	Module D [D]
Global Warming (kg CO_2eq)	9,544	301.6	2,214,515	509.9	-479
Acidification (kg SO_2eq)	29.87	1.397	4,698	2.534	-1.95
Eutrophication (kg Neq)	1.626	0.1138	224.6	0.2119	-0.03751
Smog Formation (kg O_3eq)	444.0	46.17	65,044	47.50	-13.5
Ozone Depletion (kg CFC-11eq)	-3.806E-006	1.033E-011	2.975E-006	9.374E-011	1.769E-006
Primary Energy (MJ)	154,093	4,385	4.960E+007	8,731	-5,907
Non-renewable Energy (MJ)	144,566	4,281	3.944E+007	8,164	-4,550
Renewable Energy (MJ)	9,560	106.0	1.018E+007	576.7	-1,352
Environmental Impacts / Area					
Global Warming (kg CO_2eq/m^2)	8.591	0.2714	1,993	0.4589	-0.4312
Acidification (kg SO_2eq/m^2)	0.02689	0.001258	4.229	0.002281	-0.001757
Eutrophication (kg Neq/m^2)	0.001464	1.024E-004	0.2022	1.908E-004	-3.376E-005
Smog Formation (kg O_3eq/m^2)	0.3996	0.04156	58.55	0.04275	-0.01216
Ozone Depletion (kg CFC-11eq/m^2)	-3.426E-009	9.297E-015	2.678E-009	8.437E-014	1.592E-009
Primary Energy (MJ/m^2)	138.7	3.947	44,644	7.859	-5.32
Non-renewable Energy (MJ/m^2)	130.1	3.853	35,500	7.348	-4.10
Renewable Energy (MJ/m^2)	8.605	0.09545	9,166	0.5191	-1.22

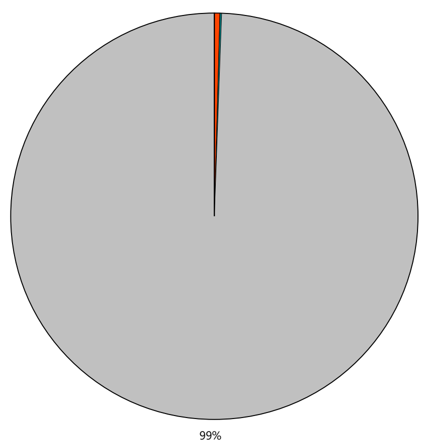
Results per Life Cycle Stage



Legend

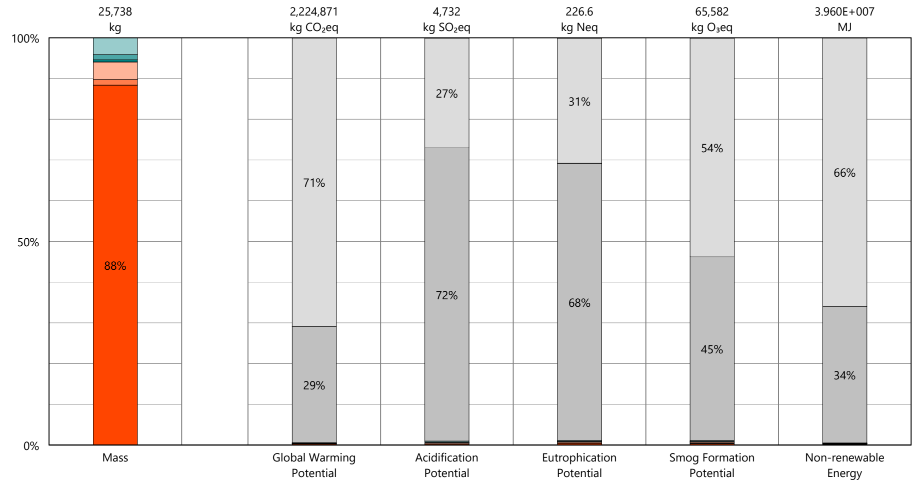
Life Cycle Stages

- Product [A1-A3]
- Transportation [A4]
- Maintenance and Replacement [B2-B5]
- Operational Energy [B6]
- End of Life [C2-C4]
- Module D [D]



Global Warming Potential

Results per Life Cycle Stage, itemized by Division



Legend

Product [A1-A3]
- 04 - Masonry
- 07 - Thermal and Moisture Protection
- 08 - Openings and Glazing

Transportation [A4]
- 04 - Masonry
- 07 - Thermal and Moisture Protection
- 08 - Openings and Glazing

Maintenance and Replacement [B2-B5]
- 04 - Masonry
- 07 - Thermal and Moisture Protection
- 08 - Openings and Glazing

Operational Energy [B6]
- Electricity
- Heating

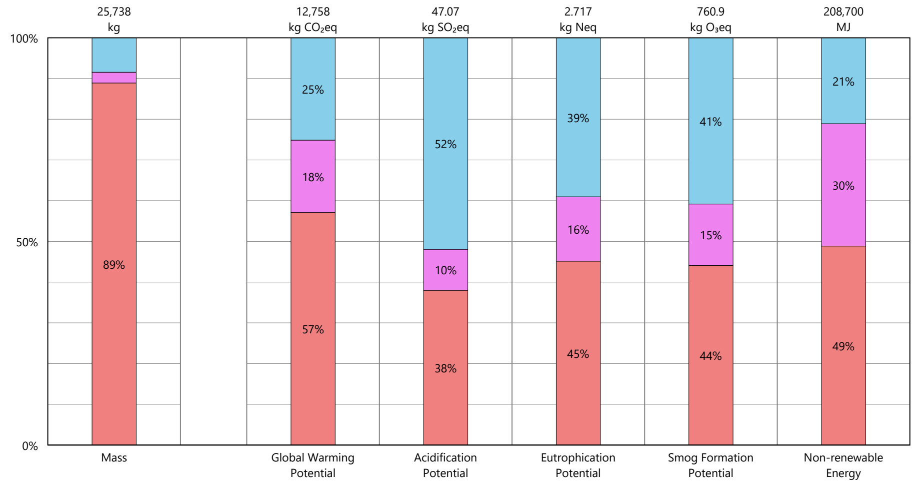
End of Life [C2-C4]
- 04 - Masonry
- 07 - Thermal and Moisture Protection
- 08 - Openings and Glazing

Module D [D]
- 04 - Masonry
- 07 - Thermal and Moisture Protection
- 08 - Openings and Glazing

08-Insetting

tally

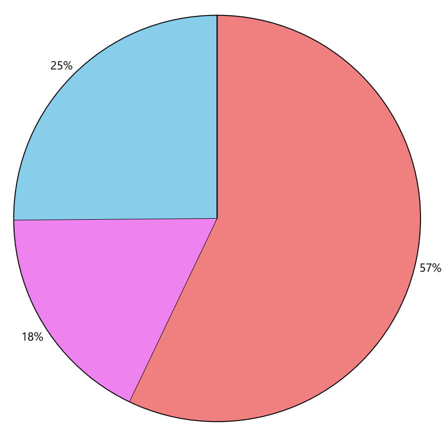
Results per Division



Legend

Divisions

- 04 - Masonry
- 07 - Thermal and Moisture Protection
- 08 - Openings and Glazing

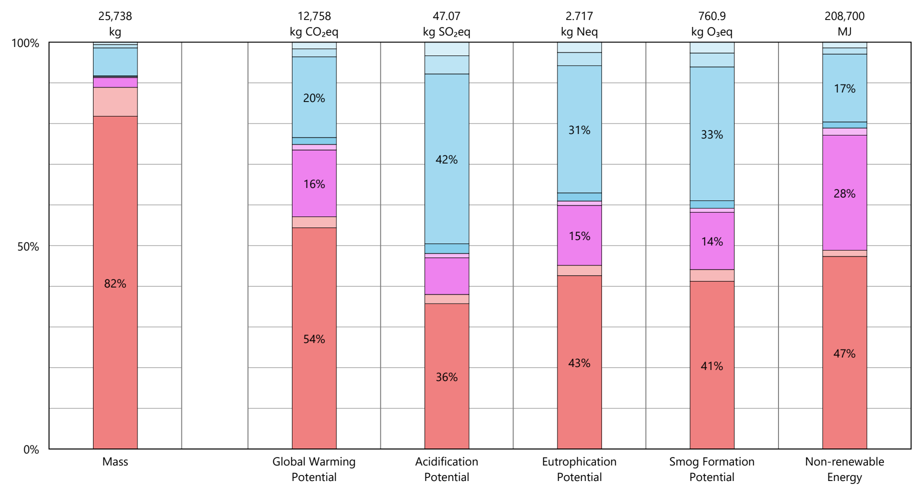


Global Warming Potential

08-Insetting

tally

Results per Division, itemized by Tally Entry



Legend

04 - Masonry
- Brick
- Solid-core CMU

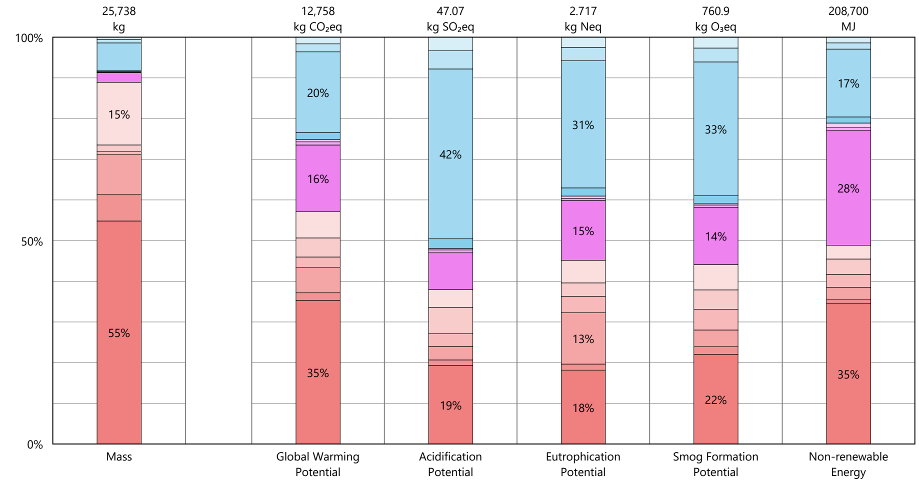
07 - Thermal and Moisture Protection
- Expanded polystyrene (EPS), board
- Polyethelene sheet vapor barrier (HDPE)

08 - Openings and Glazing
- Aluminum mullion, inclusive of finish
- Glazing, double pane IGU
- Glazing, monolithic sheet
- Glazing, triple pane IGU

08-Insetting

tally.

Results per Division, itemized by Material



Legend

04 - Masonry

- Brick, generic
- Concrete masonry unit (CMU), solid
- Lime mortar (Mortar type K)
- Paint, exterior acrylic latex
- Steel, reinforcing rod
- Thickset mortar

07 - Thermal and Moisture Protection

- Expanded polystyrene (EPS), board
- Fasteners, galvanized steel
- Polyethelene sheet vapor barrier (HDPE)

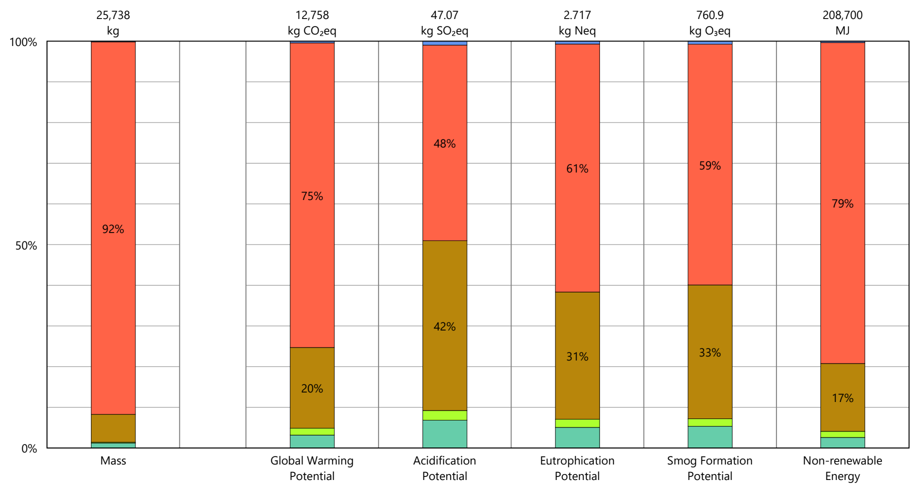
08 - Openings and Glazing

- Aluminum extrusion, anodized, AEC - EPD
- Glazing, double, insulated (air)
- Glazing, monolithic sheet, generic
- Glazing, triple, insulated (air)

08-Insetting

tally.

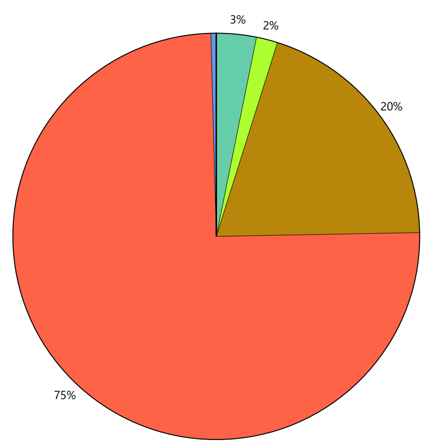
Results per Revit Category



Legend

Revit Categories

- Curtain Panels
- Curtain Wall Mullions
- Doors
- Walls
- Windows

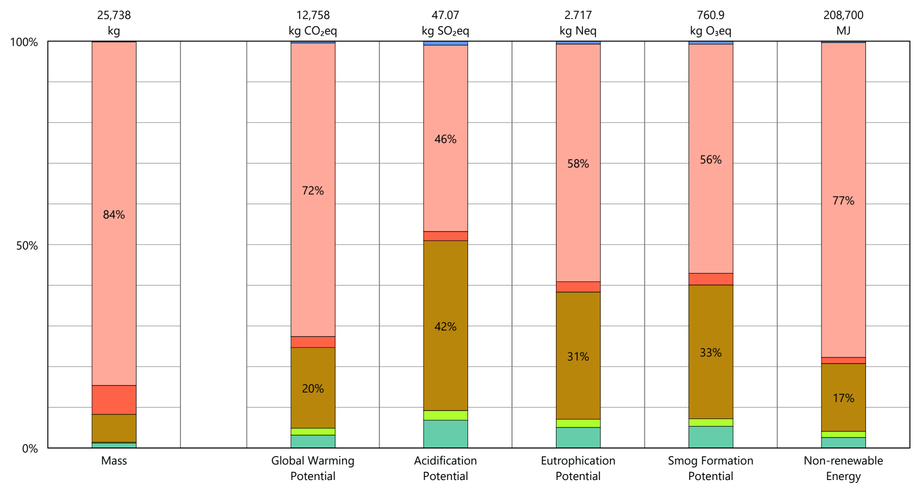


Global Warming Potential

08-Insetting

tally

Results per Revit Category, itemized by Family



Legend

Curtain Panels
- 08-Glass-WW Glazed Panel

Curtain Wall Mullions
- Rectangular Mullion

Doors
- 08-Door-Curtain Wall

Walls
- CB10-90CMU
- EW1-265-90Br-50Air-100Ins

Windows
- 08-Door-Curtain Wall-window

08-Insetting

tally.

Report Summary - 09-Layering

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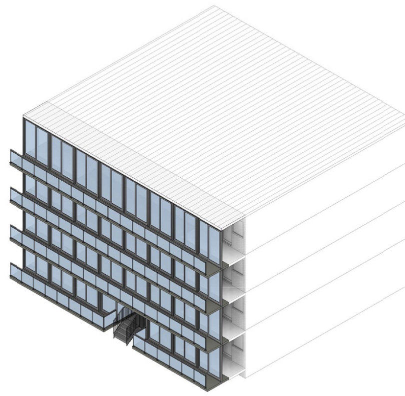
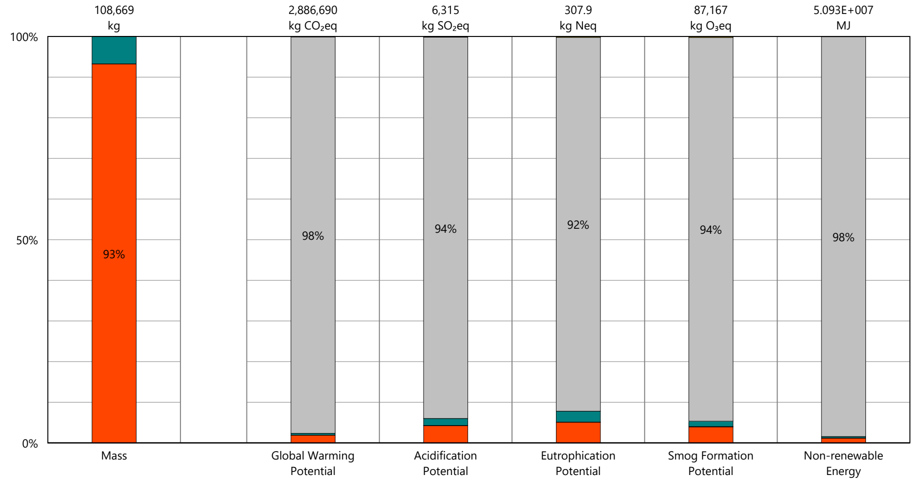
Non-commercial Version 2018.09.27.01



Location	Toronto
Gross Area	1111 m^2
Building Life	60
Boundaries	Cradle to grave, inclusive of biogenic carbon; see appendix for a full list of materials and processes
On-site Construction [A5]	Not included
Operational Energy [B6]	65028.7 kWh annual electricity use 115.87 kWh/m^2 annual heating energy use

Environmental Impact Totals	Product Stage [A1-A3]	Construction Stage [A4]	Use Stage [B2-B6]	End of Life Stage [C2-C4]	Module D [D]
Global Warming (kg CO_2eq)	54,943	518.6	2,828,348	2,879	-6,155
Acidification (kg SO_2eq)	267.8	2.403	6,033	11.08	-31.9
Eutrophication (kg Neq)	15.58	0.1957	291.5	0.6376	-0.9332
Smog Formation (kg O_3eq)	3,424	79.41	83,467	196.3	-340
Ozone Depletion (kg CFC-11eq)	1.920E-004	1.776E-011	2.291E-004	3.831E-010	6.435E-006
Primary Energy (MJ)	678,153	7,542	6.311E+007	35,546	-74,713
Non-renewable Energy (MJ)	607,660	7,362	5.029E+007	33,239	-68,673
Renewable Energy (MJ)	71,352	182.4	1.285E+007	2,347	-6,040
Environmental Impacts / Area					
Global Warming (kg CO_2eq/m^2)	49.45	0.4668	2,546	2.592	-5.54
Acidification (kg SO_2eq/m^2)	0.241	0.002163	5.431	0.009975	-0.02872
Eutrophication (kg Neq/m^2)	0.01402	1.761E-004	0.2624	5.739E-004	-8.400E-004
Smog Formation (kg O_3eq/m^2)	3.082	0.07148	75.13	0.1767	-0.3058
Ozone Depletion (kg CFC-11eq/m^2)	1.729E-007	1.599E-014	2.063E-007	3.448E-013	5.792E-009
Primary Energy (MJ/m^2)	610.4	6.789	56,801	31.99	-67.2
Non-renewable Energy (MJ/m^2)	546.9	6.626	45,261	29.92	-61.8
Renewable Energy (MJ/m^2)	64.22	0.1642	11,568	2.112	-5.44

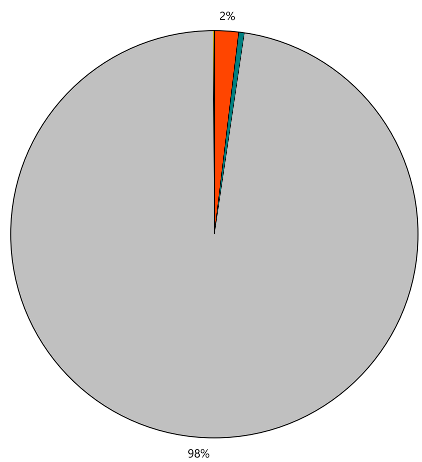
Results per Life Cycle Stage



Legend

Life Cycle Stages

- Product [A1-A3]
- Transportation [A4]
- Maintenance and Replacement [B2-B5]
- Operational Energy [B6]
- End of Life [C2-C4]
- Module D [D]

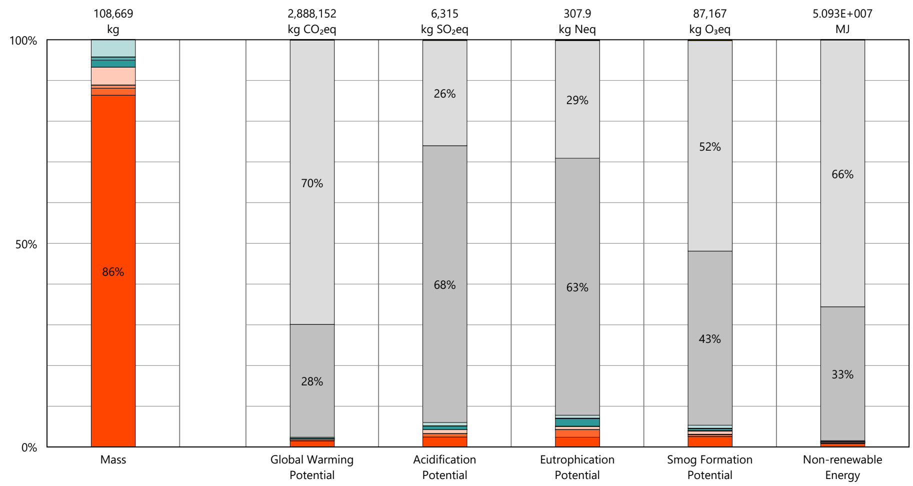


Global Warming Potential

09-Layering

tally.

Results per Life Cycle Stage, itemized by Division



Legend

Product [A1-A3]
- 03 - Concrete
- 05 - Metals
- 06 - Wood/Plastics/Composites
- 07 - Thermal and Moisture Protection
- 08 - Openings and Glazing

Transportation [A4]
- 03 - Concrete
- 05 - Metals
- 06 - Wood/Plastics/Composites
- 07 - Thermal and Moisture Protection
- 08 - Openings and Glazing

Maintenance and Replacement [B2-B5]
- 03 - Concrete
- 05 - Metals
- 06 - Wood/Plastics/Composites
- 07 - Thermal and Moisture Protection
- 08 - Openings and Glazing

Operational Energy [B6]
- Electricity
- Heating

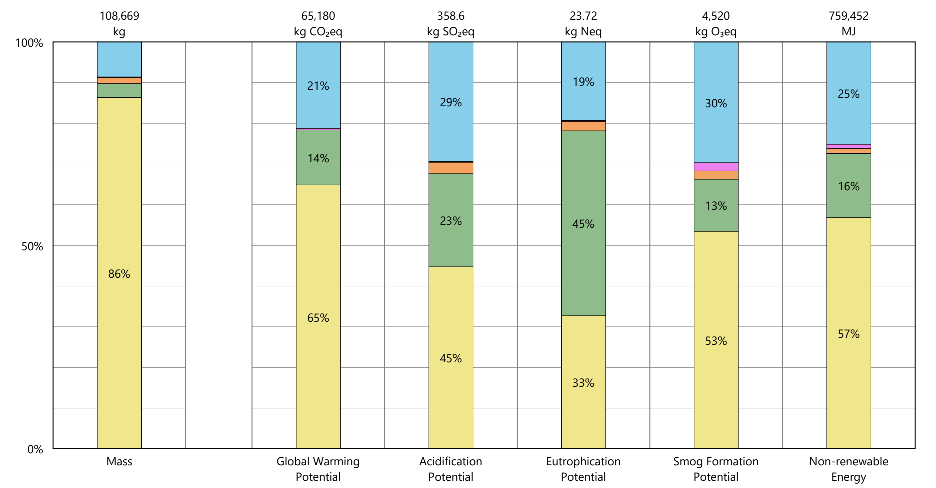
End of Life [C2-C4]
- 03 - Concrete
- 05 - Metals
- 06 - Wood/Plastics/Composites
- 07 - Thermal and Moisture Protection
- 08 - Openings and Glazing

Module D [D]
- 03 - Concrete
- 05 - Metals
- 06 - Wood/Plastics/Composites
- 07 - Thermal and Moisture Protection
- 08 - Openings and Glazing

09-Layering

tally

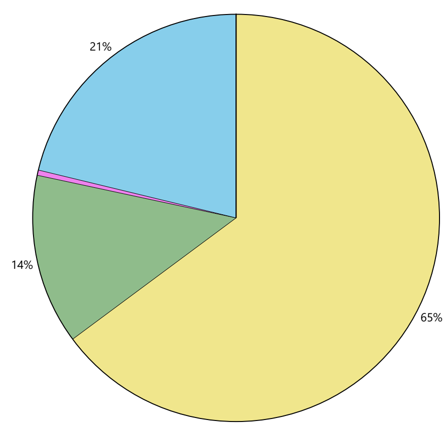
Results per Division



Legend

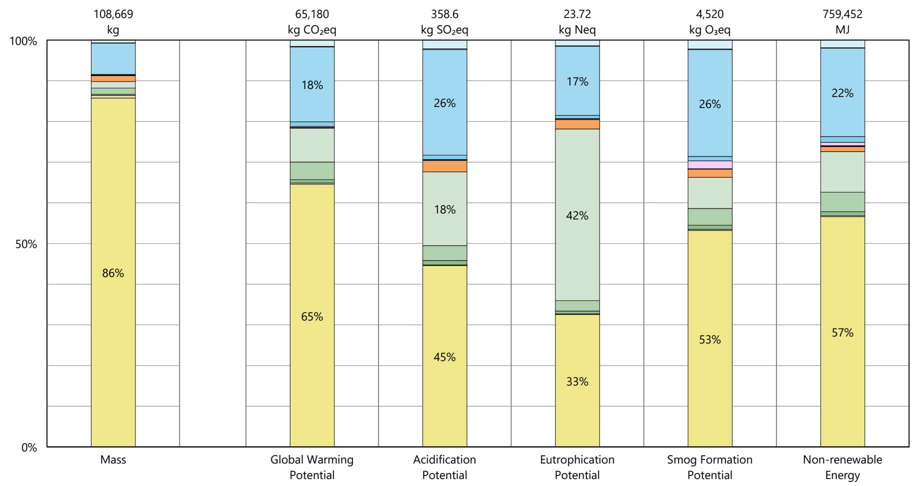
Divisions

- 03 - Concrete
- 05 - Metals
- 06 - Wood/Plastics/Composites
- 07 - Thermal and Moisture Protection
- 08 - Openings and Glazing



Global Warming Potential

Results per Division, itemized by Tally Entry



Legend

03 - Concrete

- Cast-in-place concrete, lightweight structural concrete, 2501-3000 psi
- Stair, cast-in-place concrete

05 - Metals

- Stair, laminated glass
- Steel, sheet, carbon steel
- Steel, sheet, stainless

06 - Wood/Plastics/Composites

- Plywood, exterior grade

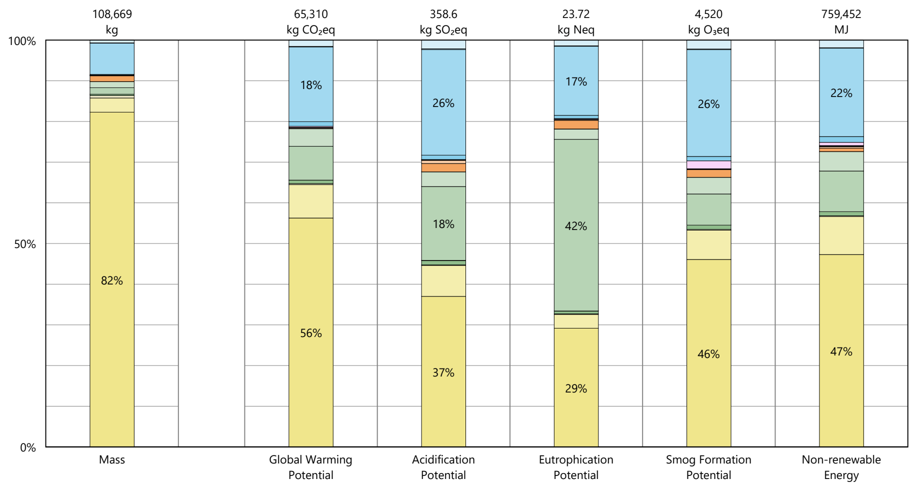
07 - Thermal and Moisture Protection

- Glass wool, batt or blown
- Polyethelene sheet vapor barrier (HDPE)
- Self adhering membrane

08 - Openings and Glazing

- Aluminum mullion, inclusive of finish
- Glazing, double pane IGU
- Glazing, monolithic sheet
- Glazing, triple pane IGU

Results per Division, itemized by Material



Legend

03 - Concrete

- Lightweight concrete, 2501-3000 psi, 0-19% fly ash and/or slag
- Steel, reinforcing rod
- Structural concrete, 4001-5000 psi, 0-19% fly ash and/or slag

05 - Metals

- Glazing, triple, 3 mm, laminated safety glass
- Paint, exterior metal coating, silicone-based
- Stainless steel sheet, Chromium 18/8
- Steel, sheet
- Tin plating, for stainless steel sheet stock

06 - Wood/Plastics/Composites

- Exterior grade plywood, US
- Paint, Brillux, Arylic facade paint - EPD

07 - Thermal and Moisture Protection

- Fasteners, galvanized steel
- Glass wool kraft faced batt, Knauf, EcoBatt - EPD
- Polyethelene sheet vapor barrier (HDPE)
- Self adhering flashing membrane, 40 mil

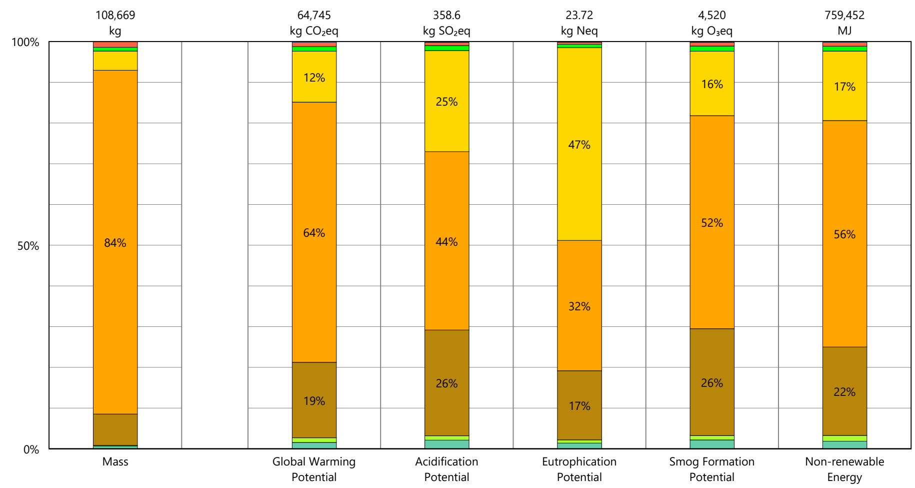
08 - Openings and Glazing

- Aluminum extrusion, anodized, AEC - EPD
- Glazing, double, insulated (air)
- Glazing, monolithic sheet, generic
- Glazing, triple, insulated (air)

09-Layering

tally

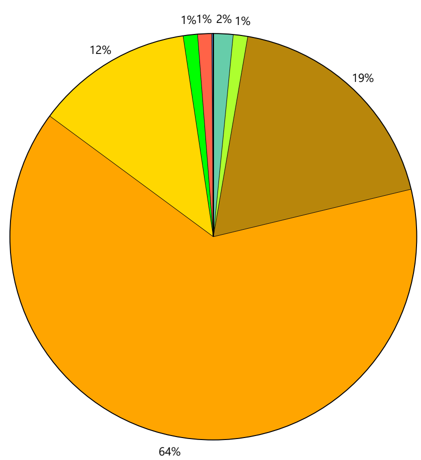
Results per Revit Category



Legend

Revit Categories

- Curtain Panels
- Curtain Wall Mullions
- Doors
- Floors
- Roofs
- Stairs and Railings
- Walls
- Windows

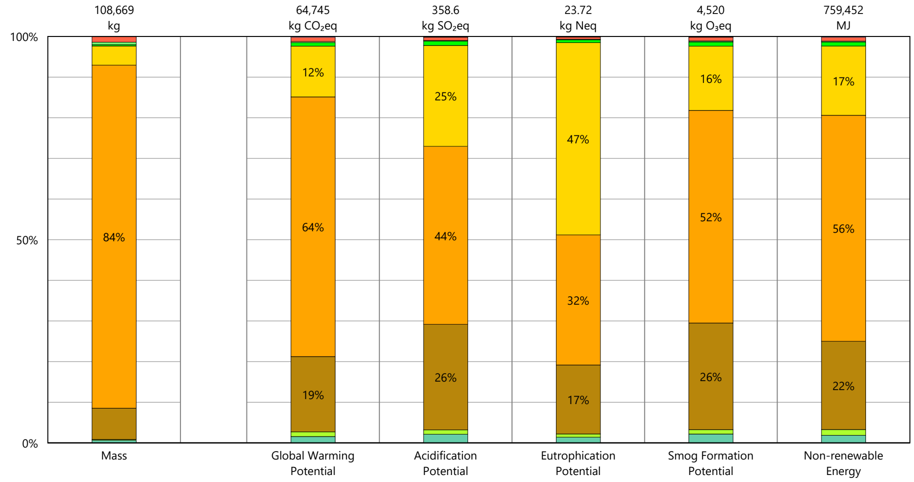


Global Warming Potential

09-Layering

tally.

Results per Revit Category, itemized by Family



Legend

Curtain Panels
- 08-Glass-WW Glazed Panel

Curtain Wall Mullions
- Rectangular Mullion

Doors
- 08-Door-Curtain Wall

Floors
- SF3-Concrete Slab 200mm

Roofs
- R3-Mtl-16Bd-100Ins-16Bd-38Mtl

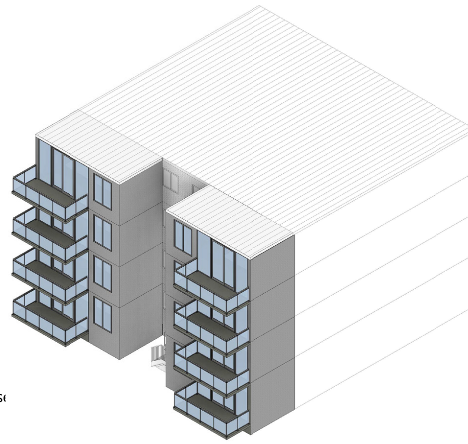
Stairs and Railings
- 05-Railing 1070mm-Handrail 915mm-Picket 13mm-Stringer-Square 38mm
- 200mm Max Rise 280mm Tread

Walls
- ST Conc-200

Windows
- 08-Door-Curtain Wall-window

Report Summary - 10-Layering

Created with Tally
Non-commercial Version 2018.09.27.01



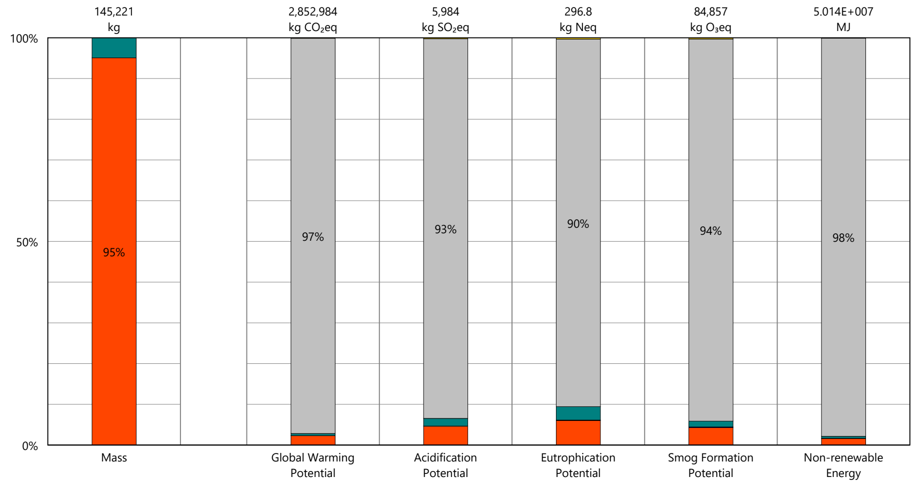
Location	Toronto
Gross Area	1111 m²
Building Life	60
Boundaries	Cradle to grave, inclusive of biogenic carbon; see appendix for a full list of materials and processes
On-site Construction [A5]	Not included
Operational Energy [B6]	59522.5 kWh annual electricity use 117.05 kWh/m² annual heating energy us

Environmental Impact Totals	Product Stage [A1-A3]	Construction Stage [A4]	Use Stage [B2-B6]	End of Life Stage [C2-C4]	Module D [D]
Global Warming (kg CO_2eq)	65,182	928.8	2,783,046	3,827	-7,099
Acidification (kg SO_2eq)	275.7	4.304	5,689	15.15	-36.6
Eutrophication (kg Neq)	17.85	0.3504	277.5	1.056	-1.13
Smog Formation (kg O_3eq)	3,626	142.2	80,826	263.0	-400
Ozone Depletion (kg CFC-11eq)	2.571E-004	3.181E-011	2.990E-004	5.104E-010	6.563E-006
Primary Energy (MJ)	892,779	13,507	6.102E+007	47,361	-85,053
Non-renewable Energy (MJ)	811,361	13,184	4.927E+007	44,287	-81,150
Renewable Energy (MJ)	81,874	326.6	1.177E+007	3,127	-3,916
Environmental Impacts / Area					
Global Warming (kg CO_2eq/m²)	58.67	0.836	2,505	3.444	-6.39
Acidification (kg SO_2eq/m²)	0.2481	0.003874	5.120	0.01364	-0.03298
Eutrophication (kg Neq/m²)	0.01607	3.154E-004	0.2498	9.505E-004	-0.001013
Smog Formation (kg O_3eq/m²)	3.264	0.128	72.75	0.2367	-0.3604
Ozone Depletion (kg CFC-11eq/m²)	2.314E-007	2.863E-014	2.691E-007	4.594E-013	5.907E-009
Primary Energy (MJ/m²)	803.6	12.16	54,920	42.63	-76.6
Non-renewable Energy (MJ/m²)	730.3	11.87	44,351	39.86	-73.0
Renewable Energy (MJ/m²)	73.69	0.294	10,597	2.814	-3.52

10-Extending

tally

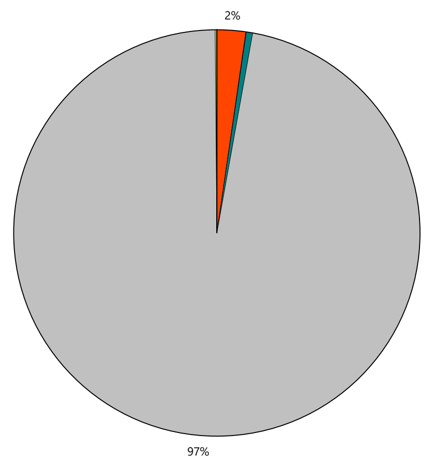
Results per Life Cycle Stage



Legend

Life Cycle Stages

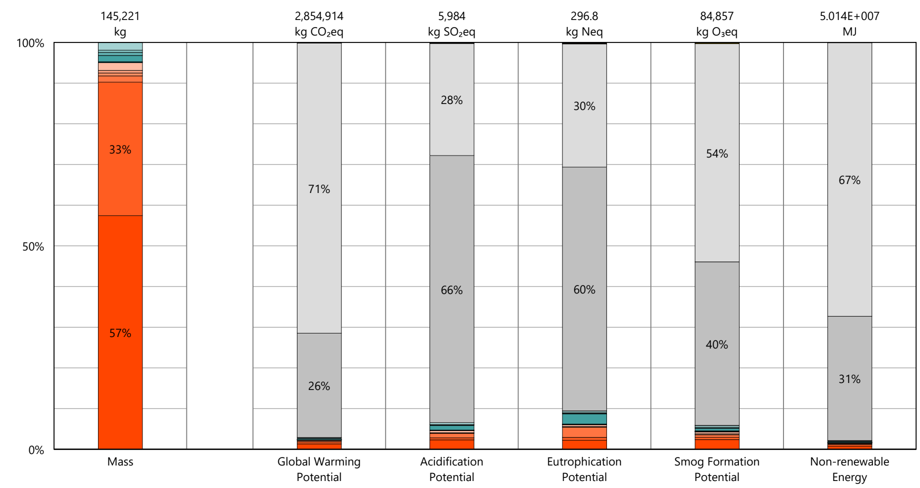
- Product [A1-A3]
- Transportation [A4]
- Maintenance and Replacement [B2-B5]
- Operational Energy [B6]
- End of Life [C2-C4]
- Module D [D]



Global Warming Potential

10-Extending

Results per Life Cycle Stage, itemized by Division



Legend

Product [A1-A3]

- 03 - Concrete
- 04 - Masonry
- 05 - Metals
- 06 - Wood/Plastics/Composites
- 07 - Thermal and Moisture Protection
- 08 - Openings and Glazing
- 09 - Finishes

Transportation [A4]

- 03 - Concrete
- 04 - Masonry
- 05 - Metals
- 06 - Wood/Plastics/Composites
- 07 - Thermal and Moisture Protection
- 08 - Openings and Glazing
- 09 - Finishes

Maintenance and Replacement [B2-B5]

- 03 - Concrete
- 04 - Masonry
- 05 - Metals
- 06 - Wood/Plastics/Composites
- 07 - Thermal and Moisture Protection
- 08 - Openings and Glazing
- 09 - Finishes

Operational Energy [B6]

- Electricity
- Heating

End of Life [C2-C4]

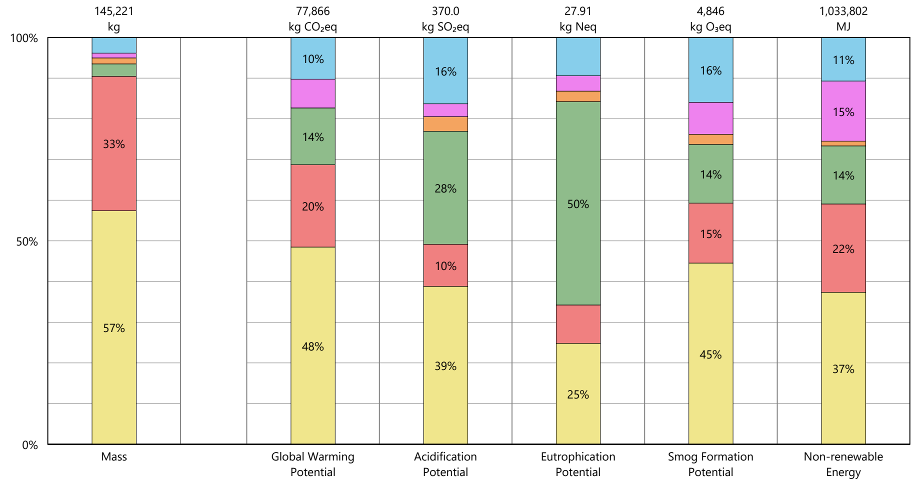
- 03 - Concrete
- 04 - Masonry
- 05 - Metals
- 06 - Wood/Plastics/Composites
- 07 - Thermal and Moisture Protection
- 08 - Openings and Glazing
- 09 - Finishes

Module D [D]

- 03 - Concrete
- 04 - Masonry
- 05 - Metals
- 06 - Wood/Plastics/Composites
- 07 - Thermal and Moisture Protection
- 08 - Openings and Glazing
- 09 - Finishes

10-Extending

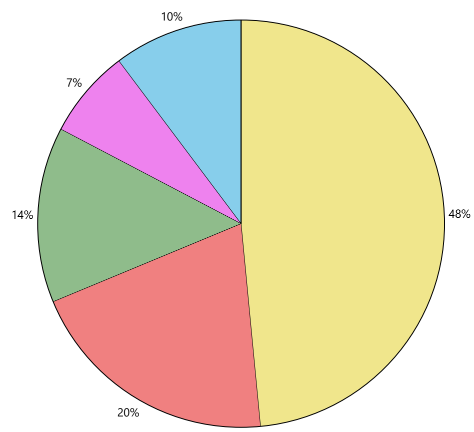
Results per Division



Legend

Divisions

- 03 - Concrete
- 04 - Masonry
- 05 - Metals
- 06 - Wood/Plastics/Composites
- 07 - Thermal and Moisture Protection
- 08 - Openings and Glazing
- 09 - Finishes

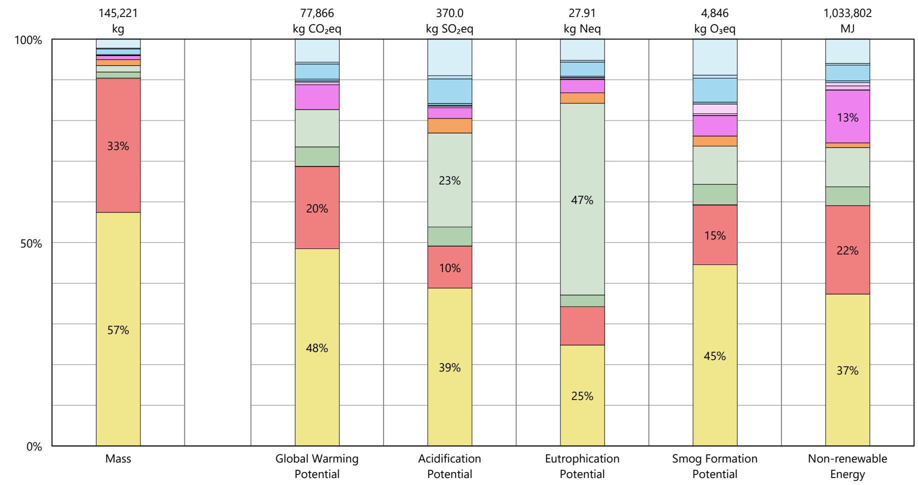


Global Warming Potential

10-Extending

tally.

Results per Division, itemized by Tally Entry



Legend

03 - Concrete
- Cast-in-place concrete, lightweight structural concrete, 2501-3000 psi

04 - Masonry
- Brick
- Solid-core CMU

05 - Metals
- Steel, C channel
- Steel, sheet, carbon steel
- Steel, sheet, stainless

06 - Wood/Plastics/Composites
- Plywood, exterior grade

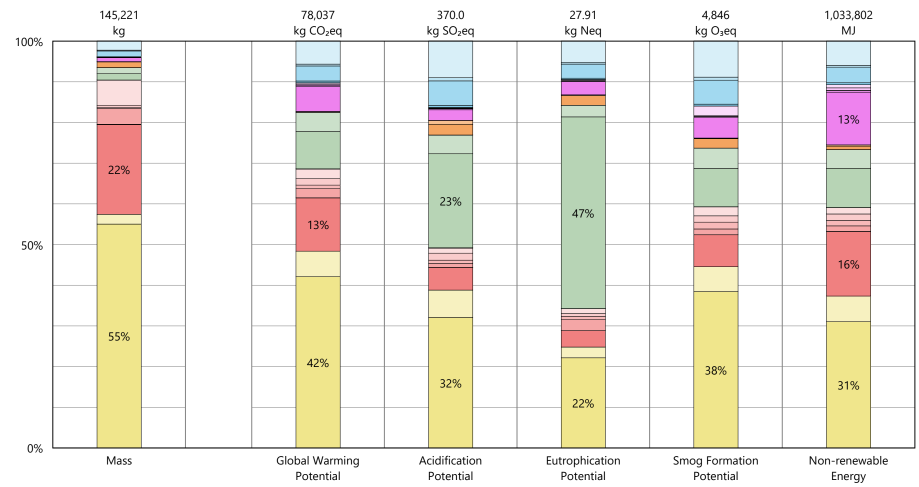
07 - Thermal and Moisture Protection
- Expanded polystyrene (EPS), board
- Glass wool, batt or blown
- Polyethelene sheet vapor barrier (HDPE)
- Self adhering membrane

08 - Openings and Glazing
- Aluminum mullion, inclusive of finish
- Glazing, double pane IGU
- Glazing, monolithic sheet
- Glazing, triple pane IGU

09 - Finishes
- Wall board, gypsum

10-Extending

Results per Division, itemized by Material



Legend

03 - Concrete
- Lightweight concrete, 2501-3000 psi, 0-19% fly ash and/or slag
- Steel, reinforcing rod

04 - Masonry
- Brick, generic
- Concrete masonry unit (CMU), solid
- Lime mortar (Mortar type K)
- Paint, exterior acrylic latex
- Steel, reinforcing rod
- Thickset mortar

05 - Metals
- Hot rolled structural steel, AISC - EPD
- Paint, exterior metal coating, silicone-based
- Stainless steel sheet, Chromium 18/8
- Steel, sheet
- Tin plating, for stainless steel sheet stock

06 - Wood/Plastics/Composites
- Exterior grade plywood, US
- Paint, Brillux, Arylic facade paint - EPD
- Paint, Brillux, Silicone facade paint - EPD

07 - Thermal and Moisture Protection
- Expanded polystyrene (EPS), board
- Fasteners, galvanized steel
- Glass wool kraft faced batt, Knauf, EcoBatt - EPD
- Polyethelene sheet vapor barrier (HDPE)
- Self adhering flashing membrane, 40 mil

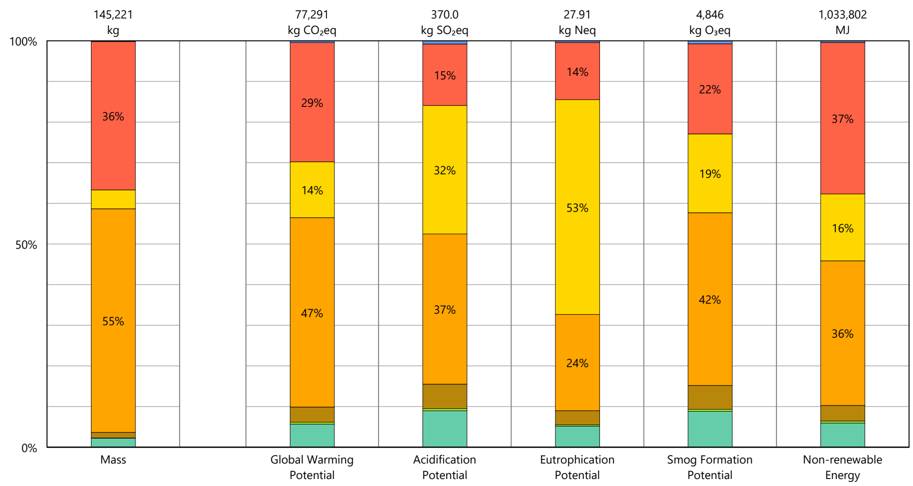
08 - Openings and Glazing
- Aluminum extrusion, anodized, AEC - EPD
- Glazing, double, insulated (air)
- Glazing, monolithic sheet, generic
- Glazing, triple, insulated (air)

09 - Finishes
- Paint, interior acrylic latex
- Wall board, gypsum, natural

10-Extending

tally

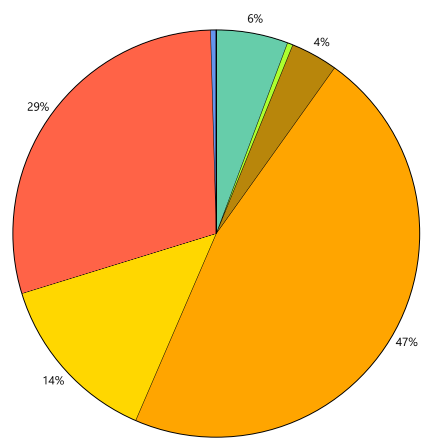
Results per Revit Category



Legend

Revit Categories

- Curtain Panels
- Curtain Wall Mullions
- Doors
- Floors
- Roofs
- Walls
- Windows

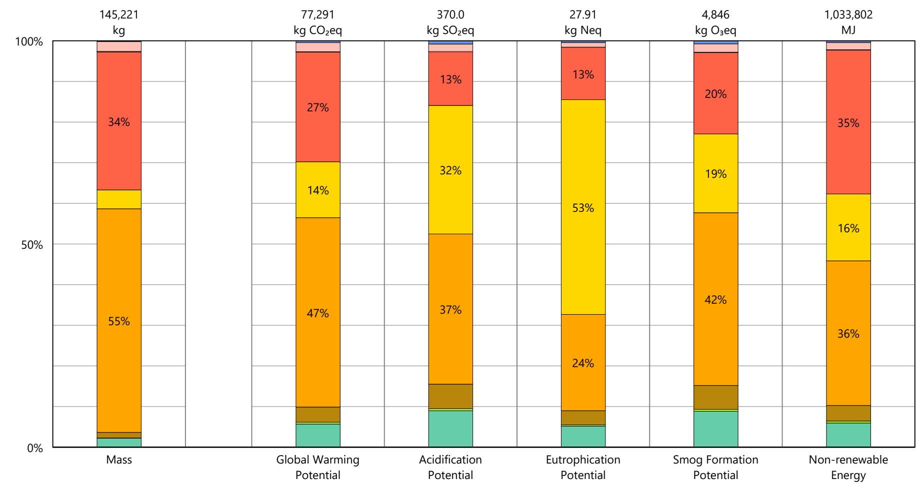


Global Warming Potential

10-Extending

tally

Results per Revit Category, itemized by Family



Legend

Curtain Panels
- 08-Glass-WW Glazed Panel

Curtain Wall Mullions
- Rectangular Mullion

Doors
- 08-Door-Curtain Wall

Floors
- SF1-Concrete Slab on Grade 100mm

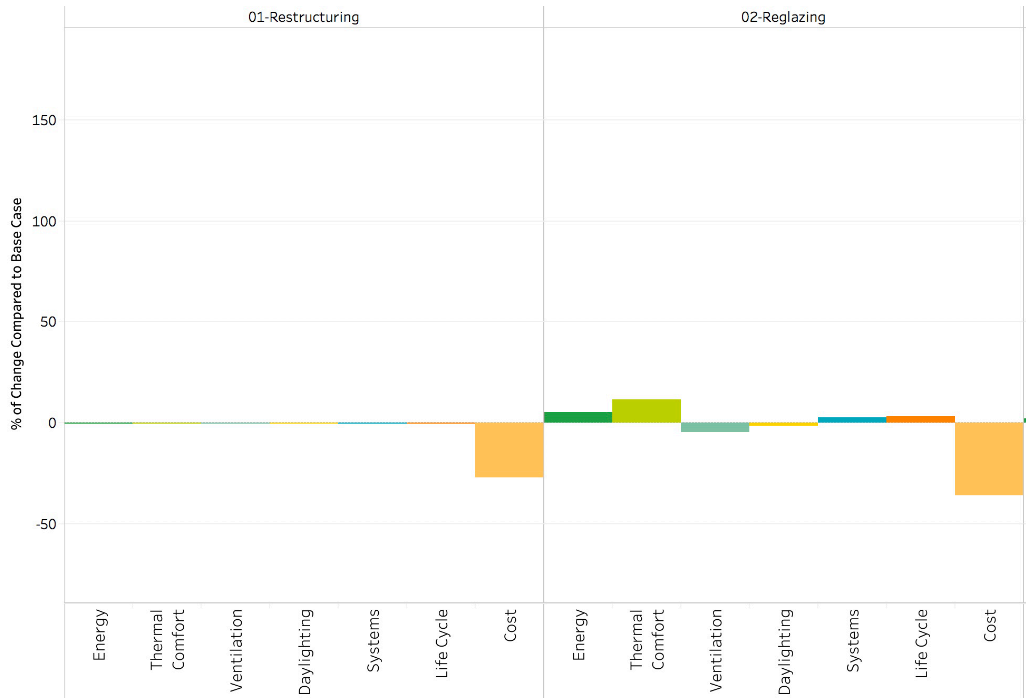
Roofs
- R3-Mtl-16Bd-100Ins-16Bd-38Mtl

Walls
- EW1-265-90Br-50Air-100Ins
- EWE 34-Brick_90Brck-20Air-90CMU-13Gyp-40Std-13Gyp
- ST Conc-200

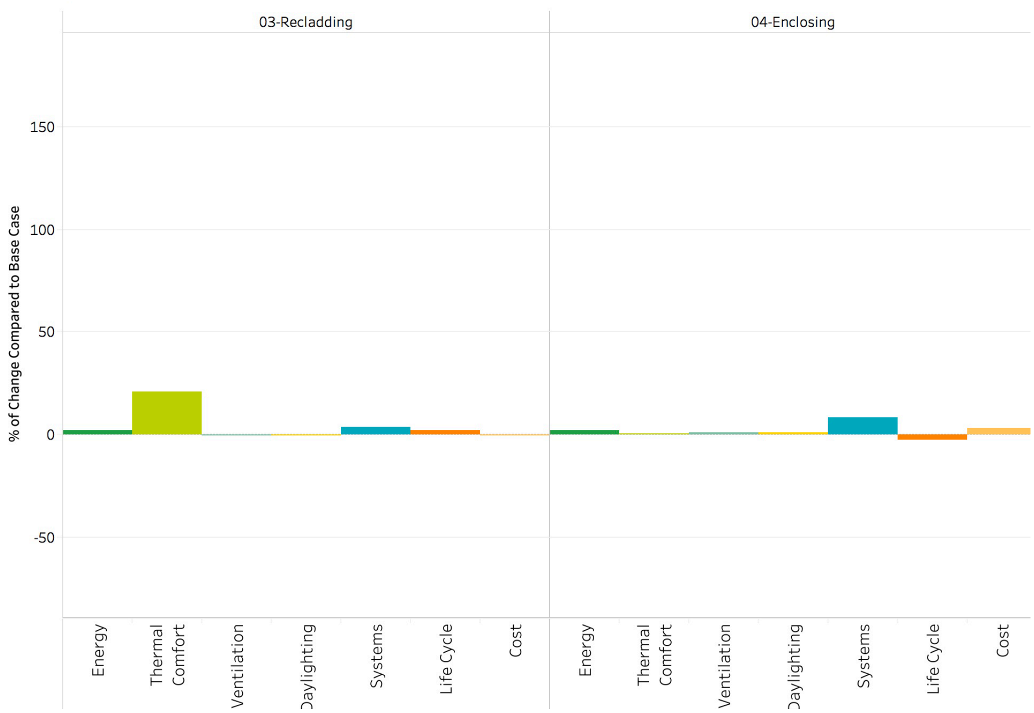
Windows
- Glass Panel

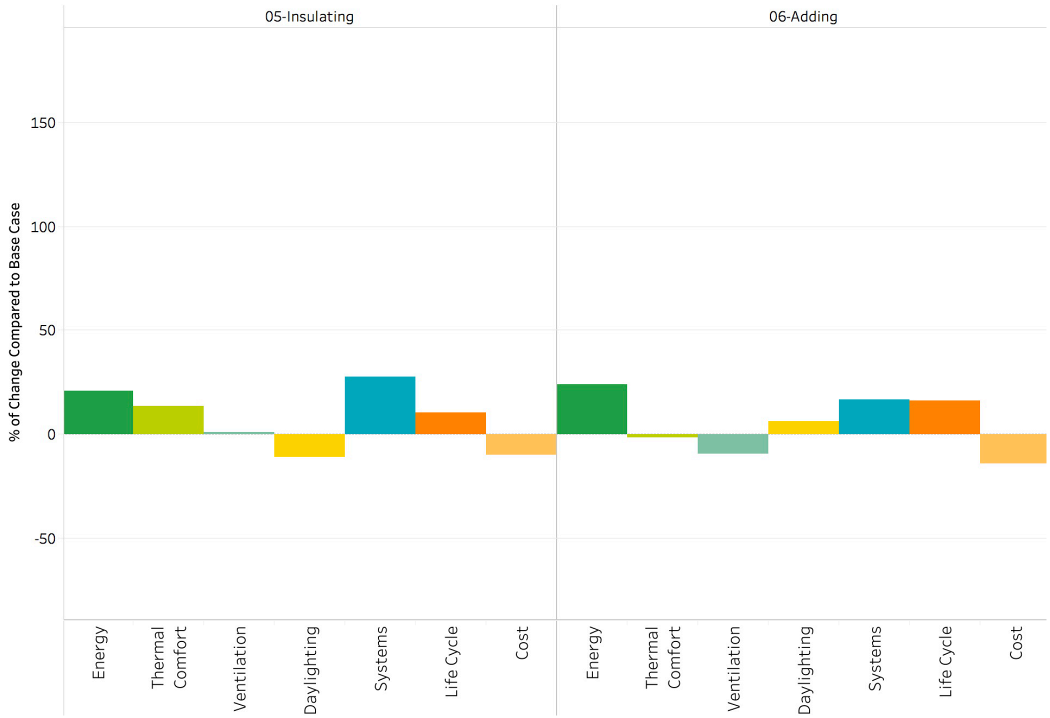
C.7 Combined Results: All Metrics

C.7.1 All Metrics: Bar Charts

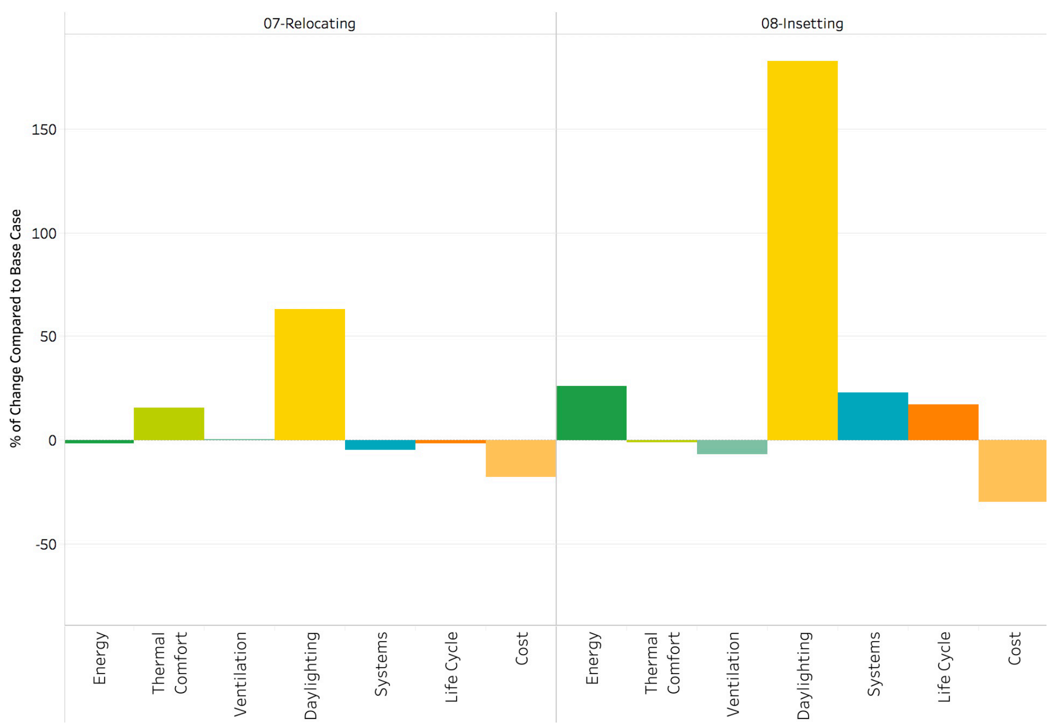


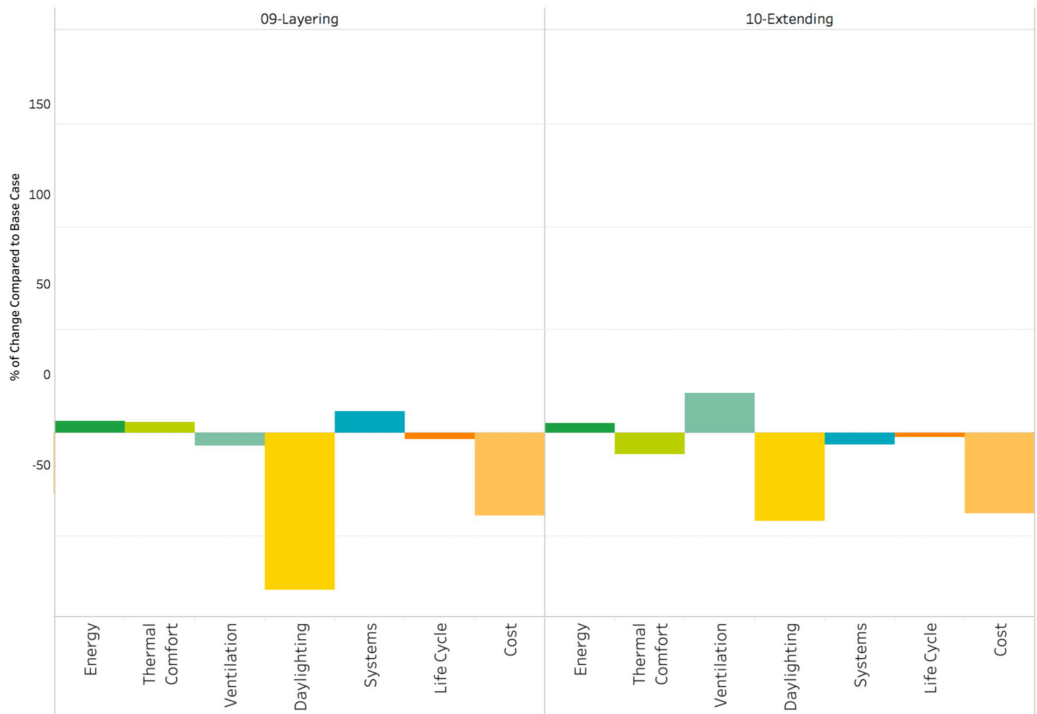
All Metrics - Results





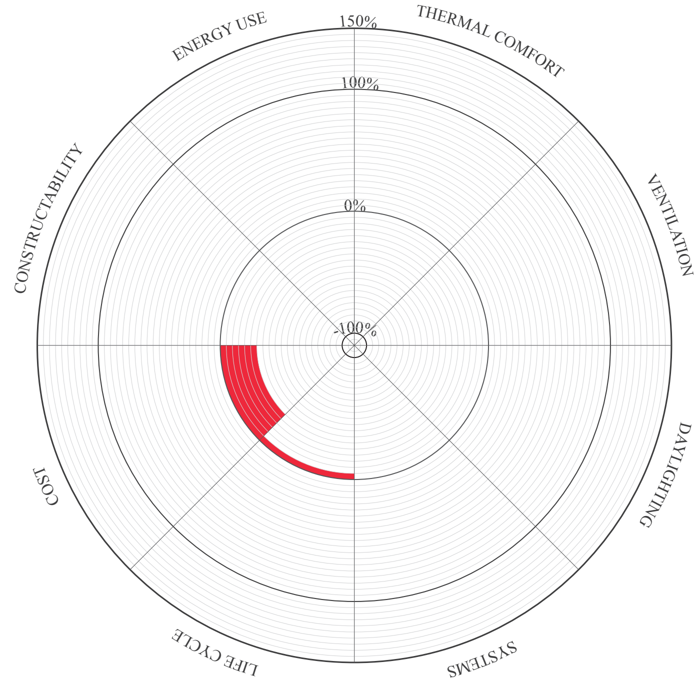
ll Metrics - Results



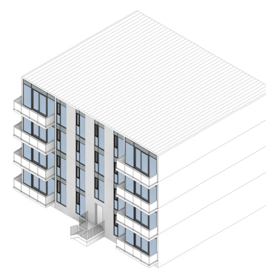


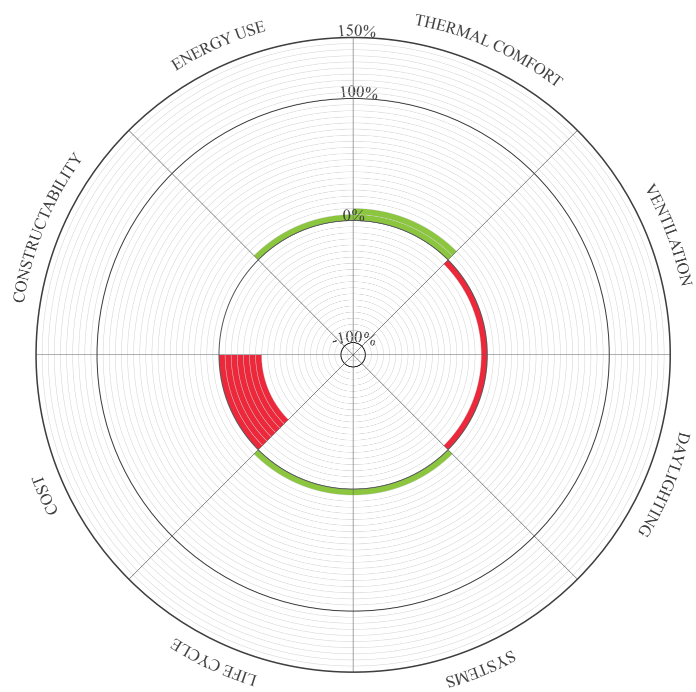
09-Layering
10-Extending
% of Change Compared to Base Case
150
100
50
0
-50
Energy
Thermal Comfort
Ventilation
Daylighting
Systems
Life Cycle
Cost

C.7.2 All Metrics: Categorized by Strategy

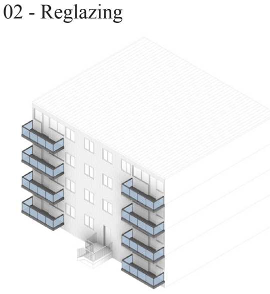


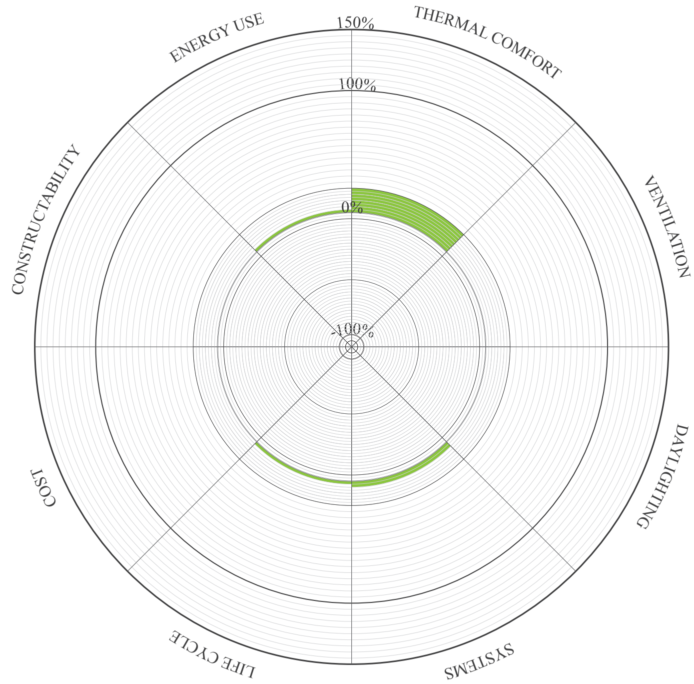
01 - Reconstruction



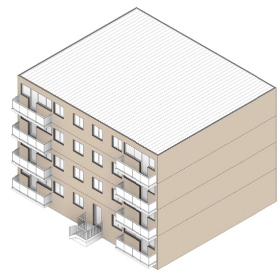


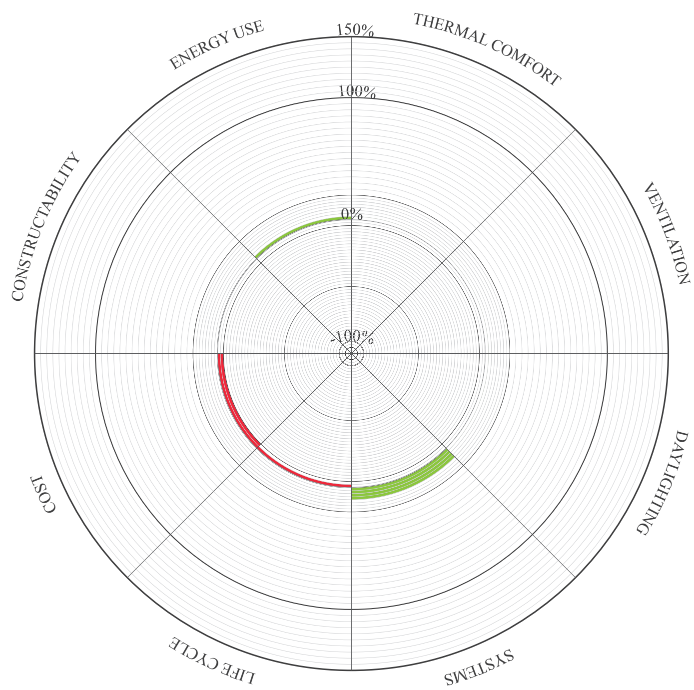
02 - Reglazing



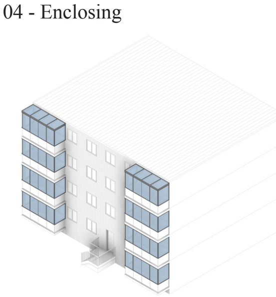


03 - Recladding

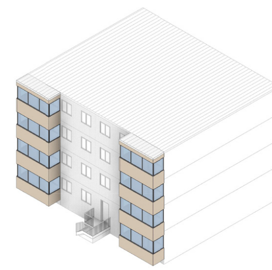


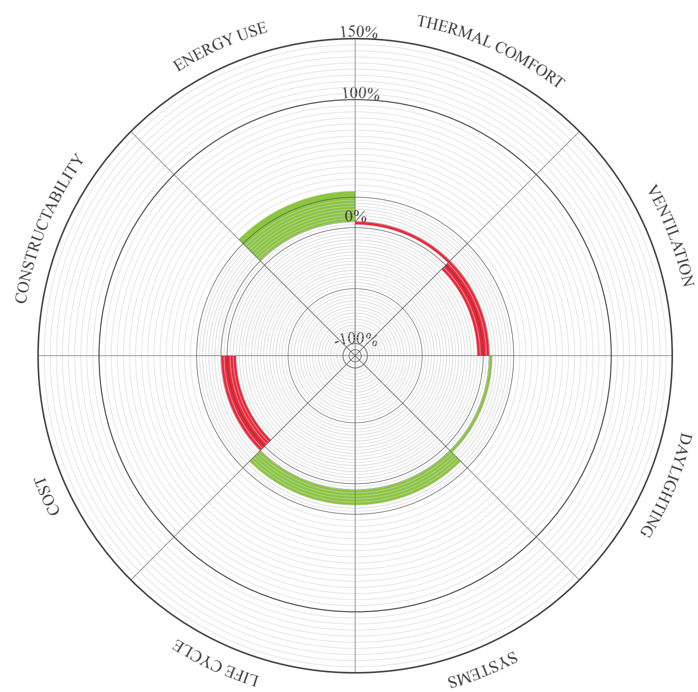


04 - Enclosing

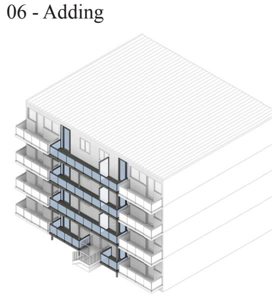


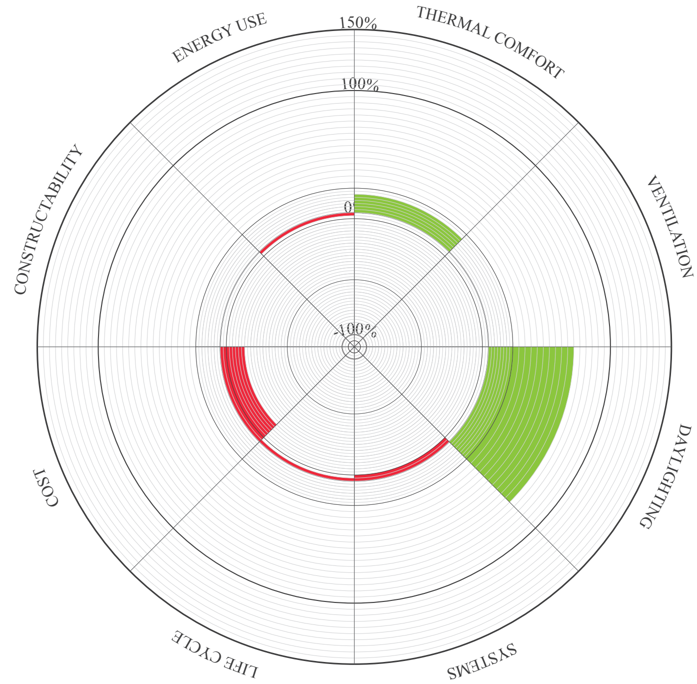
05 - Insulating



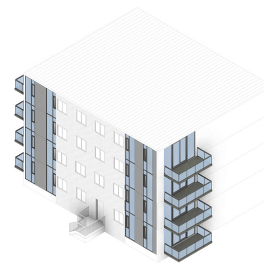


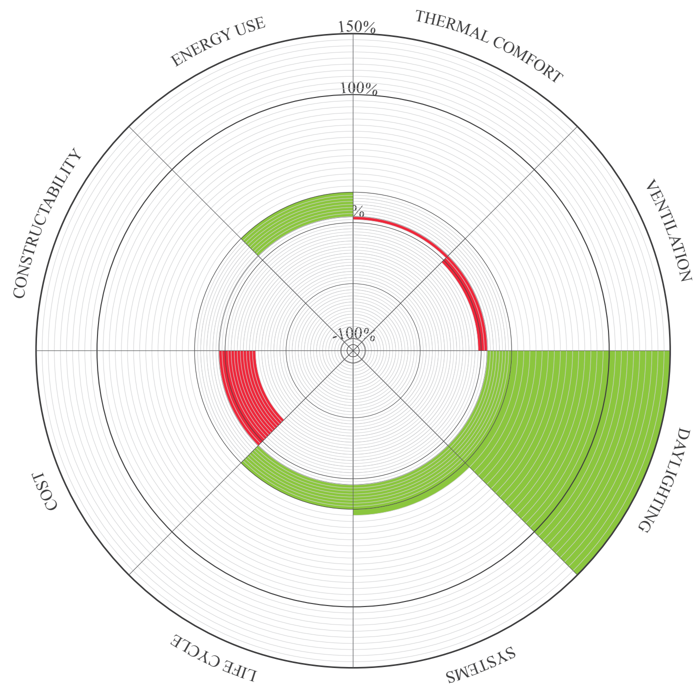
06 - Adding



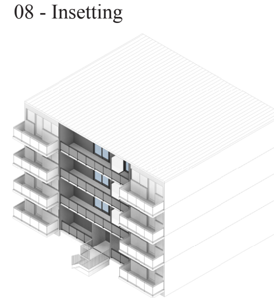


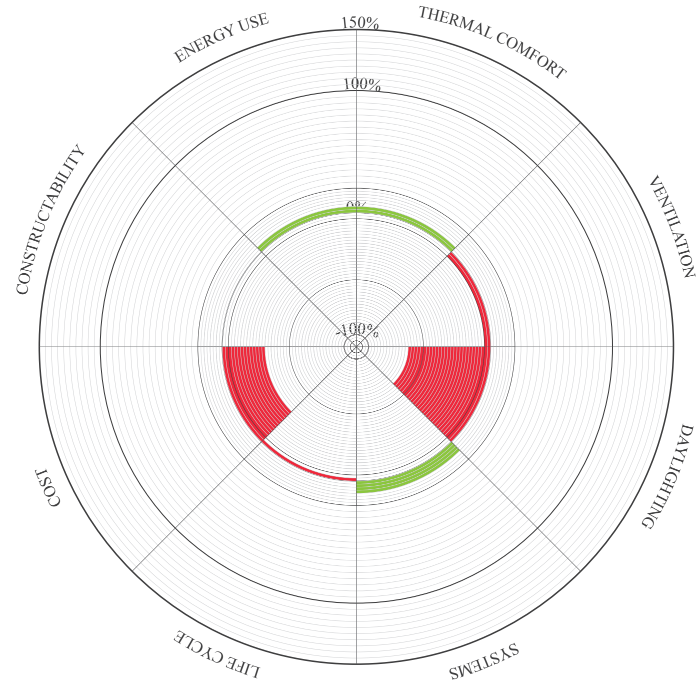
07 - Relocating



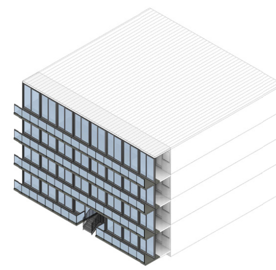


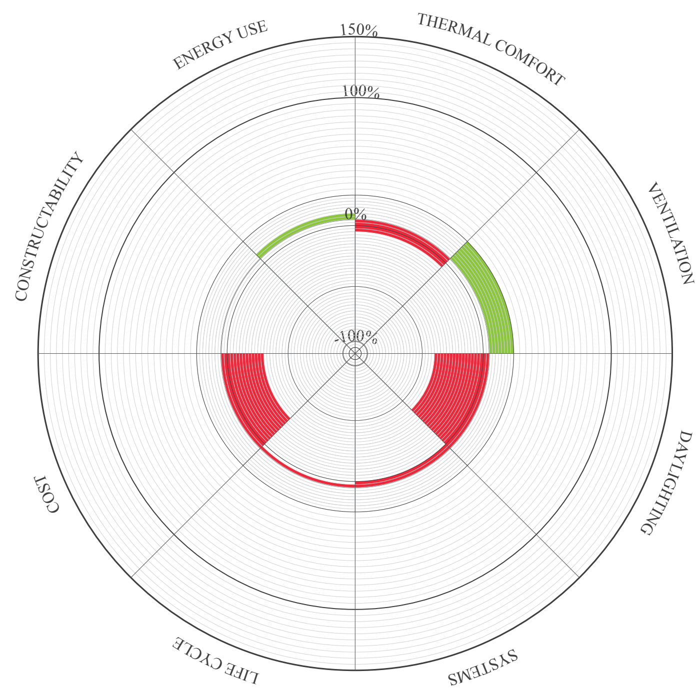
08 - Insetting





09 - Layering





10 - Extending