Valuation of in-situ Building Materials for Resource Recovery

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 2 of this thesis is partly based on a conference paper published in the proceedings of the Construction Research Congress 2022 and presented at the conference. In addition, this section contains an overall literature review and research gap identification that was summarized from the introduction and literature review sections of the four research papers outlined below, mainly from the paper referred to in Chapter 3.

Chapter 3 of this thesis has been incorporated within a journal paper published by Sustainable Cities and Society. This paper is co-authored by myself and my supervisors, Professor Carl Haas and Professor Chris Bachmann. I developed the paper's methodology and research design with assistance and guidance from my supervisors. The methodology development, programming, data collection, visualization, analysis, and illustrations were completed by me. URAs, Jessie Zhuang and Ruth Meyer, assisted in data collection and visualization.

Chapter 4 of this thesis has been incorporated within a journal paper published by Resources, Conservation, and Recycling. The article is co-authored by myself and my supervisors, Professor Carl Haas and Professor Chris Bachmann. The design of the research and methodological approach was completed by me with supervision from Professor Carl Haas and Professor Chris Bachman. I collected the required data for this analysis with assistance from a URA. The implementation of the method, analysis, visualization, and writing of the paper was completed by myself with assistance from my supervisors.

Chapter 5 of this thesis has been incorporated within a journal paper published by the Journal of Cleaner Production. This paper is co-authored by myself as the first author and my supervisors in collaboration with Professor Catherine De Wolf and her PhD student, Brandon Byers affiliated with ETH Zurich. The methodology of the paper and design of the research was done by me with assistance from Professor Carl Haas and Professor Chris Bachmann. Brandon Byers contributed to data collection from Switzerland and writing of the literature review in addition to editing the manuscript. Carolina Christovan, an exchange undergraduate research assistant helped with data collection from Brazil and the literature review. Adama Olumo, PhD Student from Professor Haas's research group, assisted with data collection from Nigeria. The application of the methods, data analysis, visualizations, and manuscript writing were completed by myself with assistance from the co-authors.

Chapter 6 of this thesis has been incorporated into a working research paper that has been submitted for publication. The paper is co-authored by myself and my supervisors, Professor Carl Haas and Professor Chris Bachmann. I carried out the development of the methodology and the design of the research paper with assistance from my supervisors. The programming, data collection, analysis, visualization, and writing of the manuscript were completed by myself with guidance and assistance from Professor Carl Haas and Professor Chris Bachmann.

Abstract

The construction industry is among the largest contributors to global raw material consumption and is responsible for 40% of annual greenhouse gas emissions. Recovery of building materials at the end of a building's life, often seen as a common circular approach, can help mitigate the environmental impacts within this sector. However, the feasibility of recovering in-situ building materials is dependent on various technical, operational, financial, environmental, and regulatory factors, making the implementation of resource recovery complex and challenging. The main objective of this research is to develop methodologies that improve the recovery of building materials at end-of-life through assessment of the value of in-situ building materials. At the core of this research, a decision support tool is developed that incorporates the main factors that impact the value of materials embedded in buildings. The tool is designed based on a multi-objective optimization model that estimates optimal end-of-life options for building components. Throughout this research, the tool is applied to various case studies and analyzed through sensitivity analyses. Using the developed tool, a novel methodology is proposed to assess the efficacy of policies focused on deconstruction and building recovery. Following that, the impact of regional factors such as labour costs, material markets, and socioeconomic factors, are assessed on building end-of-life strategies. The findings underscore the necessity of tailored policies and regulations to effectively reduce waste generation within specific regional contexts. Finally, expanding the applicability of the developed tool on future building stocks, a methodology aimed at evaluating circular design and construction strategies on the recovery potential of buildings is provided. This thesis contributes to the development of optimized material recovery processes that result in waste reduction and carbon emission mitigation. Realizing the recovery potential of building materials is a pivotal step towards fostering a more circular construction sector.

Keywords: materials recovery, reuse, circular economy, built environment, optimization, policy analysis, buildings, deconstruction, disassembly, demolition, waste, construction

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I would like to acknowledge the contributions of the undergraduate research assistants who were involved in this research, Ruth Meyer, Jessie Zhuang, and Carolina Christovan. Their dedication and hard work have been vital in gathering data and helping with carrying out analyses. Thanks to my research group for their valuable feedback and insights that made the academic environment stimulating and enjoyable. Special thanks to my peer, colleague, and great friend, Dr. Sheida Shahi for her great professional guidance throughout my doctoral journey.

I am deeply appreciative of the unending support and encouragement from my parents, Shahin and Abbas, and my sister, Sadaf. Their belief in my abilities and sacrifices made this journey possible. Finally, my gratitude goes to my husband, Shayan. His enduring patience, love, and support have sustained me through the highs and lows of this chapter of my life.

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Chapter 1: Introduction

1.1 Background and Motivation

Cities are growing at an extremely fast rate. A global trend of increasing urbanization over the next three decades is projected, with the percentage expected increase from 56% (reported in 2021) to 68% by 2050. This will result in an estimated addition of 2.2 billion people relocating to urban areas (United Nations Human Settlements Programme, 2022). Rapid urbanization is leading to additional pressure on natural resources and high rates of material consumption, projected to reach 90 billion tons per year in 2050 globally, more than twice as much as the amount reported in 2010 (IRP, 2018). The growing population will require additional resource-intensive urban infrastructure. Around 70% of the required urban infrastructure to support rapid urbanization remains undeveloped and is yet to be built, indicating a requirement for extra resources to respond to the growing urban population (UNEP, 2019). As a result of the increased material consumption rates, 2.01 billion tons of municipal solid waste was produced worldwide in 2018 and is expected to increase to 3.40 billion metric tons by 2050 (The World Bank, 2018). Additionally, global waste generation is not expected to peak any time before 2100 and by 2075 at the earliest, indicating continuous growth in solid waste generation (Hoornweg et al., 2015). The increasing demand for materials is a result of population growth and increased demand for welfare (Ghisellini et al., 2018). However, resources are scarce and finite. The ability to restock resources will eventually come to an end.

The construction industry has been identified as one of the fastest-growing sectors due to the increasing demand for new buildings and infrastructure in response to the socio-economic needs of the growing urban population (Shashi et al., 2023). However, this growth comes with environmental challenges. Currently, the construction industry is found to be responsible for over 50% of global material use and more than 60% of global waste generation (Islam et al., 2019;Arup, 2016; United Nations, 2019). Its outcome, the built environment, contributes to around 39% of CO2 emissions, with

28% coming from operational carbon and 11% from embodied carbon (Rasmussen et al., 2018; WGBC, 2019). The European Union produced around 374 million tonnes of waste in 2016 related to the construction and demolition industries, with concrete accounting for half of the generated waste (Hoang et al., 2021). In 2018 in the US, 600 million tons of construction and demolition waste was generated, where demolition waste accounted for over 90% of the total estimated waste (EPA, 2020). This is while construction and demolition waste are more than 80% recoverable through reuse, recycling, and downcycling but are not recovered at their full potential. At least 25% of the produced waste is directly ending up in landfills (EPA, 2020; Zheng et al., 2017). Recovery of these materials for their original purpose through reuse or closed-loop recycling remains limited to certain material types and components. However, the increasing rate of demolition waste generation, the limited availability of space in landfills, waste disposal fees, emerging building material recovery incentivizing policies, and strict regulations associated with dumping materials have triggered the construction industry to identify alternative approaches for managing construction and demolition waste (Rios et al., 2015).

In recent years, transitioning from a linear to a circular economy is thought to be a possible solution to mitigate global environmental impacts. Circular Economy (CE) has various definitions and implementation methods that are all aimed at decoupling economic growth from resource consumption, eliminating waste, and maintaining materials at the highest value for as long as possible (Ellen MacArthur Foundation, 2013). A broader shift to a CE may reduce the pressure on natural resources used as building materials (Ellen MacArthur Foundation, 2020). However, the implementation of circular strategies is challenging and requires innovation and growth in both technical and regulatory aspects alongside systematic interventions that can effectively accelerate the transition (de Jesus & Mendonça, 2018; Guerra & Leite, 2021; Superti et al., 2021). Automation, sharing platforms, reselling, resource recovery, and using waste as resources are some of the popular circular strategies applicable to the built environment (Guerra et al., 2021). There has been growing interest in studying the application of circular economy principles in the construction industry and in ways to address the emerging challenges in transitioning from a linear to a circular economy in this sector (Benachio et al., 2020; Çimen, 2021; Guerra and Leite, 2021; Mahpour, 2018; Ness and Xing, 2017; Pomponi and Moncaster, 2017). However, despite the efforts in shifting to circular strategies, the current global economy, including the built environment, is only around nine percent circular; meaning that only nine percent of the materials that annually enter the economy are recovered in some form (Circle Economy, 2019).

One of the most well-known circular strategies in the built environment is resource recovery, developed based on the original 3R principle of “Reduce, Reuse, and Recycle” (Ghaffar et al., 2020; Guerra & Leite, 2021). Diverting construction waste from landfills through recycling and reuse practices is proven to have financial and environmental benefits (Ghisellini et al., 2018). Enabling the secondary use of materials requires controlled demolition and deconstruction that would cause limited harm to components in buildings. The high labour costs required for such projects have resulted in the choice, typically, of more conventional demolition approaches for most advanced economies. A great opportunity exists in shifting to selective demolition and deconstruction techniques, changing demolition waste management processes, improving the recovery potential of buildings, and salvaging the existing materials; however, the lack of robust decision-making processes and adequate data is causing uncertainties in choosing circular End-of-Life (EoL) alternatives for buildings (Wijewickrama et al., 2021).

The motivation for this research comes from the uncertainty in the financial and environmental advantages and disadvantages of different building EoL options, the complexity of understanding the optimal EoL process for buildings, and the technical challenges in understanding the feasibility of building material recovery. By looking at building materials as assets, analyzing their values, and taking a more circular approach, construction materials could potentially remain in the economy for extended lifespans, which would ultimately lead to lower virgin materials consumption and lower waste generation. Additionally, building owners can gain value from the resell of salvageable materials and thus offset deconstruction costs. Prevailing demolition practices only lead to salvaging certain materials such as steel-based components (Diven & Shaurette, 2011;Tingley et al., 2017). Other building materials have the potential to be salvaged but are being landfilled because of destructive demolition processes that reduce the material and component values and their possibility to be reused.

The recovery potential of building materials is not properly captured by building owners and different contractors that are involved in the building EoL handling processes. Most decisions made regarding the EoL choices of buildings are driven by common practice that currently is mainly demolitions and disposal with some limited recycling or downcycling involved. To prevent materials from ending up in landfills, building owners require different tools and methods that helps with understanding the environmental and financial value of building material recovery as well as logistics of material handling. The limited adoption of circular business models such as resource recovery is typically because of an educational gap and the general resistance to change in the industry. It is important to facilitate the implementation of circularity measures through development of methods and tools that can be beneficial to the decision makers in the industry.

Limited knowledge of building material recovery processes and lack of quantitative methods regarding the assessment of the recovery potential of buildings at EoL is resulting in the loss of the building materials' recoverable value by building owners and demolition companies. Multiple interviews with active demolition and deconstruction companies in the industry were conducted to investigate the need for such research. Based on conversations with experienced individuals in the industry and visits to demolition and deconstruction sites, even companies that are practicing deconstruction rather than demolition are suffering from inaccurate project management, specifically considering the high cost of deconstruction and required skilled labour. This research is focused on investigating the environmental and market value of in-situ building materials and understanding the implications on existing and future building stocks. By this means, building materials can effectively get circulated back into the economy. Considering the lack of building recovery and EoL assessment tools, through this research, a decision support tool is developed and applied in different contexts to explore the impacts of policies, regional factors, and circular building technologies. The intent is to provide insight for both the demolition industry and building owners to consider building materials embedded in existing buildings as valuable assets that can support future developments. Ultimately, society can also benefit from lower material consumption and reduced pressure on natural resources.

1.2 Research Objectives

The objectives of this research are outlined below:

- Identify the main factors that impact the value of in-situ materials and develop a conceptual framework to estimate the value of materials in existing buildings based on the determined factors.
- Develop a quantitative decision support tool that can estimate the value of in-situ construction materials by identifying optimal end-of-life options for building components.
- Identify the impact of the factors used in the tool on the value of in-situ materials through sensitivity analyses and future scenario development.
- Assess the efficacy of policy tools on building material recovery at end-of-life using the developed decision support tool.

- Understand the impact of regional factors on the recovery potential of existing buildings.
- Investigate the impact of circular design and construction techniques on increasing the value of in-situ materials and improving future building material recovery using the developed tool.

The outlined objectives are addressed through the five main chapters of this thesis. The main factors that impact the value of in-situ materials are first identified through an investigation of the available literature and consultation with experts (Chapter 2). A novel quantitative decision support tool is developed based on the identified factors. The developed tool is tested through various sensitivity analysis methods to evaluate the impact of different factors on the value of materials and building recovery potential (Chapter 3). The tool is used to assess the efficacy of policy tools (Chapter 4) and the impact of regional factors on the recovery potential of existing buildings (Chapter 5). Finally, the decision support tool is expanded and utilized to assess the impact of circular design and construction techniques on improving the recoverability of future building stocks (Chapter 6).

Application of this research could begin to bring insight into how building materials can be avoided from ending up in landfills by shedding light on the environmental and financial benefits of building recovery. The proposed methodology and obtained results can be used in the decision-making process by building owners and other involved stakeholders to understand the optimal end-of-life process for a building given the different regional, technical, and regulatory conditions. Overall, implementing the methodologies developed in this thesis could be used as a decision support tool to increase building material circularity.

1.3 Research Scope

The proposed research is divided into three distinct sections. In the first section of this study, a decision support method that can estimate the recovery potential and subsequently the value of in-situ materials is developed. The development of the method requires understanding the key factors that impact the building material recovery, understanding the conceptual relationship of the factors and their implementation, and a quantitative translation of the factors into a comprehensive decision support for practical use. After the development of the method, in the second section, the developed method is expanded and applied to existing building stocks to understand the efficacy of policies in building material recovery at end-of-life as well as the impact of regional factors on building material recovery.

The third section is focused on future building stocks with the objective of understanding the impact of novel circular design and construction techniques in improving future material recovery. This final section can help improve the recovery potential of future building stocks in advance to prevent challenges that the construction industry is facing with current building stocks that have reached the end of their lifespan.

The developed research method and its expanded applications are intended to be applied to buildings, both residential and non-residential to estimate the potential value of materials embedded in them. However, the overall idea has the potential to be implemented on other urban stocks such as transportation infrastructure subject to the availability of data. Currently, there is no robust applicable method or framework available for this purpose in the construction sector. The developed method can be applied to buildings or other infrastructure that have reached their end of life and are required to be fully demolished, those that are being renovated and going through adaptive reuse, or new developments to understand future recovery potentials. The temporal scope of the method is flexible. With the availability of the age of the stock and the estimated end-of-life, it is possible to estimate the material value in a given year. As for the environmental impact scope, Global Warming Potential (GWP) is the indicator used to quantify environmental impacts since it is the most common indicator used in the construction industry to assess environmental impacts. The amount of recoverable materials in the building and the quantity of avoidable waste are also compared as environmental metrics.

1.4 Overview of Research Methodology

This research uses a scientific methodology and quantitative methods to address the defined objectives. The overall research method is to define and develop a decision-support method to estimate the value of in-situ building materials through identifying optimal EoL strategies for building components. This developed method is then expanded and utilized in different contexts to provide application scopes for existing and future buildings, particularly from the perspective of building owners. Specifically, for existing buildings, the decision support method is first used to assess the efficacy and impact of policy tools on building material recovery. Additionally, using the developed method, the impact of regional factors are also assessed on the recovery potential of existing buildings when they reach the end of their lifespan. Finally, the application of the method is analyzed in the context of circular design and construction techniques to improve the recovery and circularity of future buildings. An overview of the research structure is provided in Figure 1-1.

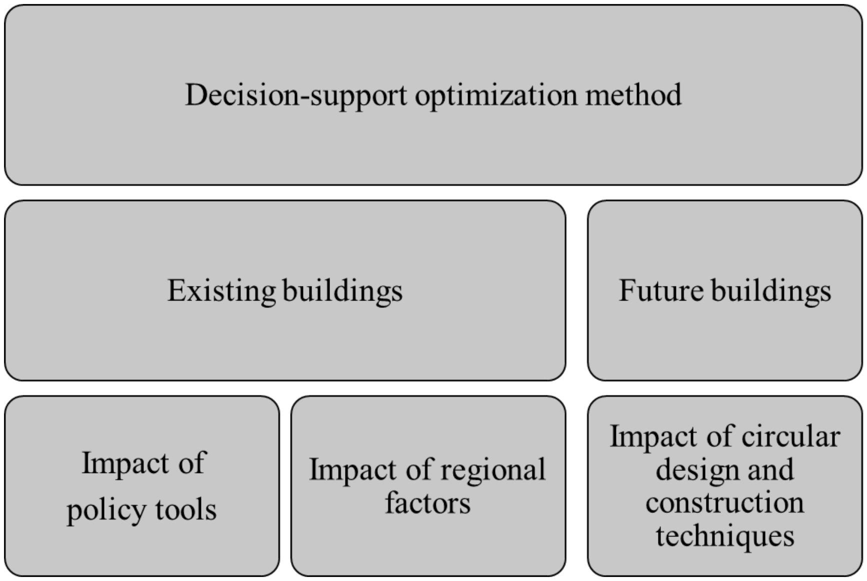

Figure 1-1: Overview of Research Structure

The research is completed in five main phases based on the identified objectives (Figure 1-2). In the preliminary phase (Phase 0), the problem is defined, and a literature review is conducted to identify the knowledge gap. In the first phase, a conceptual framework is developed that can help identify the value of in-situ materials at different scales. To develop this conceptual framework, a literature review is completed to understand the factors that affect the value of in-situ materials. These factors are then organized in a conceptual framework to understand the relationship between the identified factors. The second phase focuses on extending the conceptual framework into an optimization-based decision support method that can quantitatively estimate the value of in-situ materials at a more detailed scale. In this phase, after the collection of the required data, the developed method is applied to a case study and validated through sensitivity analyses. The impacts of the factors are also compared in this stage according to the results of the sensitivity analyses. The details of the method and optimization model are provided in section 3.2.

In the third phase, the applicability of the framework is expanded and applied to existing building stocks. First, the decision-support method is utilized to assess the efficacy of available policy tools on building material recovery. For this purpose, a review is conducted to categorize existing policies. In the next step, the policy categories are modeled in the optimization method and applied to the collected case studies. The results are then compared for gaining insight into the impact of policy tools focused on promoting end-of-life building recovery. Details of the method for this phase are provided in section

4.3. Second, the impact of regional factors on building material recovery is studied using the decision support method. In this phase, case studies and regional data are collected from different geographically distributed locations to test the hypothesis of whether regional factors impact the recovery of buildings at end-of-life. The methods for conducting this assessment are described in section 5.3.

The fourth phase includes the application of the developed tool on future building stocks to understand the impact of circular techniques that can improve the future recovery potential of buildings. In this phase, initially, common practical circular design and construction techniques are identified through a literature review. Then, the identified strategies are modeled in the decision support method and applied to a case study. The impacts of the strategies are compared and analyzed based on the different outputs from the tool. The methods for the fourth phase are provided in section 6.3. In the fifth and final phase of this research, the findings are documented and summarized into deliverables including peer-reviewed journals and conference papers that widely disseminate the knowledge to industry and academia.

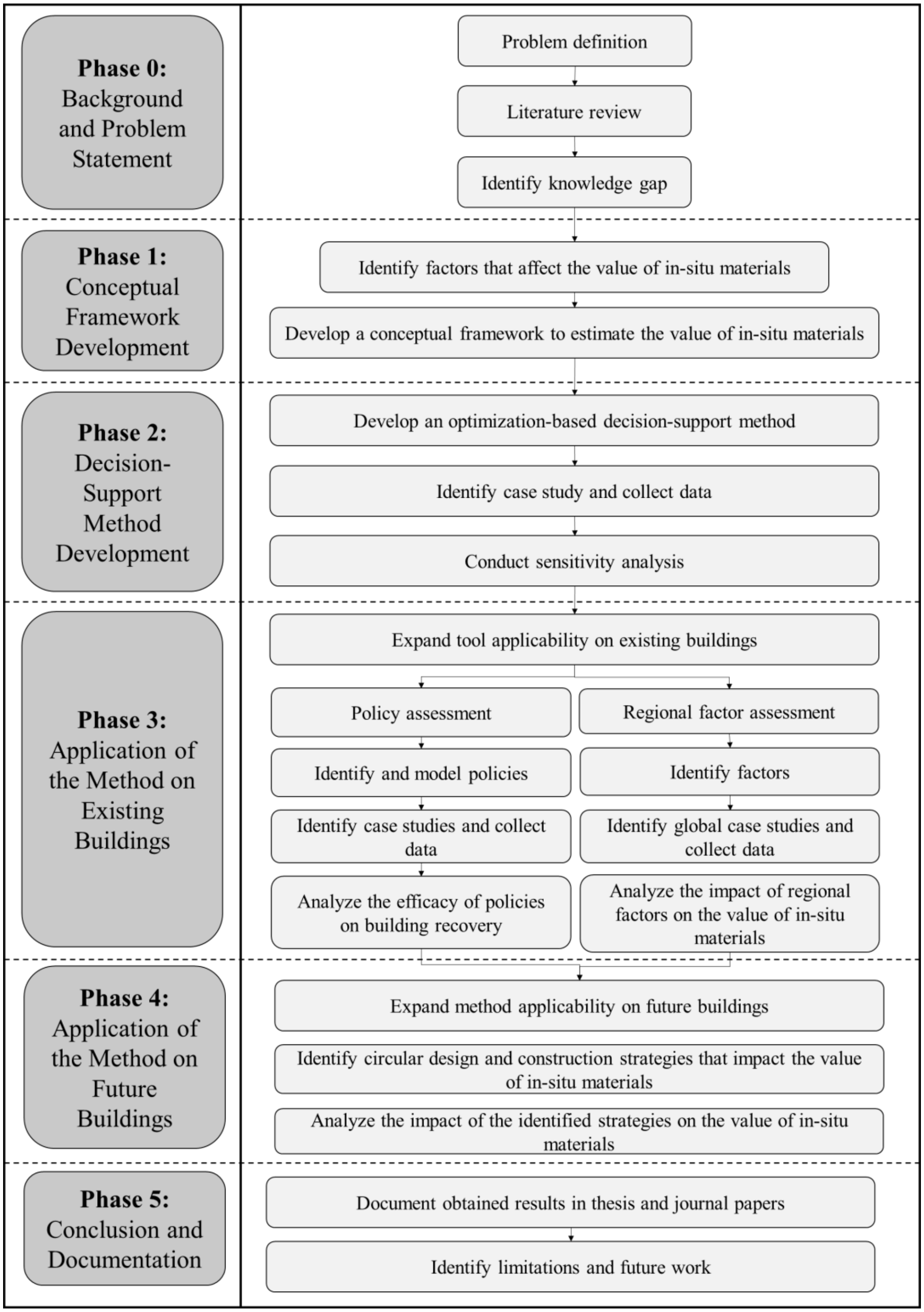

Figure 1-2: Summary of Thesis Methodology

1.5 Thesis Organization

This thesis is organized into seven main chapters and three appendices. Chapter 1 provides an overview of the background and motivation of this research alongside the objective, scope, and overall methodology. In Chapter 2 a literature review, a summary of similar work, and the developed conceptual framework from existing research are presented. Chapter 3 focuses on the development of the material value estimation decision support method, case study results, and sensitivity analyses. Chapter 4 includes the developed methodology for assessing the impact of policy tools on building material recovery using the decision support method. In Chapter 5, a global perspective on building material recovery and an analysis of regional factors on building recovery potentials is provided. In Chapter 6, a methodology to assess the impact of circular design and construction techniques is provided that can be applied to new buildings to understand and improve their recovery potential. Finally, Chapter 7 includes a summary of the research results and limitations, an overview of the path forward, conclusions, and research contributions.

The decision support method's supplementary information including the logic of the precedence relationships, environmental impact assessment methodology, and the details of the sensitivity analyses conducted in Chapter 3 are provided in Appendix A. Appendix B includes the developed algorithms for the decision support tool and the implemented expansions for policy and future construction assessments. Appendix C includes the details of the data utilized in the tool for the different case studies in the different thesis phases.

Chapter 2: Literature Review

2.1 Circular Economy in the Built Environment

Circular Economy (CE) is an alternative to the current linear economy that is focused on maintaining materials in closed loops, reducing consumption rates, and keeping products in use for longer lifespans instead of the traditional take-make-dispose approach (Korhonen et al., 2017; Pomponi & Moncaster, 2017). In a linear economy, materials are extracted, used, and disposed of in landfills. In a CE, materials are maintained in closed loops, consumption rates are reduced, and products are kept at their highest value for as long as possible (Ellen MacArthur Foundation, 2020). There is no single global definition for CE since it is still considered a novel concept with limited practical knowledge and a substantial amount of room for research and growth in this domain. Kirchherr et al. (2017) have provided 114 definitions for CE through a literature review in their research and highlighted the differences and incoherence observed in the available definitions. The authors concluded that while CE requires a broad systematic shift, reduce, reuse and recycle are the most common terminologies used in defining it (Kirchherr et al., 2017). A visual representation of CE by the Ellen MacArthur Foundation, which is a pioneer in defining CE concepts and has a great contribution in the shift towards CE implementations is presented in Figure 2-1.They have also provided the following definition for CE:

> "A circular economy is an industrial system that is restorative or regenerative by intention and design. It replaces the 'end-of-life' concept with restoration, shifts towards the use of renewable energy, eliminates the use of toxic chemicals, which impair reuse, and aims for the elimination of waste through the superior design of materials, products, systems, and, within this, business models" (Ellen MacArthur Foundation, 2013, p.7)

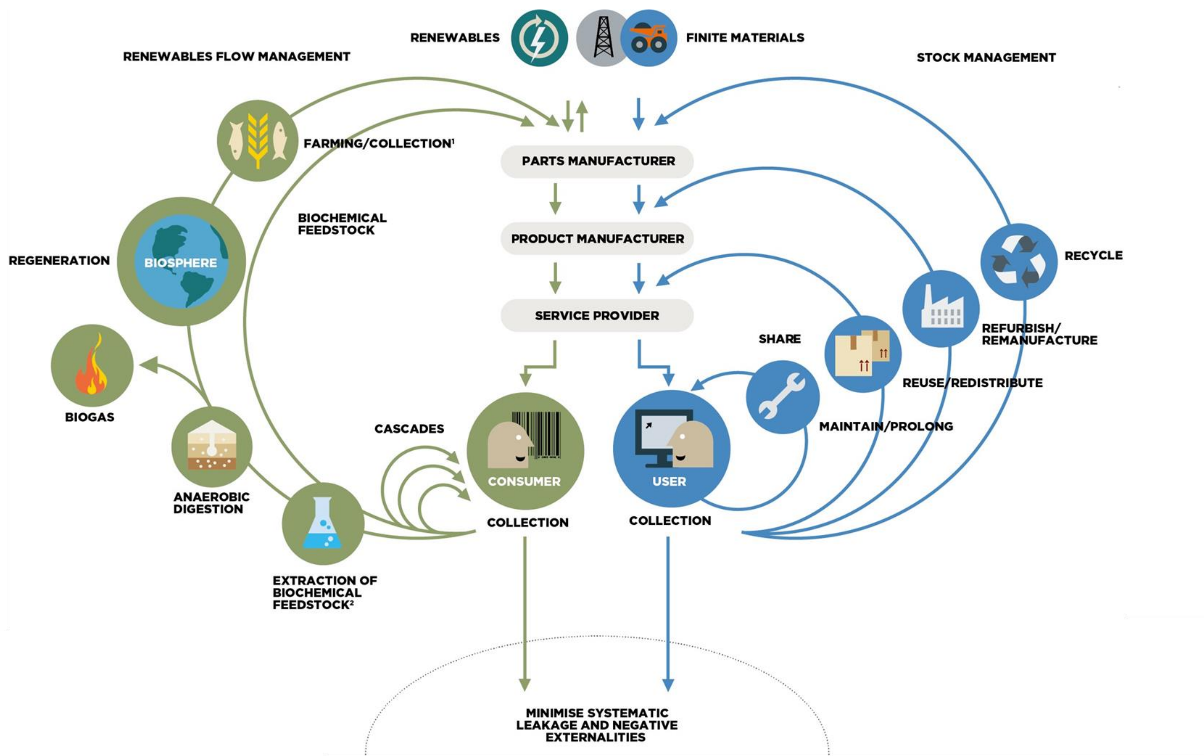

Figure 2-1: The Circular Economy System Diagram known as the Butterfly Diagram by the Ellen MacArthur Foundation (Ellen MacArthur Foundation, 2019)

In order to better manage progress in circular economy implementation, several metrics have been introduced and defined. These metrics can be used in different contexts where circular economy principles are applied. Sassanelli et al. (2019) analyzed 45 studies in the field of circular economy and identified seven main performance assessment methods in the literature that are used to assess circular economy based on the lifecycle focus of the project. These methods include Life Cycle Assessments, Input-Output, Design for X, Multi-Criteria Decision Methods, Simulations, Energy and Exergy based approaches, and Material Flow Analysis.

Successful adoption of CE in the built environment is strongly affected by the financial viabilities of the circular strategies (Linder & Williander, 2017). Therefore, strong innovative business models are required to be able to implement CE and subsequently mitigate environmental impacts (Nußholz et al., 2019). The main idea behind most circular business models is to obtain maximum value from minimum resource consumption (Geissdoerfer et al., 2020). Circular business models are designed to make interventions in the process of value proposition, value capture, value delivery, and value creation to align with circular economy principles (Rosa et al., 2019). Circular economy helps reduce dependency on virgin materials, shift towards use of renewable sources, and adopt sustainable production practices in the value chain of business models. The viability of circular business models is highly subject to the economic and political conditions. Governments can help accelerate the shift towards a circular economy through interventions such as tax incentives, subsidies, regulations, and standards (Ghaffar et al., 2020).

Various categorizations of circular business models are available. There is the ReSOLVE framework which outlines Regenerate, Share, Optimize, Loop, Virtualize, and Exchange as six main action areas in circular business model implementation (Ellen MacArthur Foundation, 2013). A review on 92 circular economy-oriented business models was conducted that identified the innovative aspects and gained values through adapting these business models (Pieroni et al., 2019). Another recent study categorizes the circular business models into cycling, extending, intensifying, and dematerializing (Geissdoerfer et al., 2020). Despite the multiple classifications, circular business models are generally focused on decreasing resource consumption, increasing service lives to gain maximum value, and mitigating pressure on natural resources (while making a reasonable profit).

Considering the growing environmental impacts associated with the construction industry, the adoption of CE principles as sustainable solutions for optimizing resource consumption, reducing waste production, and mitigating greenhouse gas is gaining interested in this sector by both researchers and industry professionals (Ghisellini et al., 2018; Huang, Zhao, et al., 2018; Benachio et al., 2021; Pomponi & Moncaster, 2017). Illankoon and Vithanage (2023) have categorized CE knowledge in the construction industry into eight distinct themes through a systematic literature review from available journal papers published between 2013 to 2023. These categories are: 1) circular business models; 2) principles related to the concept of 'R'; 3) management of construction and demolition waste; 4) the economic implications of the circular economy; 5) the impact on greenhouse gas emissions; 6) the utilization of digital technology tools; 7) offsite construction methods; and 8) the assessment of life cycles. Benachio et al. (2020) have studied applicable circular business models and circular economy practices in the built environment and categorized them based on lifecycle stages including project design, product manufacture, construction, operation, and end of life. Qualitative research through interviews, surveys, or document scanning indicates a growing interested and emergence of business opportunities in shifting toward CE implementation among construction-related companies (Adams et al., 2017; Chileshe et al., 2016; Cruz Rios et al., 2021; Giorgi et al., 2022; Govindan & Hasanagic, 2018; Guerra & Leite, 2021). Therefore, the construction industry recognizes the significance of adopting CE but faces considerable challenges since this transition is a complex sociotechnical phenomenon that requires both technological innovation and social changes (Adabre et al., 2022;Illankoon & Vithanage, 2023).

The incorporation of CE principles in the construction sector encounters numerous challenges. De Jesus & Mendonça (2018), distinguishes barriers into hard (technical and economic) and soft (institutional and social) categories, while Rizos et al. (2016) classifies barriers for small and medium-sized enterprises into five aspects including: (1) lack of capital; (2) lack of government legislation; (3) lack of information; (4) administrative burdens; and (5) lack of technical and technological knowledge. Overall, the implementation of circular economy principles in the construction sector has yet to become standard industry practice due to various challenges that can be grouped into financial, technical, political, and social barriers (Cruz Rios et al., 2021; Pheifer, 2017; Rakhshan et al., 2021; Rizos et al., 2016). On the other hand, circular economy practices are relatively new and existing knowledge surrounding them is limited, leading to uncertainty and perceived risks (Mont et al., 2017; Tingley et al., 2017). Additionally, the lack of comprehensive tools and indicators to assess both the environmental and financial consequences of adopting circular strategies holds back their widespread adoption (Charef et al., 2022; Charef & Lu, 2021; Munaro et al., 2020).

2.2 Building End-of-Life Resource Recovery

Resource recovery is considered to be one of the most popular circular business models among construction industry members. Resource recovery is focused on the End-of-Life (EoL) stage of the life cycle of a system and is related to value creation from used resources including both material and energy (Vermunt et al., 2019). The value proposition of this business model is dependent on creating value from the residual of used resources (Bocken et al., 2016). The resource recovery circular business model includes various strategies that contribute to a form of material or energy recovery that can lead to use in a new system (Velenturf & Jopson, 2019). Resource recovery covers most of the main strategies in the 9R circular economy framework including Reuse, Repurpose, Recycle, and recover (Figure 2-2); however, the majority of these strategies are considered to be among the less impactful circularity interventions (Kirchherr & Piscielli, 2019). Some of the closely related circular approaches to resource recovery in the construction industry specifically focused on reuse and recycling of building materials are waste as resource (Arup, 2017), urban mining (Brunner, 2011), and developing building material passports (BAMB, 2019; Honic et al., 2021).

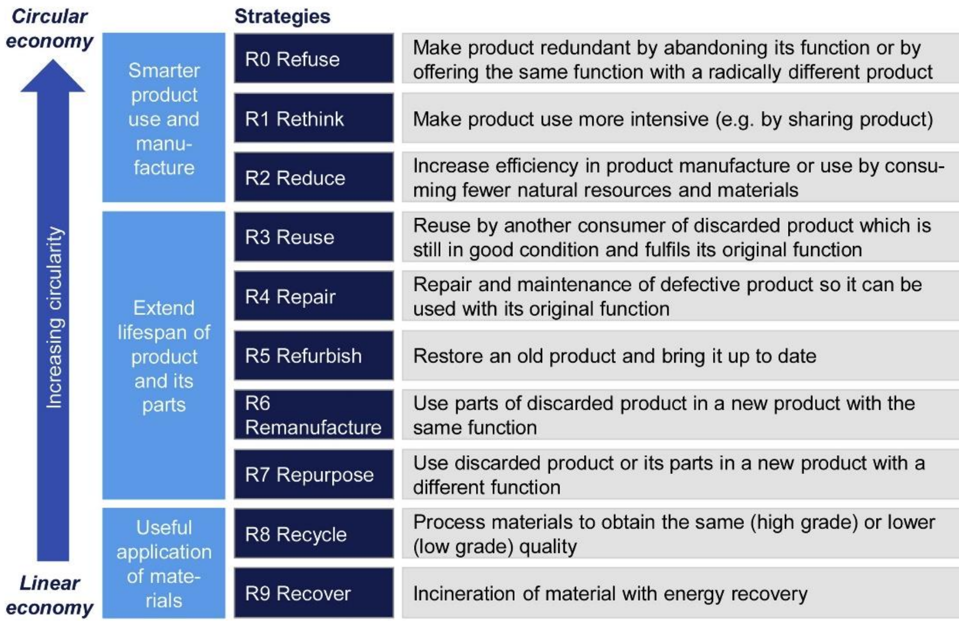

Figure 2-2: The 9R Framework in Circular Economy (Kirchherr & Piscielli, 2019)

Waste as resource means using the waste or byproducts produced from the construction and demolition stages as useful resources for a new project (Mondal et al., 2019). This strategy is focused on identifying use cases for the recovered materials that would have otherwise been disposed of as waste. Through efficient reuse and recycling processes in the construction industry, construction and demolition waste can be turned into valuable resources that can support future developments (Esa et al., 2017; Huang et al., 2018). The basis of the "waste as resource" business model is also closely linked to the original "Reduce, Reuse, and Recycle" or the 3R principle (Esa et al., 2017; Huang et al., 2018). The most optimal waste management strategy is reduce, which aims at decreasing the overall waste production. Reuse is the practice of using building components and materials after their first use with no or minimum alterations for the same function. Recycle is one of the least favorable strategies where waste materials are mixed with virgin materials and go through the production process again (Huang et al., 2018). In the current linear economy, annually, a great amount of reusable or recoverable construction materials are landfilled both legally and illegally (Silva et al., 2017).

Urban mining follows similar logic and refers to the reuse of material stocks embedded in urban areas after they reach the end of their life span (Brunner, 2011). To use these strategies, information on the availability of materials should exist. For this purpose, the “Building as Material Bank” (BAMB) concept emerged from the idea of looking at buildings not just as one-time residential or non-residential service providers, but as potentially valuable material mines that can be used when the buildings reach their EoL (Heinrich & Lang, 2019). BAMB is a European Union funded project that is focused on transparency and data collection on building materials through creating material passports (BAMB, 2017). Researchers have also made substantial efforts to compile urban level building material information in different parts of the world at different scales (Lanau et al., 2019). However, use of data from building stocks at an aggregated level has been challenging for practical reuse purposes (Rose & Stegemann, 2018). A solution was the development of Material Passports (MP) for buildings that can be used in Building Information Model (BIM) to fill the information requirement gap. These MPs can include information such as the quantity of materials, age, building connection details, material characteristics, and much more specific design information depending on the availability of data (Aguiar et al., 2019).

Available information in MPs can also be used to implement circular strategies such as evaluating the recycling and reuse potential of materials in buildings and provide decision support tools for optimized resource efficiency (Honic et al., 2019a). However, the availability of materials is only one aspect of material recovery. Additional financial, environmental, technical, and regulatory factors exist that can highly impact the process of extracting materials from buildings and circulating them back into the economy. For instance, in order to effectively understand the reusability of a building component, alongside information on the quantity and geometry of the component that is typically what is found in MPs, information on the quality and toxicity of the material, equipment required for extraction, regulations on secondary use of the specific component due to its reduced capacity, and the market value of the secondary material is also essential. The construction industry stakeholders will have a higher incentive to look into these circular strategies if an opportunity for financial gain exists.

The recovery of building materials at the end of their life cycle is not a novel concept, as recycling and reuse practices are widely recognized in the industry. When executed correctly, these practices can yield both financial and environmental benefits. However, due to the complexity of building systems and the variety of factors influencing the process, the recovery value of buildings is often underestimated. Consequently, demolition and landfilling remain common practices despite the potential benefits of resource recovery.

2.3 Factors Impacting the End-of-Life Value of Building Materials

Efficient application of resource recovery on the embedded materials in buildings requires an understanding of the economic and environmental value of the in-situ material. The required factors for making a knowledgeable decision regarding the value of in-situ materials are identified through a literature review. These factors are summarized in five main categories of building characteristics, operational, financial, environmental impact, and policy factors (Table 2-1).

Table 2-1: Factors that Affect the Value of in-situ Materials in a Building

Category	***Factor***	***Reference***
Building Characteristic	Deterioration of materials and components	(Almalki and Yuan, 2013; Akanbi et al., 2018)
	Age of structure	(Akanbi et al., 2018: Akinade et al., 2015)
	Building component life spans	(Akanbi et al., 2019)
	Geometry of structure	(Bradley et al., 2006; Yeung et al., 2015)
	Design Specifications	(Pun et al., 2006)
	Building Component Connections	(Basta et al., 2020; Bertin et al., 2020)
Operational	EoL options	(Jayasinghe et al., 2019; Rios et al., 2015)
	Technology used in Recovery Operations	(Honic et al., 2019:Volk et al., 2018)
Financial	Cost of Skilled Labour	(Guy & Mclendon, 2000; Pun et al., 2006)
	Cost of transportation	(Ghisellini et al., 2018)
	Landfill Fees	(Silva et al., 2017)
	Market value of Virgin materials	(Yeung et al., 2017; Ghisellini et al., 2018)
	Market value of secondary materials	(Huang et al., 2018; Ghisellini et al., 2018)
Environmental Impact	Environmental Impacts and Cost of Impacts	(Yeung et al., 2017; Shindell, 2015; Sanchez et al., 2019; De Wolf et al., 2020)
	Embodied Material Impacts	(Sanchez et al., 2019)
Policy and Regulations	Government policies and incentives	(Hossain et al., 2020;Nußholz et al., 2019)

	Carbon Taxes and Credits	(The World Bank, 2017)
	Climate Action Incentives	(De Jesus and Mendonça, 2018)

Building characteristics such as age, structural design, and material types have direct impacts on the recovery value that can be obtained from the in-situ materials. Old building materials that are deteriorated may have low value due to loss of structural capacity (Almalki and Yuan, 2013). Moreover, components that are connected with undetachable connections will also have a lower value compared to easily detachable connections as the separation and extraction of the components will cause damage to the materials and components making them unsuitable for reuse (Rakhshan et al., 2020).

Operational factors affecting the value of materials include the EoL option chosen for the components and the technology used to extract the materials. Two of the popular possible EoL options are conventional demolition and deconstruction. Demolition is the process of using heavy machinery, tools and labour to tear down a building. The primary goal of demolition is to remove the building quickly and efficiently, often resulting in a significant amount of waste and debris. Typically, in this process, building components are damaged and mixed, making them extremely difficult to recover. Building demolition in a conventional way has two main techniques, namely mechanical demolition and implosion (Pun et al., 2006). Implosion is a method used in high-rise and heavy industrial buildings. This technique is highly unsustainable due to the irreversible damage caused by the implosion on the building components, which makes recovering the materials extremely difficult or impossible (Diven and Shaurette, 2011). In the mechanical demolition process, the structure is pulled down in a more controlled way using hydraulic machinery including excavators and bulldozers. In this process, the demolition waste can at most get recycled or downcycled but is more often sent to landfills for sorting and disposal (Pun et al., 2006).

Deconstruction is a selective and controlled process. Unlike demolition, deconstruction focuses on carefully disassembling the building to salvage and recover components and valuable materials with the aim of recovering them for reuse or recycling (Allam & Nik-bakht, 2023). The textbook definition for deconstruction is “a process of selectively and systematically dismantling buildings to reduce the amount of waste created and generating a supply of high value secondary materials that are suitable for reuse and recycling” (Macazoma, 2001, p.14). Although deconstruction has obvious environmental advantages in the sense that materials that would have turned into demolition waste will circle back in the economy and are used as useful resources, it is considered to be labour-intensive. Specifically, in regions where labour is expensive, such as in North America, the total cost of deconstruction might be considerably higher than that of conventional demolitions (Macazoma, 2001). However, higher landfill costs and benefits from selling recovered materials can help make deconstruction more attractive for building owners.

Limited landfill availabilities and disposal restrictions have slightly shifted construction waste management strategies towards more sustainable approaches despite the higher labour costs associated with them (Rios et al., 2015a). The possibility to disassemble structures is strongly related to the original design of the building. Another available scenario for the building EoL option is the hybrid demolition technique comprising a mix of mechanical demolition and deconstruction (Van den Berg et al., 2020). These techniques are not as harmful to the environment as conventional demolition and at the same time are not as costly and labour-intensive as deconstruction methods (Diven and Shaurette, 2011; Pun et al., 2006).

Financial factors include both the operational costs and the market value of virgin and secondary materials that directly impact the cost of extracting materials and benefits gained from selling secondary materials (Ghisellini et al., 2018). Environmental impacts and cost of impacts are also crucial in determining the value of in-situ materials. Extracting materials through low impact operations and enabling the use of materials for another lifecycle after they reach their EoL in the current building, can greatly increase the value of materials in existing buildings.

Finally, policies and regulations can play an important role in the value of in-situ materials. Carbon taxes and carbon credits are two of the main policies that can increase the value of in-situ materials. If carbon emissions are accounted for and taxes are applied, extracting materials from buildings can be more economical compared to the production of raw virgin materials (The World Bank, 2017). Governments might also implement other financial restrictions and tax incentives that can encourage the use of secondary materials that will directly impact the value of in-situ materials.

2.4 Conceptual Framework

The factors that were identified to have an impact on the value of in-situ materials are used to develop a conceptual framework that is presented in Figure 2-3. The framework includes four main phases: 1) Estimation of the quality and availability of materials; 2) Estimation of the material extraction costs; 3)

Estimation of the associated cost of Environmental Impacts (EI); and 4) Estimation of the total cost and value of the in-situ materials. The conceptual framework can be applied at different scales, from a single component or material to a whole building.

In the first phase, the total quantity of materials that are embedded in the building and the total quantity available for secondary use after extraction are estimated. This can be done through deterioration modeling of the materials and components, site investigations, condition assessments of the building, and also based on the estimator's experience (Akanbi et al., 2018) Almalki & Yuan, 2013). An adjustment factor is recommended to be used after the material availability is estimated because although theoretically all the material that has not been deteriorated has the potential to be reused or recycled, some materials might be damaged in the extraction process that will not be available for secondary use. This adjustment factor is dependent on the type of material, the component of the building, building structure, and connections used in the structure (Honic et al., 2019b).

The second phase is focused on cost estimation associated with the extraction of the materials from the building. Enabling the secondary use of materials is directly related to the EoL process chosen for the building. Therefore, the cost is calculated in various possible scenarios. In this framework three scenarios are considered to be applicable: 1) Conventional demolition with disposal in landfills; 2) Demolition and material sorting to be hauled and sold to a recycling plant; and 3) Controlled deconstruction to enable material reuse and increase salvage value. In the second and third scenarios, the materials are extracted to be used for an additional lifecycle, whereas in the first scenario materials are extracted from the building and dumped in the landfill where their lifecycles come to an end. In each scenario, the cost associated with the extraction process, transportation, and all additional fees is accounted for. In the third phase, the EI associated with the extraction process and the embodied impact of the materials and components for all scenarios are calculated. The cost of EI is also calculated based on carbon prices.

In the fourth and final phase, total extraction costs and total EI costs for each scenario are calculated for the components. The salvage value for the components is also identified to estimate the potential residual value of the in-situ materials. Finally, the net cost is calculated by adding the costs calculated in phases 2 and 3 and deducting the potential value for the quantity of materials calculated in phase 1. The cost breakdowns for each phase can show the contribution of each process to the overall cost and value. In the end, a decision can be made based on the total cost and value for each scenario and based on the priorities of the decision-maker. The conceptual framework is developed based on the conducted literature review on value of in-situ materials. It is a synthesis of existing knowledge and common practices observed in the demolition and deconstruction industry.

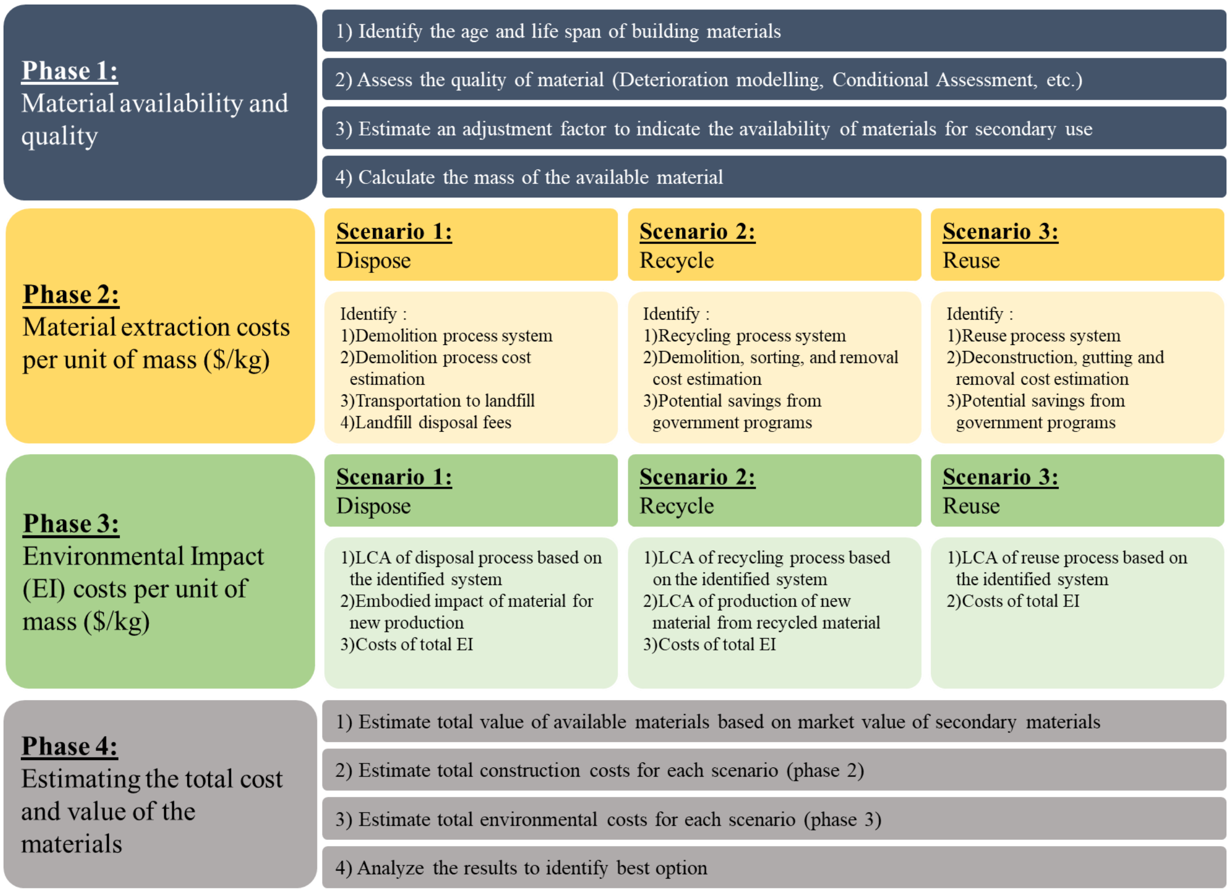

Figure 2-3: Conceptual Framework for Estimating the Value of in-situ Materials

2.5 Existing Building Recoverability Assessment Methods

Various research is conducted with the purpose of developing methodologies and frameworks that can help recover resources in existing buildings at the end of their life cycle. Researchers have investigated the recovery potential of construction materials at different scales. For instance, focusing on one single material, Yeung et al. (2017) used life cycle analysis and life cycle cost analysis to compare the impacts of recycling and reusing steel concluding that although steel reuse is more costly, the environmental impact is much lower than that of steel recycling due to fewer processes required to recover the material. On a larger scale, Sanchez et al. (2019) studied the net environmental impacts and cost performance of a non-residential building in an adaptive reuse project, comparing the two alternatives of full demolition and new construction with building adaptation. The results showed that selective demolition and renovation, which enables the components and materials in the building to be used for another lifecycle, has a lower environmental impact.

Reverse logistics, which is a relatively established concept in the manufacturing sector, is also currently being implemented in the construction industry to help recover materials in salvaged buildings and infrastructure (Hosseini et al., 2015). Reverse logistics in the construction and demolition industry refers to the strategic management of materials, components, and waste streams flowing backward through the supply chain. It involves the efficient handling, transportation, recovery, and processing of materials post deconstruction or demolition, aiming to reclaim, reuse, recycle, or responsibly dispose of these materials in a sustainable and environmentally conscious manner (Chileshe et al., 2018; Hosseini et al., 2015). Reverse logistic phases for building materials include deconstruction, preparation of material for reuse, distribution of waste, and material repurposing (Ding et al., 2023). The quality of materials is a key factor in the reverse logistics supply chain impacting the supply quantity and market value of the materials. Wijewickrama et al. (2021) argue that although reverse logistics is proven to have potential economic, environmental, and social benefits, lack of knowledge, awareness, policy, and a robust framework is leading to inefficient practices in the field.

Akanbi et al. (2018) developed a "BIM-Based Whole-life Performance Estimator" using building and material characteristics such as type of connections, number of prefabricated assemblies, hazardous materials, and material behaviors throughout the building lifecycle. The idea was later expanded to a reusability analytics tool to estimate the quantity of material available for recovery using material deterioration modeling (Akanbi et al., 2019a). The developed tools were only focused on material availability and did not consider any economic or environmental factors.

Analyzing building deconstructability is another method that has been studied by researchers which can be used to assess the building's potential for reuse and recycling. Akinade et al. (2015) developed a BIM-based deconstructability assessment score that can determine the extent of possible deconstruction in the building from the design stage. Application of the developed tool on the building model and analyzing different design alternatives to increase deconstructability will increase the value of in-situ material by enabling deconstruction as an EoL option for the components in the building. Additionally, deconstruction programming using sequential precedence relationships is another method that has been studied that contributes to the recovery of materials by identifying the efficient deconstruction plan to extract the desired component. Determining the sequence of disassembly and deconstruction is widely used in the manufacturing industry and is gaining interest in the construction industry as well (Sanchez, Rausch, et al., 2019). However, the level of detail used in these tools might not be realistic when applied at a larger scale, such as a full building demolition project.

In another study, Rakhshan et al. (2021) developed a probabilistic predictive model using machine learning methods to assess the economic impact of reusing load-bearing building elements. Through a literature review and survey, 12 dependent factors were identified to have an impact on the reusability of the load-bearing components. This tool is focused on constructing new buildings and structures using secondary materials. Therefore, various factors impacting the cost of construction from the reused components such as cost of insurance, testing, and fabrication are included as part of the analysis. Although this tool can provide a prediction of the economic reusability of components using the defined cost factors, no environmental factors have been considered in the analysis. Additionally, the tool assumes the reusable components are already available. However, these components can only be available for reuse, if a financial value was realized in extracting the materials from the previous building, which is strongly subject to the feasibility and cost of deconstruction.

Optimization-based tools and methods are also useful in determining the optimal EoL alternative of buildings. Sanchez et al. (2020) used a multi-objective analysis to determine the optimal selective disassembly and deconstruction methods based on cost and environmental impacts for adaptive reuse projects. Aidonis (2019) also used linear programming optimization to develop a decision-making tool for building EoL. Although the developed tool includes economic and environmental factors, it does not include building characteristics such as material availability and quality. Moreover, demolition and deconstruction limitations such as material precedence and extraction sequences have not been considered.

2.6 Knowledge Gap

Although research has been progressing in developing methods that can contribute to the implementation of resource recovery as a circular business model, a framework that can combine the identified factors in Table 2-1 and provide a robust decision support tool to understand the impact of resource recovery has not yet been established. Moreover, despite the development of building material accounting methodologies and availability of some data on the quantity of materials in building as urban material mines, this information is at an aggregated level, which makes the implementation of circular strategies difficult on a smaller and practical scale for building owners. Decisions made at the individual building level requires a more detailed and comprehensive analysis.

Overall, aside from simple interpretations, implementing the basics of the 3R principles has been a challenging task in the built environment. Insufficient design standards to reduce construction and demolition waste, waste collection and sorting challenges, changing landfill fees, immature reuse and recycling technologies, insufficient quality of recovered materials, uncertainty regarding the environmental benefits, and unknown market demand for recycled and reused materials are some of the main barriers in the construction industry standing in the way of successfully applying resource recovery strategies at the building level (Huang et al., 2018; Silva et al., 2017). Overall various, financial, political, social, and technological aspects influence the successful implementation of building recovery strategies that need to be evaluated.

In order to take advantage of circular strategies oriented around resource recovery, responsible decision-makers require decision making tools that can identify the potential for secondary use of the materials (Koutamanis et al., 2018). To be able to successfully circle the construction materials back into the economy, designers, builders, demolition companies, and policymakers each need to adapt accordingly. As for the demolition companies, they must shift from traditional mechanical demolition to more sustainable approaches that maintain the value of materials (Hosseini et al., 2015). It should be noted that the cost and time linked to these novel deconstruction approaches might exceed the cost of traditional approaches, which would make them unattractive options. However, this may be because the true value of the in-situ building materials is not yet fully realized. Specifically, as virgin materials become scarce, the in-use materials that have the potential to be reused will gain more value. Secondary use of materials might not always be the most economic option based on initial analysis; however, when indirect cost savings and the impact of reduced environmental harms alongside the scarcity of virgin materials are considered, the value will increase (Laefer & Manke, 2008). Therefore, developing a tool that can estimate the value of these materials would help assess the potential overall financial benefits and environmental impacts of end-of-life options for buildings.

Considering the identified knowledge gap and the review of similar research, this thesis is focused on developing and testing methodologies that help realize the value of in-situ building materials in different contexts. The core of the research includes the development of a decision support tool that serves as the main quantitative assessment method to gain insight into both economic and environmental value of building materials given different policy, regional, and building system scenarios. Additional literature review is conducted regarding each application scope that is provided in sections 4.2,5.2. and 6.2 of this thesis.

Chapter 3: Decision support tool for estimating the value of in-situ materials

This chapter corresponds to the following published article[1]:

> Mollaei, A., Bachmann, C., & Haas, C. (2023). Estimating the recoverable value of in-situ building materials. *Sustainable Cities and Society*, 91, 104455.

Abstract

Construction, renovation and demolition of buildings in our cities is driving substantial material consumption and waste streams. They can be reduced by recovering in-situ materials from buildings with controlled demolition, disassembly, and deconstruction of components and materials. To do this, a decision support tool that can be used to estimate current recoverable environmental and market values from the owner's perspective of in-situ construction materials in a specific facility must be developed. Here, a linear programming optimization methodology is used that considers cost, value, duration, environmental impacts, and building component precedence in demolition and deconstruction activities. It helps choose the optimal combination of reuse, recycling and disposal options for those materials. The resulting decision support tool is functionally demonstrated on an institutional building to find the building components' optimal end-of-life alternatives to maximize the recovered value from the in-situ materials. Sensitivity analyses add further validation. Thus, this research supports the transition to a more circular economy in cities by making it easier to realize the full value of in-situ materials for planning, asset management, and demolition project bids.

3.1 Introduction

The literature review conducted in Chapter 2 provided an overview of the main factors that impact the recovery of building materials at End-of-Life (EoL). The overarching aim of this research chapter is to develop a quantitative decision support tool based on an optimization model that can help estimate the current extractable value of in-situ construction materials by identifying optimal EoL options for

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[1] To maintain consistency with the thesis format, this chapter is slightly modified compared to the published article. The provided abstract is an exact copy of the published work.

building components. The objectives of this chapter are to incorporate the identified factors in Table 2-1 into an optimization model to develop a decision support tool, and to understand the impact of the defined factors on the building component EoLs and extractable values. The developed tool can be used to estimate the potential value of materials embedded in all building types that have reached their end of life and are required to be fully demolished, or the ones that are being renovated or going through adaptive reuse (Shahi et al., 2020).

The developed tool is applied on a case study building for validation through functional demonstration. Local market-based material extraction costs (labour, equipment and materials), local waste dumping fees, recycling prices and reuse prices are treated as inputs. Demolition project activities' precedence relationships based on prevailing local industry practices are treated as constraints. Demolition project duration, environmental impact costs, and optimal EoL options are determined for different plausible scenarios. Sensitivity analyses further support validation.

The remainder of this chapter is structured as follows: The developed decision support tool based on an optimization model and sensitivity analysis methodologies are explained in section 3.2. The results of the application of the tool on a case study as a functional demonstration and sensitivity analyses results are presented in section 3.3. In section 3.4, the results and implications are discussed, and the research contributions are highlighted. Concluding remarks of this chapter are summarized in section 3.5.

3.2 Methodology

3.2.1 Definition of terms

This section summarizes the definition of terms used in this chapter for a better understanding of the methodology and results.

- "Component" is referred to each independent unit, assembly, or subassembly in the building such as windows, doors, roof, ceiling, insulation, floor, etc. that is composed of a unique material. For example, in the case of an exterior wall, one component is the exterior wall brick, one component is the structural studs, and another is the insulation.
- "Recoverability Factor (RF)" is the factor between 0 and 1 that shows the ratio of materials in a component available for recovery.

- "End-of-Life (EoL)" options are the final stages of the component life cycle that include disposal (in landfills), recycling, or reuse.
- "Terminal value" is the final obtainable value from building components, including market "salvage value" if materials are reusable, market "scrap value" if materials are recyclable, and no value if materials are disposed of in landfills.
- "Material extraction cost" includes the operational and labour costs associated with the removal of materials from the building.
- "Cost" includes the internal costs that will be incurred by the owner of the materials. These costs include operational costs, labour costs, transportation costs, material recovery preparation costs, and landfill fees,
- "Net cost" is cost after deducting the savings gained from all terminal values.
- "Obtainable Value" is the sum of the terminal values.
- "Environmental Impact (EI)" costs are the costs associated with the environmental impacts, which are presently external costs, but could be internalized through government interventions such as carbon taxes.

3.2.2 Material availability

In order to estimate the value of in-situ materials, the available materials for recovery are first calculated. Material recovery can be either in the form of material reuse or recycling. Akanbi et al. (2018) have developed a material availability estimation methodology based on deterioration modeling. A similar approach is adopted in this research. A Recoverability Factor (RF) and recoverable mass of material ($M_{recoverable}$) are defined in this tool and are shown in Equation 3-1 and Equation 3-2, respectively. RF is calculated based on the deterioration of the materials in a component and ranges from 0 to 1 showing the available percentage of materials for recovery. RF is a function of the deterioration factor (bracketed expression in Equation 3-1) and an adjustment factor (f) that accounts for the material lost in the recovery process. The deterioration factor used in the calculation of RF is estimated based on the building age, component life expectancy, and a degradation factor ($\frac{t}{10\alpha_i}$), which accounts for the initial degradation of the components (Almalki & Yuan, 2013; Carrasco et al., 2008).

$$RF_i = f_i \times (1 - e^{t-\alpha_i} - \frac{t}{10\alpha_i}) \qquad \text{(Equation 3-1)}$$

$$M_{recoverable,i} = M_i \times RF_i \qquad \text{(Equation 3-2)}$$

where i is the component index, t is the age of the building (years), α_i is the life expectancy of the component i (years), f_i is an adjustment factor for component i ranging from 0 to 1 (unitless), $M_{recoverable.i}$ is the mass of material that has the potential to be recovered in component i (kg), and M_i is the total mass of the material in component i (kg). The deterioration factor determines the portion of the material that still has the potential to be theoretically recovered. However, in practice, the extraction of all the available material is typically impossible or not technically feasible. Therefore, an adjustment factor (f) is defined to account for the technical difficulties of material extraction, which can be a function of the geometry of the structure, design specifications, and connections used in the building. For the purpose of this research, the adjustment factor is estimated from secondary data and relevant literature (Arora et al., 2020; Honic et al., 2019b; Rasmussen et al., 2019).

3.2.3 Linear Programming Optimization

In this research, a multi-objective mixed-integer linear programming (MILP) optimization model is used for minimizing net cost and project time. The two objective functions defined in this problem are minimizing cost and minimizing time (project schedule duration), which are typically trade-offs in construction and deconstruction projects. The multi-objective optimization problem is solved using the constraint method (Revelle & Whitlach, 1996). To solve this problem, the cost is optimized, and the time (duration) associated with this scenario is calculated. Then, time is optimized and the cost for that optimized time is calculated. Using the constraint method in the cost optimization scenario, discrete time constraints are varied to the point of the minimum time (which is the time calculated in the optimized time scenario), and the optimum (minimum) costs under those time (project duration) constraints are calculated. This results in a project time-cost trade-off curve.

In this optimization problem, each building component has three EoL alternatives: 1) Demolition and disposal (no salvage value); 2) Demolition, sorting, and recycling (resulting in scrap value); and 3) Deconstruction and reuse (resulting in salvage value). Additional alternatives can be added if other options are available. Each alternative for each component has a corresponding cost, duration, environmental impact, and terminal value, for which data are required. For the second and third alternatives, additional costs for material sorting, cleaning, and preparation for recycling or reuse are included in the corresponding parameters. The optimization problem is designed in a way to show which EoL option should be used for each component while considering all necessary sequences of activities as well as the total project duration (detailed information on the activity sequences is provided in Appendix A). The results will change as the optimization shifts from minimizing cost to minimizing time using the time constraints explained previously.

The cost objective function is formulated to minimize the net cost of material extraction based on the material quantities, costs of extraction, costs of EI (Environmental Impact), recoverable material, and terminal values. In this tool, EI costs can be internalized and included in the optimization. Similarly, EI costs can remain external and be removed from the tool. The time objective function is formulated to minimize the total duration of the project. The result of the optimization will identify the method of extraction that is suitable for each component and the start and end times for each activity based on the objective function. The indices, parameters, and variables used in the model are summarized in Table 2.

Table 3-1: Optimization Model Indices, Parameters, and Decision Variables

Category	*Notation*	*Description*
Indices	i, j	Component Index, $i.j = \{1,2,\dots,n\}$ (n is the total number of components)
	E	Extraction Method Index, $E = \{1,2,3\}$ (1 is demolition and disposal, 2 is recycling, 3 is reuse)
Sets	A	Contains pairs (i, j) of window indices (i) and their supporting exterior walls (j)
	B	Contains pairs (i, j) of floor indices (i) and their supporting exterior walls (j)
Parameters	M_i	Quantity of material in component i in kg
	$C_{i,E}$	Cost of extraction method E for component i per unit of material in \$/kg
	$EI_{i,E}$	Cost of EI of extraction method E for component i per unit of material in \$/kg
	$V_{i,E}$	Value of component i in extraction method E per unit of mass in \$/kg
	$M_{recoverable,i}$	Quantity of recoverable material per component i in kg
	$D_{i,E}$	Duration of activity i corresponding to extraction method E for component i in hrs/kg
	$p_{i,j,E}$	Element of precedence matrix in extraction method E
	n	Total number of components in building
Variables	$X_{i,E}$	Binary decision variable identifying the choice associated with extraction method E for component i
	S_i	Start time of activity i corresponding to component i
	T	Total project duration in hrs

The objective functions of the optimization problem are formulated in the following way (Equations 3-3 and 3-4):

$$MIN \quad NetCost = \sum_{E=1}^{3} \sum_{i=1}^{n} X_{i,E} \left[\left(C_{i,E} + EI_{i,E}\right). M_i - V_{i,E}. M_{recoverable,i} \right] \qquad \text{(Equation 3-3)}$$

$$MIN \quad TotalTime = T \qquad \text{(Equation 3-4)}$$

The decision variables defined in this problem are the choices of extraction method for each component alongside the start time of the extraction for that component.

$$X_{i,E} = \begin{cases} 1 & component\ i\ is\ extracted\ with\ method\ E \\ 0 & Otherwise \end{cases}$$

S_i : $Start\ time\ of\ Activity\ i$

T: $Total\ Time$

The optimization will be solved subject to the following constraints:

$$\forall i \qquad \sum_{E=1}^{3} X_{i,E} = 1 \qquad \text{(Equation 3-5)}$$

$$\forall (i,j) \in A, \qquad X_{i,3} \leq X_{j,1} \qquad \text{(Equation 3-6)}$$

$$\forall (i,j) \in B, \qquad X_{i,1} \leq X_{j,1} \qquad \text{(Equation 3-7)}$$

$$\forall\ i,\ E \qquad T = \max(S_i + D_{i,E} \times X_{i,E}) \qquad \text{(Equation 3-8)}$$

$$\forall\ i, j,\ E \qquad S_j \geq p_{i,j,E} \times (S_i + D_{i,E} \times X_{i,E}) \qquad \text{(Equation 3-9)}$$

The constraint shown in Equation 3-5 limits the extraction method choice for each component to only one choice. The constraints shown in Equations 3-6 and 3-7 are used for mutually exclusive and connected components. Equation 3-6 is applied to make sure if a window is deconstructed (using the third extraction method, where E=3), the supporting wall is demolished (using the first extraction method, where E=1) due to the damage caused by the deconstruction of a window to the supporting wall. Equation 3-7 is defined in a way to ensure if a floor is demolished, the supporting exterior walls are also demolished. Any other applicable mutually exclusive constraint to the project can also be added. For this research, only the two described categories of these constraints are implemented (i.e. windows and walls, floors and walls). Equation 3-8 is defined to calculate the total project duration.

The optimization is also subject to another category of constraints (Equation 3-9) due to the components' precedence in demolition and deconstruction activities. It captures the remaining conventional precedence relationships beyond those defined in constraint sets 6 and 7, and as normally understood in critical path method scheduling (CPM), but with additional complexities. As expected, this constraint will limit the start time of activities to the correct order to satisfy the sequence rules. Connections between the components of an existing building require a sequence of activities to extract them and are therefore a type of constraint in the optimization model. However, demolition and deconstruction activities follow two different activity sequences that need to be satisfied whenever they are chosen for the components. To address this complexity, two $n \times n$ precedence matrices are generated; one for demolition activities and one for deconstruction activities, where n is the number of components in the building under study. It is assumed that each component corresponds with one activity. The elements of the matrix (p_{ij}) will take a value of 1 if activity i corresponding to component i should be completed before activity j corresponding to component j, and takes a value of 0 if otherwise.

To generate the matrices, the rule for demolition activities is that the demolition will take place level-by-level starting from the top floor (Diven and Shaurette, 2011). This means that all components in one level can be demolished within one scheduled activity duration, and any component in the lower level can only be demolished if all the upper level components are demolished.

The deconstruction activity sequences and precedence relationships follow another set of rules that enable the components to be extracted with minimum damage to be easily recovered and reused. In this matrix, the existing rule is that all doors in all levels are first removed, followed by interior walls, compound ceilings, and windows, leaving only the exterior components of the building. In the next step, the roof, exterior walls, column and beams, and the next floor are removed one-by-one in a sequence from top to bottom until the foundation is reached. The final step is to remove the foundation. The suggested deconstruction rules were developed based on the available case study and consultation with industry specialists (Diven and Shaurette, 2011; Guy and Mclendon, 2000). However, based on the specific conditions of a building, the rules can be changed accordingly and incorporated within the tool. After the matrices are generated, the precedence relationships constraint shown in Equation 3-9 is added to the optimization as an additional constraint. A schematic preview and a more detailed explanation of the precedence relationship is provided in Appendix A.

3.2.4 Sensitivity analysis methodology

To understand the robustness of the decisions and outputs, validate the results, and analyze the capabilities of the developed decision support tool, various sensitivity analyses are performed. First, a Monte Carlo analysis is conducted using triangular distributions for the parameters in the tool that have inevitable uncertainty in the data. The objective of this Monte Carlo analysis is to assess the robustness of the decisions and outputs of the decision support tool. The triangular distribution is found to be suitable for this analysis due to the limited availability of data. Use of this type of distribution is common in the construction industry, specifically for cases where collecting enough data to fit other distributions is challenging or impossible. The optimization is completed for several trials and outputs from the tool are analyzed and compared.

In the second part of the sensitivity analysis, the impact of the main individual parameters is assessed on the results of the tool. Five of the main parameters in the objective function are likely to be subject to more uncertainty: 1) landfill fees; 2) EI costs; 3) deconstruction costs; 4) terminal values; and 5) Recoverability Factors (RF). The parameters for the sensitivity analysis are chosen based on the conducted literature review on the factors that impact the value of in-situ materials summarized in Table 2-1. For this part of the sensitivity analysis, EI costs are internalized and considered as part of the net cost in order to analyze the impact of these costs on the decisions and other outputs of the optimization. Internalizing the EI costs will provide insight into the impact of potentially applying EI costs in different forms such as carbon taxes on component EoL choices. To account for the impact of these changes on the results, a One at a Time (OAT) sensitivity analysis approach is used, where the factors are varied in suitable ranges individually, and the results are calculated and compared.

After the impacts of these parameters are analyzed individually, the results are compared for all the possible combinations of the variations of the factors to understand the combined impact of changes in the above-mentioned parameters. For this analysis, the increments can be modified based on the results of the OAT sensitivity analysis to reduce the total number of scenarios and computing time of the algorithm. The all-combination sensitivity analysis provides insight into what combined parameter changes can lead to more drastic output changes. Among the results obtained from the sensitivity analysis, possible future scenarios are then chosen for further analysis. The developed future scenarios are compared with the reference case, which represents the scenario corresponding to the collected data. The future scenario analysis provides an improved understanding of real scenarios in addition to the assumed reference case, helps identify points of intervention, and recognizes required policy changes that can increase the value of in-situ materials.

3.2.5 Case Study Information

The described methodology is applied to a case study building for testing and functional validation. The chosen case study is the Martin Luther University College building, located in Waterloo, Ontario, constructed in 1963. For this research, it is assumed that the building is required to be removed with the assumed age of 57 years. The building is approximately 3,400 m^2, has three floors, and includes hundreds of components. A section of the north wing of the building is used as a case study. This section has a total area of 320 m^2 meters and contains a total of 167 components. The schematic model of the complete building and the section used for this research are shown in Figure 3-1. The model of this building is collected from a local consulting company and is modified based on available architectural and structural drawings. The component types and number of each component in the building section are extracted from the building model in Revit. The following component categories are used: compound ceilings; columns, doors, floors, roof, exterior walls, foundation walls, interior walls, and windows.

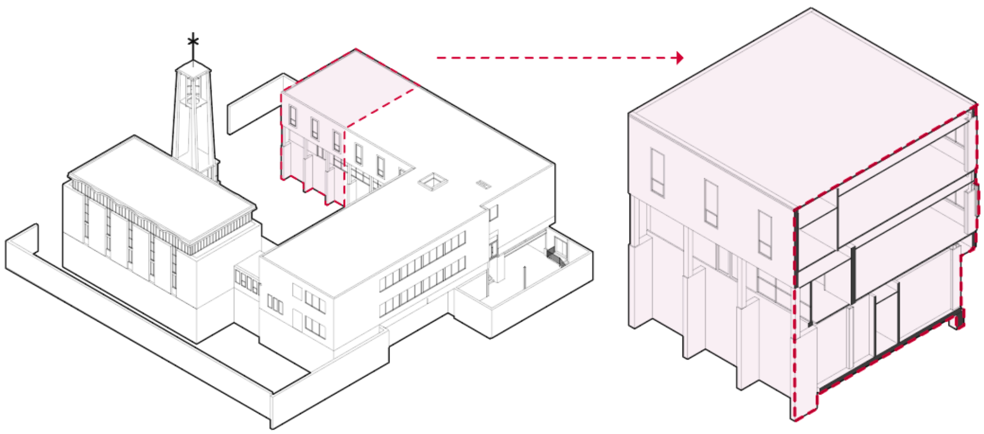

Figure 3-1: Case Study BIM Model and Extracted Section

To run the optimization on the case study, the IBM CPLEX optimization software was used. An optimization algorithm is generated for this mixed-integer multi-objective linear program. The problem is solved using the branch-and-bound algorithm. The results of the application of the tool on the case study are presented in section 3.3.

To validate the results and test the applicability of the tool, the sensitivity analysis methods were also applied to the case study. For the Monte Carlo analysis, triangular distributions were allocated to the landfill fees, salvage values, and scrap values based on the collected data, and EI costs were kept externalized. The analysis was completed for 10,000 trials and the net optimized cost, obtainable value, and component EoL breakdowns were compared. The number of trials for this analysis started from 1000 and was increased to the point where the change in the distribution of outputs was not substantial.

In the OAT sensitivity analysis, relative to the base case estimates, the landfill fees, salvage values, and EI costs were varied from 0 to 200% in increments of 10%. The deconstruction costs were varied from 50% to 200% and the RFs were varied from 0 to 100% both in increments of 10%. In the next step, for the all-combination scenarios, EI costs and terminal value increments were increased to 25% (nine variations for each factor), RF and deconstruction costs to 50% (3 variations for each factor), and landfill fees to 100% (3 variations). Ultimately, 2,187 ($9 \times 9 \times 3 \times 3 \times 3$) scenarios were analyzed in the all-combination sensitivity analysis.

Based on the results of the all-combination sensitivity analysis alongside the reference scenario, which represents the collected data and is an indication of best estimates of what the reality should be including potential EI costs, three additional future scenarios were developed. The details of these scenarios and their conditions are summarized in Table 3-2. The first scenario represents an extreme case in the future where landfill spaces are scarce and landfill fees are high, there is demand for secondary materials, material recovery is possible, EI costs are higher, deconstruction costs are cheaper due to available skill (and technology), and policies that incentivize deconstruction are in place. Scenario two shows a case closer to the current reality where landfill fees are low, demand and value for secondary materials are low, recovery is possible to some extent, and EI costs are not being internalized. Finally, scenario three is a case where it is possible to get rid of the produced waste at no cost and no terminal value is obtained.

Table 3-2: Future Scenario Conditions

Factors	*Reference (representing the collected data including internalized EI costs)*	*Scenario 1 (representing ideal recovery situation)*	*Scenario 2 (representing a close case to the current reality in North America)*	*Scenario 3 (representing the scenario where landfilling is cheap)*
Landfill Fee	100%	200%	50%	0%
Terminal Value	100%	200%	25%	0%
Recoverability Factor	100%	100%	75%	100%
Environmental Impact Cost	100%	200%	0%	0%
Deconstruction Costs	100%	50%	100%	100%

3.2.6 Data Requirements

Applying this tool requires a substantial amount of data for each phase. In order to test the methodology, the following data were collected: For the material availability, material takeoffs were collected from a BIM model, building age is assumed to be known, and building material and component technical lifespan alongside the recoverability factors are collected from the literature (Akanbi et al., 2019a; Carbon Leadership Forum, 2018). Material extraction time and costs including activities and labour associated with demolition, deconstruction, material sorting, and transportation were estimated in Sigma estimates using RSMeans data (RSMeans, 2020). Moreover, landfill fees associated with dumping construction materials were collected from local landfill websites (City of Toronto, 2021; Greater Sudbury, 2021; Niagara Region, 2021; Region of Waterloo, 2021: York Region, 2021). The EI associated with each component was calculated using the material takeoffs in OneClick LCA and the OneClick LCA inventory. The EI assessment methodology is explained in Appendix A. For this project, Global Warming Potential (GWP) is the only indicator used. Since all the values are estimated in US dollars, the calculated GWP is also in a monetary value. This is done by using a coefficient of 100 USD per ton of CO_{2eq} tons (Shindell, 2015). The embodied EI in the components is also allocated based on the material lifecycle extension enabled through secondary use of the components. Finally, salvage values for scrap and reusable materials and components were collected from marketplaces available on the web (Demolition Traders, 2021; Recycler's Exchange, 2021; Repurposed Materials, 2021; Salvage Garden, 2021). The details of the input data used for this case study are provided in Appendix C.

3.3 Results

3.3.1 Optimized Cost and Time Results

Minimizing the net cost using the described methodology on the case study building identifies the components that should be demolished (and disposed of in landfills), recycled, and reused by gaining value from the extracted materials. For this case study, it is initially assumed that the EI costs are external in the tool and therefore do not add to the project cost. Figure 3-2 summarizes the optimal EoL options for each category of building components for both the optimized time and optimized cost scenarios when EI costs are external. Figure 3-2a demonstrates the extraction method suitable for the components in the case study. Overall, among the 167 components in the case study, 86 components should be demolished, sorted, and sent to a recycling plant for recycling purposes and 81 components should be reused. The results indicate that to minimize the cost, no component should be sent to landfills. This is mainly due to the high cost associated with landfill fees. Components that have a high salvage value and low deconstruction costs, such as compound ceilings and windows, are suggested to mostly be deconstructed and reused. Other components such as floors and columns with cast-in-place concrete-based materials are suggested to be demolished and sorted for recycling purposes due to the high cost of deconstruction and low market value. As shown in Figure 3-2a, not all components in the same category will have the same EoL alternative when the cost is optimized. This is due to the difference in the mass and the precedence of the component extraction activity in deconstruction and demolition. The net cost in this scenario including the salvage benefits would be -$4,800 (i.e., $4,800 profit), where $19,700 is the cost of material extraction, and $24,500 is the potential benefits. The total project duration estimated for the optimized cost scenario is around 40 hours. This project duration is the maximum time estimated for this project.

In order to minimize the duration of the project, the cost objective function (Equation 3-3) is replaced with the time objective function (Equation 3-4). The results of the time optimization indicate that the minimum project duration for this case study is 32 hours. In this scenario, all components are demolished and disposed of in landfills. In Figure 3-2b, the extraction methods suitable for the components in the case study are shown. The net cost associated with the minimum time is $55,000, which is all due to the cost of material extraction. In this scenario, no benefits will be gained from materials since no component was extracted for recycling and reuse purposes. The net cost is significantly higher than the minimized cost scenario, mainly due to substantial landfill fees and no salvage and scrap value receipts. If a project is required to be completed in the shortest period and a penalty is applied for late delivery, the suggested extraction methods associated with the optimum time might be the better option, despite the high cost.

If EI costs are internalized, the net cost of the project when cost is minimized would be $12,500, where $20,700 is the cost of material extraction, $17,000 is the cost of EI, and $25,200 is the potential benefits. In this case, 76 components should be recycled and 91 components should be reused. In the time minimization, the net cost will increase to $85,200 due to the additional $30,200 for the EI costs. There will be no change in the components EoLs, since they should all be demolished again. The time minimization scenario also has a much higher EI cost. If a project is focused on reducing EI, minimizing the project duration is not a congruent goal.

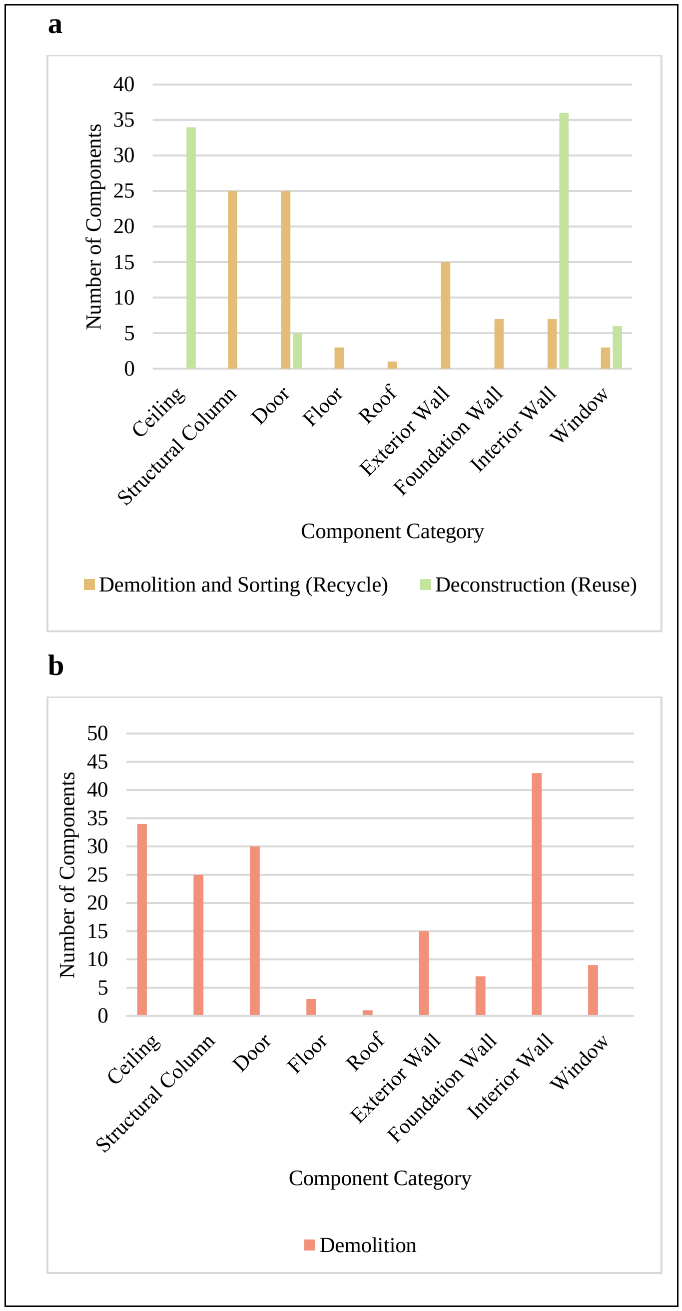

Figure 3-2: Component EoLs in a) Optimal Cost Time Scenarios with external EI Costs and b) Optimal Time Scenarios with external EI Costs

A time-cost trade-off can also be generated using the constraint method to solve the multi-objective optimization (as explained in section 3.2). Figure 3-3 demonstrates the breakdown of the project cost for three different durations including the maximum duration, minimum duration, and a time in between. Figure 3-4 shows the net cost including EI costs for the three different time scenarios. These figures show that as the duration constraint is relaxed, the net cost of the project decreases (and extraction methods are shifted towards recycling and reuse). Therefore, based on the decision-maker's priority and resource availability, they might decide to focus on an optimized time or an optimized cost approach, or decide to take an intermediate approach. In all scenarios, the applied methodology can suggest the best extraction methods to satisfy the constraints. The change in cost, broken down by: 1) demolition and deconstruction operation cost, 2) landfill fees, 3) material sorting cost, 4) transportation cost, 5) EI cost, and 6) salvage benefits, are also shown in Figure 3-3. This figure shows that as time increases, the operational cost of demolition or deconstruction increases since the extraction methods shift towards more time-intensive deconstruction methods; however, the net cost will decrease due to benefits gained from material terminal values and lower EI costs.

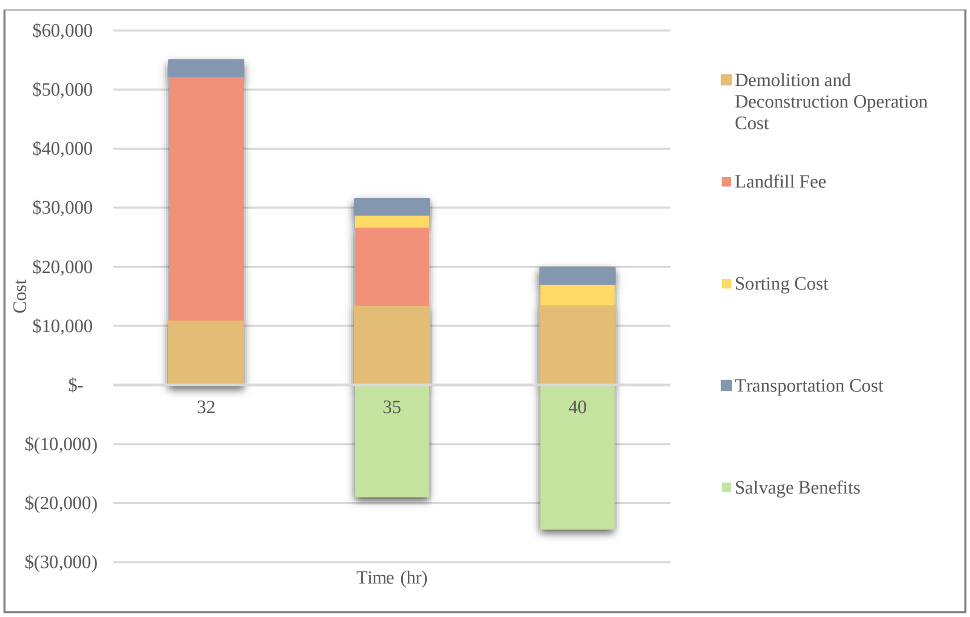

Figure 3-3: Cost Breakdown Change for Project Durations of 32, 35, and 40 hours

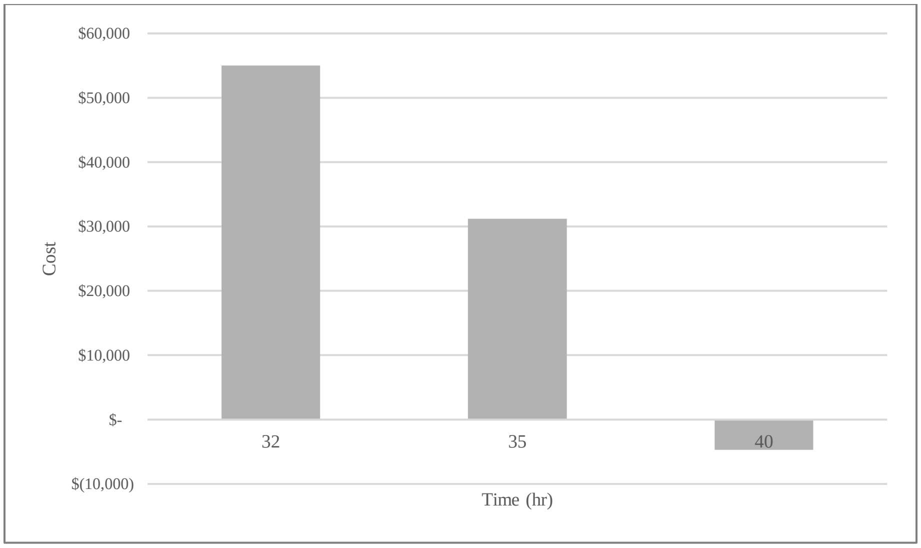

Figure 3-4: Net Cost with Internalized EI for Project Durations of 32, 35, and 40 hours

3.3.2 Sensitivity Analysis Results

3.3.2.1 Monte Carlo

The results of the Monte-Carlo analyses are provided in Figure 3-5, showing the P80 and P50 for the tool outputs including total cost, value, and number of recycled and reused components with externalized EI costs for 10,000 simulations. These results show that based on the collected data for the landfill fees, salvage values, and scrap values, with externalized EI cost, there is an 80 percent chance that cost is less than $21,700; the minimum cost is approximately $18,500 and the maximum is $23,500 (Figure 3-5a). There is an 80 percent chance of having an obtainable value of $54,500 or less, and a 50 percent chance that an obtainable value of $47,000 from the scrap and salvage materials are gained (Figure 3-5b). As for the EoL of the components in the tool, there is an 80 percent change that at least 70 components are recycled (Figure 3-5c). Similar estimation for the reuse EoL option shows that there is an 80 percent chance to reuse at least 81 components (Figure 3-5d).

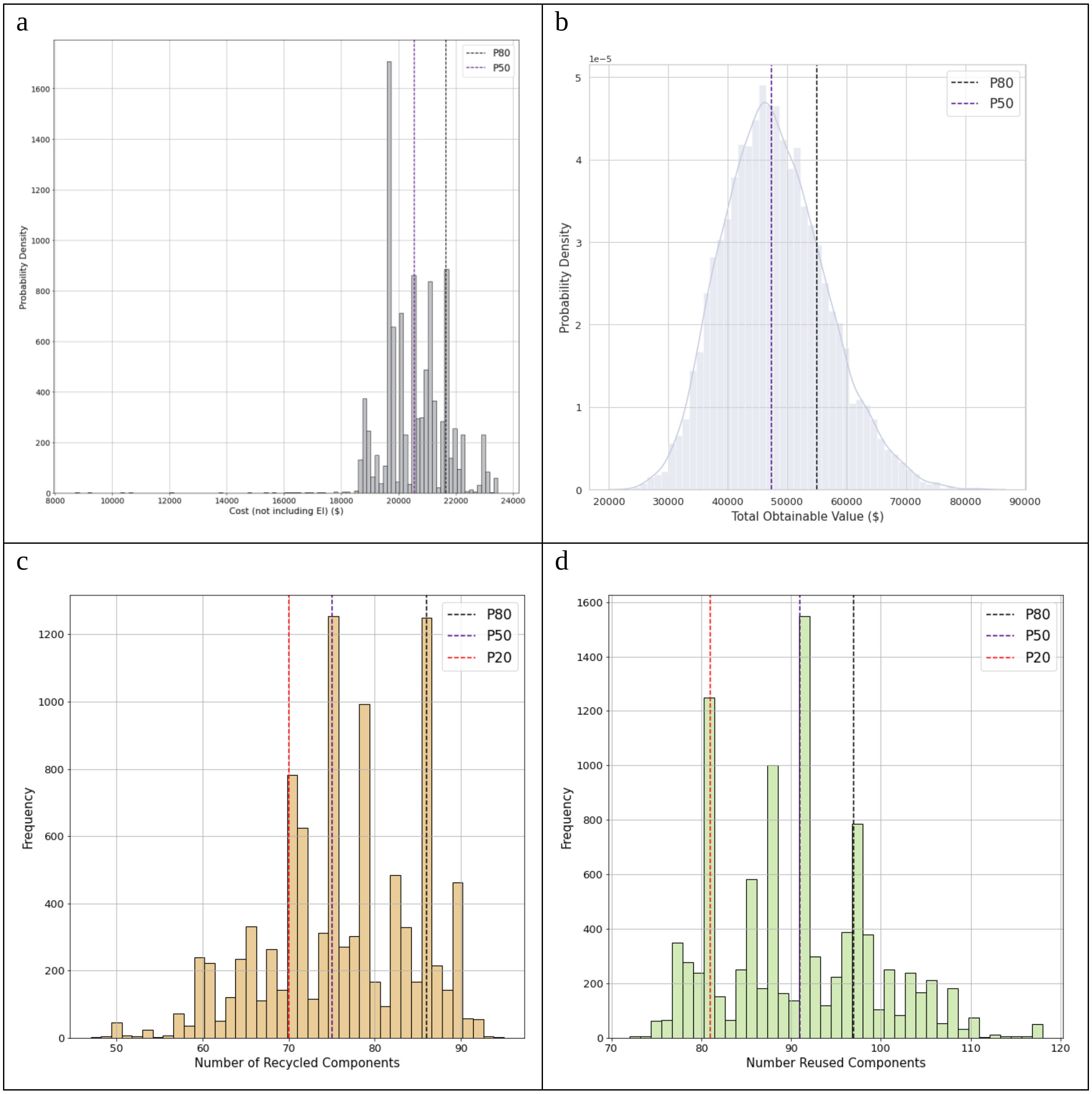

Figure 3-5: Results of Monte Carlo Analysis with External EI Costs: a) Cost; b) Obtainable Value; c) Recycled Components; and d) Reused Components

3.3.2.2 One At a Time (OAT) Sensitivity Analysis

The results of the OAT sensitivity analysis indicate how the EoL decisions, and consequently other outputs of the tool, vary as the main factors are changed individually. The results of this sensitivity analysis are demonstrated in Appendix A, Tables A-1 to A-4. The results indicate that in a cost minimization scenario, changes in landfill fees do not impact the output of the tool since the optimal EoL options do not include landfilling in the first place (recall Figure 3-2a). Additionally, according to the LCA data provided in Appendix C, the EI associated with disposal in landfills is relatively high, making the demolition and disposal in landfills an expensive and impactful option. Increasing the terminal values and RF directly impacts component EoLs, shifting them to deconstruction and reuse due to the higher obtainable value that offsets the net cost. The EI costs linearly impact the net optimized costs; however, the impact on EoL choices is small compared to the other factors.

The results of this analysis indicate that net optimized cost is most sensitive to terminal values, recoverability of materials, and EI costs. The EoL option for the components changes most when the salvage values and deconstruction costs change. The obtainable value from the recovery of materials plays a key role in this analysis and has a substantial impact on the outputs of the tool.

3.3.2.3 All-Combination and Future Scenarios

To assess the impact of changes in the factors simultaneously, the chosen factors were varied in the specified ranges. The increments used for the factors in the all-combination scenario were modified according to the results of the OAT sensitivity analysis so that the factors that had smaller impacts on the results were varied in larger increments to reduce computations. The larger increments were previously identified in section 3.5. Ultimately, 2,187 scenarios were generated indicating different variations of the factors. Visualization of the change in five factors at the same time is complex. The results of the all-combination sensitivity analysis are provided in Appendix A in Tables A-2 to A-7. These results were used to conduct a final sensitivity analysis that focused on identifying certain scenarios that represent combinations of the factors that showed more substantial changes compared to the reference case. As described in the case study information, three additional scenarios were selected from the combinations that could represent future situations (Table 3-2).

The results of this future scenario analysis are provided in Figure 3-6, which summarizes the change in the main outputs of the tool including net optimized cost (Figure 3-6a), total cost excluding EI (Figure 3-6b), obtainable value (Figure 3-6c), and component EoL breakdown (Figure 3-6d) for the four identified scenarios. These results show that the base case has the highest net optimized cost Figure 3-6a). Despite the high EI and landfill costs in scenario one, the net optimized cost is the lowest compared to the other scenarios because there is a great opportunity to gain value from the secondary materials and reduce the net cost in this scenario. Scenario two, which is a closer case to reality, has an almost similar net cost to the base case. Moreover, a comparison of the net optimized cost in scenario three with the other scenarios shows that if there is a way to get away with the disposal of materials for free (e.g., illegal landfilling), the net cost will be approximately 20% lower compared to the base case.

With respect to cost and values associated with the scenarios, in the base case, most of the cost is spent on recycling (Figure 3-6b). A similar breakdown of reuse and recycling costs is observed in scenario one. In scenario two, almost all the market costs are for recycling purposes because of the low obtainable value from salvaging materials, which makes reuse not an optimal option. The current reality of the industry in the economic region (Ontario) providing base case data is somewhere between scenario two and scenario three, where most components are either recycled, downcycled, or demolished. Results from the obtainable value in scenario one show that there is a great opportunity to obtain value from salvage and scrap materials. In Scenario 2, this obtainable value is much smaller (Figure 3-6c).

In the base case, around half of the components are recycled and half are reused whereas, in scenario one, around 75% of the components are reused (Figure 3-6d). This increase in the reuse of components is due to the high landfill fees in this scenario and the possibility to gain high terminal values from component reuse. In scenario two, all three EoL options are visible. However, demolished components make up only around 5% of the components. In the third scenario, most components are demolished due to the low cost of demolition resulting from the exclusion of landfill fees.

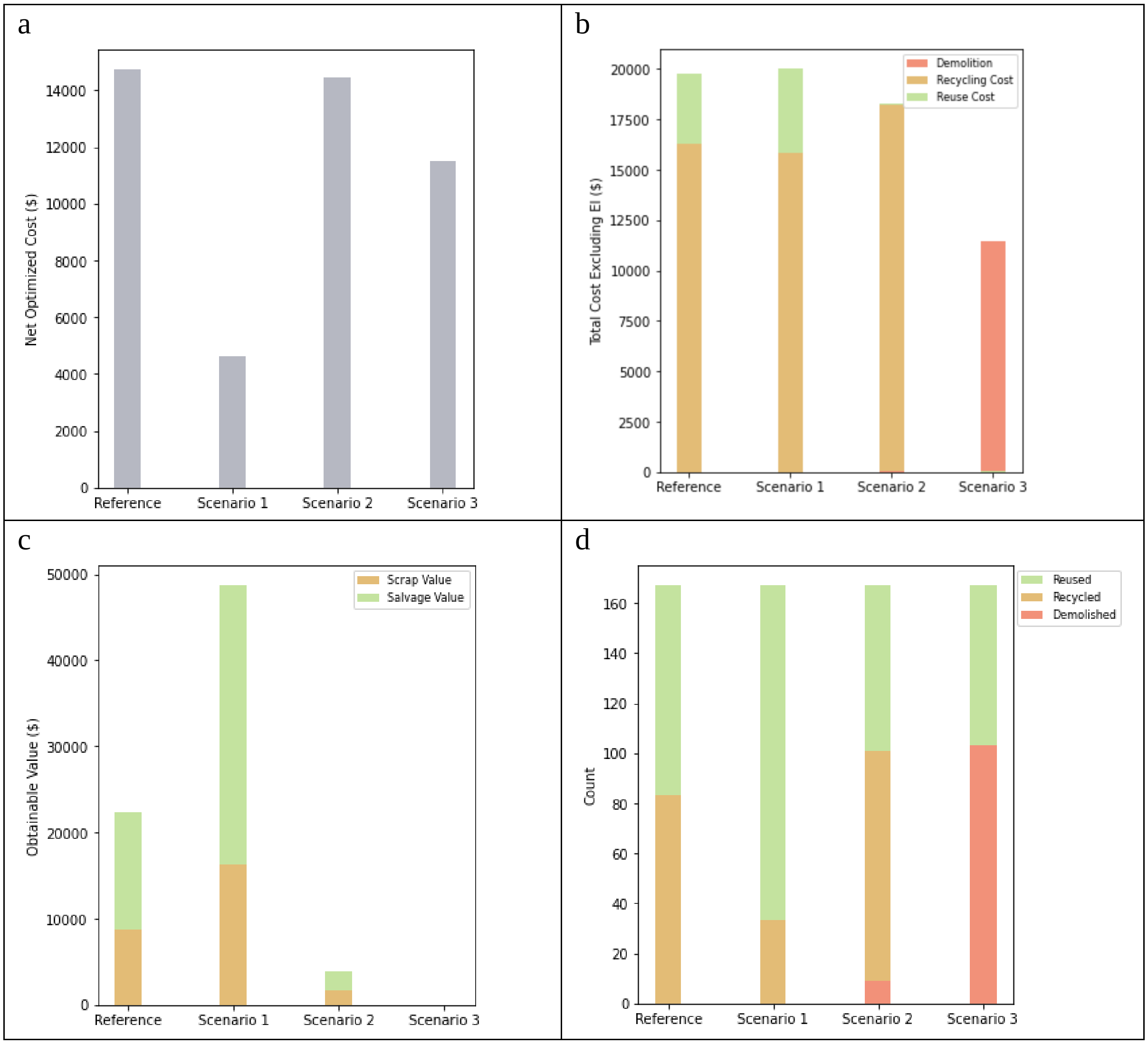

Figure 3-6: Future Scenario Analysis Results showing: a) Net Optimized Cost; b) Total Cost with Externalized EI; c) Obtainable Value; and d) Component EoL Breakdown

3.4 Discussion

An enormous amount of demolition waste ends up in landfills annually. This is mainly because of the lack of a suitable analytical approach, technical knowledge, and policy intervention. Various regional factors including costs of extraction, local labour costs, cost of environmental impacts, operation norms, municipal building waste management regulations, and landfilling logistics, impact the processes of building material recovery and need to be considered in order to reduce demolition waste production and increase construction material recovery. Such considerations can be aided by a tool that accounts for these factors and is resilient to the variabilities that occur at the city scale and differ between cities.

A robust and context resilient tool has been presented to support decision-making regarding EoL options for building components. The value of in-situ materials is treated as context-specific (e.g. labour, policies, and virgin materials availability). Situational context enters the tool through market values (e.g. wage rates and material prices). Changes in market values create price signals that inform owners to change their behavior (e.g. increasing virgin material costs signal owners to recycle or reuse more). Thus, the tool can be applied to any context for which market value information can be collected. The results of applying the decision support tool to the case study indicate that in current market conditions, reuse and recycling have a high potential return on investment if implemented correctly and systematically.

Due to significantly high landfill fees in the demolition and disposal approach, and the high EI costs, the net cost under time minimization is ultimately the highest. While landfill fees for some demolition projects may be lower than those used here, lower landfill fees are not expected in the future because most landfills are reaching their capacities and landfill space is increasingly limited. Some landfills also accept demolition waste for free and sort and recover the materials for secondary use. For those landfills, the obtainable value is shifted in the supply chain to the responsible individuals at the landfill. The end result is somewhat similar to the second alternative (demolition and preparation for recycling) assumed in this project for material extraction.

Typically, no EI costs are currently applied in demolition and deconstruction projects in the form of a carbon tax or other type of carbon pricing. Also, benefits gained from salvaged materials are subject to market demand for secondary materials and require additional labour to efficiently sell the extracted materials. Therefore, currently in practice, traditional demolition with some limited material sorting is still the favored option among industry practitioners for recycling due to the lower operation cost, lower landfill fees, and shorter project duration. Despite the differences highlighted here between current practice in the industry and the results of the optimization, the methodology can be valuable in representing future circumstances where EI costs are applied to projects, landfill fees have increased, and an established market exists for secondary materials - as expected in the future.

The developed decision support tool that is based on an optimization model can be valuable to both demolition companies and building owners. A demolition company can assess alternative EoL options to maximize their profit and recover building components that are financially viable for them. As a result of recognizing the value of salvaging materials, demolitions waste is reduced, component life service lives are expanded, and the environmental impact associated with building material landfilling is reduced. The higher quality of salvaged materials with a lower material extraction cost will lead to a more profitable project (Diven and Shaurette, 2011). An example of a success story is the deconstruction of a 1,933 SF single-family residential building that led to 44% of salvaged reused materials resulting in significant cost savings and avoidance of 9.93 tons of CO2 emissions in 2003 (EPA, 2010). Building owners can also benefit from the tool by familiarizing themselves with the value of their assets, which in this case is not only the land and building they own but also the materials embedded in their buildings, and ultimately reduce their demolition or deconstruction costs. Finally, by accounting for the environmental impact of different EoL scenarios and choosing more sustainable approaches, society will benefit from emission reductions and lower pressures on natural resources.

Assessment of the recovery potential of individual buildings will provide a feasible and practical solution in achieving material circularity. Material flow and stock analysis in cities and urban areas provides a holistic view of the overall circularity and identifies intervention points whereas, the developed tool prioritizes financial gains, which is the rational behavior seen among most owners in the built environment and provides optimal building component recovery options that are achievable within the identified constraints.

3.4.1 Comparative analysis with available tools and research

Two tools available in the construction industry are comparable with the decision support tool developed in this research. One is a commercially available decision support tool that is the "Residual Value Calculator" (TNO, 2019). The idea for this tool is to identify the financial value of residual building products. The calculator uses factors such as the price of raw materials, quality, detachability, the costs of transport, maintenance, and repairs to calculate the value of building products at any given time. However, its internal mechanisms are not explained. Moreover, it appears that TNO's tool does not fully consider the process and cost of material extraction, or in other words, the demolition or deconstruction aspect, as part of the recovery. On the other hand, the developed decision support tool in this study considers demolition and deconstruction feasibility through component precedence constraints in order to increase the accuracy of the results.

Additionally, Arup has developed a conceptual circular business model called “residual value”. The business model is focused on capturing the value of depreciated building materials through the profit that can be gained by selling the reclaimed materials. The residual value model can be used to identify opportunities to keep materials at their highest value in multiple lifecycles (Arup, 2020). The application of this circular business model on the case study showed that aside from the obvious environmental benefits, financial incentives exist for selling the salvaged materials and offsetting demolition and deconstruction costs. The residual value business model has not been applied to existing building stock to the knowledge of the authors; instead, it is intended to be used for future buildings. One reason is that a very small percentage of existing buildings have BIMs. This developed business model by Arup is a high-level circular business model idea aligned with construction industry practices whereas the presented decision support tool takes a more comprehensive and applicable quantitative approach to provide estimations of the residual value of building components. It can also help implement circular business models focused on material recovery such as Arup’s residual value circular business model.

3.4.2 Limitations

One of the main limitations of the of the proposed decision support tool is the limited incorporation of the state of the reusability of the building components. The quality of the components is related to various factors including structural capacity, environmental conditions, renovation and retrofit planning that are not modeled in this tool. Such data can be found in building conditional assessment reports**;** however, it is both challenging and out of the scope of this study to translate these reports into a quantitative estimation of the component reusability.

Another limitation that can substantially impact the applicability of the tool is related to the extensive data requirements. The user needs to collect various cost, duration, EI, and salvage value data to be able to make a better decision. Changes in these numbers can impact the results. However, even with limited data, a rough estimation can be provided, which can bring insight into possible EoL options that can increase the value of in-situ materials.

On the other hand, even with access to data, the true conditions on the site might be different from the assumed situations represented by the data and used for the optimization. Material qualities for secondary use, building component connections, and activity difficulties are some of the most important factors that can be different from what has been assumed in the methodology. Moreover, the value gained from salvage materials may not be completely obtainable due to low market demand for some salvaged materials. The methodology can be modified based on real conditions according to the user's experience and judgment. The sensitivity analysis also helps to analyze the effects of various uncertain conditions and changes.

An additional limitation that affects the optimization is that resources such as labour and machinery were unconstrained in this approach. It is assumed that all the activities that can take place at the same time will occur and there will be no limits on the available resources. However, in real projects, this will not always be the case. Resource limits can be added as a constraint to the optimization method to eliminate this limitation from the methodology. The resource constraints were excluded, since the goal of the current research is not to solve a scheduling problem, but to increase value recovered from in-situ materials while considering the project duration.

Finally, to address the objective of this research, the optimization problem is formulated using a linear programming optimization model, which can be considered a simple approach. Given the nature of the problem and the requirements of the constraints in this research, the linear programming approach provided the required complexity to generate the desired outputs for this problem. Other advanced optimization approaches can be explored in future research if the proposed optimization model becomes limiting.

3.5 Conclusions

This chapter focused on analyzing factors that impact the value of in-situ materials, developing a decision support tool, and testing the applicability of the tool. To achieve the research objectives, an optimization model was used to develop the tool and it was applied to a case study to identify the best EoL options for all building components included in the building model to achieve minimum project duration or minimum project net cost, which in the latter case results in high recovery of materials. The developed tool looks at the recovery potential of individual buildings from an owner's perspective. Results indicate that if the cost of EI and high landfill fees are applied, shifting towards deconstruction can significantly reduce the project net cost due to high potential salvage benefits. However, in this scenario, the project will take the longest to complete compared to the other options. Overall, the tool can suggest the best options and can bring insight into the possible EoL alternatives for each component, but the final decision is made by the responsible individuals in the project based on their priorities and conditions.

Additionally, through the scenario analysis in this research and visualization of the results, the main factors affecting the value of in-situ material were identified, which included component extraction operational cost, market value of secondary materials, municipal landfill fees, cost of EI, and component recovery potential. Understanding the impact of the factors can then lead to identifying required interventions, regulations, and policies shifting the industry towards more sustainable EoL options that enable the secondary use of materials. Policy makers can use tools such as the one presented in this research to test the efficacy of their developed policies and prioritize the ones that show preferred outputs such as higher carbon reductions and waste diversions. Implementing the required changes can drive the demolition industry to change its norms. Moreover, in the scenario where the cost of environmental impacts increases as a result of material scarcity and climate change, the use of the tool can prepare the demolition industry for such changes and suggest alternative solutions to offset these costs. Existing building stocks are future material mines that are currently poorly treated from a material recovery perspective. Understanding efficient ways of using these materials can help tackle possible future material shortages and decrease environmental impacts. The construction and demolition industry have largely maintained traditional approaches that have negative impacts on the environment. The use of tools similar to the one proposed in this research can help decision-makers in the industry better understand the financial opportunity of implementing circular strategies such as resource recovery.

The developed tool can be improved by expanding it to incorporate additional environmental indicators. Another interesting avenue for future search is to identify optimum thresholds in the optimization model such as a component mass threshold that switches the EoL option. The developed tool can also be improved with better incorporations of the quality and reusability of the building components based on the history of each specific building component and the conditions to which it had been exposed. The developed decision support optimization tool has the potential to be used as an indicator of the recovery potential of existing and new buildings. Understanding the impact of building recovery focused policies on building circularity, comparing the influence of regional factors on the in-situ material EoL alternatives, and evaluating the efficacy of new building technologies that enable future building recovery are three possible applications of the tool that are studied in the following chapters of this thesis.

Chapter 4: Assessing the impact of policy tools on building material recovery

This chapter corresponds to the following published article[2]:

> Mollaei, A., Bachmann, C., & Haas, C. (2023). Assessing the impact of policy tools on building material recovery. *Resources, Conservation and Recycling, 198, 107188.*

Abstract

Construction materials embedded in existing buildings have unrealized recovery potential. To help realize this potential, governments have implemented policies such as replacing demolition with deconstruction, banning landfilling, and carbon reduction to either force or incentivize resource recovery and circularity. However, the efficacy of these policies has yet to be fully investigated. A novel methodology that quantitatively estimates the potential relative efficacy of such policies is proposed here. At its center is an optimization-based tool recognizing demolition and deconstruction activity precedence relationships that yields the optimal component end-of-life options, extended to include policy levers. Variations of four policy categories were chosen and applied to five building case studies. The results suggest that policy tools can help enforce near-optimal waste reductions and carbon savings that do not necessarily increase net project costs compared to traditional approaches. The effectiveness of these policies varies based on waste and carbon savings measures and building types.

4.1 Introduction

The interest towards the application of resource recovery in the construction industry, as a lowest hanging fruit among the circular strategies applicable to the built environment is growing (Ghisellini et al., 2018;Huang et al., 2018; Pomponi & Moncaster, 2017). As part of implementing resource recovery and waste as resource, many global construction and waste reduction goals have been established such as the European Union's 50% recycling and reusing target for 2020, which was further expanded to 55% by 2035 and 65% by 2050 (Bertanza et al., 2021; European Commission, 2016). Following the

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[2] To maintain consistency with the thesis format, this chapter is slightly modified compared to the published article. The provided abstract is an exact copy of the published work.

overarching waste reduction targets established by high-level policymakers, municipalities and local governments have also recently started implementing policies that aim to accelerate the building material recovery process. However, there is a lack of historical evidence-based knowledge regarding the efficacy of these emerging policies, which can lead to slow and wasteful progress in transitioning from a linear to a circular economy in construction and the built environment. Additional impediments include: (1) the rather novel nature of CE principles to construction industry participants, and (2) the marginal return on investment achieved through the implementation of some circular strategies. Yet, collecting empirical data on policy outcomes could take decades and further stall progress in adopting much needed policy interventions (van Loon & van Wassenhove, 2020).

The goal of this chapter is to provide a methodological approach to quantitatively estimate the impact of construction waste diversion, carbon reduction, and building material recovery-focused policies on total waste reductions and carbon savings. In this study, the developed methodology is applied to policies and building archetypes based on North American precedents, norms, and regulations. The policies are formulated into the optimization based decision support tool that was developed in Chapter 3 for estimating the recoverable value of in-situ building materials. The results suggest that policies focusing on specific component recovery are less effective compared to the ones that assign generalized minimum material recovery limits, specifically for buildings that were not designed to be recovered at the end of their lifespan (which is most of the existing building stock). Additionally, depending on the distribution of the building types in a region, policies can be prioritized to achieve greater carbon and waste savings. It is worth noting that the policies, specifically those on carbon pricing, are subject to high uncertainty and change. Therefore, sensitivity analyses are required to obtain more useful assessments of potential efficacy of alternative policies. Although applied in the North American context, the methodology contributed by this study can be used in other regions where similar types of data are available, allowing policymakers to gain insight into the potential value and feasibility of their prospective policies and to help improve resource (building material) recovery and construction waste management processes in the industry.

The remainder of this chapter is structured as follows: An overview of some of the existing policies focused on resource recovery and building salvaging is provided in section 4.2. Relevant research on assessing the impact of those policies and the identified research gap is also summarized in the same section. The research methodology is presented in section 4.3. In section 4.4, the results of the application of the policy assessment methodology on five case studies is provided. Section 4.5 discusses the obtained results, the contribution of the research, and the research limitations. Conclusions and future research are summarized in section 4.5.

4.2 Literature Review

4.2.1 Current State of circular economy policy adoption in the construction Industry

Environmental-focused policies were originally oriented mostly around energy conservation and pollution reduction rather than material recovery (Chini & Bruening, 2005). Examples of regulations focused on building material recovery include limiting material landfilling through additional taxes and fees, and implementing award systems that promote deconstruction and material salvaging to reduce construction and demolition waste generation (Guy & Ciarimboli, 2008; Cruz Rios et al., 2015). In North America, policies are now gradually emerging that incentivize or mandate building material or component recovery. These policies may substantially impact the demolition industry.

For instance, the City of Victoria in British Columbia is in the process of drafting a bylaw that mandates buildings, especially heritage and older buildings, be deconstructed and salvaged instead of demolished (City of Victoria, 2021). Additional examples of deconstruction mandates are found in North America. The City of Vancouver has a mandate for a salvage audit for issuing demolition permits; in Portland, full deconstruction is required for houses built in 1916 or earlier; and in Seattle, deconstruction permits are fast-tracked over demolition permits (City of Vancouver, 2016; City of Portland, 2016; The Seattle Department of Construction & Inspections, 2021). Alternatively, several regions have assigned minimum material recovery mandates such as California and Seattle, where at least 50% of the total weight of the produced waste in a demolition project should be diverted from landfills in the form of reuse or recycling (Srour et al., 2012; Foster City, 2022; The Seattle Department of Construction & Inspections, 2021). Another type of policy that has been used in North American regions is regulations on recycling or reusing certain types of materials or components in a building. For example, in two regions, materials and components composed of asphalt, concrete, and brick cannot be landfilled and should be recovered (The Seattle Department of Construction & Inspections, 2021; Town of Chapel Hill, 2009). Alongside the above-mentioned policies that focus on the building material recovery process, carbon pricing and taxing carbon emissions are also strategies that are used to encourage low-carbon activities (Murray & Rivers, 2015). Currently, voluntary carbon credit markets are applicable to construction-related projects and can include demolition scopes as well. Additionally, there is potential for extending existing mandates on embodied carbon accounting to encompass the demolition phase, ensuring a comprehensive approach to carbon reduction throughout the building lifecycle. Although carbon pricing and taxing are economy-wide policies, the construction sector could also choose to participate. Assessment of the impact of enforcing carbon taxes in the construction industry indicates that by enforcing reasonable and optimal carbon taxes, the industry will better realize the value of the recovery process given the monetization of the environmental impacts through taxes (Cao et al., 2017; Guo et al., 2022; Liu et al., 2020).

In summary, most available policies in North America that affect construction resource recovery fall into four categories: (1) carbon pricing and taxing, (2) demolition waste reduction, (3) building component and material reuse mandates, and (4) deconstruction mandates.

4.2.2 Research gap

Considering the important role of policies and regulations in applying resource recovery strategies, there is an effort among scholars to assess the impact of political and regulatory factors on the implementation of resource recovery in the construction sector using both qualitative and quantitative research methodologies. Van den Berg et al. (2020) conducted interviews with experts in the construction field to investigate the role of policies on construction material recovery. McDowall et al. (2017) compared building recovery policies in China and Europe through an investigation of various policy documents, media articles, and journal publications. Research has also been conducted on the impact of enforced disposal fees policies on reducing construction and demolition waste production using statistical methods, generally concluding that immediate economic losses have high impacts on controlling waste generation (Li et al., 2020; Lu & Tam, 2013; Seror & Portnov, 2020; Véliz et al., 2022). Giorgi et al. (2022) examined the implementation of building material recovery focused policies in the European construction industry through semi-structured interviews with stakeholders. The results emphasize the necessity for improved coordination, policies, and actions by the European Commission, as the existing legislative framework prioritizes recycling over reuse and more effective resource management.

Traditionally, climate change policies have primarily emphasized energy efficiency as a key approach to reducing greenhouse gas emissions, neglecting materials efficiency. Moreover, among the existing policies on resource recovery, recycling has been prioritized, overlooking other potentially more effective strategies in material reuse (IRP, 2020). However, new policies are emerging globally targeting material efficiency strategies including mandating modular construction, mandating prefabrication, mandating demolition waste sorting, and mandating reuse. For instance, waste diversion mandates in demolition projects through deconstruction or setting recycling targets are observed (Delta Institute, 2018; Massachusetts Department of Environmental Protection, 2013; Ministry of the Environment - Government of Japan, 2010). Use of carbon trading policies in improving construction waste management has also been studied (Liu and Li, 2023). Recovery of construction waste offers great opportunities for carbon emission reduction that can be promoted through applying carbon prices and enabling carbon trading.

Material Flow and Stock Analysis, Life Cycle Assessment, and Life Cycle Cost Analysis are popular quantitative approaches used in construction waste management and policy assessment. Understanding the quantity and flow of material, waste, and the corresponding financial and environmental impacts brings insight into effective possible policy interventions (Augiseau & Barles, 2017; Ding & Xiao, 2014; Wu et al., 2014). Waste flows and environmental impacts are modeled under various policy scenarios, and the impacts are compared based on the collected data. (Dahlbo et al., 2015; Morris, 2017; Xu et al., 2020). Research has also investigated the positive and negative effects of policies on the process of recovering certain materials such as gravel, concrete, brick, and wood (Fořt & Černý, 2020; Zhang et al., 2020).

The literature generally indicates that implementing resource recovery as one of the Circular strategies requires highly supportive policies and regulations that accelerate the recovery process. Yet, the policies developed need to be assessed and tested both qualitatively and quantitatively to prioritize policy implementations and avoid ineffectual regulations (Yu et al., 2022). Currently, there is a lack of comprehensive systematic approaches to quantitatively understand the impact of various policies on resource recovery implementation in the construction industry. In the available literature, qualitative approaches, or limited material and environmental impact data, are used to understand the role of policy. The policies studied are mostly limited to landfilling fines/charges whereas, other categories of policies such as deconstruction permits and material disposal limitations are overlooked (IRP, 2020). The existing literature does not provide a comprehensive assessment of policies aimed at improving material efficiency, their financial feasibility, and contribution to mitigating environmental impacts.

While the impact of policies on waste recovery have been previously studied, a quantitative assessment of policies targeted at resource recovery on different building types has not been completed. This research addresses this gap by modeling the anticipated impacts of the resource recovery focused policies using the optimization-based decision support tool that represents a private building owner's profit-maximizing nature. The optimization determines the building component end-of-life options (disposal, recycling, and reuse) that minimize the net cost of deconstruction and demolition under different policy scenarios. The results help to effectively plan and implement new policies, and to adjust existing policies to better achieve their aims.

4.3 Methodology

An overview of the proposed methodology is presented in Figure 4-1. To assess CE-related policies, the proposed methodology builds on the application of the decision support optimization tool provided in Chapter 3. For this scope of the research, the developed tool is extended to include policy levers to determine their impacts on the optimal end-of-life options for a specific building's components. The policies, in this modeling approach, are implemented as additional constraints and coefficients, thus representing effectively the policy maker's intent of achieving the regional objective of minimizing environmental impact by changing the optimal decisions and thus behaviour of the owners. Seven variations of the policies (i.e. six policy scenarios in addition to one with no policy) are then each tested on five different building case studies with diverse building attributes resulting in 35 case studies in total that are analyzed to assess their comparative efficacies across this sample of building archetypes. Each building was defined as a BIM in Revit.

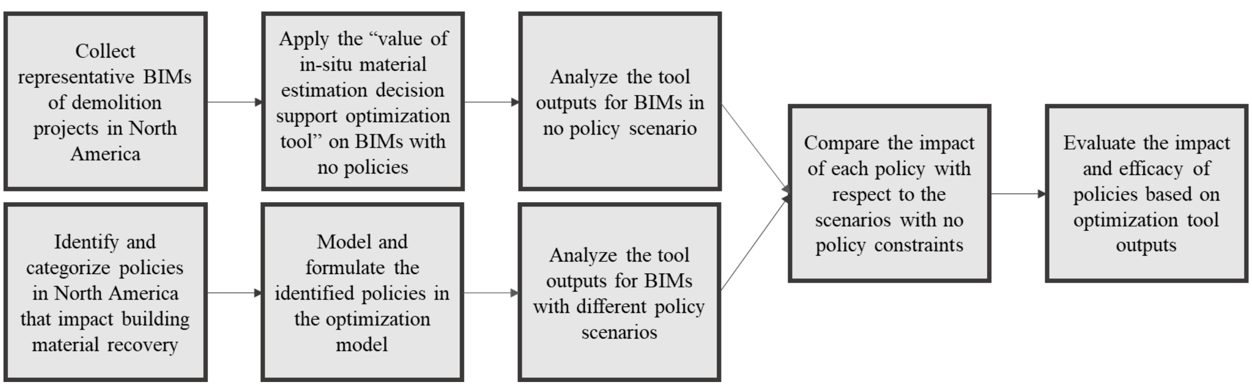


Figure 4-1: Overview of the Methodological Steps

4.3.1 Application of the Decision Support Optimization Tool

The value-of-in-situ-material estimation decision support tool is used to understand the value of building materials and the recovery potential of buildings at EoL in different policy scenarios. The tool breaks down buildings into their components and optimizes the components' EoL based on the material available for recovery, the technical feasibility of component extraction, the economic viability of the recovery process, and the environmental impact associated with the recovery process, which can include the total Global Warming Potential (GWP) and avoided waste. As described in Chapter 3, the possible EoL alternatives in this tool are assumed to be: 1) demolition and *disposal* in landfills; 2) demolition, sorting, and preparation for *recycling*; and 3) controlled deconstruction and component *reuse*. The latter two options will result in scrap and salvage values, respectively, which can offset initial component extraction costs.

For the purpose of this research, the following outputs are retrieved from the tool:

- The total building recovery rate (%);
- project net cost ($);
- total avoided carbon (tonnes CO2e);
- total avoided waste (tonnes material); and
- potential obtainable terminal values ($)

The recovery rate is estimated based on the total mass of components that are recycled or reused compared to the total mass of the building components. The avoided carbon is estimated based on the total carbon saved as a result of recycling and reuse. This value is estimated based on the carbon emissions avoided because of diverting materials from landfills and avoiding production and manufacturing emissions by enabling a second life cycle for the component while accounting for the emissions corresponding to the recovery process. The details of the carbon accounting method are provided in Appendix A. The avoided waste is calculated based on the quantity of materials that would have been disposed of in a landfill in a traditional demolition project but were instead recovered as a result of recycling or reuse. The total terminal values are estimated based on the total remaining end-of-life values obtained from the reselling of the scrap and salvaged materials for the components that were extracted from the building to be sold as secondary materials and were not disposed of in a landfill.

For each case study, according to the data requirements of the decision support tool, the cost and duration data corresponding to the demolition and deconstruction of building components were collected from a widely used North American costing reference source in 2020 USD (RSMeans, 2020). Terminal values, including the salvage value in case a component is sold for reuse, and the scrap value of materials used for recycling were also collected from data available on secondary (or informal) marketplaces on the web (Demolition Traders, 2021; Recycler's Exchange, 2021;Repurposed Materials, 2021; Salvage Garden, 2021). Representative data on salvage prices are difficult to obtain, since formal markets do not normally exist for such materials. Additionally, depending on the quality and condition of the materials, the selling price changes. To account for the uncertainty associated with these values, for each material various sources are explored, and average values are used to better represent the terminal values. Additionally, with the availability of adequate data points, a probability distribution can be assigned to the terminal values to increase the accuracy of the results. However, in this study due to the scarcity of material value data, incorporating a distribution and addressing data uncertainty in this manner would not enhance the precision of results required for the policy assessment noticeably. Since the value of secondary materials data are collected from diverse and unofficial marketplaces, access to a large amount of data is challenging.

4.3.2 Identification and Formulation of the Policies

In this research, the studied policies fall into the four categories identified earlier and included in Table 4-1. They enter the tool in the form of new optimization constraints or additional coefficients in the objective function. A summary of these policies alongside a description of how the policy is implemented in the tool is provided in Table 4-1. The policies in North America targeting reduced construction waste and carbon emissions in the construction industry are identified and categorized for investigation based on the literature review provided in section 4.2.1.

Table 4-1: Summary of the Policies used in the Analysis

Policy	Implementation in Model
1) Carbon Reduction	1a) Internalizing carbon prices in the model as part of the project cost 1b) Limiting total equivalent carbon emissions to 50% of traditional demolitions and disposal approaches
2) Demolition Waste Reduction	2) No landfilling permitted
3) Reuse Mandates	3a) Mandatory reuse option for doors, windows, and other components composed of wood, steel, and plastic 3b) Mandatory reuse for 50% of the building mass
4) Deconstruction Mandates	4) Mandatory deconstruction for at least 80% of building components

The first category of policies is focused on carbon reduction, either by applying a carbon tax or imposing a limit on carbon emissions. The carbon tax policy is formulated by internalizing the Environmental Impact cost ($EI_{i,E}$) associated with each component (i) in the corresponding extraction method (E) in the cost minimization objective function, as shown in Equation 3-3. The cost of carbon is assumed to be \$51 per tonne of CO2e based on US federal estimates (Rennert et al, 2022). Carbon prices are projected to increase differently based on various scenarios. However, since the tool is taking current cost and values for all other inputs, in order to maintain consistency, the carbon prices are also considered to be based on current values. In this new objective function formulation, EI assessment is limited to carbon and waste estimations. As outlined in Chapter 3, the carbon accounting includes a comparative embodied carbon assessment corresponding to the production and the EoL phase, for each building component in each EoL scenario.

The carbon assessment is completed using the "One Click LCA" software and the localized EPDs available in the databases (Bionova, 2018). Various methodologies, including the cut-off method, end-of-life method, and distributed allocation as discussed by De Wolfe et al. (2020), can be used for emissions accounting. In this study, the distributed allocation method is selected, assuming two applicable life cycles for each element. The two lifecycles include the current lifecycle and an additional one after the recovery. This assumption is a conservative assumption for the distributed allocation method. This method is chosen since it can be used to incentivize building owners to opt for less carbon-intensive end-of-life approaches as well as to encourage subsequent users to utilize recovered materials, whereas in methods such at the cut-off or end-of-life method either the first or second user of the building component will take credit for the avoided environmental impact. The focus of this environmental impact analysis is specifically on assessing the global warming potential in units of tonnes CO2e that is used to estimate the total avoided carbon. This metric measures the amount of carbon emissions saved through recycling and reusing specific building components compared to an all-demolition approach with materials being sent to landfills.

To assess the environmental impact of each EoL scenario (i.e. demolition and disposal, sorting and recycling, and deconstruction and reuse) only production and end-of-life carbon emissions are considered, while operational emissions are excluded due to the comparative nature of the avoided carbon metric. The LCA model within the software incorporated end-of-life operations, such as the machinery required for demolition, recycling, or downcycling processes, depending on the EoL option. This data is added to the LCA scope based on the machine hours needed for each process. The utilized method accounts for the emissions avoided as part of the alternative EoL process and avoided raw material production for the second life cycle (if recycling and reuse are chosen) as well as the emissions corresponding to the process that goes into the material recovery. The recovery processes, especially recycling, can sometimes become carbon intensive and lead to high carbon emissions, at times more than the virgin material production (Castro et al., 2022; Turner et al., 2015). Recycling and other recovery strategies might have rebound effects that can negatively impact environmental impacts. Therefore, it is important to include the recovery process impacts in the scope.

No sensitivity analysis is included in the avoided carbon estimation for this study. However, it is worth noting that assuming two lifecycles for the recovered material is considered a conservative approach. If more than two lifecycles were assumed, the estimated avoided carbon would likely increase. Moreover, to account for the uncertainty in the input data, it would be beneficial to consider a probability distribution format. This approach would provide a range of potential avoided carbon values rather than a single absolute value, thereby enhancing the accuracy and reliability of the results. While well worth doing, it is beyond the scope of this research.

For the carbon limitation policy, the total EI is forced to be less than half of the traditional demolition carbon emissions. Equation 4-1 shows how this policy was formulated as a constraint in the optimization tool.

$$\sum_{i=1}^{n}\sum_{E=1}^{3} X_{i,E} \times EI_{i,E} < 0.5 \times \left(\sum_{i=1}^{n} EI_{i,1}\right) \qquad \text{(Equation 4-1)}$$

Policy 1a entails conducting a carbon assessment of the building's end of life process, which is inherently similar to the standard embodied carbon assessment that is sometimes mandated for new construction projects. The carbon assessment for each building component should include the embodied carbon scope alongside the end-of-life and recovery process (as described in the methodology above). By this means, both the owner of the building and the user of the component in the next lifecycle will get credited for the recovery by accounting for the carbon that is avoided in the process. Based on the current formulation of the policy, a minimum 50% carbon reduction will be achieved. However, the model determines the optimal EoL options to reach this reduction target, and whether it is actually feasible from a cost perspective.

The second category of policies focuses on waste reduction. In this category of policies, landfilling is restricted, and all building components should either be reused or recycled. This does not necessarily mean that no waste is produced because certain building components or a fraction of a building component might not have sufficient quality to be recovered. Therefore, inevitably some demolition waste will be produced. The policy dictates that all building components need to be extracted and sorted on site and prepared for recovery as opposed to using a quick demolition approach that results in dumping mixed waste in landfills. This policy is formulated by adding a constraint that eliminates the intentional disposal option from the tool as shown in Equation 4-2.

$$\sum_{i=1}^{n} X_{i,1} = 0 \qquad \text{(Equation 4-2)}$$

The third category includes reuse policies. These policies normally mandate reuse for certain materials and components or impose restrictions to reuse a certain mass of the building, regardless of the material and component type. The constraint formulation for the material components is formulated in Equation 4-3, such that all components that fall under those specific material types must be reused, where P is a set of components that are composed of wood, steel, or plastic, or belong to the window or door categories.

$$\forall\ i \in P:\quad X_{i,3} = 1 \qquad \text{(Equation 4-3)}$$

For the minimum reuse by total mass policy, a constraint is formulated to ensure the total mass of the reused components exceeds 50 percent of the total building mass (Equation 4-4).

$$\sum_{i=1}^{n} X_{i,3} \times M_i > 0.5 \times \sum_{i=1}^{n} M_i \qquad \text{(Equation 4-4)}$$

The final category of policies mandate deconstruction in buildings for material reuse. To represent this type of policy, a constraint as formulated in Equation 4-5 is added to the tool, which ensures at least 80 percent of the building components are reused. An 80 percent threshold was used since certain components in the building such as foundation walls and some cast-in-place concrete components are not currently deconstructable, therefore, a full deconstruction for reuse is not feasible for all building components.

$$\sum_{i=1}^{n} X_{i,3} > 0.8 \times n \qquad \text{(Equation 4-5)}$$

Policies 3 and 4 are both related to deconstruction and subsequently, reuse. They have been differently categorized and uniquely formulated because of their real-world differences and how they can be interpreted. Policy 3a specifically demonstrates a scenario where the policy is focused on certain material reuse. Policy 3b represents a scenario where mandates are in place for reuse by mass. On the other hand, policy 4 shows a mandate only on deconstruction without a clear accounting of what should be deconstructed. Overall, policy 3b can be interpreted as the mass variation of Policy 4. However, they are intentionally modeled in such a way to understand whether the different interpretations of the policies impact their efficacy.

4.3.3 Building Archetypes to Assess the Efficacy of the Policies

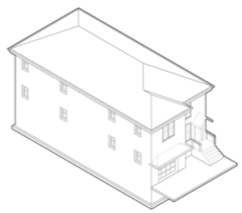
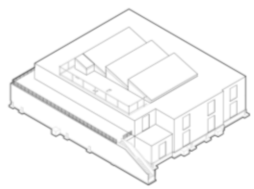
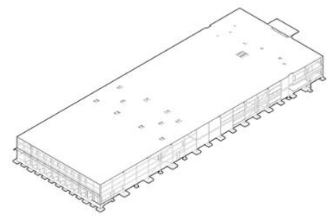
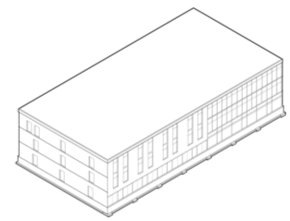
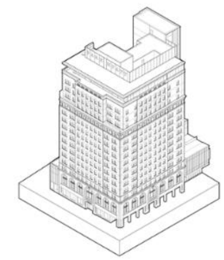
To explore the efficacy of the previously defined policies relative to different types of buildings, a set of building archetypes are used. Their selection strikes a balance between representing important sectors of the industry in terms of current stock and representing important sectors of the industry in terms of potential future building recovery, such as design-for disassembly. Their scope is limited to commercial and residential construction sector buildings in North America. This is reasonable for the purpose of validating the methodology presented (the main contribution of this chapter) and analyzing policy effectiveness for the building types in the set, yet it imposes limitations in terms of the extent to which broad conclusions, rather than narrower observations, can be drawn based on the results of the analysis presented. Such results will vary as parameter values vary and policy versions emerge, which they do continuously. Establishing and using optimal representative building sets for current building stocks within construction sectors (such as single-unit residential, multi-unit residential, industrial, commercial, and infrastructure) and global regions could extend the breadth of conclusions that might be drawn based on the methodology presented in this chapter. An approach could be used such as that used by the US BLS and Statistics Canada for establishing sets of "building models" as price deflators for tracking producer price indexes and productivity changes in sectors of the construction industry (BLS, 2016; Statistics Canada, 2022). These BLS and StatsCan building models, which took many years to develop, cannot be used directly in the methodology presented here, because they are not represented as BIMs but as separate assemblies and tables of scopes of work, thus they do not include design or precedence information. Many person-years of work would be required to produce hypothetical BIMs based on the BLS and StatsCan building models. This is a large effort beyond the scope of the authors' current resources. It could be fruitful future research, however.

Thus, in this study, five buildings with different characteristics and their Building Information Models (BIM) were selected to be used as inputs. For each BIM, the required data were collected based on the tool's data requirements. BIM-1 is a single-family detached home in North America with wood framing, and a mix of brick cladding and vinyl siding. Single family homes make up approximately 90% of buildings and a large portion of the construction volume in the USA (United States Census Bureau, 2019). Single family homes are found in suburban areas as main residential dwellings. BIM-2 is a low-rise office building composed mainly of reinforced-concrete and therefore not easily compatible with deconstruction and recovery, making it financially and technically difficult to recover. Low-rise office buildings with similar structures are usually found in small to mid-size cities where high-rise construction is not common. BIM-3 is a steel-structure building that contains large amounts of steel; it is a warehouse. Similar "big-box" industrial buildings are seen in industrial zones globally. It was chosen, because its steel content is theoretically highly recyclable or reusable and contains a high amount of embodied carbon. Steel buildings are valuable secondary sources of materials for future use (Yeung et al., 2017). BIM-4 is a newly constructed building incorporating Design for Disassembly (DfD) strategies. This building is of heavy timber construction, and most connections are dismantlable making the building a great source of materials, since the materials are largely extractable. Some new low to mid-rise developments are using similar circular construction techniques, such as the T3 Bayside complex in Toronto (Delphi Group, 2021). BIM-4 is used to understand what the impact of alternative policies would be on such buildings in the future and how implementing DfD strategies can affect future policy developments. BIM-5 is high-rise building that was retrofitted. High-rise retrofit projects are increasing rapidly, especially with recent urban core depopulation. They normally have a scope focused on selective demolition, renovation, and adaptation. An example of such retrofit projects is the Park Hyatt hotel in downtown Toronto (The Globe and Mail, 2019). A lot of building components in these buildings are extracted that can be reused.

A summary of the BIM specifications is presented in Table 4-2. The BIMs were sourced from two Canadian Engineering firms (Blackwell, n.d.; KPMB, n.d.). All models were collected in a Revit format and were reviewed prior to testing. For this analysis, the building components in the BIMs were classified into doors, windows, ceilings, interior walls, exterior walls, floors, framings, roof, foundation walls, and footings. For components that are composed of multiple materials, such as exterior walls, the component is broken down to its materials where each is treated as a separate component in the model with a unique material. The utilized BIMs for this research all had a Level of Development (LOD) of 300. The LOD of the BIMs were similar since they were collected from two companies that follow similar standards and were made by highly skilled professionals. BIM LOD is a widely accepted industry standard that establishes the level of detail and accuracy to which the 3D geometry, materials, behavior and connections of a building model is developed. It serves as a benchmark for determining the level of service or refinement needed for the model. The LOD 300 of the BIMs, ensures accurate modeling of geometry and context. In the collected BIMs, the assemblies were appropriately linked to envelope systems, and component connections were accurately represented. Notably, not all models included specifics about the connection and interrelation of structural systems. However, this omission did not pose a problem as these inputs were not factored into the model. The main input factors were the component's type, material, quantity, and the presence of a connection, all of which were effectively captured within the BIMs.

For each model, the cost of traditional demolition associated was estimated based on available traditional demolition cost data to represent the business-as-usual scenario (RSMeans, 2020). The optimization tool was initially applied to the BIMs without considering any policy constraints to establish a baseline optimal scenario where project cost is minimized.

Table 4-2: Representative BIM Models used to Assess the Policy Impacts

Model	BIM1	BIM2	BIM3	BIM4	BIM5
Isometric image of 3D Model					
Stories	2	2	2	3	17
Service Life (years)	75	65	60	65	85
Area (m^2)	210	2400	12300	4400	38000
Frame	Timber	Timber, Concrete, Steel	Steel	Timber	Concrete

The results are compared for the five representative BIMs with the application of each of the policy scenarios individually. Therefore, in addition to the five no-policy cases, 30 additional simulations were completed (i.e., six policy scenarios for each of the five BIMs). Both the overall impact of the policies and their impact specific to each building archetype are considered in this analysis. The details of the data used for the assessments are provided in Appendix C.

4.4 Results

4.4.1 Building Type Material Recovery

The results of the application of the optimization tool on the five BIMs are presented in Table 4-3 for: (1) the traditional complete demolition process (referred to as the base case), and (2) the optimized project net cost scenario, where no policies were added to the optimization tool. The first row of Table 4-3 shows the cost assuming complete demolition and disposal as a traditional approach – in other words, the decision maker does not minimize their costs by choosing the optimal EoL alternative for each component. This can be rational behaviour from a broader business perspective, if time constraints are prioritized in the project. It is often the default behaviour. This base case represents a scenario where the building is demolished in a conventional manner and materials are hauled to a landfill. The total cost includes demolition operation costs, transportation costs, and landfill fees for material dumping. The outputs of the scenario reflect the results of the decision made by the building owner and do not take into account the process of waste handling after disposal in the landfill. Many waste management facilities have processes in place to recover dumped waste through different strategies, which is one of the determining factors of the landfill fees associated with different materials. Thus, following a traditional demolition approach does not necessarily indicate that no material is recovered; however, the owner is not obtaining all potential recovery value, because the landfill operator is not passing on all of their profit and their process may be more energy intensive compared to on-site sorting.

The results corresponding to the application of the optimization tool on the BIMs in a no-policy scenario represent a combination of optimal EoL solutions that lead to the minimum net costs for the owner in the absence of project duration limitations. This is achieved by avoiding some landfill fees and gaining resell value from salvage and scrap materials. Table 4-3 shows total project cost breakdowns, obtainable value, avoided waste, and avoided carbon corresponding to each BIM in the optimization with no-policy scenario. The EoL options include a combination of disposal, recycling, and reuse. This scenario reflects the waste and carbon that can be saved in the absence of any policies, assuming logical behaviour for a fully informed owner and marginal cost for the optimization process. It is also used as a benchmark to compare the relative impact of adding policy tools on building recovery and EoL strategies with cost minimization objectives.

Additionally, project durations corresponding to the traditional demolition base case and the optimized net cost with no policy scenarios are provided in Table 4-3. The project durations are higher in the cost optimized scenario compared to the traditional demolition base case. This is due to labour and time intensive deconstruction required to reuse and salvage certain building components. When project durations constraints exist, the implementation of the optimized cost scenario and proper building material recovery may not be feasible.

To apply this methodology to policy planning in practice, analyses will likely have to be conducted for each jurisdiction (or region) with its particular built assets stocks distribution (buildings, industrial facilities, bridges, etc.), disposal fees, labour costs, demolition costs, construction technology ecosystem, and business climate. Much of these factors fluctuate over time, so each analysis will require extensive sensitivity and future scenario analysis as well. The analysis presented in this study serves mostly to validate the methodology and to shed light on some trade-offs and potential for further research.

Table 4-3: Outputs for Complete Traditional Demolition and Optimized Net Cost of Demolition and Deconstruction with No-policy

BIM Type	BIM-1: House	BIM-2: Low-rise Office	BIM-3: Warehouse	BIM-4: Modern Office	BIM-5: High-Rise Renovation
Total Traditional Demolition Cost (Base Case)	**$23,500**	**$104,000**	**$195,600**	**$244,200**	**$132,900**
Demolition Process Cost Landfill Fee Transportation Cost	$13,330 $6,840 $3,330	$49,880 $12,520 $41,600	$65,170 $56,500 $73,930	$119,660 $75,700 $48,840	$35,500 $72,200 $25,200
Traditional Demolition Project Duration (days)	8	18	57	42	45
Total Optimized Net Cost with no-policy	**$(800)**	**$(51,300)**	**$(130,300)**	**$(18,700)**	**$(272,800)**
Extraction Cost	$64,500	$141,800	$237,700	$289,700	$215,600
Demolition and Deconstruction Process Cost Landfill Fee Sorting Cost Transportation Cost	$57,500 $1,300 $3,300 $2,400	$ 94,900 $33,300 $3,400 $10,200	$146,800 $2,300 $24,100 $64,500	$159,800.00 - $91,600.00 $38,300.00	$107,400 $69,200 $14,500 $24,500
Terminal Value	$65,300	$193,100	$368,000	$308,400	$488,400
Avoided Waste Avoided EI	284 t or 66% 48 t or 41%	495 t or 31% 307 t or 31%	4933 t or 74% 1877 t or 41%	1586 t or 78% 350 t or 43%	1740 t or 35% 110 t or 5%
Optimized Net Cost with no-policy Project Duration (days)	14	25	79	68	57

For the cost optimized with no-policy scenario, Figure 4-2 shows the recovered materials for each BIM in the form of the percentage of recycling and reuse based on both the weight of materials and the number of components. Both perspectives are important. Focusing on recovering certain components such as windows and doors that are large in component number but make up a small fraction of the building mass may lead to marginal net benefits. For example, for BIM1 and BIM5, many components are reused; however, they make up a small percentage of the building mass. In the case of BIM1, the results show that 80% of the components are reused; however, these components make up only 34% of the building weight. Hence, less waste and carbon will be avoided compared to other building types since recycling processes still produce waste and emit carbon (Wang et al., 2022). If the materials that are being recycled could instead be reused, more waste and carbon savings would be achieved. The results of "cost optimized base case" serves as a benchmark for evaluating the impact of policies in the optimization model. The results of the scenario may not always represent a common practice scenario considering that traditional demolition approaches are still more favorable. However, this can be theoretically justified with the assumption of a rational (cost-minimizing) building owner. Additionally, in building waste management, there is no universally acceptable base case that can fully represent the ground truth since the base case is context and region specific.

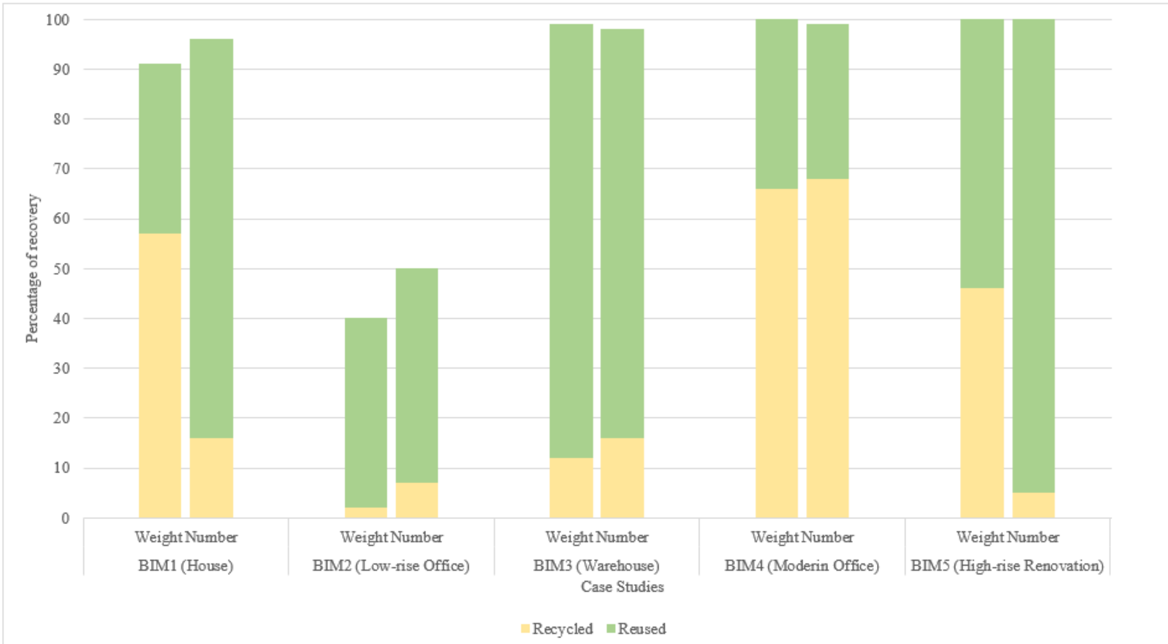


Figure 4-2: Building Component Recovery Percentage based on Component Weight and number for BIMs in the Optimized Net Cost with No-policy Scenario

The results indicate that steel-based buildings (represented by BIM3) have a high recovery rate potential, especially in the form of reuse (as shown in Figure 4-2). Deconstruction and recovery of steel both in the form of reuse and recycling are common in the construction industry (Yeung et al., 2017). Additionally, the infrastructure and technology required for steel recovery are accessible, making steel buildings a valuable source of secondary materials.

Small houses (BIM1) that make up a large part of annual demolition projects also have a relatively high potential recovery rate. These buildings contain approximately 40% wood, which is highly salvageable. Although the cost of deconstruction ($64,500) is around 3 times the demolition cost for these buildings ($23,500), there will be a high return on investment from reselling the salvaged materials ($65,300 in salvage benefits). The secondary market for reclaimed wood is much more established compared to other materials, leading to less uncertainty in terms of the obtainable value (Džubur & Laner, 2018). Some demolition companies have shifted towards deconstruction with the purpose of salvaging reclaimed wood from existing buildings (Unbuilders, 2022). There is an increasing demand for reclaimed wood, mostly for aesthetic purposes (Brol et al., 2015). In the current market, the demand is primarily for wood components obtained from older buildings. This is also because these components constitute a great portion of the current supply available in the marketplaces.

In the case of BIM4 the design for disassembly strategies used in their design and construction can reduce deconstruction costs when the building has reached its end of life (O'Grady et al., 2021). The extracted materials and components also have a higher quality leading to higher salvage values. Therefore, a high potential recovery rate is observed in these building types. Designing and constructing buildings with DfD principles is not common practice in the industry; so, it will be a while before such buildings reach their EoL. However, it is worthwhile to see how the recovery rate of the building increases compared to traditional buildings if such considerations are applied.

On the contrary, concrete frame buildings (BIM2) currently have a low potential recovery rate. It is difficult and expensive to recover in-situ concrete. The obtainable value is quite low since there is not enough demand for secondary concrete. In the current economy, concrete is at most crushed and recycled into aggregates that can be used for new concrete production (Nedeljković ei al., 2021; Tam, 2008). Limited reuse of concrete blocks is possible (Küpfer et al., 2023a); however, it is neither common practice nor currently typically financially viable. This may change.

For renovated buildings (BIM5), components such as doors and windows can be reused, which can help offset project costs. These buildings are suitable for recovery and diverting waste from landfills, since there is already selective demolition and deconstruction involved to avoid the destruction of other building components that are not required to be removed in the renovation/adaptation project.

4.4.2 Policy Analysis

The identified policies in Table 4-1 were formulated as constraints (Equations 4-1 to 4-5) in the optimization tool and applied to the representative BIM models to observe their impact in terms of avoiding waste and carbon, in comparison to full demolition and disposal in landfill. The results of the avoided waste and carbon saving percentages with respect to the base case of complete demolition and landfilling where no optimization was utilized, are presented in Table 4-4. The values show additional waste and carbon saving percentages compared to the traditional demolition base case. The table includes results for the optimized net cost with no-policy scenario alongside the six policy scenarios for the case studies.

The results indicate that BIM1 and BIM4 show more sensitivity to policies in carbon savings (particularly policy 1b). BIM2 shows a high variation of avoided waste (33 – 73%) when the various policies are applied. On the other hand, BIM4 and BIM3 show limited to no change in waste reduction when various policies are applied. In the case of BIM3, the existing financial incentive for selling reusable and scrap steel already yields the highest potential recovery; therefore, applying the four categories of policies studied in this research do not lead to much change in waste and carbon savings compared to the optimized net cost with no-policy. However, the policy scenarios are enforceable. A similar pattern of results is observed for BIM4, where the modern design also enables recovery without the policies being required to push for higher carbon and waste savings. In the cost-optimized scenario without policies, BIM4 demonstrates a notable 77% waste reduction due to its design focused on recoverable materials, reversible connections, and general compatibility with DfD principles. Therefore, when policies are introduced, there is minimal alteration in waste reduction. This is because the building's layout and component types make any additional recovery financially burdensome (as shown in Table 4-4 in the financial multiplier section), with very marginal environmental impact changes. BIM3 also follows a similar logic given the avoided waste changes by one to two percent while the cost of achieving the extra impact and satisfying the policy constraint is substantial. BIM5 has the lowest carbon savings in all policy scenarios. Since this BIM represents a selective demolition project, there are limits in recovery; going beyond those limits is not possible due to the building component precedents and limits in materials available for recovery.

Application of policy 1b, which is the carbon reduction mandate, has the highest carbon saving. However, the application of this mandate results in high deconstruction costs that may be financially unfavourable to the owners and demolition firms. Other policies can lead to more financially feasible options with slightly less savings while adequately achieving the carbon reduction goals. Policy 3a has the least impact compared to the no policy scenario. Policy 3a is a common policy where reuse is only mandatory or recommended for certain materials. While there are high financial gains in reusing those certain materials, the overall environmental impact is not significant.

Furthermore, it is important to consider that the use of reused components, such as windows, in new buildings may potentially result in higher operational carbon emissions. This is primarily due to the potential challenges that may arise regarding the performance and efficiency of these components. Policy 2 yields the highest waste savings but not necessarily the highest carbon saving. Therefore, based on the identified goals and targets of achieving carbon reduction or waste reduction, policies should be prioritized accordingly. Mandating deconstruction (Policy 4) does not show much improvement compared to the no-policy scenario. Demolition projects do occasionally have a limited deconstruction scope for certain components that have high salvage values. This deconstruction aspect normally satisfies the deconstruction mandate constraint, and the policy will not lead to additional carbon or waste savings beyond what is being implemented in common practice.

Aside from assessing the impact of the policies on carbon and waste reduction, a financial multiplier was estimated to show the expected financial impacts per dollar invested. This multiplier shows the dollar value gained from selling the scrap and salvaged building materials for every additional dollar paid compared to traditional demolition. Hence, larger multipliers show greater financial gains from the implementation of the policy. Table 4-4 summarizes the multipliers for the BIMs in different scenarios. The no-policy scenario has the highest multiplier in each BIM because the net cost can be minimized subject to no additional policy constraints. Hence, each EoL choice is optimal, whereas the policy constraints force EoL options that are less optimal from a cost minimizing (profit maximizing) perspective. The policy constraints will force the EoL decisions to reuse and recycling options that are expensive to extract but do not ultimately yield a high obtainable value that can cover the extra cost.

The optimized net cost with no policy scenario has the highest financial multiplier since it represents the least constrained environment for the owner to minimize their own financial costs. Each policy scenario will incur some additional cost greater than or equal to 0 since the policy is forcing the owner to optimize in a more constrained space. Therefore, the net cost of the policy scenarios is always higher than that of the optimized cost no policy scenario. The details of the net cost and obtainable value associated with each BIM in the different policy scenarios are provided in Appendix C.

The policy scenarios are all less economically efficient since adding additional constraints moves the results from the optimal net cost. In these scenarios, despite the higher net costs, more carbon and waste savings and a better resource recovery is achieved. Therefore, the results suggest that benefits in terms of carbon savings and avoided waste can be obtained. However, these benefits do not currently enter the financial calculus of the building owner. Additionally, while from a cost perspective, the policy scenarios are not better than the optimized net cost base case with no policy because of the additional constraints, they are better than the current practice. The policies can be impactful since the optimized net cost scenario is not yet common practice due to the trouble and challenges in deconstruction and reuse. Policies, on the other hand, are enforced.

Among the policy scenarios, policy 2 has the second largest multiplier for BIM 1, 3 and 4 and is resulting in one of the lowest multipliers for BIM 2 and 3. The substantial change in the multiplier in different BIMs for the same policy scenario highlights the importance of designing policies based on the features of different building archetypes. For instance, for buildings that are designed for disassembly (DfD) guidelines (e.g. BIM3 and 4), deconstruction policies work better as opposed to more traditional buildings (BIM2 and 5) where carbon tax policies (policy 1a) can be prioritized. This is mainly due to the high potential salvage value that can be gained through the implementation of those policies. Application of policy 1b shows a multiplier less than 1 for BIM1, BIM4, and BIM5 indicating that implementation of this policy leads to financial losses; however, if the saved carbon could be monetized (e.g., selling carbon offsets), this number could change substantially.

Table 4-4: Comparison of the Avoided Waste, Carbon Saving, and Financial Multiplier from Applying the Policies on the BIMs

Policy Scenario	Avoided Waste					Carbon Saving					Financial multiplier				
	BIM 1	BIM 2	BIM 3	BIM 4	BIM 5	BIM 1	BIM 2	BIM 3	BIM 4	BIM 5	BIM 1	BIM 2	BIM 3	BIM 4	BIM 5
Optimized Net Cost with No Policy	66%	31%	74%	77%	35%	41%	31%	41%	43%	5%	1.60	5.11	8.74	6.78	5.91
Policy 1a (Carbon pricing)	69%	38%	74%	77%	35%	41%	39%	41%	43%	5%	1.58	3.43	8.70	6.76	5.85
Policy 1b (Carbon emission limits)	72%	72%	75%	77%	54%	50%	50%	50%	50%	50%	0.84	1.51	2.95	0.81	0.44
Policy 2 (Demolition waste reduction)	72%	73%	75%	77%	54%	43%	43%	41%	43%	33%	1.58	0.18	8.26	6.78	0.59
Policy 3a (Reuse mandate by component)	66%	33%	73%	77%	35%	41%	40%	44%	48%	5%	1.43	2.26	3.20	1.38	5.80
Policy 3b (Reuse mandate by weight)	70%	40%	74%	77%	37%	46%	39%	41%	45%	12%	1.30	3.32	7.06	4.04	0.72
Policy 4 (Deconstruction Mandate)	66%	35%	74%	77%	36%	42%	40%	45%	43%	7%	1.36	2.69	3.25	3.44	0.83

4.5 Discussion

With increasing environmental concerns regarding resource depletion, policymakers have started focusing on regulating and incentivizing resource recovery. The construction industry, being one of the largest material consumers, may be substantially impacted by the implementation of these policies. Although the existing conditions and policies in place are not yet fully incentivizing the demolition industry to implement more sustainable EoL options, signs of policy change that can highly affect the demolition industry are evident. If such policies are implemented, the construction and demolition industry may be forced to shift toward less carbon-intensive operations. Externalities would be internalized, thus potentially improving general well-being.

A significant number of older single-detached houses are now reaching their end of life and are being demolished in North America (Feng et al., 2020). An opportunity exists to recirculate the materials embedded in these buildings and prevent them from being disposed of in landfills. Cast-in-place concrete buildings are not suitable for urban mining due to their low recovery rate. A possible solution is to design and construct concrete buildings with precast concrete or concrete modules that have higher reusability (Salama, 2017). Additionally, the design and construction of buildings with DfD criteria, similar to BIM4, can lead to a high recovery rate in future building stocks. While DfD may help eventually, it is important to recognize that the full impact of DfD practices may not be realized for several decades as buildings have long service lives. There is also value in salvaging building components in adaptation projects that can help offset project costs, reduce carbon, and avoid waste. Depending on a region’s common building types and construction norms, customized policies to recover materials from existing buildings should be developed and tested to increase resource recovery adoption.

Despite the existence of several policies, demolition is currently still mostly done in the traditional way, and building components are at most being recycled if not disposed of in landfills. This is partly because of the lack of an established secondary marketplace for the recovered materials, which leads to a high risk of obtaining good and predictable salvage values (Cruz Rios et al., 2015). Accurate and representative salvage values are difficult to obtain that can be effectively used to make reliable decisions regarding the optimal EoL option, resulting in the industry still implementing traditional building demolition as opposed to labour and cost intensive deconstruction approaches.

The extended duration required for deconstruction serves as a significant limiting factor that reduces the feasibility of extensive deconstruction activities. Given the increased required manual labour, deconstruction typically entails longer project durations. In the previous application of the optimization tool to a case study in Chapter 3, it was found that the cost-optimal scenario led to approximately a 30% increase in project duration, which necessitates careful consideration of additional costs (e.g. such as debt servicing). In this research, the duration of the EoL process in the optimized net cost with no policy is also around 25 to 75 percent higher than that of the traditional demolition scenario, depending on the intensity of the deconstruction and reuse process. Although project duration calculations were excluded from the policy scenarios, incorporating scheduling and time constraints can be readily integrated as supplementary constraints within the assessment to better reflect the impact of policy tools. On the other hand, project financing in demolition and end-of-life project is not of high significance due to their short project durations compared to typical lengthy construction projects.

Aside from the policies that were studied in this chapter, many other policies exist in other regions that are not yet mandatory (e.g., recommendations). Policies should be tested and chosen based on a region's priorities. For carbon targets, policies that show the highest carbon savings should be chosen (e.g. policy 1b). Policies need to be prioritized based on environmental targets and their efficacy. For instance, if the goal is to reduce waste streams, because regional landfill is no longer an option, policies such as policy 2 that reduce demolition waste should be mandated. On the other hand, less impactful policies such as policy 3a and policy 4 need to be modified to result in better environmental savings.

The City of Victoria has predicted that with the implementation of their resource recovery policies they can prevent 3,000 tonnes of demolition waste from ending up in landfills annually (City of Victoria, 2021). Foster City has various reuse and recycle mandates that fit in the category of policy 3. Although these policies appear to be mandated and penalties are in-place for violators, no report is available on the overall impact of these policies on construction and demolition waste diversion. The City of Portland has had a deconstruction mandate in effect for certain older and heritage buildings since 2016 (City of Portland, 2016). This mandate has led to a substantial increase in deconstruction activities, however the impact of this policy on material recovery has not been quantified, and therefore, the overall efficacy of the policy in environmental impact reduction is unknown (Willingham et al., 2017). Additionally, carbon taxes, markets, and offsetting programs that are used globally could be mandated for the construction industry (The World Bank, 2017). Although carbon pricing is currently not widely adopted in the construction industry, voluntary carbon markets do exist in which the construction industry can also participate (Construction Carbon, 2022).

When policies are not aligned with building owners' economic benefits, additional grants and funds may be required to help facilitate the implementation of the policies. Implementation of policies must be financially feasible for the building owners and the demolition firm to be implemented successfully. Building deconstruction and salvaging materials results in both environmental and financial benefits under effective policies and regulations. Policies such as carbon taxes are highly subject to change. For instance, in Canada various carbon price increase scenarios are defined that result in different carbon taxes. The Federal backstop scenario assumes an annual increase of 15CAD/tonne of emitted carbon till 2030 where carbon prices are fixed at 170 CAD/tonne. This is equivalent to 100 CAD/tonne in 2050 when adjusted for inflation whereas, in the evolving policy scenarios, the carbon costs will reach around 200 CAD/tonne in 2050 (Canada Energy Regulator, 2021). The change in the carbon prices and mandating the tax for the construction industry can substantially impact the market salvage values and change the obtained results. The optimization tool was previously tested in various sensitivity analysis scenarios, including the change in carbon prices that will be reflected in the Environmental Impact (EI) parameter of the tool in Chapter 3. The results indicated that changes in the EI cost led to minimal changes of the EoL choices but highly impact the net cost of the project. However, an investigation of the potential changes to the policies to understand the sensitivity of the results would be valuable.

One of the limitations of this research is that the optimization tool used for this assessment inherently assumes perfect knowledge and rational behaviour, which is not assured in practice. However, the results can bring insight into what the policy implementation can achieve in a rational setting and can be used as a reasonable starting point for planning purposes. On the other hand, policy implementation is not only driven by technical aspects but also by social and behavioural aspects that are not included in this research. A qualitative assessment, in addition to the presented method, can be valuable in better understanding the impact and role of policies.

The methodology used in this research takes into consideration the current policies, cost data, and value data available. This assumption was made to ensure consistency in the results across all buildings, allowing for better comparisons and utilizing accessible data. While the studied buildings have varying construction times and lifespans, it is important to note that the analysis was conducted under the assumption that they have reached the end of their lifespan at the present time. It is crucial to understand that this does not imply that the buildings need to be demolished prematurely. In fact, this is particularly applicable to BIM4, which is designed with Design for Disassembly (DfD) principles. Given the innovative nature of this approach, it is unlikely that buildings with similar designs would undergo demolition in the near future. The purpose of the analysis was to showcase the behavior of such buildings when they do reach their end of life. Incorporating a time-dependent financial model that accurately considers the evolution of policies, costs, and values over time would enhance the accuracy of the results and present an intriguing avenue for future research. This would provide valuable insights into the changing dynamics and potential impacts of different factors as they evolve over the lifespan of buildings.

A potential future research path following this work is to scale up and assess the impact of the identified policies or other relevant policies on a region's building stocks. Based on the distribution of the building types and demolition projects in a specific region, more impactful policies can be identified and prioritized for implementation. Additionally, each region has specific attributes including construction and demolition norms, building types, skills, knowledge, and cost factors. These factors can highly impact the recoverability of materials and the efficacy of the policies within that region.

4.6 Conclusions

This research assessed the potential impact and efficacy of in-place policies focused on promoting resource recovery and waste reduction in the construction sector. Results compared the recovery rate, cost of extraction, obtainable value, avoided waste and avoided carbon for five different building case studies that in North America. In this research, four categories of policies were modeled and tested to observe the impact of the policies on decreasing waste and carbon emissions. The comparison was based on extending the developed optimization tool that estimates the component end-of-life options (i.e., disposal, recycling, and reuse) that minimize the total building deconstruction and demolition cost. The efficacies of the policies were assessed by comparing the effect of the application of the policies on increasing construction material recovery, waste diversion, and carbon savings in building demolition processes where project cost is being minimized.

The findings of this research indicate that in the studied case study BIMs, building owners can achieve substantial waste reductions and carbon savings while also generating positive financial returns through choosing optimal EoL options that minimize their net project cost. In practice, building owners may not choose optimal EoL options for a variety of reasons including lack of perfect information, project duration constraints, logistics limitation, and access to limited resources to make such determinations. Policy tools can be used to force building owners to achieve near-optimal waste reductions and carbon savings, albeit at varying costs to the building owners, not necessarily increasing the net project cost above traditional demolition (i.e., many multipliers still greater than 1 in the policy scenarios). In the absence of optimal behaviour by building owners, these policies may represent a more pragmatic "second-best" solution for getting closer to transitioning from a linear to a more circular economy from a resource recovery perspective and should be prioritized according to their efficiency. However, the efficacy of the policies varies by measure of effectiveness (i.e., waste versus carbon savings) and building type, necessitating careful goal formulation and policy implementation targeted at local building stocks. The results can be used by government stakeholders and policymakers to gain insight into the policies that they have proposed or are planning to implement. Policymakers should focus on the policies that demonstrate positive outcomes from both environmental and financial perspectives and reconsider those policies that are proving to be less effective. The methodology presented here can help anticipate these outcomes in lieu of or in conjunction with costly real-world experimentation.

Chapter 5: A global perspective on building material recovery incorporating the impact of regional factors

This chapter corresponds to the following published article[3]:

Mollaei, A., Byers, B., Christovan, C., Olumo, A., De Wolf, C., Bachmann, C., Haas, C. (2024). A global perspective on building material recovery incorporating the impact of regional factors *Journal of Cleaner Production, 139525.*

Abstract

Recovery of buildings through the extraction of building materials at the end of the building life can contribute to the reduction of construction material consumption and waste generation. The viability of recovering in-situ building materials when they reach the end of their lifespan depends on regional factors such as construction and demolition norms, labour costs, secondary material markets, and general perceptions and culture toward material recovery processes. The objective of this study is to analyze the impact of regional factors on building end-of-life strategies. For this study, five different buildings with similar general characteristics from globally distributed locations are selected as case studies. To analyze the impact of regional factors, a previously developed decision support optimization tool is used that intakes regionally dependent factor data and generates optimal end-of-life options for each building component that reflect market-based practices based on the regional factor data. The study takes a comparative approach to analyze the recovery potential of the chosen building case studies. The results of the study highlight the importance of social economic factors in the decision-making of building component end-of-life strategies alongside material recovery-related policies, incentives, and waste disposal regulations. Labour costs are found to be less impactful than regulations and cultural norms on materials recovery decisions. The findings of this study have important implications for the construction industry, policymakers, and researchers. Construction stakeholders can better assess the feasibility and potential benefits of recovering building components based on each region's specific conditions and consequently

[3] To maintain consistency with the thesis format, this chapter is slightly modified compared to the published article. The provided abstract is an exact copy of the published work.

develop regionally focused policies and regulations that can more effectively reduce waste generation.

5.1 Introduction

The approach to managing Construction and Demolition Waste (CDW) varies widely among countries, regions, and projects despite the sector being one of the largest sources of waste worldwide. Some countries require a stated plan of controlled demolition and sorting of any CDW while others have no formal expectation of management. Demolition using machinery and dumping materials in landfills is a common approach in most regions due to the shorter project duration (Allam & Nik-bakht, 2022). Therefore, because of the often destructive` practices of building demolition, the recoverable value of construction materials is typically lost, and resource recovery is neglected (Pun and Liu, 2006; Silva et al., 2017). Technical and financial challenges in extracting materials from buildings, material recovery logistic complexities, limited regulations, and lack of incentivizing policies are among the main challenges in resource recovery implementation (De Jesus and Mendonça, 2018; Rakhshan et al., 2020; Rizos et al., 2016). Regional-specific factors can influence the relative impact of these challenges in implementing resource recovery-related strategies such as building deconstruction and material reuse (Nunes and Mahler, 2020). Yet, it is not clear why different construction material recovery practices are being observed in different countries, specifically at the building level.

The goal of this chapter is to understand the impact of regional factors on construction material recovery rates in buildings when they have reached the end of their lifespan. These factors include cost of labour and materials, construction and demolition waste management policies and regulations, and social economy conditions and norms. Thus, the objectives of this chapter are to: 1) gain an understanding of the building EoL practices in different regions; and 2) quantitatively assess the impact of regional factors on building recovery using case studies. To address the objective of this study, a comparative case study approach is used. Five regions are chosen as case studies: Canada, Switzerland, Brazil, China, and Nigeria. The regions are chosen to represent various levels of economic maturity in different geographical locations. The study is an exploratory study that provides insights into the implications of regional factors in assessing the recovery of building materials. Though not prescriptive, the findings help stakeholders in the construction industry better understand building recovery behaviors and incentives to inform region-specific interventions for more feasible adoption of circular strategies in the construction sector.

The structure of this chapter is as follows: After this introduction, section 5.2 provides an overview of construction and demolition waste management practices in different regions under the CE lens and highlights the research gaps in this area. In section 5.3, the research methodology and the details of the case study buildings and regions are provided. Section 5.4 demonstrates and describes the results and analysis of the impacts of regional factors on building material recovery as well as the limitations of the study. In section 5.5, conclusions are made alongside a description of the contributions of the research chapter and paths for future work.

5.2 Literature Review

5.2.1 Overview of CDW Practices in different regions

CDW practices vary wildly between countries, regions, and job sites. Factors such as the population's attitude toward environmental friendliness, precedence, and even costs of labour and new material all affect practices of reuse, recycling, and landfilling. As this chapter aims to explore the influence of some of these factors on the optimal EoL strategy for CDW management, in the first step, the state of CDW management across several countries worldwide is studied through a literature review. Countries are chosen based on data availability and interest in both formal and informal practices for CDW management. Each country's general policy approach for CDW and precedence for CDW reuse and recycling are explained more extensively in the following sections. A view of the geographical distribution of the studied regions is provided in Figure 5-1.

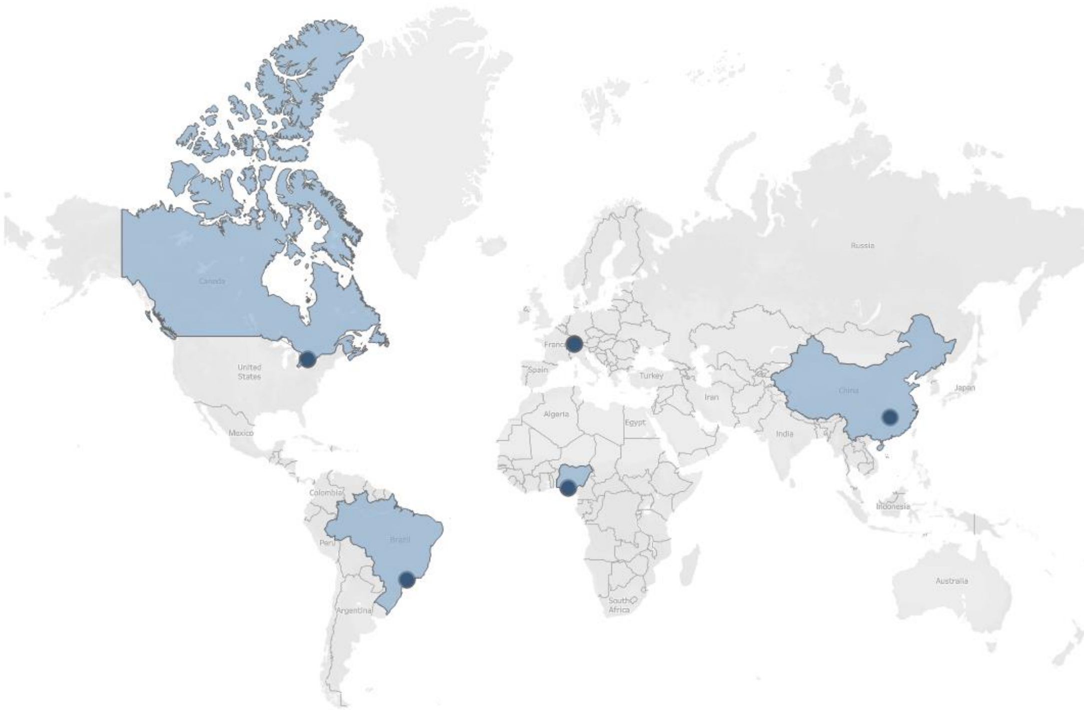


Figure 5-1: Geographical Distribution of Selected Case Study Regions

Table 5-1 provides a high-level comparison of the weight of CDW and municipal solid waste (MSW) for each country (The World Bank, 2019). CDW refers to the waste generated from construction, renovation, and demolition activities and typically includes materials such as concrete, wood, bricks, asphalt, metals, plastics, glass, and other related waste. MSW refers to the waste generated by households, commercial establishments, institutions, and public places within a municipality or urban area. It includes a broad range of materials such as paper, cardboard, plastics, organic waste, textiles, glass, metal, and other items discarded by individuals or businesses. The chosen countries are compared in Table 5-1 using high-level statistics as proxies for level of development. The first indicator, Gross Domestic Product (GDP), is the total value of goods and services in a country minus the value of goods and services required to produce them (The World Bank, 2021). The second indicator shown in the table is the Human development index (HDI) developed by the United Nations Development Programme to better track progress and country development that is not limited to just GDP. It is calculated through a geometric mean of the following: gross national income per capita, life expectancy at birth, and expected and mean years of schooling (UNDP, 2022). Measurement and reporting differences among the countries may partially explain what appear to be anomalous aspects in the data, and yet this is what has been reported.

Table 5-1: Comparison of Case Study Countries Demographics and Waste Production

Country	**Population** (2021) (The World Bank, 2021)	**Total CDW** (tons/yr; 2019) (The World Bank, 2019)	**Total MSW** (tons/yr; 2019) (The World Bank, 2019)	**GDP** (Billion 2021USD) (The World Bank, 2021)	**GDP per capita** (2021USD) (The World Bank, 2021)	**HDI Global Rank** (2021) (UNDP, 2022)
Canada	38,246,108	653,255	25,103,034	1,988	51,897	15
Switzerland	8,703,405	6,390,000	6,079,556	800	91,991	1
China	1,412,360,000	1,500,000,000	395,081,376	17,734	12,556	79
Nigeria	213,401,323	n/a	27,614,830	440	2,065	163
Brazil	214,326,223	45,158,165	79,069,584	1,608	7,507	87

Initial research broadly indicates that preventative costs, the lack of market demand, the lack of trust in reused products, and the lack of supply chain information negatively contribute to sustainable construction demolition waste management (Chileshe et al., 2018; Ghisellini et al., 2018). While in most cases reuse and recycling are shown to be environmentally and economically desirable, CDW waste treatment choice is often site-specific and depends on bespoke attributes such as component and material type, location, and site context (Ghisellini et al., 2018).

5.2.1.1 CDW in Canada

A study prepared for Natural Resources Canada, Lands and Minerals Sector, and Canadian Forest Service in 2020 estimated the total amount of material recovered and/or recycled in Canada to be over 22.3 million tonnes (Maria Kelleher, 2020). The materials include paper, steel, aluminum, lead, copper, zinc, nickel, glass, plastic, food and yard, tires, electronics, batteries, lumber, drywall, coal combustion products, steel-making residues, and wood ash. The largest amount is in the steel industry, which uses 6.7 million tonnes of scrap steel, exports 5.1 million tonnes, and recycles 2.9 million tonnes of residues (Maria Kelleher, 2020). Early research work from 2012 makes the argument that over 75% of CDW from Canada has residual value for recycling and reuse and proposes a lifecycle-based CDW index (Yeheyis et al., 2013). While some physical and online marketplaces for secondary material resell exist for this region, the secondary marketplace for building materials is not fully established for owners to organically consider reselling and buying salvaged materials (Blois et al., 2019). Additionally, other than relatively high landfill fees, no general mandates on building material recovery are currently in place. However, some policies and regulations exist in Canada’s west coast that promote salvaging certain material components, as discussed in Chapter 4.

5.2.1.2 CDW in Switzerland

Switzerland has some of the highest waste volumes in the world and relatively good recycling rates; slightly more than half of the municipal waste is collected separately and recycled (Bundesamt für Statistik, 2022). Within the Zurich canton, Article 10 of the Ordinance 712.110 for Waste Management states that construction waste must be sorted on-site into the following categories: uncontaminated excavated material, construction debris, bulky waste, and hazardous waste. Furthermore, materials shall be recovered to avoid landfilling (Stadt Zurich, 2021). The sorted waste will have high potential for recovery, especially in the form of recycling. Therefore, direct disposal of materials can be avoided and better EoL options are assessed. Generally, about 70% of deconstruction materials and 75% of excavated materials from the construction and demolition processes are recycled because of their residual value (FEON, 2018). There are around 4,000 demolition projects across Switzerland per year (“Building with repurposed material,” n.d.), from which building demolition waste can be processed into recycled building materials as mineral waste as long as there are no known hazardous materials. Mineral construction wastes are to be further separated into reclaimed asphalt, road debris, concrete debris and mixed debris (UFAM, 2006). Existing research uses an input-output model to examine how regional cost impacts and uncertainty affect circular business models within the Swiss canton Argovia (Meglin et al., 2022). Although Switzerland has strong waste management and recycling practices, the research suggests increased vertical integration for mitigating price uncertainties and securing the continuous circular flow of raw materials.

5.2.1.3 CDW in China

CDW accounts for 30% to 40% of the total amount of waste in China and the average recycling rate of CDW in China is only about 5% (Huang et al., 2018). Some of the barriers of reducing CDW in China include a lack of building design standards for reducing CDW, low cost for CDW disposal, and inappropriate urban planning (Huang et al., 2018). In addition, the barriers to reusing CDW include a lack of guidance for effective CDW collection and sorting, a lack of knowledge and standards for reused CDW, and an underdeveloped market for reused CDW (Huang et al., 2018). Lastly, the barriers to recycling CDW include ineffective management systems, immature recycling technology, underdeveloped market for recycled CDW products, and immature recycling market operation (Huang et al., 2018). Duan and Li (2016) suggested that more attention should be put on improving the management of concrete, masonry (bricks and concrete/stone blocks), mortar and ceramic wastes, since these four categories of CDW account for about 90% of the CDW in China and have the highest recycling potential. The most recent statistics known on China's CDW is from The World Bank in 2019 (Table 5-1); especially during and after the COVID-19 pandemic, the actual numbers are likely different but currently unknown. Though, in 2020 China released "Guiding Opinions of the Ministry of Housing and Urban-Rural Development on Promoting the Reduction of Construction Waste" and the "Law of the People's Republic of China on the Prevention and Control of Solid Waste Pollution" that both emphasized construction waste classification, reduction, recycling, and reuse (Li et al., 2022).

5.2.1.4 CDW in Nigeria

As a nation with slow industrialization, a rapidly increasing population, and low GDP per capita, the building sector is attractive to investors and consists of a few organized large companies and smaller unorganized companies (Wahab and Lawal, 2011). Although understanding of sustainable practices is relatively common in Nigeria, many industries tend to stick to the norm of landfilling and burying debris (Ogunmakinde et al., 2019). Additionally, the landfilled waste is typically not well managed or sorted. Research shows the construction industries suggest that the added cost of sorting the waste and the penalty fee for late delivery on the projects hinder the sorting process before landfilling (Aboginije et al., 2021; Ogunmakinde et al., 2019). However, once the materials are landfilled, certain material pickers unofficially pick the scrap metal and other useful components that can be sold for secondary use. Although there are some drawbacks to reuse or recycling in the Nigerian construction industry, some companies trade used resources of value to other sites or third-party sellers, including soil, off-cuts from steel reinforcement bars, and leftover aggregates (Ogunmakinde et al., 2019). Industry regulations are also quite poor despite the policy efforts that attempt to promote sustainable management of resources (Ogunmakinde et al., 2019).

5.2.1.5 CDW in Brazil

In 2002, the Ministry of the Environment in Brazil released guidelines for separating and sorting construction waste and makes the waste generators responsible for the process of managing the waste including hauling, storing, sorting, and final disposal (Munaro and Tavares, 2022). Additional legislation includes Federal Law 12,305, implemented in 2010 created by the National Policy on Solid Waste (NPSW) organization that mandated shared waste management (Esguícero et al., 2021). Research conducted in this region indicates that 44.5 million tons of CDW waste were collected in 2018, representing 36% of the total municipal solid waste (Esguícero et al., 2021). Yet, additional research found that the CDW flow represents over 60% of the total waste generated (Esguícero et al., 2021; Nunes and Mahler, 2020). The Institute for Applied Economic Research (Instituto de Pesquisa Econômica Aplicada, 2012) carried out a diagnosis of solid waste from civil construction in Brazil, which gathered important information for policy makers to understand the management of construction waste. A common EoL option for construction waste is found to be illegal disposal of materials in the open lands (Szigethy and Samuel, 2020). As much as policy initiatives aim to change this reality, legislation implementation faces challenges including lack of technical knowledge, negligence, and lack of financial resources (Costa and Ferreira Dias, 2020). Despite waste disposal issues, demolition with reuse in mind seems to be known practice in the industry which leads to unofficial reuse practices (SINAPI, 2019). There is little published work looking into the secondary material markets for construction materials in this region. Based on consultations with experts, most materials in secondary markets focus on gates, frames, wood, or materials of historical value such as tiles and pieces that are not easily found in construction material stores (R.E. Córdoba and S.R.M. Silva, personal communication, March 16, 2022).

5.2.2 Research Gap

The existing research is mostly around identifying barriers, drivers, and enablers of CE adoption at different geographical scales, primarily through literature reviews and qualitative research approaches. Coelho and De Brito (2011) studied the impact of varying economic data influenced by local conditions on deconstruction implementation in Portugal and concluded that labour costs and disposal fees are the main factors influencing the choice of deconstruction. Caldera et al. (2020) conducted a global scale study on the barriers and enablers of establishing secondary construction material marketplaces through a systematic literature review. The findings indicate the importance of local operational and governance factors in developing such marketplaces. Other research has also highlighted the significance of region-specific regulatory and economic measures in driving the adoption of building material recovery strategies (Jiménez-Rivero and García-Navarro, 2017). On the other hand, Cruz Rios et al. (2021) recognized education and culture as the main aspects influencing material reuse in the US whereas, regulation and technological limitations were more impactful in the studied European countries.

The available literature shows a lack of quantitative assessments on various waste management practices in different locations, specifically around the recovery of building materials when the building has reached the end of its use. Similarly, there is limited comparative work on CDW management strategies, particularly between continents and additionally with an added focus on CE. Without an understanding of the key factors and drivers affecting resource recovery adoption, making effective changes remains challenging. Therefore, this research aims to begin to quantify the impact of region-specific economic, social, and regulatory factors on optimal end-of-life strategies for building components. Results can help improve building material recovery by identifying key intervention points.

5.3 Methodology

The methodological steps for this research are summarized in Figure 5-2. Five regions with substantially different geographical, economic, and cultural conditions were chosen for study. Canada, Switzerland, Brazil, Nigeria, and China were chosen as case study regions with the first two being examples of regions in North America and Europe, and the remaining as regions in South America, Africa, and Eastern Asia, respectively. In each region, data on a case study building were collected that can adequately represent a common building archetype in that area. The building data are collected in a BIM with a Level of Detail (LOD) of at least 300. In the next step, for each region, a literature review on the state of construction and demolition waste management practices, general construction and demolition norms, and applicable regulations to building material recovery at its EoL was conducted. Additionally, consultation and interviews with experts in each region were completed to gain better insight into the reality of the built environment conditions in that region. A summary of the communications is provided in Appendix C. The findings of the completed literature review and communications were previously summarized in section 5.2.1.

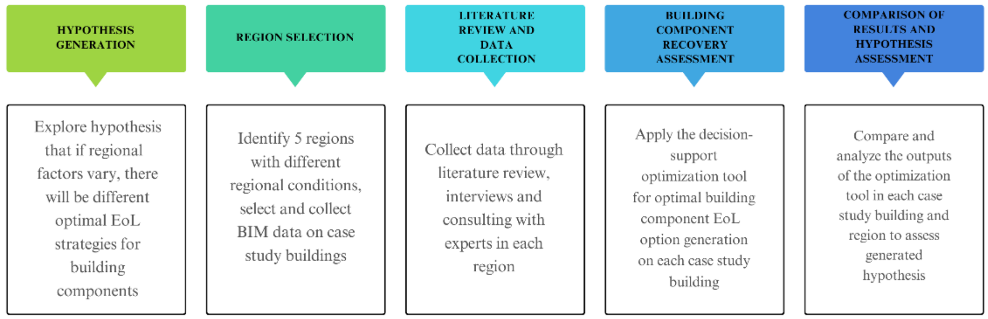


Figure 5-2: Summary of Research Methodology Steps

5.3.1 Application of the Decision Support Optimization Tool

To quantitatively assess the EoL strategies and optimal recovery potential of the case study buildings in different regions, the developed decision support optimization tool in Chapter 3 is used. The building model alongside additional inputs directly influenced by the regional conditions was fed into the tool to estimate the value of the in-situ building materials and the maximum feasible recovery potential of the building based on each component's optimal EoL option. In a sense, use of the tool is a proxy for an extensive survey of practices in each region (for which resources are not available); this is reasonable, because the tool incorporates relevant regional market factors (which are available) and assumes rational behaviour considering those factors. In order to utilize the tool, extensive data on demolition and deconstruction costs for different building components, labour costs, building material disposal fees, regulatory constraints on material dumping and waste management, and secondary market value of different materials and components were collected for each case study building. The details of the regions, case studies, and collected data are provided in section 5.3.2. In the final step, the outputs from the optimization tool were compared and analyzed to gain insight into the impact of regional factors on building material recovery. All the required data and data sources alongside a description of the data is provided in Appendix C.

The main outputs from the optimization tool that are used in this research are as follows:

- **Total building component extraction cost:** the sum of the demolition and deconstruction cost of the building components according to their optimal EoL option

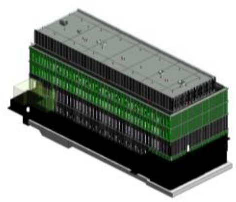
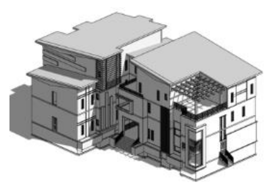
- **Total obtainable value:** the total scrap and salvage value obtained from the resell of building materials in the building
- **Recovery rate:** the proportion of the weight of the recycled and reused components to the total weight of the building that can be used as a high-level indication of the circularity potential of the building
- **Avoided waste:** the total quantity of materials in tonnes that is diverted from landfills as a result of the chosen recycling and reuse EoL options

The project duration objective of the optimization is excluded from the scope of this study and the optimization is solely based on the cost of the project. The outputs of the model are highly dependent on the configuration of building components and general construction of the building in addition to various financial parameters including labour and material costs. Therefore, the tool provides the required flexibility to assess how the regional factors directly impact the feasible recovery potential of the building. For this study, the BIM was assumed to be correctly modeled based on each location's norms. The monetary values are all calculated in 2020 USD. It should be noted that market exchange rates were used to convert each region's currency to 2020 USD rather than purchasing power exchange rates.

5.3.2 Overview of the Case Study Buildings

A description of the five case study buildings and their corresponding regions is provided in this section. Each building and its region present unique characteristics that make them valuable case studies for this research. In selecting the building characteristics for this study, a range of factors were considered, including the availability and accuracy of the BIM, their level of representation of common construction types in the region, their general design, their compliance with local design codes, and their categorization as mid-sized commercial or residential structures. For each case study, an overview of the representative region, specific norms, applicable policies and regulations, case study building characteristics, and the required data sources to utilize the optimization model are highlighted. The details of the collected data are provided in Appendix C for the case studies. The values used are primarily intended to be used directionally and in order of magnitude, and not as exact representations. Table 5-2 presents a summary of the case study buildings including building location, schematic 3D model, Gross Floor Area (GFA), building frame type, component counts in the model, and total weight of the building.

Table 5-2: Overview of Case Study Buildings

Case Study	Region	Schematic 3D Model	Details	
Building 1	Canada		GFA (m^2)	2400
			Frame Type	Timber, Concrete, Steel
			Number of Components	689
			Building Weight	1592 tonne
Building 2	Switzerland		GFA (m^2)	5770
			Frame Type	Concrete, Steel
			Number of Components	3101
			Building Weight	14,008 tonnes
Building 3	China		GFA (m^2)	2100
			Frame Type	Concrete
			Number of Components	384
			Building Weight	3850 tonnes
Building 4	Nigeria		GFA (m^2)	950
			Frame Type	Concrete
			Number of Components	900
			Building Weight	2005 tonnes
Building 5	Brazil		GFA (m^2)	3300
			Frame Type	Concrete
			Number of Components	1751
			Building Weight	4541 tonnes

5.3.2.1 Canadian Case Study

The first chosen case study region is in southern Ontario in Canada. The building chosen for this region is a 2,400 m^2 two-story office located in the city of Waterloo. The building has a hybrid frame of mass timber and concrete, which are two of the most common construction materials used in Canada (Bone Structure, 2015). The building model is collected from a local development company. The construction and design of the building allow selective demolition and deconstruction but require additional labour due to the use of cast-in-place concrete and relatively irreversible connection systems in certain parts of the building frame and assemblies (e.g connection between columns and foundations). The operation labour costs and material value data are collected from costing references and available data on local web-based marketplaces (RS Means, 2020; Demolition Traders, 2021; Recycler's Exchange, 2021; Repurposed Materials, 2021; Salvage Garden, 2021).

5.3.2.2 Swiss Case Study

The building chosen for exploration in the European region is located in Zurich, Switzerland. Specifically, the building is a partial office extension of the HIF building on the ETH Zurich Hönggerberg University campus with a GFA of 5770 m^2. The material used is in the building is primarily cast-in-place concrete, as is customary for the country and region. It also includes prefabricated metal and glass facade panels. Input parameters on cost and labour comes from other Swiss examples found on the web, some local specialized deconstruction and reuse contractors, and Eberhard Bau AG (a large Swiss construction contractor). The data on assumed demolition costs are averaged from two projects from Volken and two projects from Eberhard, which are then corroborated approximately in similar research work (Meglin et al., 2022). Assumed average rates on reused, recycled, and landfilled waste come from the organization Urban Mining, an Eberhard enterprise (Eberhard, n.d.). Data on transportation costs and rates are also taken from Eberhard reports (Eberhard, 2022). The transportation costs are assumed the same per material and from the job site to the construction waste management facilities on Eberhard's campus. Costs, volumes, policies, and waste removal are taken from the City of Zurich's website where the project is based in (Stadt Zurich, n.d.). The costs of salvaged and reused building materials are taken from approximately equivalent materials on Swiss material marketplaces UseAgain and Materiuum (Materiuum – Creative association, n.d.; UseAgain, n.d.). Lastly, the labour costs and durations for demolition and dismantling work, along with specific estimates for the landfill fees are provided in confidence by a specialty regional contractor.

5.3.2.3 Chinese Case Study

The third case study building is located in Hunan, China. The building is a 2,100 m^2 three-storey cast-in-place concrete building in the Hunan Industrial and Trade Vocational School, cladded with brick veneer and painted architectural concrete. Although government-level regulations exist on controlling construction and demolition waste generation, there seems to be a lack of alignment and supervision at the local and regional levels where buildings are actively being demolished (AECOM, 2018). Therefore, no additional regional-specific policy constraints are added to the optimization tool in the case of this building. The average demolition cost is around 30 Yuan/m^2 (i.e. around 5 USD/m^2) (Zhang and Tan, 2020). Deconstruction costs are different depending on the type of the building component with an average 50-80% higher rates compared to demolition costs (Construction Together, 2022). Landfill fees exist for waste disposal ranging from 3-12 Yuan/m^3 of solid waste (Lin, 2019). However, illegal landfilling is also found to be a favorable option for waste disposal (Zhang and Tan, 2020). Moreover, the recovery of building materials, especially for cast-in-place concrete buildings is at best normally limited to recycling (Ding and Xiao, 2014).

5.3.2.4 Nigerian Case Study

A low-rise three-story building in Delta State, Nigeria is examined as a case study building in Africa. The case study is a hotel building with a GFA of 900 m^2. Delta State is located in the southern part of Nigeria. The literature review and interviews with experts in this region indicate that there seems to be no established deconstruction and salvaging procedure. Therefore, the recovery option for components of the building is limited to recycling. Additionally, no trackable salvage and scrap value can be obtained from material extraction for the owner. Therefore, in reality, the only recovery option for buildings similar to that studied in this research is the possibility of scrap pickers taking certain components from the site and the owner not paying additional landfill fees due to the reduced quantity of waste materials. For this research, components made from metals, windows, and doors are assumed to have both disposal and recycling options in the optimization tool whereas other components will only be disposed of in landfills. For recycled components, the value gain from the owner's perspective is the lower extraction cost due to reduced landfill fees. Demolition cost is assumed to be around 1500 NGN/SF (i.e. around 22 USD/m^2) based on the information gathered from a local company (Jiji, n.d.).

5.3.2.5 Brazilian Case Study

The last case study is a building in the region of São Paulo, Brazil, representing a South American region. It is a five-story building with a GFA of 3,300 m². The building is mainly constructed from cast-in-place concrete and brick masonry, which is a common construction technique in the region (Parsekian et al., 2018). The National System for Research of Civil Construction Costs and Indexes (SINAPI) and some additional tools are used to extract demolition and deconstruction costs required for the optimization tool (SINAPI, 2019; SINAPI, 2021). In this case study region, the market for secondary materials remains relatively underdeveloped. The websites "Mercado Livre" and the “OLX” were used to collect data on the value of secondary materials (Mercado Livre, 2022; OLX, 2022). There seem to be no official landfill fees applicable in the region. Additionally, illegal landfilling is also observed due to a lack of supervision (Szigethy and Antenor, 2020). However, waste disposal in landfills will require transportation of the materials to the landfill through waste hauling services, which was considered as input data in the optimization tool for the disposal EoL scenario. Disposal cost data were collected from two waste transportation companies called "Fran Terra" and “Agrobill” in São Paulo (Agrobill, 2022; Fran Terra, 2022).

5.4 Results and Discussion

5.4.1 Comparison of the Optimization Tool Outputs

The results from the optimization model show how drastically different the cost of building material extraction for recovery is in each of the five case studies. The obtainable value and the net cost (i.e., total cost of component extraction minus total obtainable value) are also found to be in a wide range among the studied regions. Figure 5-3 demonstrates the normalized building component extraction cost and obtainable value per square metre of Gross Floor Area (GFA) of each case study building. Building 2 has the highest component extraction cost per GFA due to the higher labour costs in the region. The Obtainable value is also higher than that of the other case studies. The obtainable value is only 25 percent of the total extraction cost, while buildings 1 and 5 show much higher relative obtainable values compared to the extraction cost.

The total absolute component extraction cost, obtainable value, recovery rate, and avoided waste are also summarized in Table 5-3 for all buildings. The monetary values are all reported in 2020 USD. Results indicate that in regions with lower average construction and demolition labour costs, total component extraction costs are lower, but this does not directly lead to higher recovery rates despite the cheaper labour required for component reuse. The recovery rate of the case study in Switzerland is much higher than that of the other regions resulting in substantial waste savings. The Swiss building also has the highest net cost, despite the high recovery rate. Both the Chinese and Nigerian buildings show low recovery rates and close to zero obtainable values. The Brazilian and Canadian buildings show relatively lower net costs, with the latter being the only region where a negative net cost (i.e., profit) was observed.

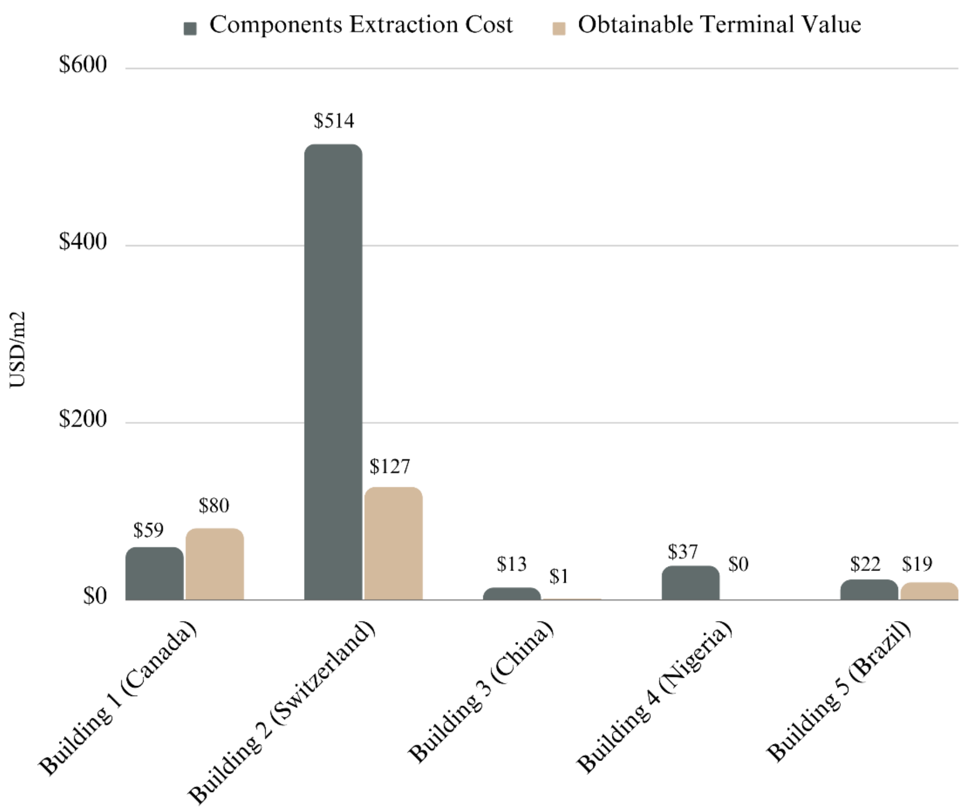


Figure 5-3: Building Component Extraction cost (i.e. total cost of building component demolition, sorting, and deconstruction process) and Obtainable Terminal Value (i.e. gained value from resell of recycled and reused components) Normalized by GFA

Table 5-3: Summary of the Financial and Environmental Impacts associated with the Optimal Building End-of-Life Options in each case study building

	Building 1 (Canada)	**Building 2 (Switzerland)**	**Building 3 (China)**	**Building 4 (Nigeria)**	**Building 5 (Brazil)**
Total Component Extraction Cost (2020 USD)	$141,800	$2,967,850	$27,915	$34,800	$71,820
Total Obtainable Value (2020 USD)	$193,100	$734,550	$1,815	None	$62,480
Recovery Rate by Weight of Components (%)	38%	70%	11%	2%	39%
Avoided Waste (tonne)	495	9827	413	48	2764
Avg Construction Labour Cost (2020 USD/hr)	$20	$37	$5.50	$13	$14

Figure 5-4a presents the breakdown of the component EoL options in each case study building based on the number of components. Figure 5-4b provides the EoL breakdown according to the weight of materials. These figures show that in all buildings smaller components in weight are reused, which could become misleading if only the number of components are accounted for, as the weight of materials diverted from landfills turns out to be smaller than expected. Moreover, the process of extracting components for reuse and recycling unavoidably generates waste. Therefore, even if components are not targeted to end up in landfills, waste will still be produced as part of the recovery process that should be disposed of in landfills. This assumption is reflected in the recovery factor calculated for each building component as a required input for the optimization model that is multiplied by the mass of the building component to indicate the total recoverable material. This recoverable mass is lower or at best equal to the mass of the building component. For instance, in the case of Building 2, although no direct waste disposal option was observed, the waste generated as part of the recycling and reuse process of some components is not negligible.

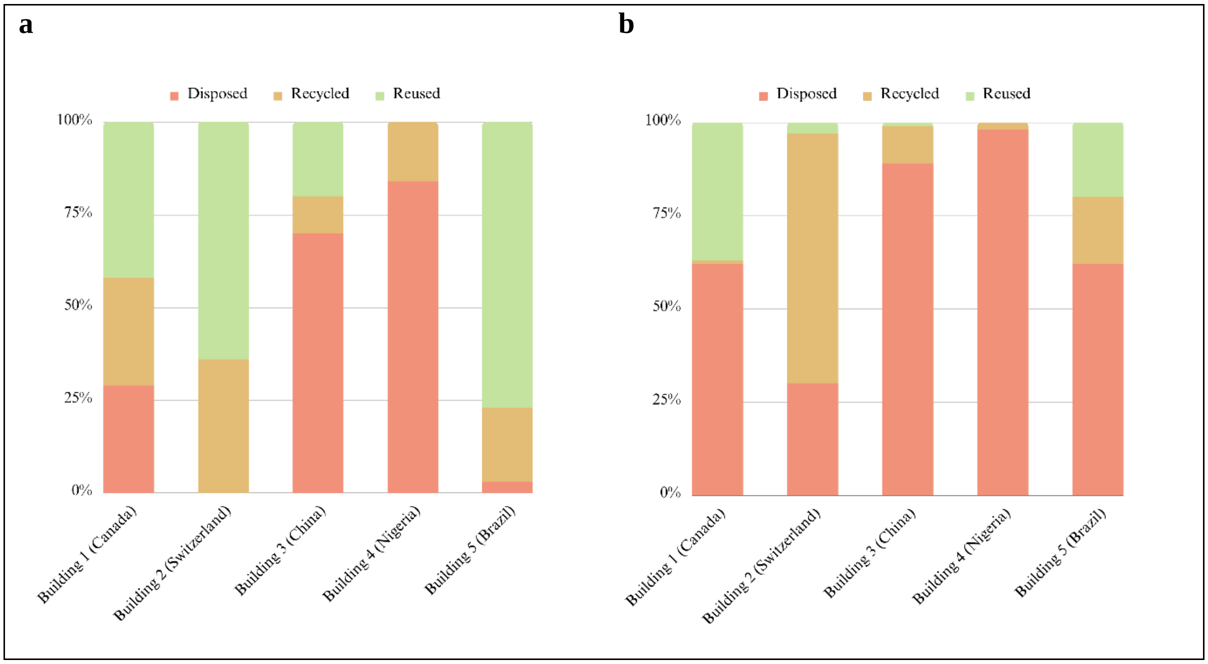


Figure 5-4: Normalized Breakdown of End-of-Life options based on a) Building Component Count b) Weight of Materials.

Comparing the EoL breakdown between the regions indicates that the optimal solution results in the disposal of more than half of materials in landfills for all regions except for Building 2 (Figure 5-4b). This is because the legislation in the second building's region mandates material sorting and preparation for recovery, regardless of whether it is the more financially feasible option (i.e., constrained in the optimisation). Results also show that generally, recycling is the more favorable option as opposed to reuse since the cost of material sorting and preparation of recycling is lower than that of controlled deconstruction and material reuse. This trend is not observed in Building 1 which can be a result of the specific type of material, such as wood frames, used in this building, making it more favorable for reuse.

5.4.2 Region-Specific Insights from Building Case Studies

The results from Building 1 show that the building has a high total obtainable value that can potentially offset building component extraction costs. This is due to the fact the studied building has highly recoverable wood-based components that do not have technical reusability constraints, in addition to the presence of an established secondary market in Canada for reclaimed wood (Quinton Blois et al., 2019). On the other hand, landfill fees are expensive and illegal landfilling is not common practice in Canada making recovery options more favorable despite the higher initial component extraction costs. Moreover, the emergence of deconstruction firms and salvaging auditing mandates are signs of positive cultural change regarding the adoption of circular strategies (Delphi Group, 2021).

In Building 2, the results of the optimization tool show extremely high building component extraction costs in the optimal solution, but only around 25% of this cost can be paid back from the obtainable salvage and scrap values. The strict mandates in Switzerland on waste disposal, material sorting obligations, and policies on CDW reductions lead to lower waste production rates and higher recovery of building materials. The regulations require materials extracted from the building to be sorted and recovered to their full potential. This means that building components should not be disposed of as mixed waste in the landfill. Therefore, in implementing the optimization model on this case study building, a constraint was added to the model such that all components were forced to be sorted and prepared for some form of recovery, preventing the direct landfilling option. Higher recovery rates are observed in this building due to the existence of the regulations that were translated into constraints despite resulting in moving away from the minimum cost scenario where no mandates are added.

Even with the in-place mandates and policies, it was observed that although many reusable components were identified in the building, the contribution of those components to the total weight of the reused materials is little, thus leading to around 70% of the building being recycled (Figure 5-4), which is considered a less ideal circular strategy compared to reuse. Overall, the building has a high recovery rate because of the mandatory recovery regulations discussed in Section 2.2.2, the type of materials used in the building, and its higher design compatibility with deconstruction.

Building 3, representing an East Asian region, has the second lowest recovery rate compared to the other regions (Table 5-3). Despite low labour costs, building component reuse and recycling were not the dominant optimal EoL solutions for the building. In fact, only 20% of the building components are recovered with the rest going directly into landfills. Additionally, the official market for secondary materials shows low values. The building is also not designed for EoL recovery making reuse technically infeasible for most building components. However, research on building demolition audits in the region identified unofficial building material recovery does happen on site, which is not adequately tracked and not reflected in the data used for the optimization tool (Zhang and Tan, 2020).

Building 4 has the least recovery potential. This is due to the lack of any construction and demolition waste diversion policies in Nigeria, the use of construction and design techniques that make the recovery of building components difficult, expensive, or infeasible, and the lack of skilled labour for deconstruction and building material reuse. The results of the application of the optimization tool on the building produce results not too different from a conventional demolition approach. The unofficial reuse is also limited to scrap pickers taking certain smaller components and is hardly traceable. Circular Economy adoption is also very limited in the region leading to little knowledge and effort in shifting toward circular strategies (Zuofa et al., 2023).

The component extraction cost and the total obtainable value of Building 5 are quite close, with the extraction cost being slightly higher. This indicates that reselling of recovered building materials in Brazil may cover a substantial part of demolition and deconstruction costs, albeit limited CDW regulations in this region. In the case study, more than 50% of the building weight was disposed of in landfills despite the reuse of a high number of building components (Figure 5-4). This is because of the component breakdown used in the BIM model, and the larger size and weight of the disposed components. The costing reference in this region includes a category dedicated to "demolition with reuse," which aligns closely with the concept of deconstruction (SINAPI, 2019). This underscores the endorsement of material reuse as a viable EoL solution for buildings. The culture of using non-destructive demolition techniques for the removal of small and midsize buildings in this area makes the shift toward deconstruction easier with less required marginal cost. Additionally, demand for secondary materials exists in the non-official reseller markets making material reuse more financially feasible.

The uncertainty associated with the input data in the optimization model for each case study may impact the outputs of the model and the comparison of the results. The optimization model was assessed through various sensitivity analyses, including one-at-a-time (OAT) sensitivity analysis, Monte Carlo analysis, which accounted for uncertainties and probability distributions in input data, and scenario analysis, which explored results in various extreme scenarios in Chapter 3. The result of the analyses indicated that the model is most sensitive to landfill fees, material recovery rates, salvage values, and scrap values. However, the range of change in the outputs is not substantial. Although a case-specific sensitivity analysis was excluded from this research, the listed inputs can be further investigated to improve the validity of the results in future research.

5.4.3 Key Regional Factors that Impact Resource Recovery

The main regional factors in this study and their relationship for each case study building are presented in Figure 5-5. In this figure, five factors including labour costs, landfill fees, regulations, secondary material market, regulations, and cultural perception are visualized. For the labour costs and landfill fees, scores ranging from 1 to 5 are assigned to the buildings, that are directly proportionate to the values of labour costs and landfill fees, with 5 signifying the most favorable conditions that can improve building recovery (i.e., lowest labour costs and highest landfill fees) and 1 reflecting the least favorable (i.e., highest labour cost and lower landfill fees). For the remaining factors, scores were assigned to denote their presence or absence in each region, classifying them as max, mid, or min scores. For instance, Building 2's region (Switzerland) was marked as 'max' for the presence of regulations, Building 1's region (Canada) received a 'mid' score since some incentives and policies were observed in the region, and regions for Buildings 3, 4, and 5 (China, Nigeria, and Brazil respectively) showed no regulations putting them at the min score. A similar approach was utilized to assign scores to the secondary material market and cultural perception factors, informed by data collected from the case studies and their corresponding regions. The recovery factor estimated for each building alongside the building location is shown in the legends.

The figure indicates that according to the recovery rates estimated for the case study buildings (Table 5-3), lower labours costs do not improve the building recovery since regions with lower labour costs such as Buildings 3 and 4 do not have higher recovery rates. Building 2 covers the largest area in the figure and has the highest recovery rate among the studied regions. On the contrary, Building 4 covers the smallest area and has the lowest recovery rate. Furthermore, the figure indicates that in all case studies where some sort of cultural perception existed, a relatively higher building recovery rate was observed, highlighting the importance of this factor.

Figure 5-5: Relationship Between Key Regional Factors for Case Study Buildings

Although building deconstruction and reuse are labour-intensive, no strong relationship was observed between lower labour costs and higher building recovery rates or reuse implementation. In the case of Buildings 3 and 4, lower labour costs did not lead to higher recovery rates, whereas Building 5 had the second highest recovery rate among the case studies with a similar labour cost to Building 4. This is while labour, equipment, and material costs alongside strict project schedules are normally considered to be the main drivers for building EoL choices (Arora et al., 2021; Dantata et al., 2005).

The results indicate that a region's construction and demolition norms are one of the main factors that result in more sustainable EoL choices. When buildings are not properly designed and constructed for future recovery, material reuse becomes technically infeasible (Rakhshan et al., 2020). Aside from the technical factors associated with building recovery, without reverse logistics infrastructure, building recovery is hardly financially viable (Ding et al., 2023). Limited knowledge of the Circular Economy in some regions has led to ignorance of the value of secondary materials. Proper recovery of building materials requires skilled labour in deconstruction and technical experience, which directly impacts the cost and feasibility of building component extractions (Ababio and Lu, 2023; Arora et al., 2017; Gorgolewski, 2008).

On the other hand, having an established secondary material marketplace can also substantially influence the attitude toward reuse. The market creates financial incentives and leads to higher returns on investments in deconstruction-focused projects (Arora et al., 2017; Caldera et al., 2020). Unofficial reuse practices (similar to what was observed in Building 3 and 4) are also observed in many regions, especially in developing economies (Grant and Oteng-Ababio, 2016). These types of reuse practices are hardly tracked and accounted for but do have positive impacts in diverting waste from landfills and reducing material consumption rates (Arora et al., 2017). However, the lack of regulations and control on the process leads to lower financial gains and scalability challenges that can demotivate the construction industry from reuse in the longer term. With better management and effective collaboration between the formal and informal reuse sectors, high recovery rates can be achieved within the built environment (Wilson et al., 2009).

Regulations and policies are found to be extremely important in driving resource recovery strategies. In regions where strict landfill fees and waste diversion policies are implemented, more recycling and reuse practices are observed (Building 1 and Building 2) as opposed to regions where waste can easily be dumped in landfills at no extra charge (Building 3 and Building 4). Illegal landfilling should be controlled in facilitating building component reuse and recycling. Policymakers can play an important role in facilitating sustainable construction and demolition waste management, specifically when policies are developed, implemented, and controlled at the regional level (Jain et al., 2020; Shooshtarian et al., 2020; Su et al., 2020).

Overall, the results from the application of the model on the case studies show that general perception towards reuse and social economy factors are important factors that can impact building material recovery alongside regulations and policies. For instance, in regions where deconstruction and reuse are not commonly practiced (like Nigeria in this study), salvaging could still potentially offer a cost-effective approach. However, the limited prevalence of these practices means that the true value of reusing materials is not yet captured. While other studies found that intraregional wage differences influence CDW practices (Coelho and De Brito, 2011), the results from this study suggest that interregional wage differences do not seem to be an influential factor in building recovery practices.

Possibly, this is because the other factors such as construction norms and legal constraints typically are relatively constant within a region.

By learning from the impact of regional factors in building material recovery, implementing more impactful interventions can significantly improve end-of-life practices. To enhance building material recovery, it is crucial to implement specific regional considerations. The establishment of a regional secondary marketplace dedicated to material salvaging is crucial. Such marketplace simplifies the logistics of reselling secondary materials and increases the demand for recovered building components. Moreover, the development and enforcement of policies that actively encourage material recovery, whether through mandates or incentives, can be instrumental in shaping regional practices. Increasing landfill fees and rigorously enforcing associated legislation provide a financial incentive for responsible waste management, further emphasizing the importance of recovery. Lastly, fostering a better understanding of circular economy principles and building material recovery within the region can help cultivate a culture that gradually shifts regional norms towards more sustainable and resource-efficient practices.

5.4.4 Limitations

Given the early stage, the broad scope, and the exploratory nature of this study, limitations are unavoidable. One of the main challenges in conducting this research was collecting accurate data on building demolition and deconstruction costs in each region at the building component level. Access to construction and demolition data is generally quite difficult. The costing references also only provide average rates based on reported projects and might not be fully reliable (though they are used when no other information exists, because their inaccuracies tend to balance each other over a complex project cost estimate). Moreover, costing references do not exist for all regions. Data collection for this study was completed using a combination of extracting data from costing references, secondary data from the literature, direct consultation with companies and experts, and available data sets on the web, which can lead to inconsistency and inaccuracy of results between regions. Due to the sensitive and variable nature of this data, it was not possible to corroborate all numbers with real building waste management projects. Market exchange rates were used to convert each region's currency to 2020 USD rather than purchasing power exchange rates. Therefore, some of the disparity in the results between case studies are due to this factor. The research is also limited by using the described optimization model as the quantification method, which is solely based on optimal building component recovery options at EoL with an assumption of a profit maximizing firm. Other tools and frameworks can be tested alongside the provided methodology in the future to validate results.

Another limitation is the different LODs and modeling standards used in the BIMs. The BIMs were collected from local companies to better represent regional construction norms. Differences were observed in the way the components were labeled in the building and the detailed information of each component depending on each region's conventional modeling techniques. Moreover, the process of cleaning and extracting data from the BIM introduces potential human errors that might affect the accuracy of the input into the tool. This process can be improved by automating quantity take-off and component breakdowns.

Finally, the chosen case studies are unique buildings with specific attributes. The degree that any one model or set of models could represent a region, is a challenge (although this is an ongoing objective of some national statistics agencies such as the BLS in the USA). Yet, the models are qualitatively representative, and choosing one building for all five countries was not a reasonable alternative, given their different building codes, preferred building materials, existing estimating data, and architectural norms. Case study buildings were picked for consistency between the size, complexity, use, and construction type, knowing that the functional unit was not exactly equivalent. The outputs were also normalized by floor area before comparison. However, more case studies should be tested for further validation of the results and a deeper understanding of how regional differences affect optimal CDW management at the building level.

5.5 Conclusions

This study investigates the impact of regional factors on the recovery of building components using five geographically distributed case study buildings. The case studies were assessed in different regions with varying conditions, using an optimization model to estimate the recovery potential of building components. This chapter provides insights into the impact of regional factors on building material recovery at the end-of-life based on the outputs generated from the optimization model for the case study building. Though further systematic research should aim to test and confirm these findings using a larger sample or a more comprehensive methodology, this research underscores the significance of decision-makers avoiding uniform approaches and emphasizes the value of gathering and analyzing regional-level data. The data collected on building component extraction cost and processes, recovery processes, the value of recovered materials, and construction and demolition norms are also valuable and can be used in future research for a deeper investigation of building material recovery processes. In summary, the findings emphasize the importance of cultural perception and social economy factors, in addition to regulations and policies, in impacting building material recovery. Additionally, it appears that labour cost variations between regions do not have a substantial impact on building recovery practices.

Potential future research can include the extension of the research scope to include other regions and case studies for a thorough statistical analysis of the relationship between regionally dependent factors and building recovery at EoL. Additionally, considering the noticeable impact of cultural norms and social factors in this study, a possible future research path is a focused investigation of how such factors can be used to intervene accelerating the shift towards a circular economy in the built environment. CE adoption research is at times more focused on mitigating the technical challenges of CE implementation, whereas behavioral and social factors can highly impact the process and are sometimes overlooked, especially by technical stakeholders.

The results validate the hypothesis that some regional factors can influence the recovery of building components, and interventions should consider region-specific factors. However, it is important to acknowledge that the presented results offer a general perspective based on a small sample and only offer preliminary insights. The findings from the case studies provide valuable insights into the complexities and nuances of building recovery practices in the construction industry and highlight the need for further investigation into the drivers behind these practices, especially the social and cultural factors. The research contributes to a necessary foundation for understanding the current state of adoption of circular economy in the construction industry and can inform policymakers and industry professionals as they work towards more circularity-enabled practices. By promoting a better understanding of sustainable practices in the construction industry, the research contributes to the shift towards a more circular economy that maximizes resource utilization and minimizes waste.

Chapter 6: Evaluating the potential impact of building design options on material recovery during deconstruction

This chapter corresponds to the following working article[4]:

Mollaei, A., Bachmann, C., & Haas, C. (2024). Evaluating the potential impact of building design options on material recovery during deconstruction. (Under Review)

Abstract

Construction accounts for 11% of the embodied carbon and 50% of the solid waste in our economy. Recovering materials from deconstructed buildings at the end of their life cycles can reduce embodied carbon and waste over the long term. A methodology to evaluate the impact of common circular design and construction strategies on the future recovery potential from buildings is proposed in this paper. Four main strategies were identified and modeled using an example of a newly constructed modular building in Ontario to validate the evaluation methodology. Quantitative estimates are made of the impact of the strategies on future component recovery using a decision support optimization tool. The tool helps select optimal end-of-life options for each building component thereby resulting in maximum recovery rates and projected value from materials resale. Application of the methodology indicates that among the diverse strategy outcomes observed, mono-material construction has the highest end-of-life recovery potential and the lowest environmental impact. Furthermore, the results show variability in end-of-life process costs among strategies for achieving equivalent recovery rates. Coupling such estimates with conventional construction cost and embodied energy estimates may become an important consideration during the initial design and construction phases. Construction stakeholders can leverage similar assessments to effectively understand the impact of applying alternative strategies to any building design. This methodology has the potential for broader application to emerging circular building design and construction strategies.

[4] To maintain consistency with the thesis format, this chapter is slightly modified compared to the submitted article. The provided abstract is an exact copy of the submitted work.

6.1 Introduction

Among the EoL-focused circular strategies, resource recovery is one of the most common strategies, with high embodied carbon reduction potential that prevents building materials from ending up in landfills through reuse, recycling, and other recovery processes (Esa et al., 2017; Geissdoerfer et al., 2020). However, the recovery of materials from buildings when they reach their EoL is highly dependent on the decisions made throughout the building life cycle as early as the design and construction phases (Dams et al., 2021). Previous research has identified some early design stage circular strategies applicable to buildings such as Design for Disassembly (Bogue, 2007; Dams et al., 2021), design for longevity and extending material lifecycle (Antonini et al., 2020), and generating building material passports and digital twin implementation in initial building development stages (Byers & De Wolf, 2023; Honic et al., 2019b). However, the impact of these strategies on the future recovery of materials is not well estimated quantitatively, partly leading to their limited implementation by construction stakeholders. To fill this gap, the overarching goal of this chapter is to estimate the impact of circular design and construction strategies on recovery potential in the building design phase. To achieve this goal, the following research objectives are addressed:

- Identify common practical circular strategies that can impact the future recovery of building materials;
- Propose a method for assessing circular design and construction strategies in the building design phase using BIM and optimization tools; and
- Apply the proposed method to assess the impact of the identified circular strategies on the future recovery potential of a case study building and provide an analysis of the results.

The remaining section of this chapter are structure as follows. Section 6.2 presents a literature review aimed at identifying circular strategies applicable to the early stages of a building's life cycle. This section summarizes four of the most commonly encountered strategies in this context. In section 6.3, a methodology is proposed that can be used to quantitatively estimate the impact of the identified strategies on building material recovery. The methodology is applied to a case study building. Section 6.4 summarizes the findings of the study alongside a discussion of the impact of each strategy and addresses the study's limitations. Finally, section 6.5 provides conclusions drawn from the research findings and suggests potential avenues for future work in this area.

6.2 Overview of Circular Building Design and Construction Strategies

In the context of existing buildings, the decision to pursue resource recovery is mainly influenced by the chosen EoL process. Traditional demolition, involving machinery and mixed waste disposal in landfills, is the prevalent EoL approach (Diven & Shaurette, 2011). A less favored option is deconstruction, a more resource-recovery-oriented method that entails the careful disassembly of a building through manual labour to salvage and reclaim components (Allam & Nik-Bakht, 2023). Deconstruction demands skilled labour, is time-intensive, carries inherent uncertainties related to the quality and market value of recovered materials, and may be infeasible in certain cases due to building configurations and the building's material composition (Dantata et al., 2005; Koc & Okudan, 2021). Many of these challenges are closely tied to decisions made during the initial phases of the building life cycle, particularly during design and construction (Crowther, 2022). Learning from these challenges is vital; it leads to considering proactive steps to address the highlighted issues and ensure that future building stocks are designed with EoL recoverability in mind.

The design and construction phases of a building are important for aligning with the transition from linear to circular principles over the life cycle of a building (Van den Burg & Vos, 2019). During these stages, critical decisions are made regarding building geometry, materials, connection types, construction techniques, and component specifications (Eckelman et al., 2018). Recognizing the importance of decisions made during the early phases of the building's life cycle, researchers have investigated different circular interventions aimed at enhancing the potential for building recovery at EoL (Arora et al., 2018; Machado et al., 2018; O'Grady et al., 2021).

The EoL of a building is firstly dependent on the type and characteristics of the materials and components used in that building (Hillebrandt & Seggewies, 2019). Hence, the inherent recoverability of the materials and components highly influences the future recovery potential of the building system. Choosing materials that are recyclable, non-toxic, require little maintenance, and possess high secondary market values can enhance the building's recovery potential (Bertino et al., 2021; Rahla et al., 2021). Therefore, considering the use of durable materials in the design of the building can improve the recovery potential of individual materials and thus improve the circularity of the building at EoL (Akanbi et al., 2019a). For instance, the use of structural materials with high durability ensures improvements in the quality of the extracted materials from the building for use as new resources (Hooton & Bickley, 2014).

A potential circular strategy at the component level is the adoption of systems and assemblies crafted from single materials, often referred to as mono-material assemblies (Roithner et al., 2022). This approach significantly reduces the effort required for material sorting and detachment during the deconstruction process, thereby making the operation less labour-intensive (Binder & Riegler-Floors, 2019). Mono-material construction is an effective strategy for improving building recoverability at EoL considering the limited required labour for detaching assemblies and separating materials.

In building components made of multiple materials, the designed ease of material separation within the building assemblies can facilitate building recovery by improving material sorting and processing at EoL (Akanbi et al., 2018; Akinade et al., 2015). Furthermore, recovered building components should adhere to standard specifications considering their sizes and use cases, promoting their reuse in various locations rather than relying on highly unique components (Coelho et al., 2020; Küpfer et al., 2023). The use of standardized detachable systems in buildings helps easily separate individual materials with little damage, making them more suitable for reuse.

Beyond the considerations at the material and component level, early design circular strategies can also apply to the building system. Alignment of the building design with Design for Disassembly (DfD) principles plays a key role in ensuring a building has high recovery potential at the end of its life cycle (Dams et al., 2021; O'Grady et al., 2021). DfD involves pre-planned methods for the optimal recovery of a building during construction without causing damage to what is being removed or the surrounding components (BSI, 2020). Successful DfD implementation necessitates early integration in a project when it is cost-effective. One of the primary DfD strategies involves utilizing easily reversible connection systems between building components, especially structural components (Durmisevic, 2019; Kim & Kim, 2023). Like the importance of detachability of materials within a component or assembly, individual building components should also be easily disassembled to improve overall building recoverability (Riegler-Floors & Hillebrandt, 2019).

Based on the available literature and standards, circular strategies applicable to the design and construction phase of buildings are categorized into four main practical implementation scenarios in Table 6-1. The scenarios provide a list of basic strategies. However, different combinations of the strategies can also be implemented. Construction techniques such as prefabrication and modular construction include a combination of the mentioned circular strategies and highly align with DfD considering their ease of separation, use of standard design elements, and detachable connections (BSI, 2020; Minunno et al., 2018).

Table 6-1: Summary of Identified Circular Building Design and Construction Strategies that Impact Future Material Recovery

Circular Strategies	Description
Strategy 1	Durable Materials
Strategy 2	Mono-Material Assemblies
Strategy 3	Separable Envelope Systems
Strategy 4	Detachable Connections

The circular strategies summarized in Table 6-1 are primarily focused on basic implementable strategies; their impact can be quantified using the proposed methodology. Other abstract circular strategies exist. For instance, digitization of buildings from the early stages of design has also emerged as a solution that can impact building circularity (Honic et al., 2019b; van den Berg et al., 2021). Employing BIM and building material passports enables a comprehensive understanding of the building's material composition and the condition of its components. The digital model functions as the building's 'source of truth,' continually updated throughout its life cycle (Atta et al., 2021; BAMB, 2017).The data can facilitate more precise estimations of the recoverable value of the building. While many new buildings incorporate digital models, accurately modeling existing structures is challenging (Honic et al., 2021). Considering the uncertainties in the building's life cycle having an updated digital model of a building can substantially improve the confidence in the application of the practical strategies.

6.2.1 Research Gap

A review of the existing literature underscores the growing interest in exploring early circular interventions and their influence on resource recovery considering building circularity improvement. DfD principles have been widely investigated in the circular economy context and applied to diverse building systems (Anastasiades et al., 2021; Eckelman et al., 2018; Piccardo & Hughes, 2022). Furthermore, various studies have attempted to quantify these principles using scoring systems and checklist frameworks for high-level assessment (Minunno et al., 2018; O'Grady et al., 2021; Ostapska et al., 2021). Additionally, the potential for deconstruction in buildings, a pivotal factor shaping their EoL recovery potential, has been examined using various methodologies and frameworks (Akinade et al., 2015; Durmisevic, 2019; Mattaraia et al., 2021). For instance, Akanbi et al. (2019b) introduced a BIM-based deconstruction assessment score that considers building connection systems, materials, age, and construction methods. Kim and Kim (2023) delved deeper into building connections, employing graph-based building models to quantify a building's deconstructability and assess the influence of these connections on reusability and the overall environmental impact. At the material scale, individual materials and building systems have been assessed for their future recovery potential using Life Cycle Assessment tools and sustainability scoring (Bakhoum & Brown, 2012; Chiang et al., 2014). Despite these significant contributions, quantitative assessments of circularity strategies in building recovery are still in their early stages of development (Dams et al., 2021). Moreover, the existing literature lacks scalable methodological approaches applicable to a broader scope for assessing the impact of circular strategies on entire buildings, especially during the early stages of decision-making. Therefore, this research addresses this gap by identifying common circular strategies (and potential combinations thereof), presenting a quantitative methodology for assessing their recovery impact, and testing the method's applicability using a case study.

6.3 Proposed Methodology for Evaluating Building Circular Strategies

The methodology for this research includes five main steps that are summarized in Figure 6-1. In step one, a literature review is completed to understand the circular strategies that can be implemented in the initial building life cycle phases to improve the future recoverability of the building. The result of the literature review is the identification of four common strategies that are provided in Table 6-1. In step two, the strategies are modeled in the previously developed optimization decision support tool that estimates the reuse and recycle value of building materials at EoL. Each strategy is studied separately to isolate and identify how it impacts the parameters of the optimization tool. The baselines and the circular strategies are modeled in different scenarios. The third step includes the identification of a case study building to test the proposed methodology and apply the chosen circular strategies. For each scenario, the required input data for implementation of the strategy using the optimization tool is collected. These data include demolition and deconstruction cost and labour data for each building component, scrap and salvage value of existing building materials, landfill fees for waste disposal, building material attributes and recovery potential in each scenario, and building component configurations for deconstruction feasibility assessment. In the final step, the optimization is applied to the case study building in the defined scenarios and results are compared to evaluate the impact of the modeled strategies on recovery.

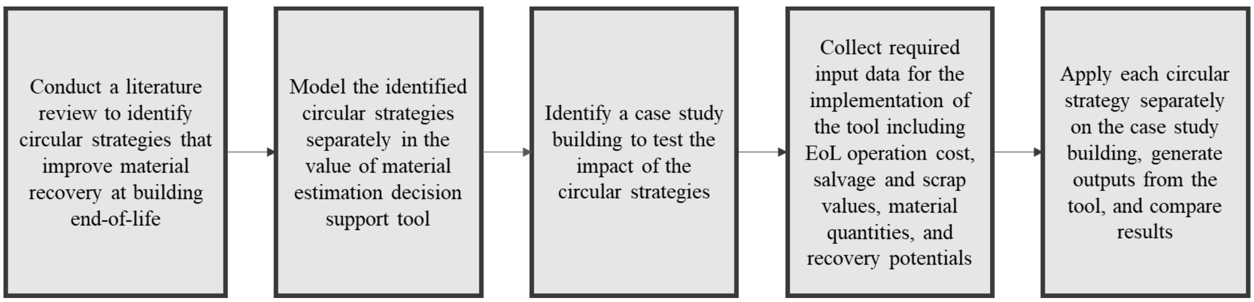


Figure 6-1: Overview of Research Methodology

6.3.1 Estimating the recovery potential of buildings

6.3.1.1 Application of the Decision Support Optimization Tool

To quantitatively evaluate the recoverability of buildings at EoL, the decision support optimization tool that estimates the value of in-situ materials is used as a starting point. The optimal EoL is estimated by only minimizing the net building demolition and deconstruction costs, which include the total cost corresponding to the extraction of materials subtracted by the total value obtained from resale of the recovered materials, while minimizing the overall project duration.

A BIM models is used as the main input for the tool. Information regarding the quantity of materials, material types, and the sequence in which components need to be removed in demolition and deconstruction projects, based on their configurations are extracted from the model. In the next step, for each building component, a recoverable mass is calculated based on the component's Recovery Factor (RF). For each component, collected data on the demolition and deconstruction costs, labour expenses, disposal fees, and the secondary market values for salvaged and scrap values are assigned to the corresponding building components individually. The optimal EoL choices for building components are then found such that the project net cost and duration are minimized subject to the precedence relationship between building components and the deconstruction and demolition feasibilities influenced by the connections between components.

The following economic and environmental outputs are used from the optimization tool to evaluate and compare the impact of the identified circular strategies:

- **Demolition Cost:** Total cost of traditional demolition operations, material transportation, and disposal in landfills
- **Recycling Cost:** Total cost of building material extraction through selective demolition, material sorting, and transportation to recycling centers
- **Reuse Cost:** Total cost of building deconstruction and preparation for reuse
- **Recycle Value:** Total obtainable value from resale of scrap and recyclable materials and components
- **Reuse Value:** Total obtainable value from resale of salvageable materials to be used for similar purposes
- **Net Cost**: Sum of all demolition cost, recycle cost, reuse cost, recycle value, and reuse value
- **Avoided Waste:** Total amount of waste diverted from landfills in the scenario compared to a traditional approach where buildings are landfilled
- **Avoided Carbon**: Total amount of saved carbon emissions in the scenario compared to a traditional approach as a result of recovering building materials

Overall, the optimization tool is used as a quantitative method that provides an estimation of the recovery potential of buildings. Although there is uncertainty associated with the input data, the tool provides a proxy estimate for comparison and evaluation of the impact of the strategies.

6.3.1.2 Applied changes to the decision support optimization tool

The structure of the existing tool enables modeling some features of the strategies by modifying certain parameters and inputs of the model. However, two main extensions are made to the original optimization model in this research. The RF, which is a value between 0 and 1 accounting for the recovery potential of each component, was previously considered fixed for both the reuse and recycling EoL options. This is a conservative assumption for recycling, since it is assumed that the portion of the component that has deteriorated over time does not have recycling potential and should be dumped. However, recycling might still be possible since the performance of the material can be improved in the recovery process. To better incorporate the impact of Strategy 2 (using durable materials), separate RFs for recycling and reuse are considered in this research. It is assumed that in case of reuse, the conservative RF is applicable; however, for recycling, a 20% higher RF (up to a maximum of 1) is considered (Akanbi et al., 2019a; Honic et al., 2019a).

To further account for the connections between structural components in the building, a connection matrix is added to the optimization model. The concept of representing building components using graph theory, where building elements are shown on nodes and connections are presented on edges has been previously utilized in the domain of BIM (Khalili & Chua, 2015). Kim & Kim, (2023) have utilized this theory to assess the detachability of building components and account for the impact of connection types on the environmental impacts and reuse potential of building elements. The connection matrix introduced in this research is a symmetric matrix serving as another representation of the building graph model. With n components in the building, an $n \times n$ connection matrix is generated.

When two components in the building are connected, a score ranging from 1 to 5 indicating the "work" required to detach the two components is assigned to the corresponding array of the matrix representing the connection between the two elements (Riegler-Floors & Hillebrandt, 2019; Rosen, 2019). For each component, a total score is calculated by summing the row corresponding to that component. The summed number is used as an indicator of the deconstruction difficulty for each component's connection type (corresponding to each connection strategy) that impacts the deconstruction cost and is directly mapped to the deconstruction cost. The deconstruction cost is assumed to be a linear function of the total score (Rosen, 2019).

Equation 6-1 shows the formulation of the connection matrix.

$$S_{i,j} = \begin{cases} 0 & \forall\ i = j \text{ or is not connected to } j \\ w & \forall\ i \text{ is directly connected to } j \end{cases} \quad , where\ \ w \in \{1,2,3,4,5\} \qquad \text{(Equation 6-1)}$$

where $S_{i,j}$ is the element of the matrix representing the connection between component i and j, and w is the work score. Equation 2 represents the calculation of the connection score.

$$CS_i = \sum_{j=1}^{n} S_{i,j} \qquad \text{(Equation 6-2)}$$

where CS_i is the connection score corresponding to component i and n is the total number of components in the building. $C_{i,3}$, which is the deconstruction cost of component i (as defined in Table 3-1 alongside other parameters of the optimization tool), is assumed to be a linear function of the component's connection score (CS_i).

6.3.2 Implementation of Circular Strategies in the Optimization Tool

The impacts of the circular strategies identified in Table 6-1 on the future recovery potential of new buildings are assessed in four separate scenarios. Alongside these scenarios, a traditional demolition scenario and a base optimization considering current building conditions with no circularity measures implemented are also analyzed to benchmark the impacts and compare the results. The details of modeling the six scenarios (i.e., two baselines and four circular strategies) are explained individually below.

6.3.2.1 Traditional Demolition

In the traditional demolition scenario, the building is assumed to be demolished in a conventional manner. This process involves the use of heavy machinery and labour to dismantle the building, aiming for a time-efficient removal, but often generating substantial waste. Building materials are often damaged and hardly separable in this scenario. This is one of the most practiced EoL approaches in the industry due to the shorter project durations and easier access to skilled labour to complete the project (Allam & Nik-Bakht, 2023). For each material, the cost of demolition, transportation, and landfill fees are utilized to calculate the project cost. No recycle and reuse values are obtained in this scenario.

6.3.2.2 Base Case Optimization

In the base case optimization, the decision support tool is applied to the building considering all the current design and construction methods as outlined in the building documentation with no consideration of circularity. The required input data including material attributes, demolition and deconstruction costs, resale values, and connections between structural components as described in the input requirements for the tool are used in the optimization tool to estimate the optimal recovery potential of the building. In this scenario, recovery is normally limited to certain components such as windows, doors, components made of metals, and high-quality wood frame materials that are both easier to disassemble and have higher resale value.

6.3.2.3 Durable Materials

Improving the durability of building components by using better quality and longer-lasting materials reduces the deterioration and depreciation of building components (Hooton & Bickley, 2014) Therefore, when the building reaches the end of its lifecycle, the materials embedded in the building can have adequate performance requirements for reuse. An example is the use of durable structural concrete in buildings that enables a longer-lasting building structure, which can be useful for adaptive reuse (Alexander et al., 2017). The impact of this strategy is modeled by increasing the design-life of the structural components in the building by 50 percent. The design-life increase directly impacts the

RF estimated for the building component at the common strategy-comparison deconstruction-date; that affects the reuse and recycle values of the components and the building.

6.3.2.4 Mono-Material Construction

Performance requirements in envelope systems have led to the use of various layers of materials. Recovering these envelope systems when they reach their EoL requires substantial effort in the separation of the system and sorting of materials making them unsuitable for future building recovery. However, the use of mono-materials largely reduces the work required in the demolition process and improves the recovery potential of buildings (Binder & Riegler-Floors, 2019). Use of mono-material systems entails using assemblies that have low Statistical Entropy (SE). When a product is made up of only one type of material, this leads to the lowest SE, whereas the SE increases in the presence of mixed materials (Roithner et al., 2022). Generally, building components with lower SE have higher reusability and recyclability. Although in these designs, recycling, and reuse of building components becomes simpler, additional measures should be considered to ensure the thermal and structural performance of the assemblies are sufficient. Examples include solid timber construction, which mainly includes solid wood elements joined without glue or metal fasteners, and aerated concrete brick wall systems.

To model this scenario, the existing wall systems of the building are replaced with appropriate mono-material assemblies. For instance, in a wood frame building, the wall systems can be replaced with solid timber walls with equivalent thermal performance. Using mono-material assemblies improves the recoverability of the building components and reduces deconstruction cost by around 30 percent considering the reduced labour required for dismantling (RSMeans, 2023). The above-mentioned impacts are considered in the optimization tool as part of replacing the existing wall assembly with mono-material systems.

6.3.2.5 Separable Envelope System Assemblies

The recoverability potential of building systems relies on both the ability to separate each building material cleanly by their type as well as the quality of each material for recovery after their separation. Therefore, the use of envelope systems in the roof and façade of the building that are made of materials that naturally have high recovery capacity and are connected with easily separable connections can improve the building’s recovery at EoL. Using dry-laid brick shell or ventilated curtain façade on a load-bearing exterior wall are good examples of separable and recoverable envelope systems. This scenario is modeled in the optimization tool by assuming the use of exterior wall systems in which the shell is easily separable from the wall structure. Therefore, considering the easier separability of the wall systems, the deconstruction cost corresponding to the exterior wall structure and cladding system is reduced by 65 percent as suggested by Rosen (2019).

6.3.2.6 Detachable Connections

The connections between building elements can be categorized by their physical principles in three groups: positive locking (e.g. fasteners, hook-and-loop), friction locking (e.g. screws, nails, bolts), and material bonding (e.g. welding, gluing, adhesive) (Riegler-Floors & Hillebrandt, 2019). The feasibility of component deconstructions is largely dependent on the reversibility of connections used in the building. When building components are easily detached, less labour is required in the deconstruction process. Additionally, materials are easily separated for more effective recycling and reuse (BSI, 2020). In order to quantify the impact of connection detachability, Rosen (2019) suggested a scoring system from 1 to 5 assigned to connectors that represent the amount of "work" required to detach the components.

The impact of connections between structural elements is included in the optimization tool through the connection matrix. The connections that fall in the category of material bonding have a score of 5, the ones with friction locking are assumed to have a score between 3-4 based on the number of used connections, and finally, the positive locking connections get a score of 1 or 2 depending on the shape of the connectors. To model the impact of connection detachability, the elements of the connection matrix greater than 1 were subtracted by 1, assuming that they are replaced with a suitable alternative that is relatively easier to detach. As described in section 3.1 regarding the connection matrix, the new score for each component is applied to the deconstruction cost of that component. It is assumed that the existing connection score represents the default deconstruction cost, which is based on the data used from existing costing references. The deconstruction costs are changed linearly as the connection scores change.

6.3.3 Overview of Case Study

The case study chosen for this study is a newly constructed building located in southern Ontario, Canada. The building is a multi-unit residential building with 24 residential units. The building has three stories and a Gross Floor Area (GFA) of 1575 m^2. In its original design, a wood framing system and a modular construction approach have been utilized, making the building highly reusable in current conditions. Figure 6-2 shows an overview of the schematic building model. A BIM model of the building is created in Revit from the architectural and structural drawings collected from the building owner. Required costing data for the analysis are collected from RS Means (RS Means, 2023). The reuse and recycle market value of materials and components are collected from online secondary marketplaces (Demolition Traders, 2021; Recycler's Exchange, 2021; Repurposed Materials, 2021; Salvage Garden, 2021). A reuse expert was also consulted to validate data and findings (D.Bennink, personal communications, May 9, 2023)

To generate the connection matrix for the case study building, the structural drawings including the connection details are reviewed. The connectors are compared and mapped with available examples of connection detaching efforts as outlined in Hillebrandt et al. (2019). For the case study, the beam to column connection is given a score of 4 considering the use of large number of nails. Connections between joists with the rims are given a score of 3 since nails are used at a lower density. The same score is considered for beam to beam and shear wall connections.

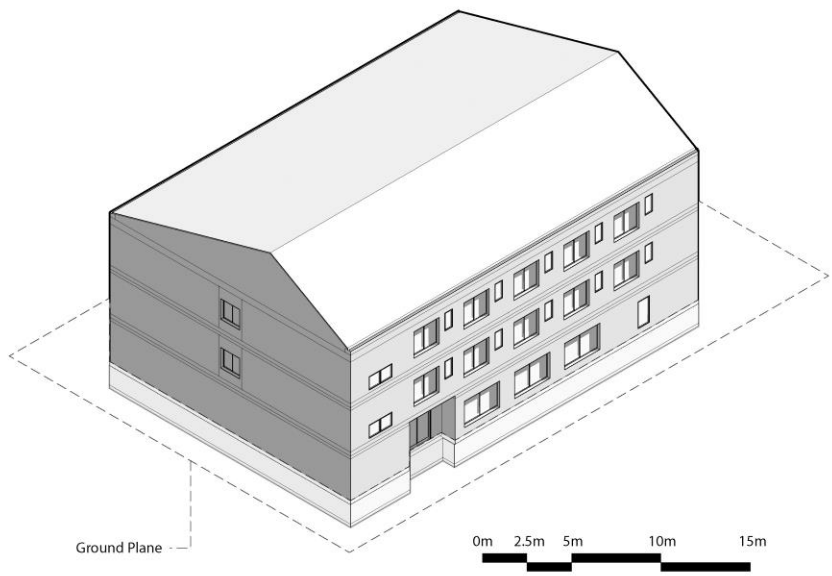


Figure 6-2: Case Study Building Isometric 3D Model

6.4 Caste Study Application Results and Discussion

6.4.1 Impact of Studied Circular Strategies on Future Building Recovery

The results of this research show the recovery potential of the case study building in six different scenarios. In the traditional demolition and base optimization scenarios, no additional circularity measures are applied. These two scenarios are analyzed to benchmark the impact of the studied circular strategies modeled in the other four scenarios. In the traditional demolition scenario, the decision maker does not aim to minimize expenses by selecting the best EoL option for each component. This approach can make sense from a broader business perspective, especially when duration to completion takes precedence in the project, as it often does by default. On the other hand, the optimized base case serves as a reference point for assessing how implementing the circular strategies impacts the outputs of the optimization tool compared to the current conditions. The base case optimization is also considered a logical behaviour with the assumption of the rational firm with cost-minimization objectives. It is important to note that the results from this scenario may not always align with common practices, as traditional demolition methods are often preferred (e.g., due to time constraints). However, in the field of building waste management, there is no universally applicable baseline scenario that can accurately capture the true situation, as the choice of a base case depends on the specific context and region.

Figure 6-3 shows the count of different building component categories used in the optimization tool. Considering that the building has a wood frame, the majority of the building components are framing components including beams, columns, wall structure studs, and joists. The total weight of each building component category is provided in Figure 6-4. Comparing the weight and count of components (Figure 6-3 and Figure 6-4) indicates that the main structural components compose a smaller portion of the total building mass compared to the number of components. The building also has a relatively lightweight framing system, which can positively impact its recovery potential.

In the traditional demolition scenario, the deconstruction project's net cost is approximately $83,000. This cost includes the cost of demolition labour, machinery, waste handling and hauling, and disposal fees based on average North American costs. There is no recovery value or environmental benefit in this scenario. However, the project will be completed in the shortest duration (21 days), which can be a deciding factor for some building owners.

In the cost-optimized base case, it is assumed that the building owner minimizes project net cost by finding the best EoL alternative for each building component given the cost of component extractions and potential reuse and recycle values subject to the deconstruction feasibility and the sequence of extraction activities. The results of applying the optimization on the base case scenario show the current maximum recovery potential of the building. In this scenario, the cost of extracting materials from the building is estimated to be approximately $106,200 and takes 29 days, which includes a combination of building demolition, material sorting, and deconstruction activities given the optimal EoL option for building components. The total reuse and recycle value is approximately $100,800, resulting in a net cost of $5,400. Around 58% of the building mass is recyclable and 5% is reusable. This scenario leads to the diversion of 99 tonnes of waste and 26 tonnes of carbon reduction as a result of the optimized material recovery process.

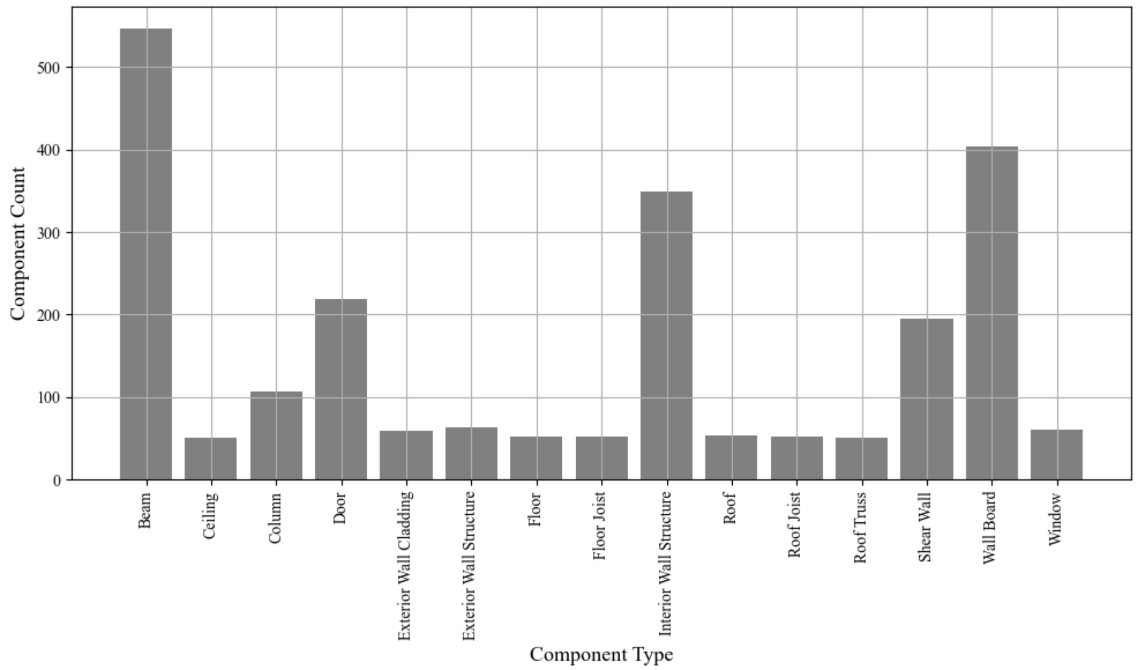


Figure 6-3: Breakdown of Building Component Counts by Type in the Case Study Building

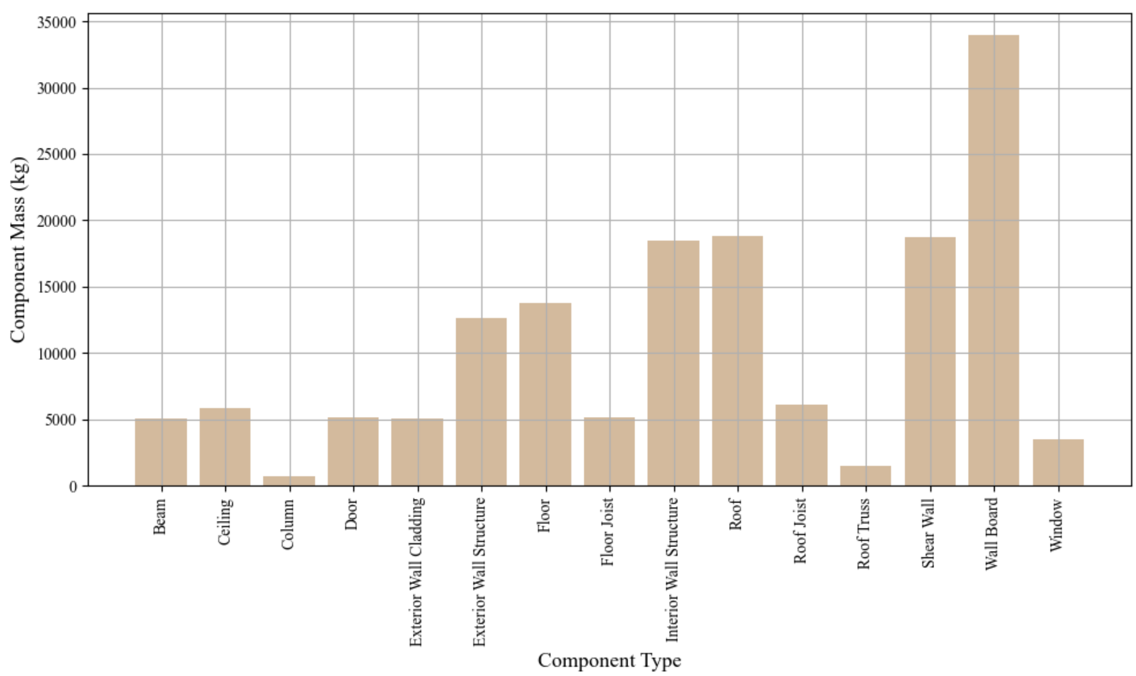


Figure 6-4: Breakdown of Building Component Mass by Type in the Case Study Building

Figure 6-5 demonstrates the breakdown of component extraction costs for the three EoL choices (positive) alongside reuse and recycle obtainable values (negative) for six scenarios (i.e. traditional demolition, net cost optimized base case, and the four circular strategy implemented scenarios). The traditional demolition approach has the lowest building EoL cost. However, no value can be gained in this scenario from material recovery. In the base case optimization, recycling has the highest EoL cost. Reuse makes up only approximately 22% of the total extraction cost, while the value gained from resale of reused materials is substantial.

Scenario 2 (Mono-Material Construction) has the highest extraction cost as well as the highest recycle and reuse value. This circular strategy improves the reusability of the building assemblies by facilitating the deconstruction process and increasing the salvage value of the components. Use of detachable connections (Scenario 4) has the second highest reuse value indicating the impact of improving the deconstructability of structural components in the building on making reuse a cost-optimal EoL option. Although the reusability of the building increases, recycling costs are still higher than that of disposal and reuse (same as the base optimization). This is because while the structural system becomes more reusable, certain interior and envelope components are still recycled making up a large portion of the extraction cost. Scenarios 1 and 3 do not show much impact compared to the base optimization. The results indicate that pursuing these circular strategies does not substantially improve the future recovery of this case study building. Since the implementation of these strategies (1 and 3) requires additional initial construction costs, it might not be financially logical to implement these strategies in this case.

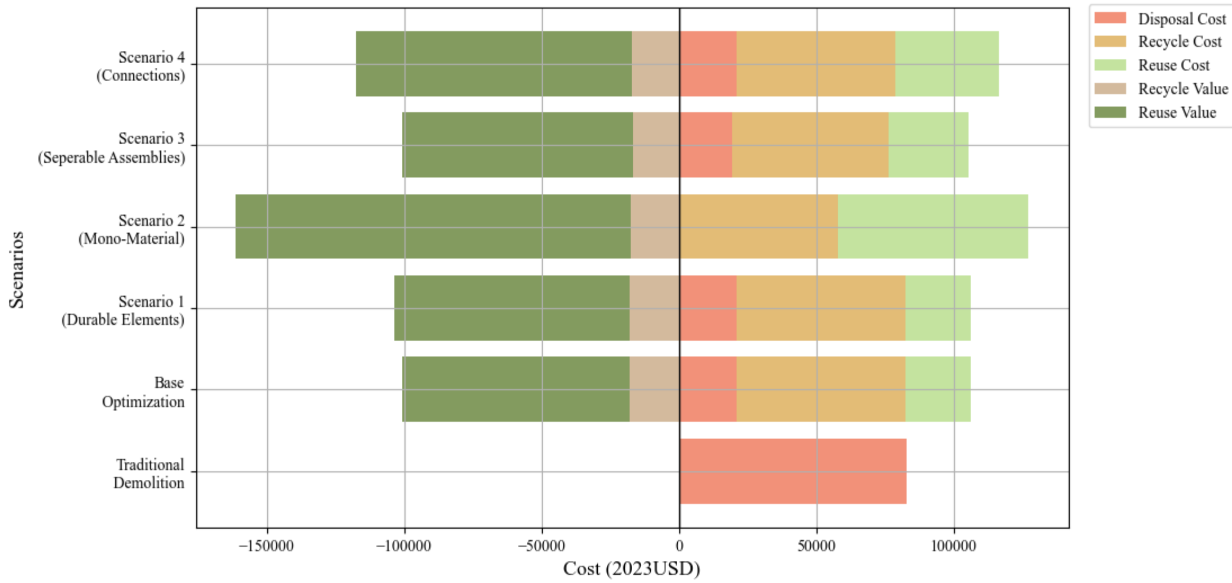


Figure 6-5: Building End-of-Life Cost and Value Breakdown in each Scenario

Figure 6-6 shows the net cost corresponding to each scenario. The traditional demolition scenario has the highest net cost since no value can be obtained from the building materials to offset the EoL costs. The lowest net cost is observed in scenario 2 because of the high salvage value that can be obtained from the envelope systems constructed from mono-material assemblies. Scenario 4 has the second lowest net cost indicating the impact of improving the detachability of the building connections on the EoL costs. The base optimization also has a lower net cost compared to the traditional demolition, even with no additional circularity measures applied to the building. This is mostly because of the type of materials used in the building. The building had a substantial amount of wood, which is a highly reusable building material. Additionally, scenarios 1 and 3 have similar net costs to the base case, with scenario 1 being slightly cheaper. In these scenarios, the trade-off of initial cost and the EoL circularity impact of the strategy should be considered in order to assess whether the strategy should be implemented or not.

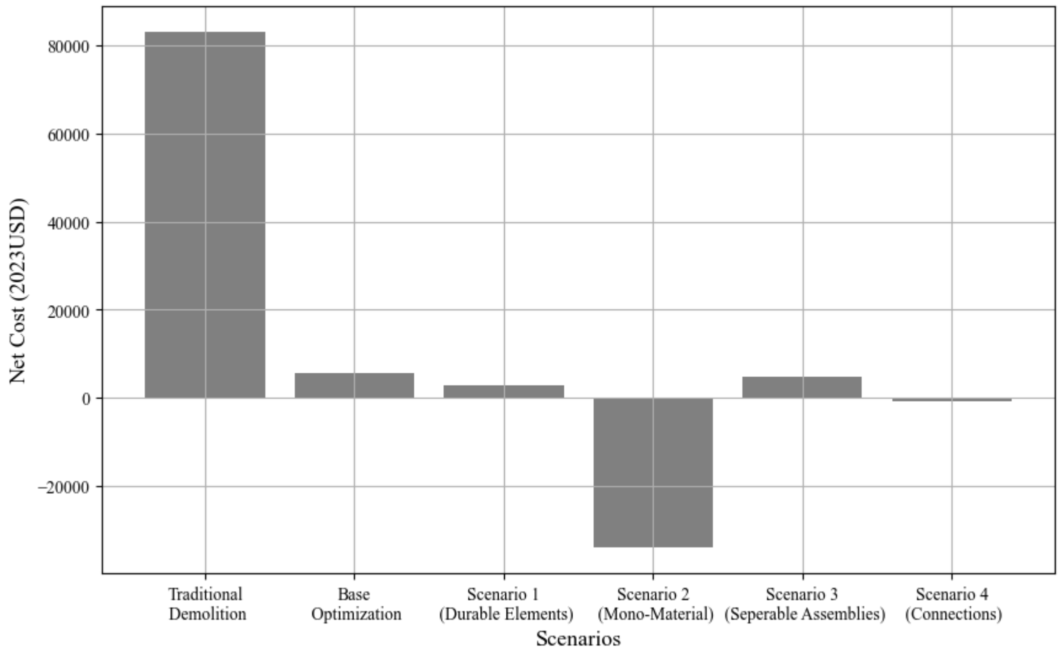


Figure 6-6: Building End-of-Life Net Cost in each Scenario

Figure 6-7 shows the breakdown of the three EoL options for all building components in each scenario by component weight (Figure 6-7a) and by component count (Figure 6-7b). Since the process of extracting components for reuse and recycling unavoidably generates waste, both the component number and weight breakdowns are presented. In Figure 6-7b, the fraction of the component material that is not recovered (as estimated by the RF for each building component in the tool) is included in the disposed weight; hence, the disposal by weight percentage is slightly more than the disposal by component count in all scenarios. Scenario 2 (mono-material) has the least disposal and highest amount of reuse measured by weight and component. The base optimization, scenarios 1, 3, and 4 have nearly similar EoL breakdowns, with scenario 3 having a slightly higher reuse rate. Across these four scenarios, the building's recovery rate is around 64%, with recycling accounting for 59% and reuse for 6%. Notably, scenario 4 has lower net costs (Figure 6-5) and higher reuse dollar values (Figure 6-6). Therefore, the findings suggest that, for an equivalent recovery rate (among the base optimization and scenarios 1,3, and 4), employing detachable connections (scenario 4) results in lower costs and higher salvage values, making this strategy a more advantageous choice for this building from a cost perspective.

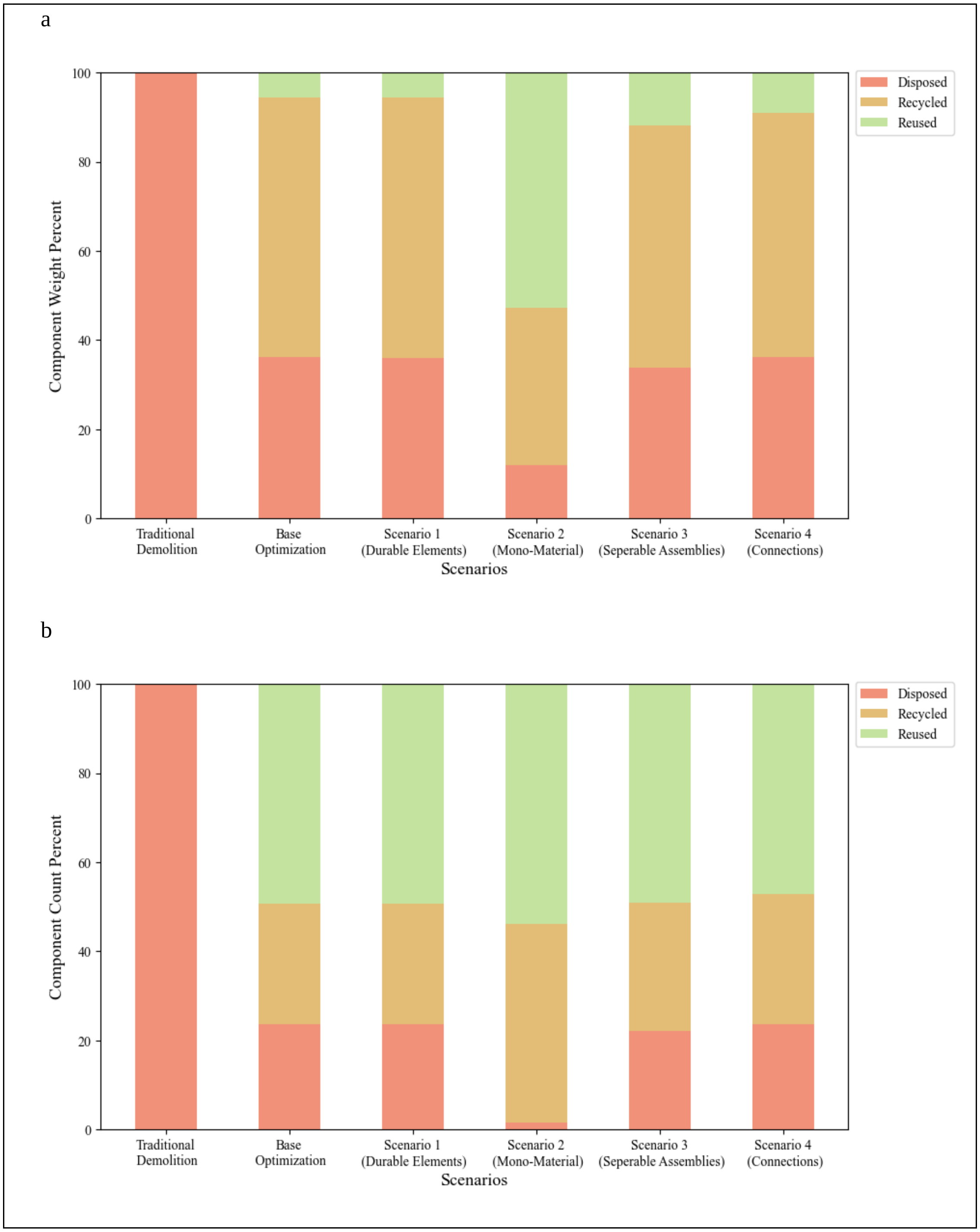


Figure 6-7: Breakdown of Building Component End-of-Life in each Scenario by a) Component Weight and b) Component Count

The environmental impact of each scenario using avoided waste and avoided carbon metrics is presented in Figure 6-8. The avoided waste and carbon are estimated based on the amount of material that is recovered through recycling or reuse. Therefore, the trend observed in this figure is similar to the trend of EoL breakdown by weight for the studied scenarios (Figure 6-7a). The environmental impact of the mono-material construction scenario is the highest among the other scenarios. Aside from the reuse improvements observed in this scenario, for this particular case study, replacing the wall assemblies with solid timber increases the carbon savings in the recovery process. Scenario 3 also shows slightly better carbon and waste savings after scenario 2. However, the net cost of achieving the optimal EoL combination for the building components that results in the shown savings is higher than that of scenarios 1 and 4 (as shown in Figure 6-6).

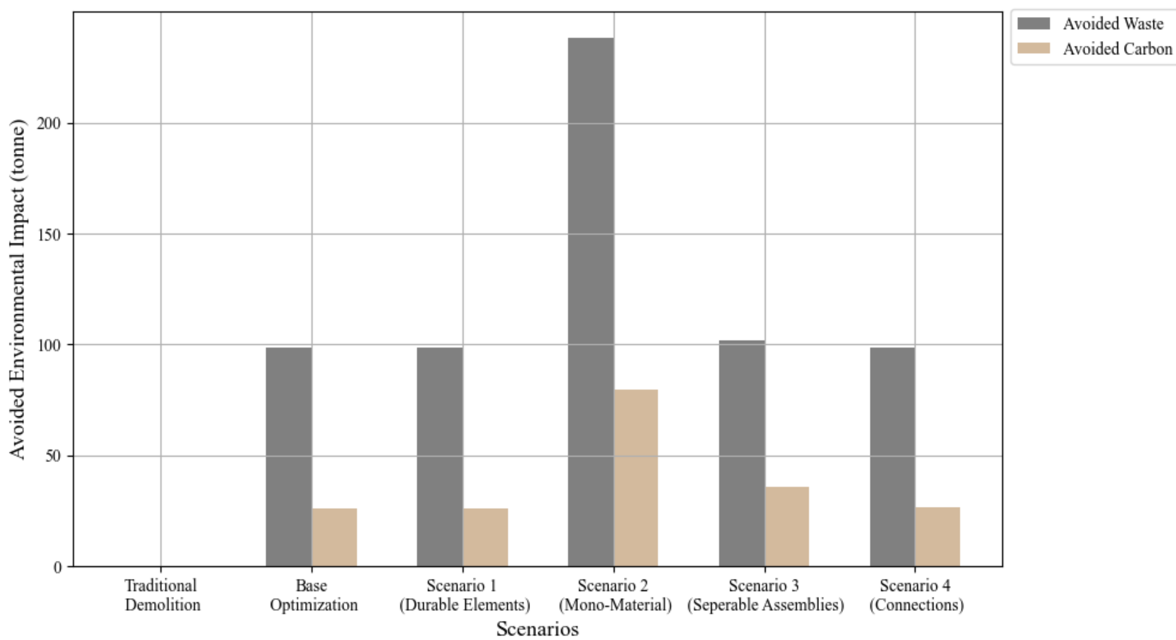


Figure 6-8: Waste and Carbon avoided by Mass in each Scenario

Overall, the results of utilizing the proposed method for evaluating the impact of the four circular strategies on the future recovery of the case study building show variations in EoL cost, obtainable terminal values, and environmental impacts for each scenario. The similarity observed in scenarios 1 and 3 with the base optimization does not necessarily indicate that these strategies have lower impacts on a building's recovery potential. Rather, the specific case study features might not sufficiently capture the way these strategies would help the EoL recovery process in other buildings. Additionally, the described scenarios are illustrative for the purposes of demonstrating the methodology. In practice, designers would have more precise estimates of how the strategies would impact their designs based on specific design and material specifications.

6.4.2 Practical Implications

The proposed methodology and results from the applications in the case study provide insight into how early-stage circular strategies can impact the building's future recovery potential. This methodology for quantitative comparison of different strategies enables stakeholders to make more informed decisions from the initial phases of building development. Circular design and construction decisions are crucial for maximizing material recovery and minimizing landfill waste at EoL. Existing metrics and tools in this area are often qualitative or lack clear definitions (Dams et al., 2021; Minunno et al., 2018; O'Grady et al., 2021; Rahla et al., 2021). The presented methodology is focused on understanding the future recovery potential in different scenarios and can serve as an indicator for comparing the circularity of different building design and construction strategies. In this context, circularity is measured in terms of the future recovery potential of materials and the amount of avoided waste from landfills. Assessment of the prospective recovery potential in various scenarios can be used as a comparative indicator for gauging the circularity impact of design scenarios. Although costs and values are subject to change and acquiring future data can be challenging, the results provide valuable insights from a comparative standpoint.

The primary beneficiaries of this research include building owners and consultants involved in the decision-making process during the early design stages of construction projects. Currently, there is a limited emphasis on the EoL phase of buildings in the construction industry (Kayaçetin et al., 2022). This gap has resulted in substantial waste production. Typically, recycling is the dominant approach for EoL materials, driven mainly by legislation, and reuse is often overlooked (Arora et al., 2020). Additionally, learning from the difficult recovery of existing buildings, future buildings need to be constructed in a way that this issue does reoccur in the future. By incorporating the research findings into their practices, they can enhance the future circularity and recovery potential of building elements. The construction industry's understanding of the circular strategies that can be implemented is pivotal in shaping a more sustainable and circular built environment.

6.4.3 Limitations

The proposed methodology and its application in the case study does not consider the initial construction costs associated with implementing the studied circular strategy in each scenario. Comparisons are solely based on future recovery potential, EoL process costs, and obtainable values without accounting for the initial construction costs of implementation. For some of the proposed strategies, such as mono-material construction, additional construction costs are necessary, potentially influencing the decision to adopt such strategies during the early building phases. Moreover, the technical feasibility of implementing these strategies is not fully explored. However, given the study's primary focus on introducing a quantitative methodology for assessing the EoL value of building components and comparing the impact of strategies based on EoL costs, the consideration of initial costs was excluded. In practice, the addition of these initial costs is a simple calculation.

Another limitation is the absence of temporal considerations regarding the building's recovery potential. The results are all estimated under the assumption of conducting a recovery assessment at present, even though the EoL for a new building may be in the distant future. This approach is conducted under the 'ceteris paribus' principle, whereby all other factors are held constant, rather than attempting a forecast. While it is acknowledged that the inputs may change under future conditions, the uniform application of the same condition across all scenarios remains suitable for comparative purposes. Future implementations could consider forecast values if available. Furthermore, it should be noted that the assessments were reliant on assumptions for costs and values, derived from general reference averages. This may introduce limitations, as construction and demolition costs, as well as material values, are highly subject to change due to varying economic conditions.

6.5 Conclusions

This research introduces a method to quantitatively assess circular strategies in early building design and construction stages. A discussion of four practical circular strategies that can enhance material recovery at a building's end-of-life is provided. The impacts of four of the introduced strategies are compared using the proposed methodology considering both financial and environmental aspects. The core of the methodology includes the multi-objective optimization that intakes building information and was extended to estimate the optimal recovery potential of buildings adopting different circular strategies. The methodology is tested on a mid-rise multi-unit residential building. The results indicate that circular strategies can result in different EoL costs that might lead to similar building recovery rates. In the case of this building, mono-material construction is identified as the most impactful circular strategy. In this scenario, the future reusability of the building is substantially improved by increasing the obtainable value of building components as well as reducing EoL costs. This research provides decision-makers with the tool needed to select and implement circular strategies that can improve building recovery in the early development stages when it matters most. Ultimately, this work promotes informed, sustainable choices, fostering a shift toward circular construction practices that benefit both the economy and the environment.

Future research can be focused on enhancing the cost assessment by including initial construction costs and integrating a financial model to better understand future values. To improve the accuracy of circular strategies, localized studies with precise regional databases on circular assemblies and construction systems should be conducted for the assessment of more feasible design options. Additionally, the methodology could evolve by considering the performance of recovered materials post-recovery and delving deeper into the impact of connections, expanding its applicability beyond the conceptual level. Advancement of quantitative methods for assessing potential building recoverability can help future-proof the circularity of the built environment.

Chapter 7: Conclusions and Contributions

7.1 Thesis Summary

The construction, renovation, and demolition of buildings are driving substantial material consumption and waste streams, thus highly contributing to global embodied carbon emissions. A great portion of construction and demolition waste is disposed of in landfills, despite having recovery potential that could be taken advantage of through the application of proper circular strategies. To address the environmental challenges associated with building materials, the construction industry is increasingly recognizing circular economy implementation as a viable solution. The transition to a circular economy presents an opportunity to create closed material loops and decouple value creation from virgin material consumption.

Resource recovery, a well-recognized circular strategy within the construction industry, can highly contribute to the reduction of construction material consumption and waste generation. It is often considered the lowest-hanging fruit among the applicable circular business models in the built environment with the potential for a high return on investment when executed correctly. Resource recovery primarily targets the EoL phase of buildings, aiming to prevent valuable building materials from ending up in landfills. Despite demonstrating both substantial environmental and financial benefits, the application of resource recovery remains limited. This is primarily due to the incomplete understanding of the value of in-situ building materials and the feasibility of material recovery in buildings leading to uncertainty in the process.

The decision-making process concerning material recovery at the end of a building's life is highly influenced by various factors, making it challenging to achieve optimal solutions that are financially and environmentally beneficial as well as technically feasible to implement. A comprehensive quantitative tool capable of combining the influential factors and estimating the value of materials embedded in buildings has not been available. Moreover, various external factors, including policy considerations, regional factors, and construction and design technologies, substantially impact the potential for building material recovery. These factors need to be analyzed and efficiently utilized to achieve optimal building material recovery in existing and future building stocks.

In the second chapter, a literature review was conducted to identify the factors that impact the value of in-situ materials in buildings. The main identified factors were categorized into five groups of building characteristics, operational, financial, environmental impacts, and policies. These factors were summarized into a conceptual framework that can be used to guide the process required to understand the high-level value of different materials in existing buildings. The conceptual framework included four main phases: 1) Estimating the available recoverable mass of materials; 2) Estimating the cost of material extraction operations; 3) Estimating the environmental impacts of the process; and 4) Estimating the net cost of the material extraction including the obtainable value from material recovery.

In the third chapter, the developed conceptual framework and the identified factors that impact the value of in-situ materials were turned into a quantitative decision support tool that can be used to estimate current recoverable environmental and market values of in-situ construction materials from the owner's perspective. In this tool, a mixed integer multi-objective linear programming optimization methodology was used that considers building material recoverability, cost, value, duration, environmental impacts, and building component precedence in demolition and deconstruction activities. It helps choose the optimal combination of reuse, recycling, and disposal options for those materials. The results of the tool incorporate a cost-time trade-off considering the longer duration of deconstruction activities to enable material recovery as opposed to conventional demolition approaches. The developed decision support tool was functionally demonstrated on an institutional building to find the building components' optimal EoL alternatives to maximize the recovered value from the in-situ materials and project duration. The results indicated that in a cost-optimal scenario, the demolition and deconstruction costs can be offset with the obtained recoverable value of the existing building. However, this scenario was found to have around 30% higher project duration compared to a time-optimized scenario. Sensitivity analyses including OAT, monte-carlo, and scenario analysis were conducted for further validation and quantitative assessment of the impact of key factors on building EoL.

In the fourth chapter, the decision support tool was utilized in the context of existing buildings with a focus on evaluating policy efficacy. Considering the unrealized recovery potential of construction materials embedded in existing buildings, governments have implemented policies such as replacing demolition with deconstruction, banning landfilling, and carbon reduction to either force or incentivize resource recovery and circularity. However, the efficacy of these policies has yet to be fully investigated. In this chapter, a methodology that quantitatively estimates the potential relative efficacy of such policies was proposed. At its center is the developed optimization-based decision support tool that yields the optimal component EoL options. The tool was extended to include policy levers through additional constraints and changes in input parameters. Variations of four policy categories were chosen and applied to five building case studies. The results suggested that policy tools can help enforce near-optimal waste reductions and carbon savings that are not necessarily increasing net project costs compared to traditional approaches. The effectiveness of these policies varied based on waste and carbon savings measures and building types.

The fifth chapter provided a global perspective on the viability of recovering in-situ building materials when they reach the end of their lifespan incorporating regional factors. These regional factors include construction and demolition norms, labour costs, secondary material markets, and general perceptions and culture toward material recovery processes. In this chapter, the impact of regional factors on building EoL strategies was analyzed. To conduct this assessment, five different buildings with similar general characteristics from globally distributed locations were selected as case studies. To analyze the impact of regional factors, the decision support optimization tool was used as the main quantitative assessment method considering its flexibility in taking regionally dependent factor data and generating optimal EoL options for each building component. The results of the optimization reflected market-based practices based on the regional factor data. The study took a comparative approach to analyze the recovery potential of the chosen building case studies. The results of the study highlighted the importance of socioeconomic factors in the decision-making of building component EoL strategies alongside material recovery-related policies, incentives, and waste disposal regulations. Labour costs were found to be less impactful than regulations and cultural norms on materials recovery decisions.

Lastly, in the final scope of this research, the developed tool was expanded for application on future building stocks in the sixth chapter. While research is progressing on diverse strategies that enhance building circularity, there has been no quantitative evaluation of the efficacy of these strategies on the future recovery of new buildings. Therefore, a methodology to evaluate the impact of common circular design and construction strategies on the future recovery potential from buildings was proposed. Four circular strategies were identified and modeled using an example of a newly constructed modular building in Ontario to validate the evaluation methodology. Quantitative estimates were made of the impact of the strategies on future component recovery using the decision support optimization tool. The tool helps select optimal EoL options for each building component thereby resulting in maximum recovery rates and projected value from materials resale. Application of the methodology indicated that among the diverse strategy outcomes observed, mono-material construction has the highest EoL recovery potential and the lowest environmental impact. Furthermore, the results showed variability in EoL process costs among strategies for achieving equivalent recovery rates.

This research supports the application of resource recovery in building and thus the transition to a more circular economy in the built environment. The presented methodologies help realize the full value of in-situ building materials, provide a comprehensive understanding of building recovery potential, and facilitate well-informed decisions in the realm of resource recovery. Construction stakeholders can leverage similar assessments to effectively understand the value of in-situ materials for asset management, demolition and deconstruction project planning, policy intervention, and circularity planning for new buildings.

7.2 Research Conclusions and Contributions

A summary of the conclusions and key contributions of the three main scopes of this research are provided below.

7.2.1 Development of a decision support tool for building recovery assessment

In chapter 2 of this research, a critical gap was identified by recognizing the absence of a comprehensive quantitative tool for assessing building recovery at the EoL. Previous studies have been either fragmented, focusing on specific aspects of resource recovery, or qualitative in nature, relying on checklists and scoring systems coupled with subjective judgments to evaluate building recovery potential. One of the primary methodological contributions of this study is the development of a decision support tool for optimal assessment of building EoL recovery. This tool takes into account the most influential factors, as identified in the literature review, as its primary inputs and subsequently generates an optimal recovery plan. The optimal scenarios are generated such that the project duration or net cost is minimized, the latter of which results in a higher recovery of materials.

This research underscores the significance of recognizing existing building stocks as future material mines, often underutilized from a material recovery perspective. Efficient utilization of these materials can play a vital role in addressing potential future material shortages and reducing environmental impacts. The construction and demolition industry, which has traditionally utilized approaches with negative environmental impacts, can benefit from the adoption of tools like the one proposed here. Decision-makers within the industry will be better equipped to comprehend the financial opportunities associated with the implementation of resource recovery as a circular strategy. Furthermore, understanding and quantifying the impact of the identified factors can pave the way for necessary interventions, the development of regulations, and the implementation of policies. These measures can drive the industry toward more sustainable EoL options, facilitating the secondary use of materials and enhancing the construction industry's resilience concerning future environmental challenges.

7.2.2 Assessment of the efficacy of relevant policies for building recovery

The decision support optimization tool was used to develop a methodology to assess the efficacy of policies focused on building material recovery. Additionally, a categorized list of policies was identified that can improve building resource recovery. Policymakers can conduct similar assessments to test the efficacy of their proposed policies prior to introducing them to industry and prioritize the ones that show preferred outputs such as higher carbon reductions and waste diversions while incorporating financial constraints. Implementing the required changes can drive the construction and demolition industry to change its norms. Building owners may not always select the most optimal EoL choices due to factors like lack of information, project duration constraints, logistical limitations, and limited access to necessary resources for such determinations. Policy tools can serve as a means to force building owners to achieve near-optimal waste reductions and carbon savings, even if this incurs varying costs for them. In instances where optimal behavior by building owners is lacking, effective policies can be enforced to move closer to a more circular economy.

7.2.3 Understanding the impact of regional factors on building material recovery

Chapter 5 delves into the impact of regional factors on building material recovery at the end-of-life, drawing from the outputs of the optimization tool applied to the globally distributed case study buildings. The results validate the hypothesis that regional factors influence the recovery potential of building components, emphasizing the need for region-specific interventions. The results of the research show the complex nature of these influences, highlighting that cultural perceptions and socioeconomic factors, in addition to regulatory and policy considerations, substantially shape building material recovery outcomes, while labour costs do not appear to have a high impact on building recovery practices. The findings emphasize the urgency for further investigation regarding the underlying drivers of these practices, with particular attention to the role of local social and cultural factors in improving building recovery rates. Construction stakeholders can better assess the feasibility and potential benefits of recovering building components based on each region’s specific conditions. Instead of adapting one-size-fits-all circular approaches, regionally focused policies, regulations, and other factors should be assessed in depth using robust methods to effectively reduce waste generation and circulate building materials.

7.2.4 Assessment of circular design and construction impacts on future recovery potential of new buildings

Chapter 6 of this research contributes to the application of circular strategies applicable to new buildings. Previous research has led to the identification of possible early design circular strategies that can be applied to buildings to improve their future recoverability potential. These strategies were summarized in Chapter 6. A method for the quantitative assessment of circular strategies during the early stages of building design and construction is presented that can be utilized for adequately incorporating circularity measures in building design. The proposed approach serves as a valuable tool to effectively select and implement circular strategies, particularly in the critical early development stages when their influence is most significant. The aim is to promote informed and comprehensive decision-making that includes various aspects of building design including future recovery. Coupling such estimates with conventional construction cost and embodied energy estimates may become an important consideration during the original design and construction phases. Construction stakeholders can leverage similar assessments to effectively understand the impact of applying alternative strategies to any building design. The methodology has the potential for broader application to emerging circular building design and construction strategies.

7.3 Practical Implications

The developed building recovery decision support method and the proposed methodologies outlined in this thesis offer practical implications with specific relevance to building owners and, at a broader level, municipalities. Building owners can strongly benefit from the insights provided by these methods into the recovery potential of buildings. This knowledge, in turn, empowers them to make informed decisions aimed at embodied carbon reduction, selecting optimal deconstruction pathways, and maximizing the value of material resale. Building owners can extend the application of the methods beyond environmental considerations to practical and financial aspects. The generated outputs can be used to review and analyze demolition and deconstruction quotes and processes offered by contractors, enabling them to make financially sound decisions and capture the full value of their recovery assets. Municipalities, on a governance level, can leverage similar methods and tools for effective policy interventions. This approach enables them to identify pivotal governance points, leading to reduced challenges and enhanced resource recovery. By implementing these methodologies, municipalities can play a crucial role in shaping circular economy practices at scale.

Despite what the data shows in the application scopes presented in this research, widespread adoption of resource recovery and such methodologies by building owners is challenging. Data accessibility and collection, logistical complexities, illegal landfilling, and contractual arrangements between demolition contractors and owners are some of the problems in the path of implementing optimal building recovery strategies. In many cases, ownership of materials is transferred to the contractor during a demolition project, a practice justified by the time and effort involved in project management and material handling. The project timeline, being a limiting factor, also adds complexity to this process resulting in going back to traditional demolition and disposal approaches. Overcoming these obstacles is essential for realizing the full potential of the developed decision support method and methodologies outlined in this research.

7.4 Limitations

Limitations exist within this research and were provided in each chapter as they were encountered. The overall research limitations are also summarized in four main categories in the following sections.

7.4.1 Limitations with the structure of the decision support optimization tool

One notable limitation of the decision support optimization tool that serves as the core quantitative assessment of the proposed methodologies in the chapters of this research is the absence of considerations for the time value of money. The outcomes generated do not factor in the financial implications of project duration extensions. While this assumption was deemed appropriate due to the typically short duration of building demolition and deconstruction projects, enhancing the accuracy of results could be achieved by incorporating a time-dependent financial model that accounts for the evolution of policies, costs, and values over time. Another limitation inherent to the optimization tool is its underlying assumption of perfect knowledge and rational behavior. The tool presumes input certainty and does not assign probability distributions to these inputs. While in Chapter 3 sensitivity analyses and Monte Carlo simulations were conducted to address this limitation, introducing probability distributions to model inputs would enhance result reliability.

Furthermore, the developed tool also does not adequately account for the quality and quantity of the recovered materials and components. The tool employs the Recovery Factory (RF) parameter, following a typical deterioration modeling approach that is defined as a function of the building's age and the component's lifespan. However, the estimated RF may not consistently align with the actual recoverable mass of building components. Although this research adopted a conservative approach to ensure estimate accuracy, factors such as a component's renovation history and the environmental conditions it has been exposed to can substantially influence its recoverability, which were excluded from this research.

The optimization is also formulated using a linear programming model. Given the level of complexity of this problem and the defined constrains, this approach was found to be suitable to address the objective of the research. The global optimal EoL options were generated in a reasonable computation time. However, other optimization techniques can be explored as the problem gets more complex in future research.

7.4.2 Feasibility of implementing the recovery strategies

The suggested EoL options proposed by the optimization tool in various studied contexts may encounter implementation limitations. These limitations are partly tied to the uncertainties of the tool, primarily concerning the quality and quantity of materials. In practice, it is possible that materials recommended for recovery may not be in suitable condition for recovery and may require disposal instead. Furthermore, the actual configuration of the building may be different from the input data used in the optimization, possibly making the suggested EoL option unfeasible. Additionally, the obtainable salvage and scrap value assigned to recovered materials is heavily influenced by market conditions and is subject to fluctuation. Consequently, the tool may recommend an optimal EoL option for a specific component, considering a higher resale value that may not be realistically attainable, thereby making the suggested output suboptimal in practice.

7.4.3 Limited availability of data

The effectiveness of the developed methodologies is closely tied to the information available within the digital building models (e.g. BIMs). While these BIMs can be adjusted with additional inputs, doing so requires thorough document review and manual adjustments to the model. It is essential to note that although the primary goal of this research was not to establish a fully automated workflow for estimating the value of in-situ materials, the methodology's design assumed the presence of a well-constructed BIM with accurate information. The breakdown and definition of materials and components detailed within the BIM can impact building component categories, material quantities, project activity sequences, and the ultimate outcomes of the optimization process.

In addition to building model data dependency, the level of uncertainty associated with costs, material values, and project durations in the case studies is an important consideration. Construction projects inherently carry a high degree of uncertainty, and project management often relies on numerous assumptions. Furthermore, as the methodologies are all centered around cost and time optimization, the accuracy of cost-related data plays a pivotal role in determining outcomes and can lead to altered results when adjustments are made. To conduct this research, data was collected from standard references, general publicly available data, and consultation with experts. However, projects can have unique characteristics that might influence the cost and duration of the project.

7.4.4 Uncertainty in future building recovery potentials

In terms of the recovery of future building stocks and the proposed methodological approach to evaluate the impact of various early design and construction circular strategies, limitations exist when it comes to the practicality of implementing these proposed strategies. The method and the examined case study exclusively concentrate on assessing the EoL recovery potential of a building, neglecting the important aspect of the feasibility of implementing alterations and construction in each scenario. This consideration may be a critical deciding factor that can be integrated into the analysis for a comprehensive evaluation. Furthermore, the uncertainty surrounding future predictions is another limitation in the context of new buildings, as the trajectory of a building during its lifecycle and the potential changes in the quality and quantity of materials are unknown variables. The assessment did not factor in the conditions the building may encounter over its lifespan. Nevertheless, the methodology proves to be useful for comparative purposes since the assessed strategies operate under similar conditions, allowing for reasonable comparisons.

7.5 Future Research

Potential future research for further developing the work presented in this thesis is categorized into three possible paths that are discussed in separate sections below.

7.5.1 Improving accuracy and reliability of the developed decision support optimization tool

Reflecting on the identified limitation of the developed tool, a potential future path is to improve the reliability of the tool's outputs by incorporating the time value of money in the optimization, accounting for the uncertain nature of the input data, and extending the recoverable building component mass estimation. Specifically, incorporating the time value of money into the optimization process is crucial. This modification would account for the dynamic financial aspects that impact decision-making over time, providing a more realistic representation of economic considerations. Furthermore, each of the five main input categories—building material quantities, component recoverability, material extraction costs and durations, terminal values, and environmental impacts—can be adapted to include additional factors and moved away from static inputs for more accurate estimation. This expansion of inputs enables a more comprehensive and robust model that produces outputs with higher reliability. In addition to these enhancements, the tool can benefit from a closer integration with BIM technologies. By streamlining the data intake process and automating aspects of the analysis, the tool can become more efficient.

7.5.2 Exploring the implementation feasibility of circular strategies

A summary of some possible early-stage circular strategies that can improve building recovery at EoL for new buildings was provided in this research. While the initial strategies have been assessed using the proposed methodology, a more comprehensive evaluation can be achieved by encompassing a broader range of other potential circular strategies. Moreover, it is important to incorporate a feasibility assessment of implementation, considering factors such as regional material availability, structural design, thermal performance of materials, and compatibility of the new design with the building system. These considerations will provide a more holistic view of the impact and practicality of suggested circular strategies in diverse contexts. Furthermore, the exploration of DfD principles, specifically focusing on the detachability of building components through building graph modeling, presents an intriguing avenue for further research. While this topic was introduced in this research, there is substantial potential for more in-depth investigation. This would involve examining how building components and the connections of the building can be modeled with graphs that can be used to assess the detachability of the building and subsequently understand the recovery potential of the building.

7.5.3 Investigating suitable use cases for recovered building components

This research places its primary focus on the EoL phase of buildings, with a specific emphasis on the processes, factors, and decisions made to extract materials from the building. Throughout the various case studies and contexts where the optimization tool was applied, the underlying assumption of decision-making for optimal building component extraction at EoL was considered. It is equally crucial to investigate the possibilities and applications for the recovered components once they become available for recovery. This involves a comprehensive evaluation of the characteristics of the recovered components, including analysis of dimensions, structural capacity, material condition, and thermal performance. Through this analysis, optimal use cases can be identified leading to efficient ways to reintegrate these materials into new projects and developments. Furthermore, the logistics involved in transporting materials from the original building to the location of their second use entail a range of supply chain and transportation challenges that need to be addressed. Overall, the current research is dedicated to enhancing building recovery, aiming to improve the supply of recovered materials from existing buildings. However, a comprehensive circular system necessitates a deeper analysis of the demand for these recovered materials, an exploration of potential secondary use cases, and the optimization of the supply chain that can be explored as the next steps followed by this research. A holistic circularity framework can be developed for the built environment by connecting the required assessments that include all the steps required for resource recovery and ultimately use of the waste as a resource in new projects.

7.6 Publications

Journal papers and peer-reviewed conference papers from this thesis are listed below.

7.6.1 Peer-reviewed Journal Articles

Mollaei, A., Bachmann, C., & Haas, C. (2023). Estimating the recoverable value of in-situ building materials. *Sustainable Cities and Society*, 91, 104455.

Mollaei, A., Bachmann, C., & Haas, C. (2023). Assessing the impact of policy tools on building material recovery. *Resources, Conservation and Recycling*, 198, 107188.

Mollaei, A., Byers, B., Christovan, C., Olumo, A., De Wolf, C., Bachmann, C., Haas, C. (2023). A global perspective on building material recovery incorporating the impact of regional factors *Journal of Cleaner Production, 139525.*

Mollaei, A., Bachmann, C., & Haas, C. (2024). Evaluating the potential impact of building design options on material recovery during deconstruction (Submitted, Under Review)

Guerra, B. C., Shahi, S., **Mollaei, A.**, Skaf, N., Weber, O., Leite, F., & Haas, C. (2021). Circular economy applications in the construction industry: A global scan of trends and opportunities. *Journal of cleaner production*, 324, 129125.

7.6.2 Peer-reviewed conference papers:

Mollaei, A., Bachmann, C., Haas, C., A framework for estimating the re-use value of in-situ building materials. CI & CRC Joint Conference 2022, Arlington, Virginia.

Mollaei, A., Bachmann, C., Haas, C., An optimization-based decision support framework to estimate the reuse and recycling market value of in-situ materials. NHICE-03, 2022, Victoria, BC.

Mollaei, A., Eliote, G., Guerra, B., Shahi, S,. Weber, O,. Leite, F., Haas, C,. A Transition Management Framework for Implementing Circular Economy in the Construction Industry. CI & CRC Joint Conference 2024, Des Moines, Iowa

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Appendix A

Decision Support Optimization Tool Supplementary Information

Precedence Relationship Constraints in Deconstruction and Demolition of Buildings

Precedence relationships in buildings are a notion mostly used in construction management planning and project scheduling. It is used to signify the sequence of activities in construction projects. The precedence relationships are dictated by the connections between the components in the building and the accessibility of the components. The same rule applies to demolition and deconstruction projects, which is an example of unbuilding the built structures. Demolition projects have fewer constraints on precedence relationships since most components can be torn down at the same time from accessibility and technical perspectives whereas, in deconstruction projects, the sequence of component removal is of high importance to predict unwanted damage to the building components.

In the developed optimization tool, an important constraint of the building component recovery is the accessibility to the component and the sequence of activities required to reach each component that is supposed to be recovered. Therefore, an optimization complexity occurs when a combination of two (i.e. demolition and deconstruction) precedence rules apply that depend on the chosen EoL option. In this research, two precedence matrices were developed that are modeled in the constraints of the optimization algorithm. The choice of the decision variable impacts which precedence rule is being applied. Schematic examples representation of the precedence matrices in demolition and deconstruction scenarios are presented in Figure A-1. Examples of two demolition and deconstruction matrices are provided in Equations A-1 and A-2 based on a schematic structure represented in Figure A-1.

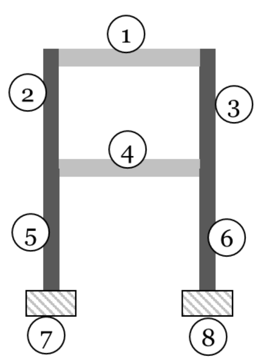


Figure A-1: Schematic Structure to Demonstrate Precedence Relationships

$$P_{demolition} = \begin{pmatrix} 0 & 0 & 0 & 1 & 1 & 1 & 1 & 1 \\ 0 & 0 & 0 & 1 & 1 & 1 & 1 & 1 \\ 0 & 0 & 0 & 1 & 1 & 1 & 1 & 1 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & 1 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & 1 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & 1 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{pmatrix}, \begin{cases} p_{ij} = 1 & component\ i\ is\ demolished\ before\ j \\ p_{ij} = 0 & otherwise \end{cases}$$

(Equation A-1)

$$P_{deconstruction} = \begin{pmatrix} 0 & 1 & 1 & 1 & 1 & 1 & 1 & 1 \\ 0 & 0 & 0 & 1 & 1 & 1 & 1 & 1 \\ 0 & 0 & 0 & 1 & 1 & 1 & 1 & 1 \\ 0 & 0 & 0 & 0 & 1 & 1 & 1 & 1 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{pmatrix}, \begin{cases} p_{ij} = 1 & component\ i\ is\ deconstructed\ before\ j \\ p_{ij} = 0 & otherwise \end{cases}$$

(Equation A-2)

Environmental Impact Assessment Methodology

The value of in-situ material estimation decision support tool includes an assessment of the avoided waste and carbon as environmental impact metrics for each building. The avoided waste is calculated based on the total mass of materials that were diverted from landfills as a result of choosing either the recycling or reuse EoL options. The carbon impact is estimated based on the Global Warming Potential (GWP) corresponding to the chosen EoL option of the component. The estimated GWP for each EoL option and each component is then combined with the optimal EoL option results to calculate the avoided carbon emissions.

The scope of the building component carbon assessment for each EoL scenario (i.e. demolition and disposal, sorting and recycling, and deconstruction and reuse) only includes production and end-of-life carbon emissions, while operational and use stage emissions are excluded due to the comparative nature of the avoided carbon metric. The carbon assessment is completed using the “One Click LCA” software (Bionova, 2018). For the production phase (A1-A3), localized EPDs available in the software’s database are mapped to the component based on the specifications of the materials in the building component. For the EoL phase including the recovery potential (C and D), required data for end-of-life operations, such as the machinery required for demolition, recycling, downcycling processes, landfilling, and transportation requirements are added to the assessment scope based on the machine hours needed for each process and transportation distances. The required machine hours are extracted from RSMeans. Transportation distances are also assumed based on average local data. To account for the impact of component recovery in the carbon assessment, various methodologies, including the cut-off method, end-of-life method, and distributed allocation as discussed by De Wolfe et al. (2020) exist. For the purposed of this research, the distributed allocation method is chosen to account for the reduced environmental impacts of the reuse and recycling EoL options. In this method, the component that is recovered is considered to have two life cycles where the production emissions are allocated equally between the two life cycles. The two lifecycles involve the existing lifecycle and a subsequent one post-recovery of the component. This is considered a conservative assumption for the distributed allocation approach. This particular method is selected for its ability to incentivize building owners towards adopting less carbon-intensive end-of-life practices and to prompt subsequent users to employ recovered materials. Unlike methods the cut-off or end-of-life approach, where either the initial or subsequent user takes credit for the reduced environmental impact, the distributed allocation method allows for a more equitable distribution of this credit across both lifecycles. Tables C-5 to C-11 in Appendix C provide a summary of the case study buildings' carbon assessment results for each component for the three EoL scenarios.

Sensitivity Analysis Results

In order to validate the developed decision support tool in Chapter 3 and quantify the impact of the main parameters in the optimization model, various sensitivity analyses were conducted using the case study building data described in Chapter 3. The details of the conducted analyses are provided in the following sections.

One At a Time (OAT) Sensitivity Analysis Charts

The results of the OAT sensitivity analysis are presented in Table A-1. In this table, the outputs of the model including Net cost including EI costs, Total cost breakdown, Total obtainable value breakdown, and Component EoL breakdown are presented in each row individually. The columns of the table correspond to the factors that were varied one at a time for the analysis. The results of the OAT sensitivity analysis when minimizing the cost of the project indicate that changes in landfill fees do not impact the results of the model, since landfilling does not occur when all materials are recycled or reused. Even when landfill fees are assumed to be zero, since there is the possibility to gain value from recycling and reusing, demolition and landfilling will not be chosen as optimal options.

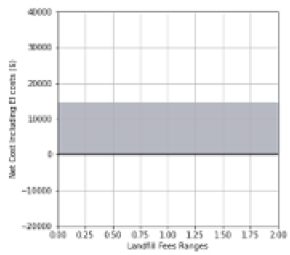
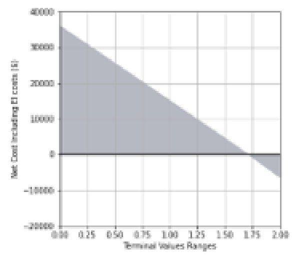
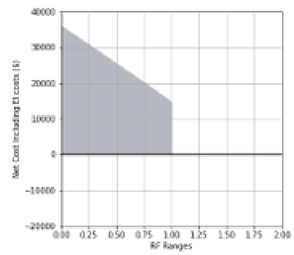
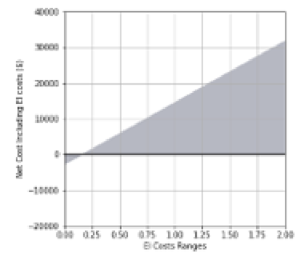
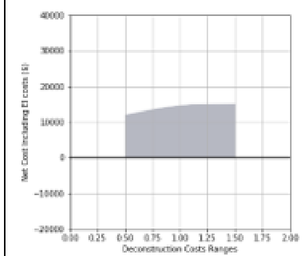
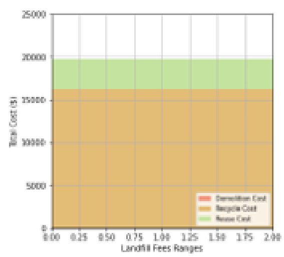
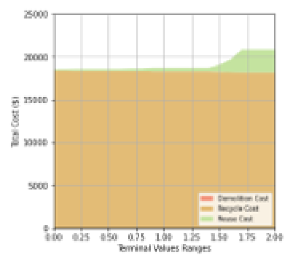
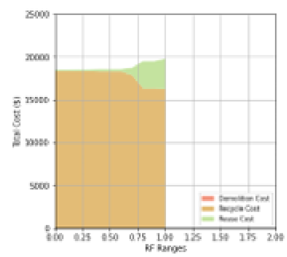
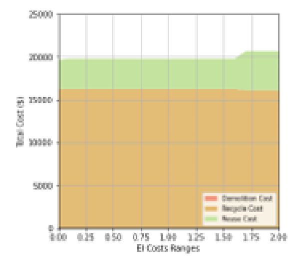
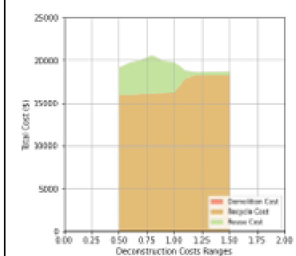
Increasing the salvage values results in in lower net costs since more value can be gained from selling secondary materials. As the obtainable salvage values increase, the shift towards reuse from recycling increases. Therefore, with the increase of demand for secondary materials and subsequently the increased market values of these materials, reuse will be a more favorable option and the net costs of deconstruction projects will also decrease.

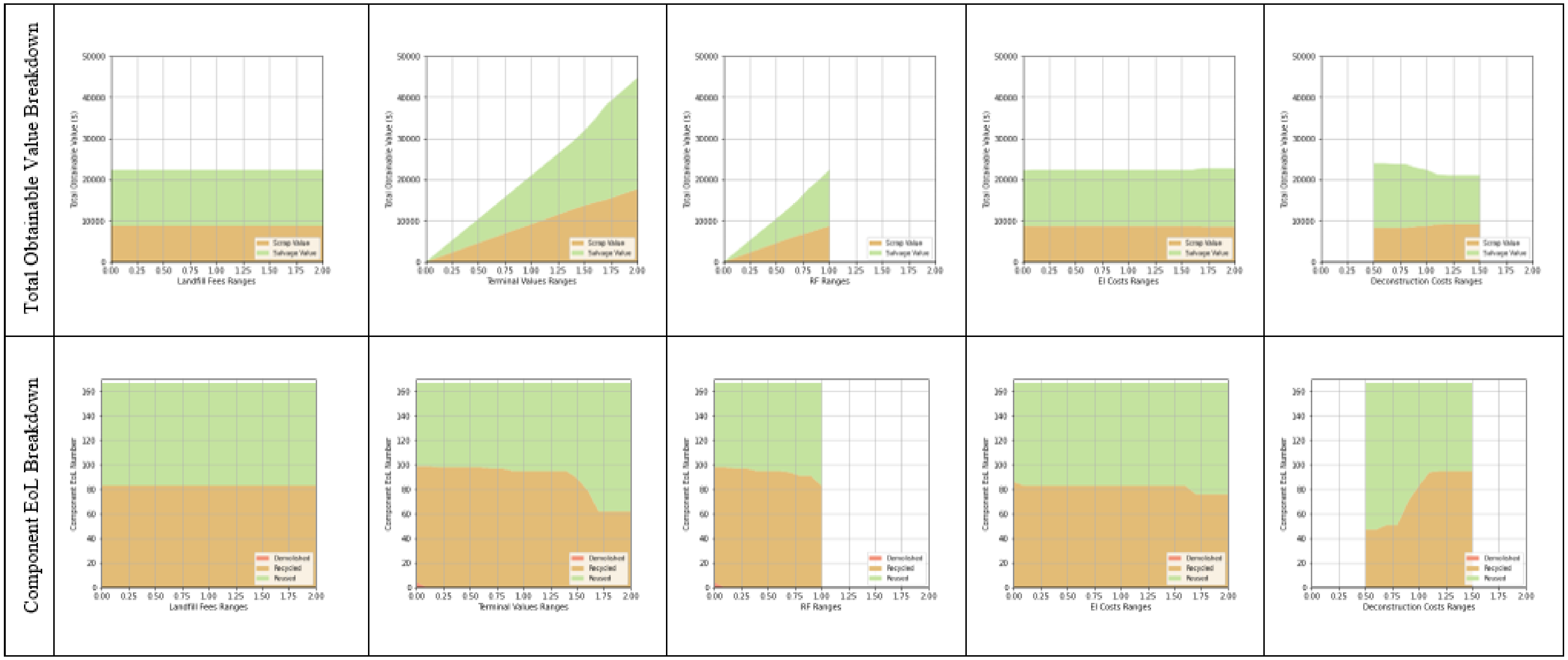
As the RFs of the components increase, the net optimized cost decreases, and the obtainable value increases due to the higher potential value from the more available materials. Moreover, the reuse cost increases at higher RFs due to the larger share of material requiring deconstruction. The EoL option also shifts towards reuse with higher recovery rates since this way higher value can be obtained that can reduce the net cost.

EI costs have direct impacts on the net optimized cost. With higher EI costs, the net optimized cost is proportionally higher since additional EI costs are incurred. There is no substantial impact from the increase of the EI cost in the specified range on the EoL decisions from the optimization model. As EI costs increase, there is a slight shift towards reuse, which also increases the cost of reuse. The change in the EI costs need to be much higher than the range explored to have a substantial impact on EoL decisions.

An increase in deconstruction costs increases the net optimized cost. However, this increase is not proportional to the change of deconstruction costs. As deconstruction costs reach around 115 percent of the current costs, it is not optimal to continue with reuse of some components, and recycling becomes the more preferable option.

Table A-1: One at a Time Sensitivity Analysis Results

	Landfill Fees	Terminal Values	RF	EI Costs	Deconstruction Costs
Net Cost Including EI Costs					
Total Cost Breakdown					


Total Obtainable Value Breakdown
Component EoL Breakdown
Total Obtainable Value ($)
Component EoL Number
Scrap Value
Salvage Value
Demolished
Recycled
Reused
Landfill Fees Ranges
Terminal Values Ranges
RF Ranges
EI Costs Ranges
Deconstruction Costs Ranges

All Combinations Scenario Charts

In the all combinations scenarios sensitivity analysis, 2,187 scenarios were generated indicating different variations of the landfill fees, terminal values, RF, EI costs, and deconstruction costs. The charts representing the results of this analysis are presented in Tables A-2 to A-7. Each two subsequent tables correspond to one of the three outputs: component EoL breakdown, total cost, and obtained value. The first table shows the results for the scenario when RF is 50% of the base case and the second where RF is maximum. Each table contains 9 charts that illustrate the change in the desired output based on EI and Terminal value corresponding to various combinations of Landfill and Deconstruction cost percentages.

Table A-2: Component EoL Breakdown Results (RF = 50%)

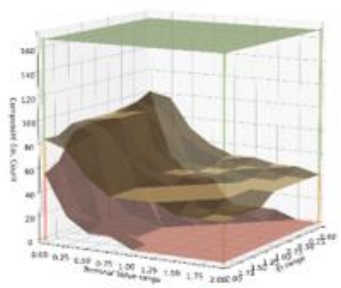
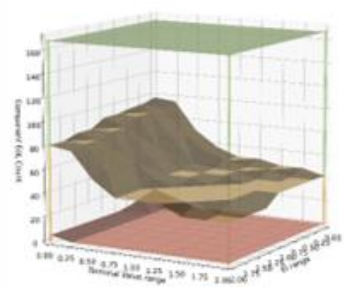
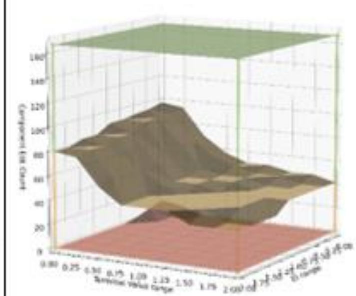
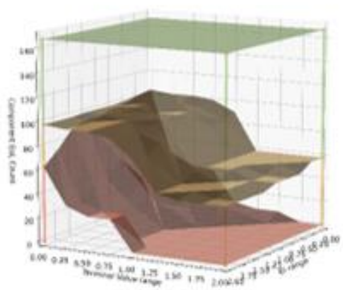
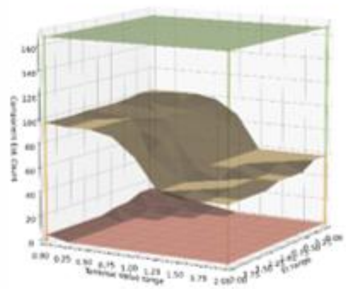
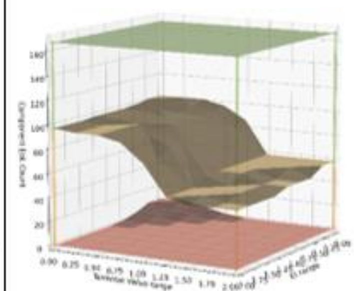
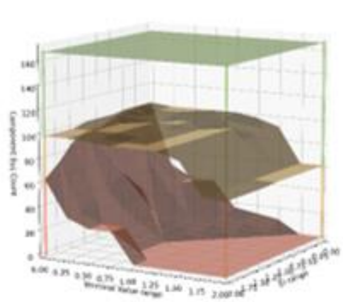
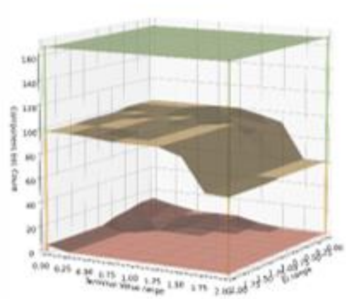
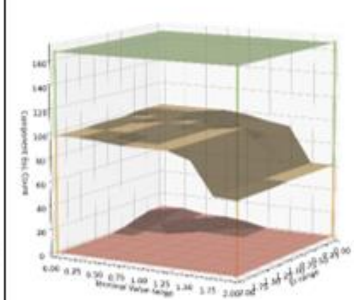
	Landfill Fee = 0%	Landfill Fee = 100%	Landfill Fee = 200%
Deconstruction Cost = 50%			
Deconstruction Cost = 100%			
Deconstruction Cost = 150%			
Legends:	Demolished	Recycled	Reused

Table A-3: Component EoL Breakdown Results (RF = 100%)

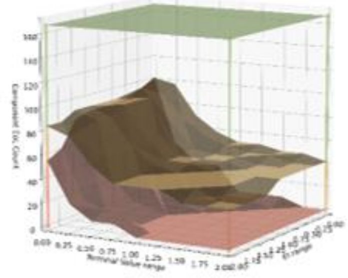
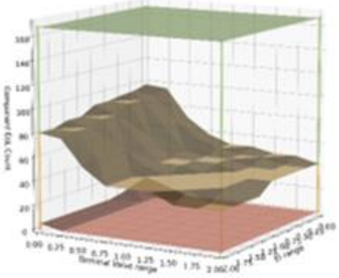
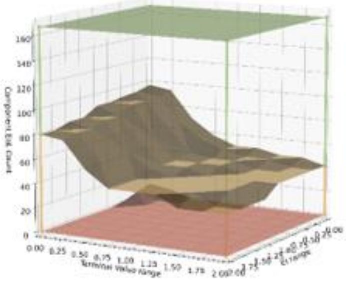
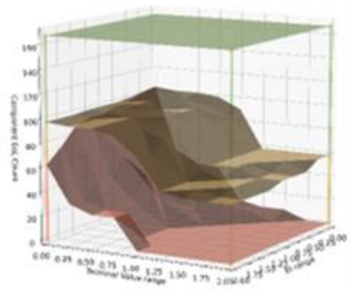
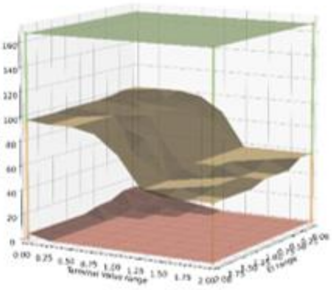
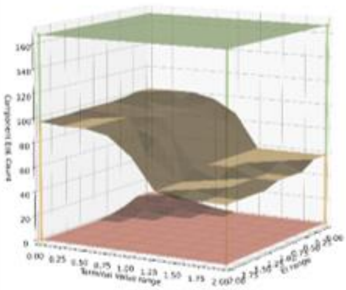
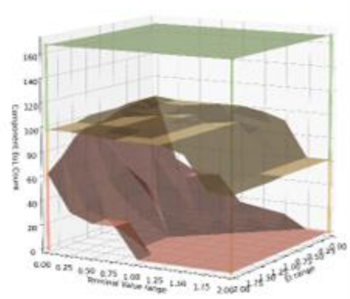
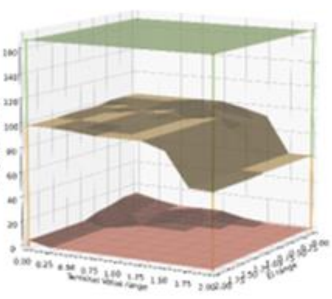
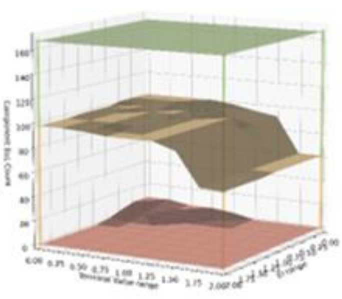
	Landfill Fee = 0%	Landfill Fee = 100%	Landfill Fee = 200%
Deconstruction Cost = 50%			
Deconstruction Cost = 100%			
Deconstruction Cost = 150%			
Legends: Demolished Recycled Reused			

Table A-4: Obtainable Value Results (RF = 50%)

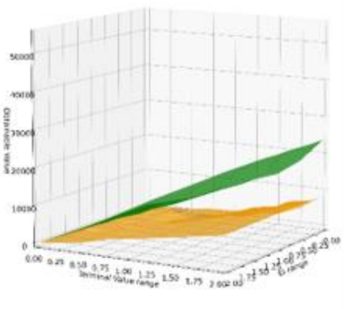
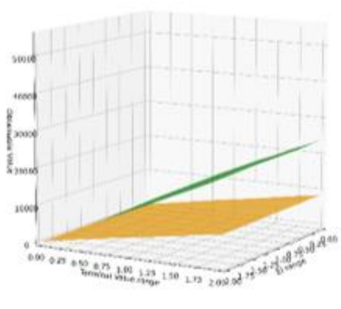
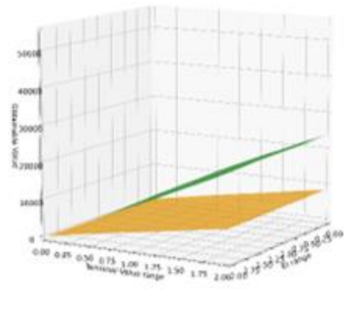
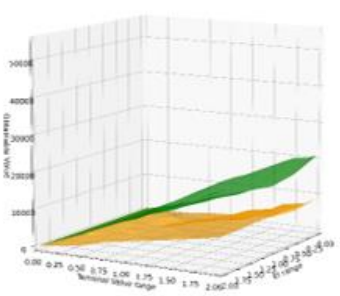
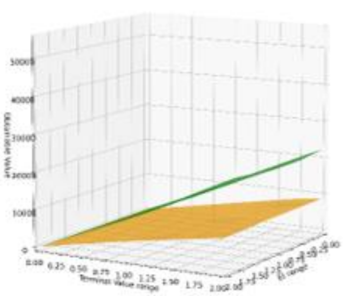
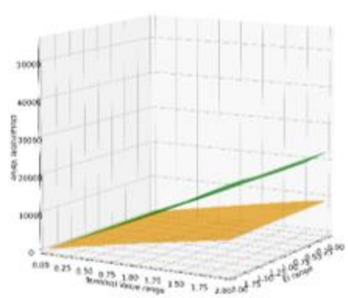
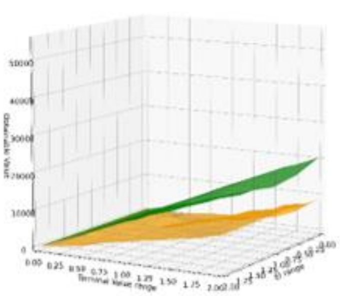
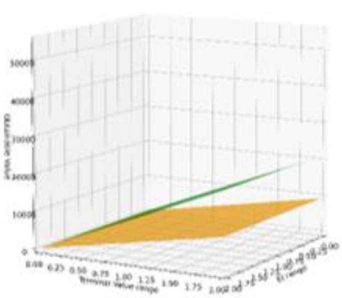
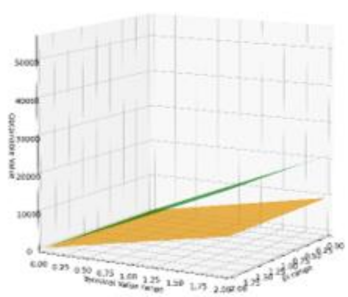
	Landfill Fee = 0%	Landfill Fee = 100%	Landfill Fee = 200%
Deconstruction Cost = 50%			
Deconstruction Cost = 100%			
Deconstruction Cost = 150%			
Legends: Scrap Value Salvage Value			

Table A-5: Obtainable Value Results (RF = 100%)

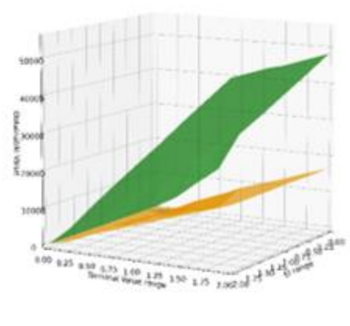
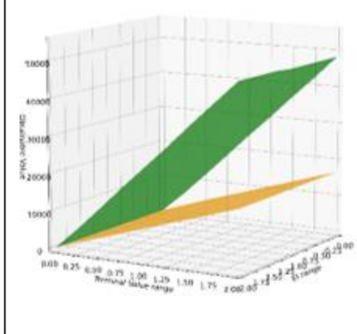
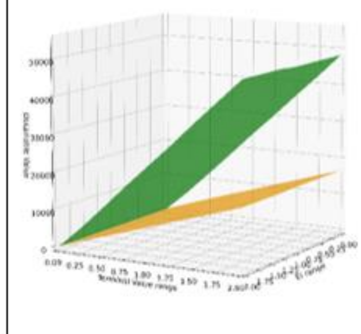
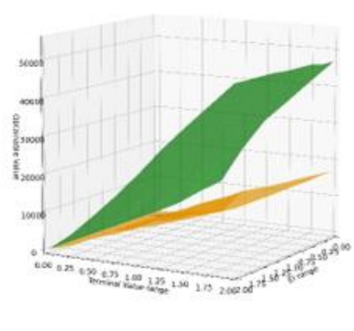
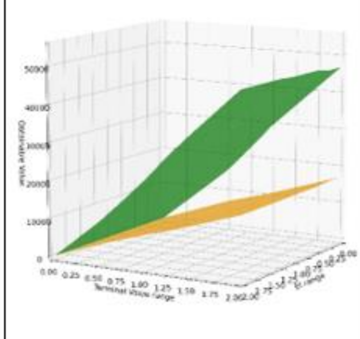
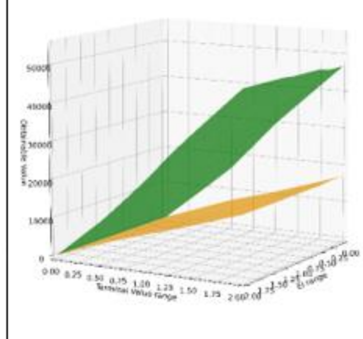
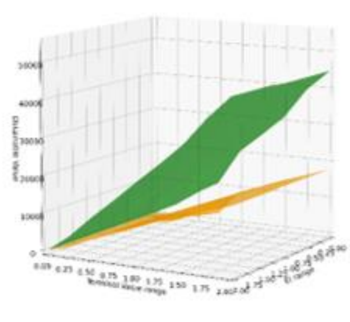
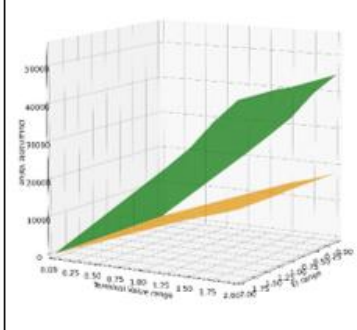
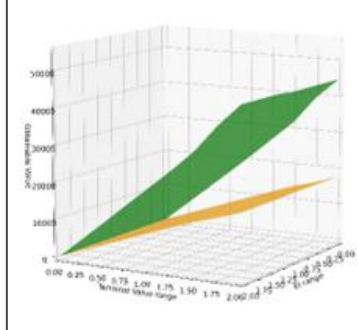
	Landfill Fee = 0%	Landfill Fee = 100%	Landfill Fee = 200%
Deconstruction Cost = 50%			
Deconstruction Cost = 100%			
Deconstruction Cost = 150%			
Legends: Scrap Value Salvage Value			

Table A-6: Total cost excluding environmental impact costs (RF = 50%)

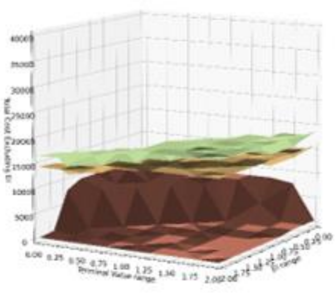
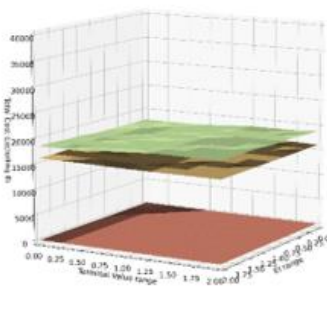
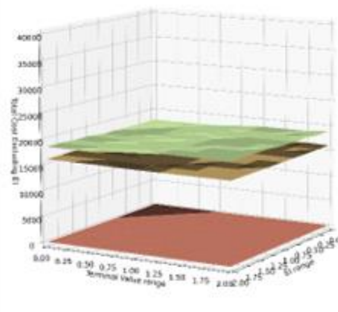
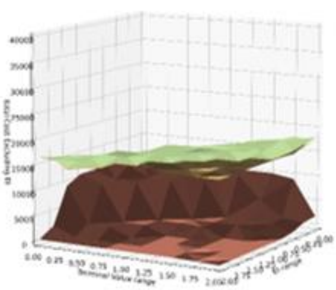
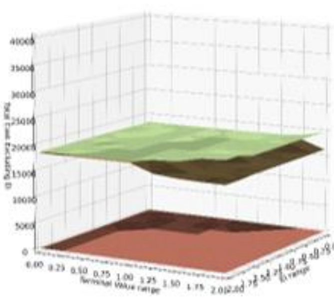
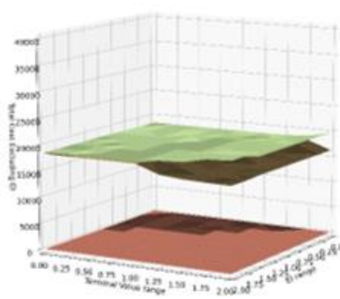
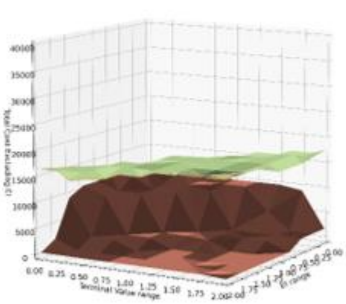
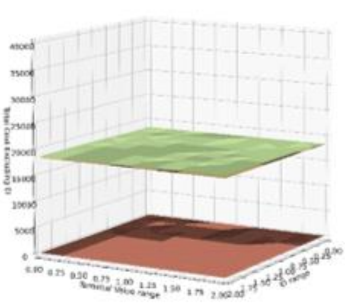
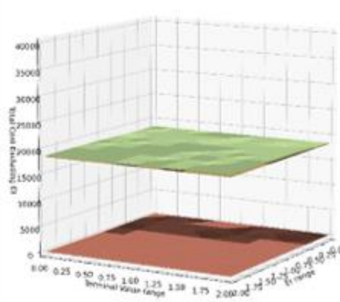
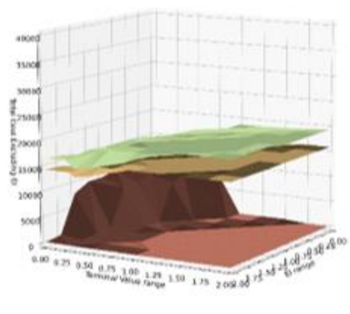
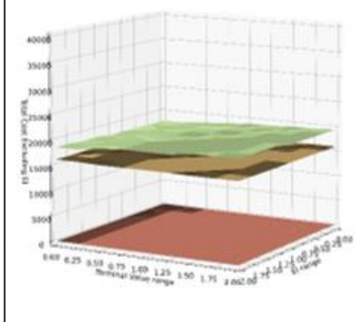
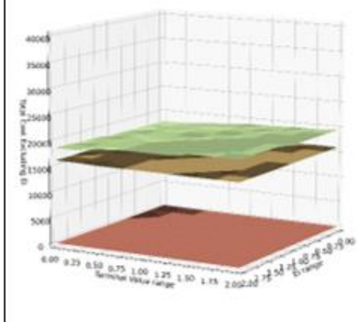
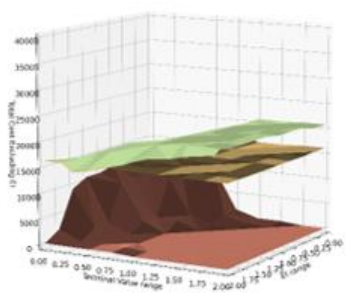
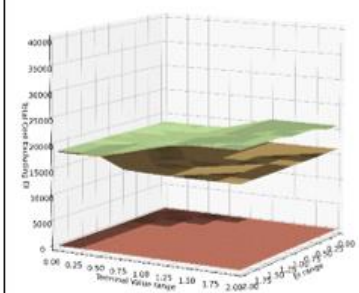
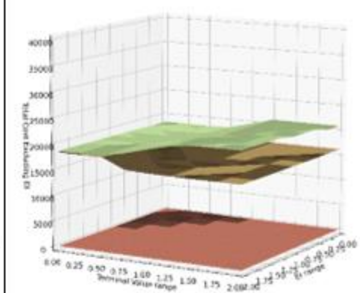
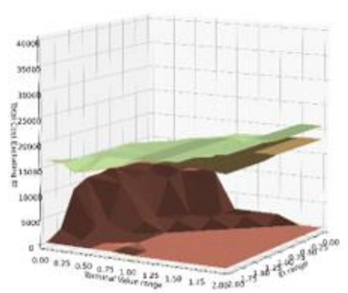
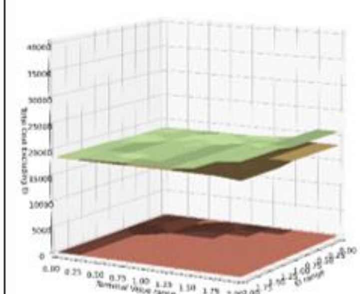
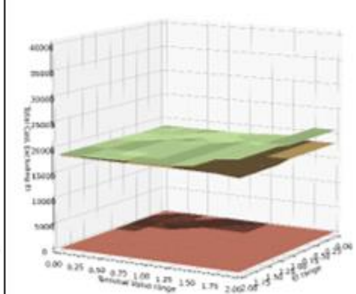
	Landfill Fee = 0%	Landfill Fee = 100%	Landfill Fee = 200%
Deconstruction Cost = 50%			
Deconstruction Cost = 100%			
Deconstruction Cost = 150%			
Legends: Demolished Recycled Reused			

Table A-7: Total cost excluding environmental impact costs (RF = 100%)

	Landfill Fee = 0%	Landfill Fee = 100%	Landfill Fee = 200%
Deconstruction Cost = 50%			
Deconstruction Cost = 100%			
Deconstruction Cost = 150%			
Legends: Demolished Recycled Reused			

Appendix B

Algorithms

Decision Support Optimization Tool in CPLEX IBM ILOG

The decision support tool optimization algorithm in CPLEX IBM is as follows:

```
//parameters

int n=...; //number of components ID
int m=...; //extraction methods used

range components = 1..n;
range extraction = 1..m;

//input the ID range of exterior walls in each floor
range wall_ext_0 = 94..96;
range wall_ext_1 = 97..102;
range wall_ext_2 = 103..108;

tuple Connect {
  int windows;
  int walls;
}

//input the ID tuples of window and wall connections
{Connect} Connection={<159,96> ,<161,94>,<162,99>,<163,102>,<164,
107>,<165,104>,<166,104>,<167,104>};

float Cost[components][extraction]=...;
float EnvI[components][extraction]=...;
float Mass[components]=...;
float Salvage[components][extraction]=...;
float recf[components]=...;
float duration[components][extraction]=...;
int precedenceDem[components][components]=...;
int precedenceDec[components][components]=...;


//variables
dvar boolean X[components][extraction];
dvar float+  S[components];
dvar float T;
```

```
//model
minimize sum(i in components, e in extraction)
X[i][e]*Mass[i]*(Cost[i][e]+EnvI[i][e]-Salvage[i][e]*recf[i]);

minimize max (T);


subject to {

 //logic of one choice
 forall(i in components)
    sum(e in extraction) X[i][e] == 1;
 forall (i in {109,110,111,112,113,114,115})
   X[i][3]==0;


 //walls and floors
 forall (e in 1..2, i in wall_ext_0)
   X[91][e]<=X[i][e];
 forall (e in 1..2, i in wall_ext_1)
   X[92][e]<=X[i][e];
 forall (e in 1..2, i in wall_ext_2)
   X[93][e]<=X[i][e];

  //walls and windows
forall (<i,j> in Connection)
   X[i][3]<=X[j][1]+X[j][2];

//Demolition precedence
 forall(i in components, j in components)
   if (precedenceDem[i][j]==1)
        S[j]>=precedenceDem[i][j]*(S[i]+duration[i][1]*X[i][1]);


//Recycling precedence
 forall(i in components, j in components)
  if (precedenceDem[i][j]==1)
   S[j]>=precedenceDem[i][j]*(S[i]+duration[i][2]*X[i][2]);

//Deconstruction precedence
 forall(i in components, j in components)
  if (precedenceDem[i][j]==1)
   S[j]>=precedenceDec[i][j]*(S[i]+duration[i][3]*X[i][3]);

//input max duration limit
T== max (i in components, e in extraction) (S[i]+X[i][e]*duration[i][e]);
 T<= 100;
    }
```

Example Data in CPLEX IBM ILOG

```
n=167; //identify number of components
m=3; //identify extraction methods used

//connect to input data table with separate fields for all input parameters as
outlined below

SheetConnection my_sheet("Model_Components.xlsx");
Cost from SheetRead(my_sheet,"'Components'!U2:W168");
EnvI from SheetRead(my_sheet,"'Components'!X2:Z168");
Mass from SheetRead(my_sheet,"'Components'!J2:J168");
Salvage from SheetRead(my_sheet,"'Components'!AA2:AC168");
recf from SheetRead(my_sheet,"'Components'!M2:M168");
duration from SheetRead(my_sheet,"'Components'!AD2:AF168");
precedenceDem from SheetRead(my_sheet,"'Precedence Demo'!B2:FL168");
precedenceDec from SheetRead(my_sheet,"'Precedence Dec'!B2:FL168");

//record decision variable results
X to SheetWrite(my_sheet,"'Results_Cost'!B2:D168");
T to SheetWrite(my_sheet,"'Results_Cost'!AG2");
```

Precedence Matrices Algorithms

The following algorithm generates the component precedence matrix for demolition.

```
import pandas as pd
import numpy

#the function takes a data frame that includes all the building elements and the
required fields for the decision support tool
def demo_prec_matrix_generator(df):
      df['joined'] = list(zip(df_prec_demo.ID, df_prec_demo.Level))
      joined_list = df_prec_demo["joined"].tolist()

      precedence_total_demo = []
      for i in range(len(joined_list)):
          precedence_demo = []
          for j in range(len(joined_list)):
              if joined_list[i][1] > joined_list[j][1]:
                  p = 1
              else:
                  p = 0
              precedence_demo.append(p)
          precedence_total_demo.append(precedence_demo)
      return precedence_total_demo

#input is a csv that includes the "ID" of elements and their "Level" in the model
df_prec_demo = pd.read_csv('component_inputs.csv')
prec_matrix_demo = demo_prec_matrix_generator(df_prec_demo )


#output can be captured in a nxn table in a csv where n is the total number of
components in the building
prec_matrix_demo = pd.DataFrame(precedence_total_demo)
prec_matrix_demo.to_csv('prec_output_demo.csv')
```

The following algorithm generates the component precedence matrix for deconstruction.

```
import pandas as pd
import numpy

#the function takes a data frame that includes all the building elements and the
required fields for the decision support tool alongside lists that include
element type deconstruction priorities
def dec_prec_matrix_generator(df,list_dec_1,list_dec_2, list_dec_3,
list_dec_4):
      df ['joined'] = list(zip(df.Item, df.Level, df.Type))
      joined_list = df_prec_dec["joined"].tolist()

      precedence_total_dec = []
      for i in range(len(joined_list)):
          precedence_dec = []
          for j in range(len(joined_list)):

            if joined_list[i][1] in [4]:
              if joined_list[j][2] in list_dec_1:
                p=0
              else:
                p=1


            elif joined_list[i][1] in [0]:
              p=0

            elif joined_list[i][1] in [1,2,3]:
              if joined_list[j][1] in [0]:
                p=1
              elif joined_list[j][1] in [1,2,3]:
                if joined_list[i][2] == "Door":
                  if joined_list[j][2] == "Door":
                    p=0
                  else:
                    p=1
                elif joined_list[i][2] in list_dec_2:
                  if joined_list[j][2] in list_dec_1
                    p=0
                  else:
                    p=1
```

```
          elif joined_list[i][2] in list_dec_3:
            if joined_list[j][2] in list_dec_1:
              p=0
            elif joined_list[i][1]>joined_list[j][1]:
              p=1
            elif joined_list[i][1]==joined_list[j][1]:
              if joined_list[i][2]=="Floor":
                if joined_list[j][2]!="Floor":
                  p=1
                else:
                  p=0
              elif joined_list[i][2]=="Wall Exterior":
                if joined_list[j][2] in list_dec_4:
                  p=0
                else:
                  p=1
              else:
                p=0
            else:
              p=0
          elif joined_list[j][1] in [4]:
            if joined_list[i][2] in list_dec_1:
              p=1
            else:
              p=0
        precedence_dec.append(p)
      precedence_total_dec.append(precedence_dec)
  return precedence_total_dec

#input is a csv that includes the “ID” of elements, their “type”, and “Level” in
the model – the “type” strings are standardized.
df_prec_dec = pd.read_csv('component_inputs.csv')

#exmple of deconstruction priorities for the case study in chapter 3
list_dec_1 = ["Door","Wall Int","Ceiling","Window"]
list_dec_2 = ["Wall Int","Ceiling","Window"]
list_dec_3 = ["Wall Ext","Column St","Floor"]
list_dec_4 = ["Floor","Wall Ext"]
prec_matrix_dec =
dec_prec_matrix_generator(df_prec_dec,list_dec_1,list_dec_2, list_dec_3,
list_dec_4)
```

```
#output can be captured in a nxn table in a csv where n is the total number of components in the building
prec_matrix_dec = pd.DataFrame(precedence_total_dec)
prec_matrix_dec.to_csv('prec_output_dec.csv')
```

Policy Assessment Algorithm

The following algorithm is used to assess the efficacy of the policy scenarios, as outlined in Chapter 4.

```
#this function takes the required data for the decision support tool in a data
frame and organizes the parameters for the optimization
def optimization_param_creator(df_input):
  component = range(len(df_input))
  eol=range(0,3)

  weight_array = df_input['Material_Weight']

  cost_1 = list(df_input['Demo_Cost'] + df_input['Dumping_Cost'])
  cost_2 = list(df_input['Demo_Cost'] + df_input['Sorting_Cost'] +
df_input['Recycle_Cost'])
  cost_3 = list(df_input['Decon_Cost'] + df_input['Transport_Cost'])
  cost_array = np.array([cost_1, cost_2, cost_3]).T

  value_1 = [0]*len(df_input)
  value_2 = list(df_input['Scrap_Value'])
  value_3 = list(df_input['Salvage_Value'])
  value_array = np.array([value_1, value_2, value_3]).T

  co2_1 = list(df_input['CO2_Landfill'])
  co2_2 = list(df_input['CO2_Recycle'])
  co2_3 = list(df_input['CO2_Reuse'])
  co2_array = np.array([co2_1, co2_2, co2_3]).T

  RF_array = df_input['RF']
  optimization_param_dict = {
      'component':component,
      'eol':eol,
      'cost':cost_array,
      'value':value_array,
      'co2':co2_array,
      'RF':RF_array,
      'weight':weight_array

  return optimization_param_dict
#this function takes the policy scenario identified, required data for the
decision support tool in a data frame, a list of component IDs that should be
```

```
reused as dictated by the policy, a list of general non-reusable and non-
recyclable components IDs, and tuples of mutually exclusive connected component
IDs – the output is the decision variables for each component for each scenario
that can be used to calculated the required outputs of the model
def salvage_optimizer_with_policies(
policy_scenario,reuse_component_set,df_input,non_reusable_index,non_rec
yclable_index,connections):

  optimization_param_dict = optimization_param_creator(df_input)


  #Decision Variable
  x_var =LpVariable.dicts("X", ((i, e) for i in
optimization_param_dict['component'] for e in
optimization_param_dict['eol']), lowBound=0, cat='Binary')

  # Cost Optimization
  cost_model=LpProblem("MinimizeCost",LpMinimize)
  if policy_scenario == '1a':
    cost_model += lpSum
(x_var[i,e]*optimization_param_dict['weight'][i]*(optimization_param_di
ct['cost'][i][e]+optimization_param_dict['co2'][i][e]-
optimization_param_dict['value'][i][e]*optimization_param_dict['RF'][i]
) for i in optimization_param_dict['component'] for e in
optimization_param_dict['eol'])
  else:
    cost_model += lpSum
(x_var[i,e]*optimization_param_dict['weight'][i]*(optimization_param_di
ct['cost'][i][e]-
optimization_param_dict['value'][i][e]*optimization_param_dict['RF'][i]
) for i in optimization_param_dict['component'] for e in
optimization_param_dict['eol'])

  #logical Constraints
  for i in optimization_param_dict['component']:
    cost_model += lpSum(x_var[i,e] for e in
optimization_param_dict['eol'])==1

  #restrictions on reuse and recycling
  for i in non_reusable_index:
    cost_model += x_var[i,2]==0
  for i in non_recyclable_index:
```

```
    cost_model += x_var[i,1]==0

  #mutually exclusivity of connected elements
  for (i,j) in connections:
    cost_model += x_var[i,3]<=x_var[j,1]+x_var[j,2]


#policy constraints
  if policy_scenario == '1b':
    EI =
min((df_input['CO2_landfill']*df_input['Material_Weight']*0.5).sum(),(d
f_input['CO2_Reuse']*df_input['Material_Weight']).sum())
    cost_model +=
lpSum(x_var[i,e]*optimization_param_dict['cost'][i][e]*optimization_par
am_dict['weight'][i] for i in optimization_param_dict['component'] for
e in optimization_param_dict['eol']) <= EI

  if policy_scenario == '2':
    cost_model += lpSum(x_var[i,1] for i in
optimization_param_dict['component'])==0

  if policy_scenario == '3a':
    for s in reuse_component_set:
          for i in s:
            cost_model += x_var[i,3]==1

  if policy_scenario == '3b':
    waste = df_input['Material_Weight'].sum()
    cost_model += lpSum(x_var[i,3]*optimization_param_dict['weight'][i]
for i in optimization_param_dict['component']) >= 0.5*waste

  if policy_scenario == '4':
    cost_model += lpSum(x_var[i,3] for i in
optimization_param_dict['component']) >= 0.8*int(len(assessment_df))

  cost_model.solve()
  status = LpStatus[cost_model.status]

  if status == 'Optimal':
    result = cost_model,x_var
  else:
```

```
  result= 'no optimal solution found'

return result
```

Circular Strategy Assessment Algorithm

The following algorithm is used to evaluate the impact of the four circular strategies as outlined in Chapter 6.

```
#this function generates tuples for the connections based on a data
frame that shows whether connections exist between all component IDs
based on the headings of the columns in the data frame - the column
headings identify the type of the connection (as defined in the
connection type dictionary.
def connection_tuple_generator(df_connect):
  connection_list = []
  for key in list(df_connect.drop('ID',axis=1).columns):
    for i in range(len(df_connect)):
      if pd.isna(df_connect[key][i]):
        pass
      else:
        connection =
(int(df_connect['ID'][i]),int(df_connect[key][i]),key)
        connection_list.append(connection)

  return connection_list

#this function generates the connection matrix based on the tuples
def connection_matrix(df_input,df_connect,dec_score_dict):

    connection_list = connection_tuple_generator(df_connect)
    connect_arr = np.empty((len(df_input),len(df_input)))

    for item in range(len(connection_list)):
      score = dec_score_dict[connection_list[item][2]]
      ID_1 = int(connection_list[item][0])-1
      ID_2 = int(connection_list[item][1])-1

      connect_arr[ID_1][ID_2] = score
      connect_arr[ID_2][ID_1] = score

    return connect_arr


#this function calculates the connection score for each element
def connection_score(df_input,df_connect,dec_score_dict):
```

```
    connect_arr = connection_matrix(df_input,df_connect,dec_score_dict)
    dec_score_list=[]

    for i in range(len(connect_arr)):
        dec_score = connect_arr[i].sum()
        dec_score_list.append(dec_score)
    return dec_score_list

#this dictionary shows the impact of the scenarios on the optimization
parameters
scenario_dict = {
    'Scenario_1':{
        'name':'durable_elements',
        'factors':{
            'Age':1.5,
            'Sorting_Cost':1,
            'Decon_Cost':1
        }
    },
    'Scenario_2':{
        'name':'mono_material',
        'factors':{
            'Age':1,
            'Sorting_Cost':0,
            'Decon_Cost':1
        }
    },
    'Scenario_3':{
        'name':'seperable_assemblies',
        'factors':{
            'Age':1,
            'Sorting_Cost':1,
            'Decon_Cost':0.35
        }
    },
    'Scenario_4':{
        'name':'detachable_connections',
        'factors':{
            'Age':1,
            'Sorting_Cost':1,
            'Decon_Cost':1
```

```
        }
    }

}

#this function creates the optimization parameters based on the
identified circular strategy using the scenario key
def optimization_param_creator(
df_input,scenario_key,dec_score_dict_base,dec_score_dict_scen4):
  component = range(len(df_input))
  eol=range(0,3)

  weight_array = df_input['Material_Weight']

  cost_1 = list(df_input['Demo_Cost'] + df_input['Dumping_Cost'])
  cost_2 = list(df_input['Demo_Cost'] +
df_input['Sorting_Cost']*scenario_dict[scenario_key]['factors']['Sortin
g_Cost'] + df_input['Recycle_Cost'])


  if scenario_key=='Scenario_4':
    dec_list_base =
connection_score(df_inputs,df_connect,dec_score_dict_base)
    dec_list_scen4 =
connection_score(df_inputs,df_connect,dec_score_dict_scen4)

    df_input['Base_Score']=dec_list_base
    df_input['Scen_Score']=dec_list_scen4

    cost_3 =
list(df_input['Decon_Cost']*scenario_dict[scenario_key]['factors']['Dec
on_Cost'] +
df_input['Transport_Cost'])*df_input['Scen_Score']/df_input['Base_Score
']



  else:
    cost_3 =
list(df_input['Decon_Cost']*scenario_dict[scenario_key]['factors']['Dec
on_Cost'] + df_input['Transport_Cost'])
```

```
  cost_array = np.array([cost_1, cost_2, cost_3]).T


  value_1 = [0]*len(df_input)
  value_2 = list(df_input['Scrap_Value'])
  value_3 = list(df_input['Salvage_Value'])
  value_array = np.array([value_1, value_2, value_3]).T

  co2_1 = list(df_input['EI1'])
  co2_2 = list(df_input['EI2'])
  co2_3 = list(df_input['EI3'])
  co2_array = np.array([co2_1, co2_2, co2_3]).T


  df_inputs['Recovery_Factor_Reuse'] = np.where(
    # Value if condition is True
    df_inputs['f'] == 1,
    1,
    # Value if condition is False
    df_inputs['f'] * (1 - np.exp(60 -
df_inputs['Age']*scenario_dict[scenario_key]['factors']['Age']) - (60 /
(10 *
df_inputs['Age']*scenario_dict[scenario_key]['factors']['Age'])))
  )

  RF_1 = [0]*len(df_input)
  RF_2 = list(df_input['Recovery_Factor_Recycle'])
  RF_3 = list(df_input['Recovery_Factor_Reuse'])
  RF_array = np.array([RF_1, RF_2, RF_3]).T

  optimization_param_dict = {
      'component':component,
      'eol':eol,
      'cost':cost_array,
      'value':value_array,
      'co2':co2_array,
      'RF':RF_array,
      'weight':weight_array}

  return optimization_param_dict
```

```
#this function generates the optimal EoL scenarios for a set of input
data frame given a circular strategy scenario
def salvage_optimizer_circular_strategy(
df_input,scenario_key,df_input_scen2,non_reusable_index,non_recyclable_
index,connections):

  if scenario_key=='Scenario_2':
    optimization_param_dict =
optimization_param_creator(df_input,scenario_key)
  else:
    optimization_param_dict =
optimization_param_creator(df_input_scen2,scenario_key)


  #Desicion Variable
  x_var =LpVariable.dicts("X", ((i, e) for i in
optimization_param_dict['component'] for e in
optimization_param_dict['eol']), lowBound=0, cat='Binary')

  # Cost Optimization
  cost_model=LpProblem("MinimizeCost",LpMinimize)
  cost_model += lpSum
(x_var[i,e]*optimization_param_dict['weight'][i]*(optimization_param_di
ct['cost'][i][e]-
optimization_param_dict['value'][i][e]*optimization_param_dict['RF'][i]
[e]) for i in optimization_param_dict['component'] for e in
optimization_param_dict['eol'])

  #logical Constraints
  for i in optimization_param_dict['component']:
    cost_model += lpSum(x_var[i,e] for e in
optimization_param_dict['eol'])==1


  #restrictions on reuse and recycling
  for i in non_reusable_index:
    cost_model += x_var[i,2]==0
  for i in non_recyclable_index:
    cost_model += x_var[i,1]==0

  #mutually exclusivity of connected elements
```

```
  for (i,j) in connections:
    cost_model += x_var[i,3]<=x_var[j,1]+x_var[j,2]

  cost_model.solve()
  status = LpStatus[cost_model.status]

  if status == 'Optimal':
    result = cost_model,x_var
  else:
    result= 'no optimal solution found'

  return result


#example data for case study
df_input_base = pd.read_csv('new_con_input_base.csv')
df_input_scen2 = pd.read_csv('new_con_input_scen2.csv')
df_connect = pd.read_csv('connection.csv')

dec_score_dict_base = {'column':4, 'floor-joist':3, 'roof-joist':3,
'shear-wall':3, 'parallel-beam':3, 'perpendicular-beam':3, 'top-
beam':3}
dec_score_dict_scen4 = {'column':2, 'floor-joist':2, 'roof-joist':2,
'shear-wall':2, 'parallel-beam':1, 'perpendicular-beam':2, 'top-
beam':1}

#example results for case study in Scenario 4
results =
optimization_param_creator(df_inputs,'Scenario_4',dec_score_dict_base,d
ec_score_dict_scen4)
```

Appendix C

Analyses Data

Building Data

The details of the building models of the case studies used in this research are provided in Table C-1. The table includes information regarding the owner of the building model and the changes made in the original model or building documentation to prepare it for the decision support tool. All building models are in collected Revit.

Table C-1: Overview of Building Model Data

Model	Original Building	Model Owner	Notes
Chapter 3			
Institutional Building Case Study in Canada	Martin Luther University College	Provided in UW Grad Course for research purposes	Families, Types, and Building Material Types were slightly modified to include all required information
Chapter 4			
BIM1 - House	Hypothetical example of Canadian house archetype	Authors	
BIM2 - Office	NA	Blackwell Structural Engineers	Families, Types, and Building Material Types were slightly modified to include all required information
BIM3 - Warehouse	NA	Blackwell Structural Engineers	Families, Types, and Building Material Types were slightly modified to include all required information
BIM4 - Modern Building	Hypothetical Example of modern timber building	Authors	
BIM5- Highrise	Park Hyatt Toronto	KPMB Architects	Only the demolition phase of the project was extracted
Chapter 5			

Canadian Case Study	NA	Blackwell Structural Engineers	Families, Types, and Building Material Types were slightly modified to include all required information
Swiss Case Study	HIF building in ETH Zurich campus	ETH Zurich	
Nigerian Case Study	Commercial building example	Nigerian Building Firm	
Chinese Case Study	Recreation of a school building in China	Authors	The Revit model was created by authors using the provided structural and architectural drawings
Brazilian Case Study	Hypothetical example of an apartment building in Brazil	Authors	The Revit model was created by authors using provided structural and architectural drawings
Chapter 6			
New Construction Case Study	Mid-rise multi-unit residential building under construction	City of Hamilton	The Revit model was created by authors using provided structural and architectural drawings

Material End-of-Life Cost, Duration, and Value Data

The cost and duration of demolition and deconstruction-related activities for the North American case studies were collected from RSMeans 2020 and RSMeans 2023. Specifically, these data were used for the case study in Chapter 3, all BIMs in Chapter 4, the Canadian case study in Chapter 5, and the case study in Chapter 6. For the later building, data from the newer edition of RSMeans were used. For the remaining case studies in Chapter 5, data were collected from various global sources as described in detail in Chapter 5. The main line items used from RSMeans as input data for the decision support tool are provided in Table C-2. The table provides a summary of some of the mostly used items for cost estimations in this research. For each case study, depending on the building and the component's characteristics other proper items were utilized.

Table C-2: Cost and Duration of Demolition and Deconstruction-related Activities used from RS Means

Description	Reference code in RS Means	Daily Output	Total cost including O&P (2020USD)	Total cost including O&P (2023USD)	Unit
Building Demolition (Large Urban Project)	02 41 16.13 0100	20100	$0.39	$0.54	CF
Building Demolition (Small Building - Wood)	02 41 16.13 0500	14800	$0.40	$0.47	CF
Demolition of Single-Family House	02 41 16.13 1020	0.5	$11900	$13800	Ea
Building Demolition - Footings	02 41 16.17 1120	200	$18.55	$24.00	LF
Building Demolition - Foundation Wall	02 41 16.17 2080	4000	$0.92	$1.18	SF
Building Demolition - Slab on Grade	02 41 16.17 0240	5000	$0.74	$0.95	SF
Selective Demolition - Concrete Slab	02 41 19.16 0050	75	$39.50	$42.50	CF
Selective Demolition - Concrete Wall	02 41 19.16 0650	80	$37	$40	CF
Selective Demolition - Brick Wall	02 41 19.16 2060	18	$164	$177	Ea
Selective Demolition - Concrete Block	02 41 19.16 2440	27	$109	$118	Ea
Selective Demolition - Gypsum Block	02 41 19.16 2620	70	$42	$45.50	Ea
Selective Demolition - Interior Wall (Drywall)	02 41 19.16 6100	24	$21	$23.50	Ea
Selective Demolition - Wood Frame Floor	02 41 19.16 7200	5	$101	$113	Ea
Selective Demolition - Wood Frame Roof	02 41 19.16 7310	6	$84.50	$94	Ea
Selective Demolition - Wood Frame Wall	02 41 19.16 7410	7	$72.50	$80.50	Ea
Deconstruction - Doors	02 42 10.20 0710	21	$66.50	$69.50	Ea
Deconstruction - Windows	02 42 10.20 0820	18	$76.50	$80.50	Ea
Deconstruction - Drywall	02 42 10.20 0910	1775	$0.57	$0.63	SF
Deconstruction - Built-up Roof	02 42 10.20 1010	570	$1.78	$1.97	SF
Deconstruction - Roof sheeting	02 42 10.20 2010	570	$1.78	$1.97	SF
Deconstruction - Roof Framing	02 42 10.20 2020	760	$1.33	$1.48	LF
Deconstruction - Beams (example for 10x12)	02 42 10.20 2080	100	$15.40	$17.10	LF
Deconstruction - Interior Wall Framing	02 42 10.20 2150	1230	$0.82	$0.92	LF
Deconstruction - Ceiling Joists	02 42 10.20 2100	800	$1.27	$1.41	LF

Deconstruction - Floor Joists	02 42 10.20 2170	2000	$0.51	$0.56	LF
Deconstruction - Wood Siding	02 42 10.20 2200	1300	$0.78	$0.87	SF
Deconstruction - Exterior Wall Framing	02 42 10.20 2300	1600	$0.63	$0.70	LF
Deconstruction - Exterior Brick Wall	02 42 10.20 3000	200	$5.05	$5.65	SF

The landfill fees and required data for an estimation of the terminal value of materials were collected from available dumping rates on municipality websites and online secondary material marketplaces, respectively. An average of the collected data was used for the above-mentioned case studies. A summary of the input data for landfill fees is provided in Table C-3. Available average material terminal values are provided in Table C-4. This Table contains information on the terminal values of some typical materials. In each case study, in case of availability of data for a specific material type or component, more accurate data was utilized.

Table C-3: Average Landfill Fees used for North American Case Studies

Component/Material Category	**Average Landfill Fee (2020USD/kg)**	**References**
Asphalt	0.07	(City of Toronto, 2021; Niagara Region, 2021; Greater Sudbury, 2021; Region of Waterloo, 2021: York Region, 2021)
Brick	0.08	
Concrete	0.07	
Glass	0.02	
Gypsum	0.09	
Wood	0.05	
Steel	0.05	
Window	0.02	
Door	0.05	
Precast Concrete	0.07	
Mixed Waste	0.08	

Table C-4: Average Terminal Values used for North American Case Studies

Component/Material Category	**Average Scrap Value (2020USD/kg)**	**Average Salvage Value (2020USD/kg)**	**References**
Brick	0.23	0.75	(Demolition Traders, 2021; Recycler's Exchange, 2021; Repurposed Materials, 2021; Salvage Garden, 2021)
Concrete	0.03	0.04	
Gypsum	0.14	0.60	
Wood	0.20	0.94	
Steel	0.67	0.99	
Window	0.10	0.51	
Door	0.25	1.25	
Precast Concrete	0.03	0.08	

Environmental Impact Data

The Global Warming Potential (GWP), which was the metric used to assess the environmental impact of case studies, corresponding to each component category in the unit of kgCO2e/kg was estimated for each case study as one of the required parameters for the decision support tool. The environmental impact assessment methodology is explained in Appendix A. The unit GWP data estimated for each end-of-life option in the case studies are provided in Tables C-5 to C-11. No carbon avoidance was estimated for the case studies in Chapter 5.

Table C-5: Summary of the Global Warming Potential of Building Components in End-of-Life Scenarios for Chapter 3 Case Study

Component Category	**Environmental Impact of Demolition and Disposal (kgCO2e/kg)**	**Environmental Impact of Demolition, Sorting, and Recycling (kgCO2e/kg)**	**Environmental Impact of Deconstruction and Reuse (kgCO2e/kg)**
Ceiling	0.697	0.465	0.348
Structural Column	0.177	0.194	0.088
Door	0.111	0.074	0.055
Floor	0.060	0.040	0.030
Roof	0.062	0.041	0.031
Exterior Wall	0.025	0.016	0.012
Interior Wall	0.030	0.020	0.015
Foundation Wall	0.019	0.012	0.009
Window	0.308	0.205	0.153

Table C-6: Summary of the Global Warming Potential of Building Components in End-of-Life Scenarios for BIM 1 in Chapter 4 Case study

Component Category	**Environmental Impact of Demolition and Disposal (kgCO2e/kg)**	**Environmental Impact of Demolition, Sorting, and Recycling (kgCO2e/kg)**	**Environmental Impact of Deconstruction and Reuse (kgCO2e/kg)**
Door	0.083	0.055	0.042
Window	1.613	1.075	0.806
Interior Wall	0.009	0.006	0.005
Ceiling	0.011	0.007	0.006
Exterior Wall	0.007	0.005	0.004
Floor	0.005	0.003	0.002
Slab	0.032	0.021	0.016
Roof	0.023	0.015	0.011
Beams	0.159	0.106	0.079
Wall Frame	0.036	0.024	0.018
Floor Frame	0.037	0.025	0.018
Roof Frame	0.007	0.005	0.004
Foundation Wall	0.006	0.004	0.003

Table C-7: Summary of the Global Warming Potential of Building Components in End-of-Life Scenarios for BIM 2 in Chapter 4 Case study

Component Category	**Environmental Impact of Demolition and Disposal (kgCO2e/kg)**	**Environmental Impact of Demolition, Sorting, and Recycling (kgCO2e/kg)**	**Environmental Impact of Deconstruction and Reuse (kgCO2e/kg)**
Door	0.019	0.013	0.010
Window	0.262	0.174	0.131
Interior Wall	0.005	0.003	0.003
Ceiling	0.017	0.011	0.008
Exterior Wall (Wood siding)	0.018	0.012	0.009
Exterior Wall (Concrete Block)	0.017	0.011	0.009
Curtain Wall	1.802	1.201	0.901
Floor	0.006	0.004	0.003
Slab	0.009	0.006	0.004
Roof	0.032	0.021	0.016
Wood Frame	0.008	0.005	0.004

Steel Frame	0.115	0.113	0.057
Structural Concrete	0.011	0.007	0.005
Wall Frame	0.033	0.022	0.016
Floor Frame	0.004	0.003	0.002
Roof Frame	0.014	0.009	0.007
Foundation Wall	0.003	0.002	0.001
Footing	0.011	0.007	0.005

Table C-8: Summary of the Global Warming Potential of Building Components in End-of-Life Scenarios for BIM 3 in Chapter 4 Case study

Component Category	**Environmental Impact of Demolition and Disposal (kgCO2e/kg)**	**Environmental Impact of Demolition, Sorting, and Recycling (kgCO2e/kg)**	**Environmental Impact of Deconstruction and Reuse (kgCO2e/kg)**
Door	0.014	0.009	0.009
Window	0.036	0.024	0.020
Exterior Wall (Steel)	0.011	0.081	0.007
Exterior Wall (Brick)	0.071	0.047	0.037
Steel Deck	0.064	0.116	0.033
Slab	0.020	0.014	0.012
Beam	0.064	0.116	0.033
Column	0.282	0.262	0.143
Foundation Wall	0.006	0.004	0.005
Footing	0.020	0.013	0.012
Door	0.014	0.009	0.009
Window	0.036	0.024	0.020

Table C-9: Summary of the Global Warming Potential of Building Components in End-of-Life Scenarios for BIM 4 in Chapter 4 Case study

Component Category	**Environmental Impact of Demolition and Disposal (kgCO2e/kg)**	**Environmental Impact of Demolition, Sorting, and Recycling (kgCO2e/kg)**	**Environmental Impact of Deconstruction and Reuse (kgCO2e/kg)**
Window	0.345	0.230	0.172
Ceiling	0.015	0.010	0.008
Exterior Wall (Wood Siding)	0.033	0.022	0.016
Interior Wall	0.045	0.030	0.022
Curtain Wall	0.206	0.137	0.103
Wall Frame	0.017	0.011	0.008
Floor	0.020	0.013	0.010
Slab	0.008	0.005	0.004
Floor Frame	0.013	0.009	0.007
Roof	0.022	0.015	0.011
Roof Frame	0.026	0.017	0.013
Beam	0.017	0.011	0.008
Column	0.009	0.006	0.004
Structural Concrete	0.012	0.008	0.006
Foundation Wall	0.006	0.004	0.003
Footing	0.005	0.003	0.003

Table C-10: Summary of the Global Warming Potential of Building Components in End-of-Life Scenarios for BIM 5 in Chapter 4 Case study

Component Category	**Environmental Impact of Demolition and Disposal (kgCO2e/kg)**	**Environmental Impact of Demolition, Sorting, and Recycling (kgCO2e/kg)**	**Environmental Impact of Deconstruction and Reuse (kgCO2e/kg)**
Door	0.024	0.016	0.012
Window	0.068	0.045	0.034
Exterior Wall (Concrete)	0.047	0.031	0.023
Exterior Wall (Brick)	0.086	0.058	0.043
Curtain Wall	0.120	0.080	0.060
Interior Wall	0.005	0.004	0.003
floor	0.047	0.031	0.023

roof	0.047	0.031	0.023
Door	0.024	0.016	0.012

Table C-11: Summary of the Global Warming Potential of Building Components in End-of-Life Scenarios for Chapter 6 Case study

Component Category	**Environmental Impact of Demolition and Disposal (kgCO2e/kg)**	**Environmental Impact of Demolition, Sorting, and Recycling (kgCO2e/kg)**	**Environmental Impact of Deconstruction and Reuse (kgCO2e/kg)**
Door	0.932	0.711	0.576
Window	0.430	0.376	0.325
Wall Board	0.488	0.415	0.354
Exterior Wall Cladding	5.691	3.884	2.956
Exterior Wall Structure	2.424	2.116	1.938
Interior Wall Structure	1.983	1.656	1.482
Shear Wall	0.712	0.564	0.466
Ceiling	0.458	0.395	0.339
Floor	0.444	0.386	0.332
Floor Joist	0.538	0.448	0.379
Roof	8.587	7.134	6.384
Roof Joist	0.538	0.448	0.379
Roof Truss	0.588	0.482	0.404
Column	0.351	0.324	0.286
Beam	0.351	0.324	0.286

Project Cost and Terminal Value in Different Policy Scenarios

In Chapter 4, eight different scenarios were analyzed: a traditional demolition base case, an optimized net cost with no policy, and six policy-constrained scenarios. The component extraction cost, the potential obtainable terminal value from the scrap and salvage materials, and net project costs for each scenario and each BIM are summarized in Table C-12. These values were used to calculate the financial multipliers that show the expected financial impacts per dollar invested and are presented in Table 4-4 (Chapter 4).

Table C-12: Extraction Cost, Terminal Value, and Net Cost Outputs in each Policy Scenario

		BIM1	BIM2	BIM3	BIM4	BIM5
Traditional Demolition Base Case	Extraction Cost	$ 23,500	$ 104,000	$ 195,600	$ 244,200	$ 132,900
	Terminal Value	-	-	-	-	-
	Net Cost	$ 23,500	$ 104,000	$ 195,600	$ 244,200	$ 132,900
Optimized Net Cost with No policy	Extraction Cost	$ 64,500	$ 141,800	$ 237,700	$ 289,700	$ 215,600
	Terminal Value	$ (65,300)	$(193,100)	$ (368,000)	$ (308,400)	$ (488,400)
	Net Cost	$ (800)	$ (51,300)	$ (130,300)	$ (18,700)	$ (272,800)
Policy 1a	Extraction Cost	$ 64,800	$ 163,700	$ 237,900	$ 289,800	$ 216,600
	Terminal Value	$ (65,300)	$ (204,600)	$ (368,000)	$ (308,400)	$ (489,300)
	Net Cost	$ (500)	$ (40,900)	$ (130,100)	$ (18,600)	$ (272,700)
Policy 1b	Extraction Cost	$ 112,800	$ 260,200	$ 328,000	$ 702,500	$ 2,625,200
	Terminal Value	$ (74,600)	$ (235,300)	$ (390,000)	$ (372,800)	$ (1,092,300)
	Net Cost	$ 38,200	$ 24,900	$ (62,000)	$ 329,700	$ 1,532,900
Policy 2	Extraction Cost	$ 65,000	$ 229,500	$ 240,400	$ 289,800	$ 1,703,600
	Terminal Value	$ (65,500)	$ (22,700)	$ (370,000)	$ (308,500)	$ (928,500)
	Net Cost	$ (500)	$ 206,800	$ (129,600)	$ (18,700)	$ 775,100
Policy 3a	Extraction Cost	$ 70,000	$ 194,600	$ 318,300	$ 517,200	$ 217,400
	Terminal Value	$ (66,600)	$ (205,196)	$ (393,200)	$ (373,700)	$ (489,700)
	Net Cost	$ 3,400	$ (10,596)	$ (74,900)	$ 143,500	$ (272,300)
Policy 3b	Extraction Cost	$ 78,600	$ 165,700	$ 247,700	$ 320,400	$ 982,500
	Terminal Value	$ (71,900)	$ (205,000)	$ (368,000)	$ (307,600)	$ (609,200)
	Net Cost	$ 6,700	$ (39,300)	$ (120,300)	$ 12,800	$ 373,300
Policy 4	Extraction Cost	$ 76,600	$ 180,900	$ 315,100	$ 342,800	$ 766,000
	Terminal Value	$ (72,100)	$ (206,500)	$ (388,500)	$ (339,500)	$ (527,900)
	Net Cost	$ 4,500	$ (25,600)	$ (73,400)	$ 3,300	$ 238,100

Summary of informal communications for data collection and validation

The global analysis conducted in Chapter 5 required the collection of data from local experts. In order to validate the methodology, inputs, and outcomes of this research, multiple consultations and unofficial interviews are conducted with experts. The communications alongside the purpose of those communications are provided below.

- Demolition company in Ontario, Canada: To understand the demolition process, cost, and labour in Canada.
- Deconstruction company in BC, Canada: To understand the deconstruction process, additional labour requirements, and differences with demolition.
- Salvage material store in Ontario, Canada: To understand the market for secondary materials in Canada
- Reuse Expert in BC, Canada: To understand the process of estimating the value of salvageable materials and finances of building reuse.
- Engineering firm in China: To obtain building models and understand the construction norms.
- Demolition company in Zurich, Switzerland: To understand the demolition and waste handling processes in Zurich.
- Contractors in Delta State, Nigeria: To obtain the building model and understand demolition processes.
- Engineering firms in São Paulo, Brazil: To understand the construction norms in the region and demolition waste handling processes.
- Waste Management Facility in São Paulo, Brazil: To understand building material recovery cost and processes in Brazil

The communications are kept anonymous since interviews were not conducted officially. Additionally, the authors of the paper had experience working in four of the five studied regions. Therefore, bringing engineering expertise and knowledge in validating the results.