

Automating Construction Material Sourcing and Distribution for Circularity

by

Adama Olumo

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Examining Committee Membership

The following served on the Examining Committee for this thesis. The decision of the Examining Committee is by majority vote.

External Examiner:

Amin Hammad

Professor (Concordia Institute for Information Systems
Engineering)

Supervisor:

Carl Haas

Professor

**Internal Committee
Members:**

Costa Kapsis

Professor

Joyce Kim

Professor

Internal-External Member:

Olaf Weber

Professor

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.

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Statement of Contributions

This thesis is the original work of the author, Adama Olumo, conducted under the supervision of Professor Carl Haas at the University of Waterloo. All research presented was developed and carried out by the author, with guidance from the supervisor. The conceptual development, framework design, model implementation, and writing were led by the author. Details of co-authorship and contributions are as follows:

Chapter 3 presents the Integrated Material Sourcing (IMS) framework. This work was co-authored by Adama Olumo and Professor Carl Haas. Adama led the conceptualization, data collection, model development, scenario design, analysis, and manuscript writing. Professor Haas provided academic supervision, feedback, and contributed to revisions of the manuscript.

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Chapter 4 introduces the Assembly Restoration Framework (ARF), this chapter was co-authored by Adama Olumo, Professor Carl Haas, and Professor Costa Kapsis, with Professor Kapsis as the second author. Adama was responsible for the framework development, implementation, analysis, and manuscript writing. Professor Kapsis contributed to refining the research direction, guiding framework development, and offering feedback on interpretation of results. Professor Haas provided academic guidance and editorial feedback.

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Chapter 5 expands the application of the IMS framework to include risk factors and policy impacts. This work was co-authored by Adama Olumo and Professor Carl Haas. Adama conducted the model application, data analysis, and writing. Professor Haas contributed to supervisory guidance, review, and manuscript refinement. Note, this manuscript is in review.

All other sections of the thesis were written solely by the author. Contributions by collaborators were limited to academic supervision, conceptual feedback, and manuscript review. Collaborative works not included within the scope of this thesis are not addressed in this statement.

Abstract

Circularity in the construction industry is developing, with increasing emphasis on extracting resources from existing infrastructure. Given the growing number of resources embedded in the current housing stock, sustainability within the industry is critical. To support the large-scale reuse of Reclaimed Construction Materials (RCMs), through active reuse strategies, it is essential to develop tools and frameworks for sourcing RCMs. This study contributes to that effort by providing insights into the creation of such frameworks and emphasizing the value of material reuse within the construction sector. Although material reuse is considered an excellent circular strategy, the application of reuse across the industry still faces technical, social, and environmental limitations.

A significant drawback of material reuse is the complexity of finding RCMs that fit a design with limited alterations required for use. Furthermore, the environmental and economic cost of acquiring and reusing RCMs is taxing, compared to acquiring New Construction Materials (NCMs). Additionally, there is limited insight into other options for restoring existing building resources before replacement. Therefore, this thesis develops decision support frameworks for component level assessment of RCMs and assembly level assessment of RCMs. The component level assessment tool is designed to integrate 3D scanning, Optimization Programming Languages (OPL), Life Cycle Assessment (LCA) and Building Information Modeling (BIM) tools to create an enhanced digital supply sourcing system; whereby RCMs at secondary sources can be found with basic required information like; cost, proximity and dimensions to enable planning and implementation.

The component-level assessment framework is refined and extended through a policy assessment study, demonstrating its adaptability to diverse challenges presenting both risks and potential benefits for policy implementation. This thesis is fundamentally based on real-world data gathered from RCM stores and it challenges the current ongoing building design practices that deem material reuse as a problematic approach by enabling flexible sourcing of used and new building materials and providing an assessment framework for selecting appropriate restoration strategies. The approach alters the social perspective to consider partial integration of RCMs at varying levels of integration in new building projects.

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List of Abbreviations

RCM -Reclaimed Construction
Material

GWP -Global Warming Potential

NCM -New Construction Material

IBM -International Business Machines

BIM -Building Information
Modeling

NDT -Non-Destructive Testing

ARF -Assembly Restoration
Framework

RFID -Radio Frequency Identification

IMS -Integrated Material Sourcing

SLAM -Simultaneous Localization and
Mapping

PVC -Polyvinyl Chloride

GHG -Greenhouse Gas

OPL -Optimization Programming
Language

AEC -Architecture, Engineering, and
Construction

EPD -Environmental Product
Declaration

AI -Artificial Intelligence

GIS -Geographic Information
Systems

TMS -Timeless Material Store

THD -The Home Depot

API -Application Programming Interface

HH -Habitat for Humanity

IGU -Insulated Glazing Unit

Chapter 1: Introduction

1.1 Background and motivation

The disregard for limits of natural resources has existed long before the birth of the industrial revolution. Early modernity experienced the "consumption revolution," which was estimated to have begun after the 1690s. During this period, the economic expansion of Europe stemmed from colonial capitalism; the resulting demand for cash crops led to extensive deforestation on surrounding tropical islands (Kneese, 1988). The multi-national races for economic wealth, post-industrial revolution, have exacerbated unsustainable practices in countries around the world. As a result, the exponential rate of resource consumption and environmental degradation led to a call for a new era of economic growth (Ekins, 1993). The IUCN World Conservation Strategy (1980) was one of the first global attempts to align conservation with development, asserting that sustainability must enable conservation rather than hinder it (Klarin, 2018). Think tanks like the Club of Rome, established in 1968, offered early warnings about resource depletion and population growth through publications like "The Limits to Growth". Likewise, the United Nations has made significant contributions through its Millennium Development Goals (2000-2015), focused on poverty reduction in developing countries, and the current Sustainable Development Goals (SDGs), which enables integration of environmental, social, and economic factors into development strategies (Sachs, 2012).

The development of the Brundtland Report in 1987 was a pivotal moment, coining the term "sustainable development", defined as "the ability to meet the needs of the present without compromising the ability of future generations to meet their own needs" (Moldan et al., 2012). Since the development of the Brundtland Report, the term sustainability has revolutionized and evolved in the industrial world; it has inspired the development of various sustainability models across industries, championing a growth that is aggressive and yet socially and environmentally sustainable (Ekins, 1993). The circular economy, one of the significant terminologies, emerged first in 1988; as explained by The Ellen MacArthur foundation, the circular economy is based on three principles; designing-out waste and pollution, keeping products and materials in use longer, and regenerating natural systems (Ellen MacArthur Foundation, 2021).

The principles defined by the Ellen Macarthur foundation have become widely adopted across different sectors like the biological, technological, and the built environment industry. The built environment industry is one of the largest consumers of natural resources and a major waste-producing sector (Yeheyis et al., 2013). However, the industry is gradually changing its linear practices and adopting technological advancements to mitigate environmental impact across planning, design, construction, maintenance, and end-of-life phases.

Technology, long regarded as a driver of sustainable development, remains a double-edged sword. While innovation improves production efficiency, it often accelerates consumption and shortens product lifecycles. As Binswanger (2001) notes, increased efficiency does not inherently reduce overall resource use; instead, it can lead to faster cycles of production and greater volumes of waste. Industries such as automotive, technology, and fashion have historically offloaded waste by channelling second-hand products into developing countries. This dynamic has fostered a global imbalance, where externalities are transferred to lower-income regions through the export of used vehicles, electronics, and clothing (Allan, 2021). Unlike other industries, the built environment sector lacks the ability to efficiently offload its waste to developing regions due to the physical nature of construction resources, regional factors and the high costs associated with transport. As a result, most construction waste is sent directly to landfills. This presents a unique opportunity: to harness digital technologies to address the challenges of resource waste.

By leveraging technologies such as 3D scanning, digital inventories, and optimization tools, we can begin to trace, assess, and redirect RCMs away from landfills and back into the value chain through circular strategies like reuse, recycling, and more. The adoption of technology across the built environment industry is progressive, although significant lapses in the adoption of automated systems are still evident in the end-of-life stage in comparison to design, construction and maintenance. The building industry has adopted the principles of circularity in different subsections of construction with the aid of advanced technology systems like; Building Information Modelling (BIM), Geographic Information Systems (GIS), material passports and others (Çetin et al., 2021). The application of such systems has significantly enhanced the industry's performance by optimizing processes and limiting waste in the building industry. Advantageously, the technologies can be applied to enable circular strategies such as slowing, narrowing, closing, and regenerating the loop

(Çetin et al., 2021). In this thesis, circular strategies in construction aim to manage resources through three main interventions: slowing the resource loop, closing the resource loop, and narrowing the resource loop (Figure 1-1). Within each strategy, different types of interventions support the overall objective of maintaining resources within the system. The first strategy, slowing the loop, focuses on designing and constructing resources to be durable, adaptable, and deconstructable (Ellen MacArthur foundation, 2021). It improves the potential of resources to undergo refurbishment, recycling, or reuse later in their lifecycle. If resources are not built to be durable, adaptable, or easily deconstructed from the start, they are more likely to exit the system prematurely. Strengthening design and construction practices to prioritize durability and adaptability can avoid resource exits and allow resources to remain active within their first lifecycle or transition smoothly into secondary cycles (Iacovidou & Purnell, 2016; Mollaei et al., 2023).

The second strategy, closing the loop, involves applying interventions such as reuse, refurbishment, or recycling when resources approach the end of their initial use phase. These interventions prevent resources from exiting the system and instead allow them to take on new forms or functions while remaining within the resource stream (Ellen MacArthur foundation, 2021). Although some circular economy frameworks group reuse, refurbishment, and repair under the umbrella of “slowing the loop,” this study distinguishes between slowing, which focuses on extending the initial lifecycle through durability and maintenance, and extending, which targets multiple lifecycles through reuse and refurbishment after a product’s initial use phase.

The third strategy, narrowing the loop, focuses on reducing the demand for virgin resources by reintegrating recovered resources into new construction processes. Resources that successfully go through extension strategies contribute to narrowing the loop by minimizing the need for newly extracted resources (Ellen MacArthur foundation, 2021). However, even after extension strategies are applied, resource exits still occur. Salvaged resources that undergo deconstruction may not always re-enter construction projects. Some resources degrade during the transition phase due to a lack of proper maintenance, while others, although extracted, remain unsold at RCM stores (Iacovidou & Purnell, 2016; Mollaei et al., 2023). In many cases, salvaged resources are recycled rather than treated as high-value assets that could be directly upgraded or reintroduced into new projects. Resource exits pinpoint areas demanding further interventions to improve the value and

lifespan of RCMs. A clear understanding of resource loops facilitates the development of strategies and policies to effectively limit waste.

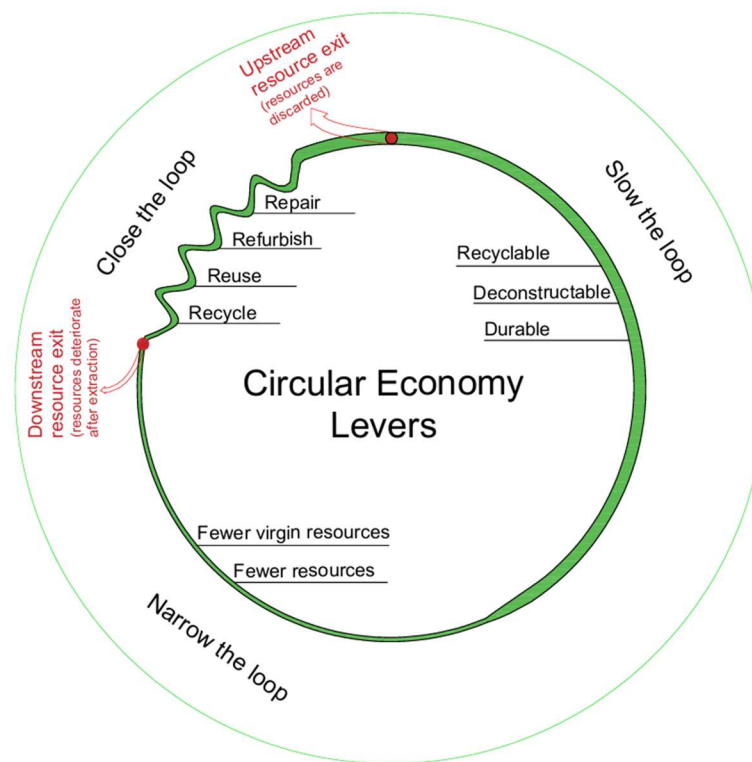


Figure 1-1: Circular economy levers with resource exits.

Previous research has explored various circular strategies and sought to address existing gaps in the application of these strategies through technology. For example, the study by Brütting et al., (2019) employed an optimization tool to assess the suitability of different components for integration into new structural designs. Similarly, the study by Mollaei et al., (2023) focused on optimizing the extraction of construction resources from buildings to support more efficient and intentional deconstruction processes. The study by Brütting et al., (2019) aligns with a downstream-oriented approach, aiming to ensure that resources are effectively reintegrated into new construction projects by facilitating the optimal selection of building components. In contrast, the study by Mollaei et al., (2023b) represents an upstream strategy, emphasizing the redirection of components at the point of deconstruction. Rather than demolition, this approach promotes salvaging components, thereby preserving their value and supporting reuse. Other studies have investigated the implementation of circular strategies using different tools and technologies. This

study contributes to that body of work by focusing on strategies that support the reintegration of resources into the construction cycle.

This thesis posits that existing digitisation tools, like Building Information Modeling (BIM), 3D scanning, Optimization Programming Language (OPL), and Life Cycle Assessment (LCA), can be incorporated into systems that facilitate optimal acquisition of New Construction Materials (NCMs) and RCMs for construction projects. It focuses on the development of decision support frameworks for both assembly and component level assessments. The potential benefit of the developed frameworks is the enhancement of RCM sourcing.

Therefore, the research questions addressed are as follows.

- 1) Can the application of integrated component and assembly sourcing frameworks enhance the consideration of RCMs in new construction projects?
- 2) Does the implementation of the developed frameworks add value to current RCM sourcing practices?
- 3) Are the frameworks adaptable to different components or assemblies when different factors are considered?

1.2 Research objectives

The objectives of this thesis are as follows.

- Collect 3D scans and supplementary information on RCMs and NCMs from construction material stores.
- Develop a component-level assessment framework to support partial integration of RCMs into new construction projects.
- Demonstrate the use of the component level assessment framework for optimized building components sourcing, for various building materials, under different sourcing scenarios.
- Develop an assembly-level framework to model restoration strategies for the end-of-life management of building assemblies.

- Demonstrate the application of the assembly-level framework in evaluating restoration strategy options.
- Assess the efficacy of the applied frameworks in enhancing RCM use in construction.

This study was motivated by the observed lag in reuse practices within the built environment industry. Thus, the objectives are addressed through the four main chapters in this research. The initial phase of this research focused on building a foundational understanding of the identified knowledge gap. As such, basic knowledge was built in the subject area through extensive reading of relevant literature and field interactions (Chapter 2). Then, the acquired knowledge from the literature and the field study is used to design adaptable frameworks for different resource integration challenges. These frameworks are tested through applications for component-level procurement assessment (Chapter 3) and assembly-level procurement assessment (Chapter 4). Finally, the component-level procurement assessment framework is further tested and applied to incorporate policy strategies and risk factors, offering a broader perspective on the framework's potential as a decision support tool (Chapter 5).

1.3 Defined Terms

To effectively address and articulate the concepts of circular strategies, it is crucial to clarify any ambiguities in terminologies, as some terms are used interchangeably with varying meanings. Therefore, this study has established precise terminology for commonly used terms within industry and academic literature, offering guidance on their appropriate application and usage in this thesis. The use of terms in Table 1-1 are aligned with usage across sources such as Rakhshan et al., (2020); Byers et al., (2024); Iacovidou et al., (2018).

Table 1-1: Terminology for Resource Recovery and Hierarchy.

Term	Definition	When to Use It
New Construction Material (NCM)	A material that has never been used in a previous application.	When referring to fresh-from-manufacturer products.

Used material	A material that has been previously installed or applied in a structure.	After first use, regardless of whether it has been salvaged, recycled or reused yet or not.
Salvaged material	A material recovered before disposal from a demolition or renovation site. Typically acquired during the sorting process.	When it has been removed from a building but not yet reused or recycled
Reclaimed Construction Material (RCM)	Similar to salvaged may imply intention or preparation for reuse or recycling. Notably, the material ought to be at its source for new acquisition or post-use.	Interchangeable with “salvaged” in most industry contexts; whereas in this context used to describe a salvaged resource waiting to be reused or recycled.
Extracted material	Similar to salvaged or reclaimed but inferring that a uniform and automated process was used.	When for example, a material such as construction aggregates have been separated from their binder.
Recovered material	A broader term encompassing all resources before salvage.	Used when intent for reuse, recycling or disposal remains to be determined (e.g. by sorting).
Reused (material/ component or assembly)	A material that has been installed again in a new context. It undergoes none to minimal changes (e.g., cleaning).	Only after actual reintegration into a new project.
Recycled (material/ component or assembly)	A material that has been physically processed and reformed into a new product.	When transformation occurs before use.
Refurbished (material/ component or assembly)	A material that has been improved or restored through minor modifications or repairs, but not fully reprocessed.	When the item has been repaired or upgraded to function effectively again.
Material	The raw or base substance (e.g., wood, steel, concrete) used to form a product.	When referring to the elemental level of construction.
Component	A discrete, manufactured unit made from one or more	Use when focusing on individual products with a specific function.

	materials (e.g., a handle, pipe, beam).	
Assembly	A larger functional system composed of multiple components (e.g., a window unit, partition wall).	Use when referring to grouped components performing a collective role.
Resource	A more general term encompassing materials, component and assembly in the context of circularity.	Used in broader modeling discussions of reverse logistics and circularity in the built environment.

In this thesis, a component refers to a discrete building part assessed independently for sourcing and reuse within the Integrated Material Sourcing (IMS) framework. In contrast, within the Assembly Restoration Framework (ARF), items such as windows are treated as assemblies due to their composition of multiple interacting components (e.g., frames, panes, seals), which may be separated and restored independently. Although the same physical object may be classified differently across the two frameworks, this distinction reflects the analytical focus of each model rather than a contradiction in terminology.

1.4 Scope

The developed frameworks are designed for applicability across various building types, industrial, residential, and commercial. In this thesis, the application is limited to residential buildings due to the nature of the component types available at RCM stores. These stores typically stock a variety of items, such as furnishings, cabinetry, kitchenettes, wardrobes, doors, windows, flooring, toilet and light fixtures, reclaimed porch poles, staircases, mixed wood, lumber logs, and masonry.

For this thesis, the focus is on doors, windows, and flooring components (specifically wooden slats) due to their non-load-bearing characteristics and their prevalence across RCM stores. Basic dimensional attributes such as length, width, and surface area serve as the primary matching criteria within the frameworks. However, some resources have unique shapes, such as arches, curves or irregular shapes, that fall outside standard rectangular or planar forms. These resources are beyond the scope of this thesis. Future adaptations of the framework could incorporate tools that support matching based on complex shapes and contours. Finally, this study does not evaluate the mechanical properties of salvaged components. Although mechanical characteristics are

integral to a material's performance in new construction, they are beyond the scope of this study. However, the Assembly Restoration Framework (ARF) presented in this study does partially examine performance through the lens of operational energy in the case of windows (Chapter 4). Although this does not fully reflect the mechanical behaviour of the window components, it demonstrates one way in which performance-based assessments can be incorporated. Future studies could incorporate mechanical properties such as stress, strain, fatigue, and buckling for structural components like concrete sections, steel beams and others.

1.5 Research methodology

This section outlines the approach used to develop and analyze the frameworks presented in this study. It highlights the research stages and explains how the frameworks were developed, applied, and tested.

The focus of this thesis is the development of frameworks to enhance RCM sourcing. The approach to developing the frameworks is discussed across the following three stages: (1) problem definition using existing literature, (2) framework development, and (3) evaluation & refinement. The approach to developing the frameworks presented in this thesis are discussed under the three aforementioned stages.

Stage 1: The definition of the problem, based on the analysis of literature and field interaction.

The approach to the first part of this thesis is to develop a significant level of understanding in relation to the proposed identified knowledge gap. The identified knowledge gap is the lag in the introduction of RCMs into new building infrastructure. While there is a growing number of infrastructures being deconstructed and resources are exiting these structures, yet their reintegration into new construction projects lags behind, highlighting limitations in current practices, this gap forms the primary motivation for this research. As such, basic knowledge was built in the subject area through extensive reading of relevant literature and field interactions. The study's readings were initially focused on material reuse, reverse logistics, and reuse case studies. However, field interactions led to a deeper comprehension of the extent of the problem and resulted in extending the readings to include OPL, LCA, BIM and 3D scanning.

The field interactions with RCM store managers prompted the exploration of digitization tools that could aid the process of RCM use. Therefore, the RCM stores, namely, the Timeless Material Store (TMS) and the Habitat Restores, were instrumental in data collection for the framework. There are over 900 Habitat Restores across Canada, Puerto Rico and the United States. The Timeless Material store stocks reclaimed aggregates, masonry, wood, roofing, beams, columns, doors, windows, stairs, banisters, flooring and other components salvaged from deconstructed buildings. Meanwhile, the Habitat Restores stocks kitchenettes, doors, windows, furniture, banisters, tiles, vanity and all other interior non-load-bearing components. A total of nine RCM stores were visited across the western Ontario region.

Stage 2: The development of the proposed solution to the problem.

The field interactions led to a deeper understanding of the study. The potential of the digitization systems became apparent through experimental practices, which involved using 3D scanning equipment of various calibres to scan resources found at the RCM stores. The use of the systems inspired a possible solution to increase the efficiency of integrated material sourcing through the combined use of digitization systems. The acquired knowledge from the literature and the field study is used to design a framework that is adaptable to multiple problems. This study's proposed Integrated Material Sourcing (IMS) framework structure for the component level assessment comprises three segments: the core engine, the real environment, and the model environment. Within the three segments, multiple digitization tools can be applied for data creation, data extraction and data processing. The digital tools applied in this research are 3D scanners, a building information modeling system, a visual programming language, a spreadsheet software, an optimization tool, and a life cycle assessment tool. Furthermore, the assembly level assessment framework only incorporated a lifecycle assessment tool and a mathematical formulation for an Assembly Restoration Framework (ARF) that assesses both embodied and operational energy of windows.

Stage 3: Relaxing constraints and increasing the complex application of the framework

To assess the bounds of the frameworks in this research, increasing the complexity of their application is paramount. The purpose of the developed IMS framework is to rationalize multiple

components to produce a set of optimal selections based on desired factors, like cost. Therefore, to test the framework, it was applied to a sample structure to achieve an optimal selection of window and door components. The scenarios presented in this thesis assess the sourcing of doors and windows from multiple locations with a focus on optimizing the cost and embodied energy of sourcing these components (Chapter 3). The framework was then modified to account for windows being sourced as assemblies rather than individual components. This shift was inspired by the realization that windows can be treated as standalone assemblies, allowing not only for optimized sourcing of complete window units but also for the exploration of strategies to deconstruct them and source individual parts (Chapter 4). To further develop and test the IMS framework, it was applied to a different component, flooring. This application focused on introducing risk factors and modelling policy mechanisms within the system. The objective was to investigate the framework's capacity to incorporate regulatory incentives and demonstrate the tools' usefulness for decision-making (Chapter 5). Figure 1-2 depicts the research methodology in this thesis.

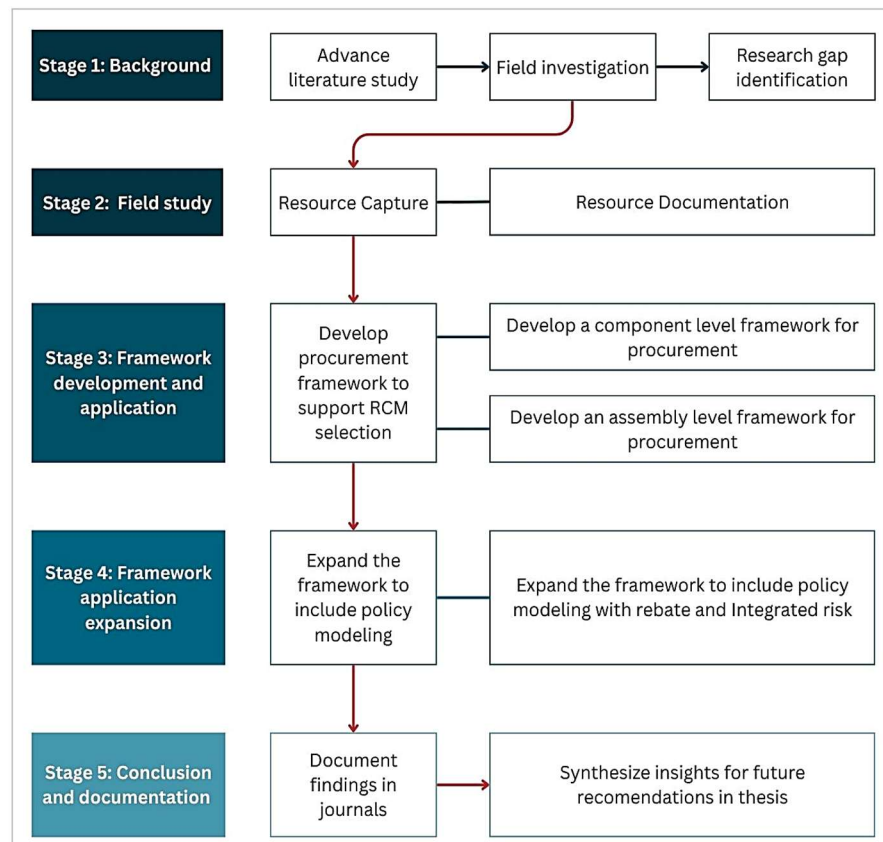


Figure 1-2: Research Methodology

1.6 Thesis structure

This thesis is divided into six chapters, structured as follows.

Chapter 1: Introduces the study area and discusses the motivation of the research study. It states the study's aims, objectives and research process, highlights the research problem, and explains how the proposed topic addresses the research problems.

Chapter 2: Presents a detailed review of the literature supporting the study. It examines segments contributing to the body of work, such as construction and demolition waste management practices, BIM, LCA, 3D scanning, and OPL. Then it discusses the key papers that contribute directly to the body of work and addresses the papers that are related to the study's objectives.

Chapter 3: Presents the component-level framework design, specifically the IMS framework. It assesses the application and the prospective outcome of applying the framework to different scenarios. It also examines the interpretation of results and identifies potential limitations in the technical approach.

Chapter 4: Introduces the assembly-level framework design (ARF). It details the prioritization of evaluating separable components and provides a framework application example. It presents key findings and highlights study constraints.

Chapter 5: Expands the component-level assessment framework by applying it to a different material (flooring) and incorporating additional factors such as risk. It demonstrates the framework's potential as a policy-informing tool. It presents the findings and discusses the study's limitations.

Chapter 6: Concludes the thesis by summarizing key findings, limitations, and recommendations for future work. It also reflects on the practical implications of the study and its contribution to advancing circularity in construction.

Chapter 2: Literature review

The novelty of this study is the contribution of digitized frameworks that enable the value assessment of building resources to a project before procurement, by analysing the economic and environmental factors of available resources from both new and reclaimed sources. Therefore, this section discusses the literature relevant to the concepts applied in this study. First, it reviews construction and demolition waste management, then reverse logistics of building resources, then Reclaimed Construction Material (RCM) reuse, followed by a discussion on digital technologies applied in this study, like Building Information Modelling (BIM), 3D scanning, Optimization Programming Languages (OPL), and Life Cycle Assessment (LCA). Finally, it discusses the precedence of integrated material use and similar works.

2.1 Construction and demolition waste management

Construction and demolition waste management continues to be a challenge worldwide, particularly at the building end-of-life phase. Many of the resources obtained through demolition, deconstruction and renovation activities end up at landfills. These are valuable resources that cannot be easily retrieved or regenerated, and the process of regeneration itself can be expensive (Rakhshan et al., 2020). Waste generated from construction and demolition activities is a significant contributor to the municipal solid waste stream (De Silva et al., 2023; Yeheyis et al., 2013). Construction waste makes up as much as 50% of municipal solid waste, and the resources extracted from the earth for construction activities represent about 40% of all virgin materials extracted (Yeheyis et al., 2013). Adopting stricter regulations and integrating waste management systems can greatly reduce environmental impacts, by incorporating green strategies like recycling, reuse, waste-to-energy options, and ensuring safe disposal methods, with the latter being considered the least favorable strategy (Amarasinghe et al., 2024; Yeheyis et al., 2013).

As urbanization increases and more structures are built to meet housing and infrastructure needs, there is growing concern about the sustainability of continually relying on virgin materials. Circular strategies in construction aim to address this challenge by conserving existing resources, minimizing new extraction, and extending the lifecycle of built assets (Wardani et al., 2022; Iacovidou & Purnell, 2016).

Circular strategies in construction include interventions like reuse, recycling, repair, and refurbishment:

- Reuse involves using salvaged resources from deconstructed or demolished buildings with minimal processing.
- Recycling requires extracting resources and reprocessing them into new construction components.
- Repair focuses on fixing defective or worn resources of existing structures.
- Refurbishment is the upgrade of older resources to meet new performance standards.

These interventions are typically applied before or after resource extraction. Repair and refurbishment are often carried out while the material is still in use, while reuse and recycling occur post-extraction. If none of these interventions are implemented, the resources are discarded, resulting in a loss of resource value (Wardani et al., 2022; Vargas, 2021).

2.2 Reverse logistics for construction materials

After World War II, construction and demolition waste management regulation came into focus, due to the significant increase in wastage and depletion of resources. Growing environmental concerns spurred the creation of government waste-management agencies, such as the European Commission's Waste Framework Directive (Rakhshan et al., 2020). However, there is still a notable gap in the introduction of RCMs, into new builds. As materials reach the end of their first lifecycle, only a few resources are incorporated into new construction. Some are lost early to landfills, while others, though initially diverted, ultimately still end up as waste.

A critical enabler of circular construction is reverse logistics, which refers to the movement of resources from their point of extraction or consumption back into productive use (Hosseini et al., 2015; Rogers & Tibben-Lembke, 2001). The reverse logistics process has two main material flows, material reuse and recycling, which are typical methods for processing resources reclaimed from demolition, refurbishment, or new construction projects (Hosseini et al., 2015). The implementation of reverse logistics faces numerous barriers, including lack of standardized certification for salvaged materials, fragmented construction supply chains that impede material recovery coordination, high labour and processing costs associated with deconstruction compared to demolition, market uncertainty for salvaged materials, leading to low demand, and perceptions

among designers and clients that salvaged resources are inferior or risky to use (Hosseini et al., 2015; Iacovidou & Purnell, 2016; Vargas et al., 2021; Wardani et al., 2022). Additionally, reverse logistics often suffer from low prioritization within organizations, further complicating investment in recovery systems and infrastructure (Rogers & Tibben-Lembke, 2001). Figure 2-1 depicts the reverse logistics process of resources (material reuse and recycling).

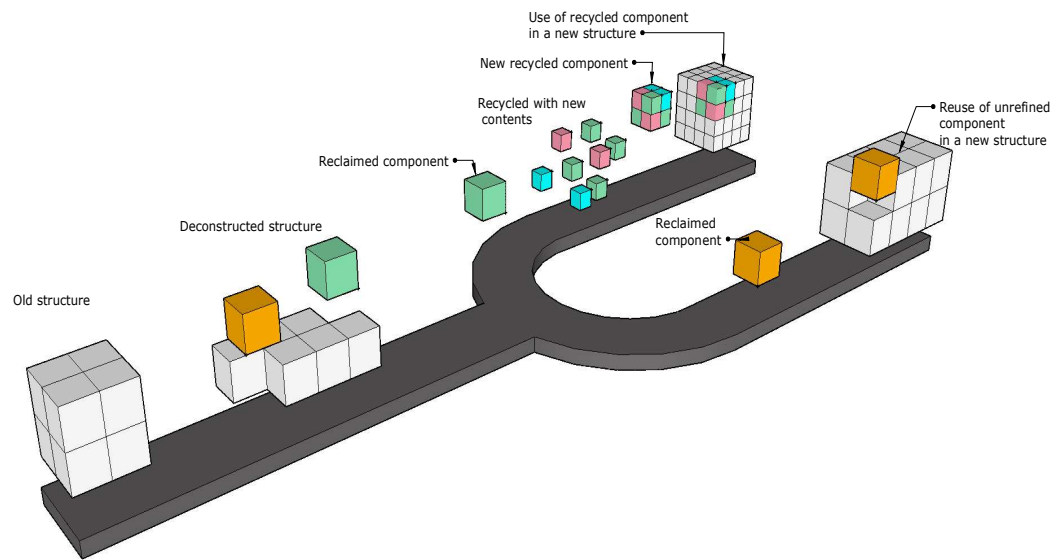


Figure 2-1: Shows the recycling and reuse processes of deconstructed structures.

2.3 Reclaimed Construction Material (RCM) Reuse

The Institution of Civil Engineers (ICE) (2008) strongly advocates for the reuse strategies that place reuse-in situ and reuse-ex-situ above recycling because it is more favourable to the environment and avoids resource-intensive and emission-heavy reprocessing. However, compared to recycling, reuse may be more challenging and expensive. Reuse can be carried out in two main ways: building adaptation or building with used components salvaged from a different site.

Building adaptation is a prominent practice for restoration projects in the built environment industry. It entails varying levels of building construction processes and involves activities like structural rehabilitation, conservation, restoration, reuse and so on (Shahi et al., 2020). Although building adaptation also encompasses reuse, it differs slightly from reuse because the initial underlying structure is assessed to retain some of its good resources, and additional resources from new and used sources are added.

A cited building adaptation study demonstrated an approach to estimate the net environmental impact and cost of adaptive reuse for structural systems. The approach of the study was to estimate the value of keeping the resources in use rather than removing the entire structure. It assessed structural systems like concrete slabs, walls, steel beams, slab on grade, wall footings and foundations, and used the life cycle analysis tool to assess the environmental and cost factors related to the material, equipment, and labour (Sanchez et al., 2019). The study identified different scenarios for resources that can be reused, and the findings suggest that concrete resources had significant environmental emissions. As such, reusing or recycling resources made with concrete, on-site will have a considerable environmental impact on the building adaptation project.

The process of reusing RCM's is dependent on the state and source of the RCM. Several studies, such as Rose & Stegemann (2018), Brütting et al. (2019), Pongiglione & Calderini (2014) and Gorgolewski (2008), have assessed material reuse in construction. The study by Rose & Stegemann (2018) assessed the efficiency of circulating resources carted from demolition sites to ongoing construction sites within a 25km radius. The study revealed that the process was inefficient because of insufficient time for reviewing materials at each location and the process was labour intensive. Simply, the demand for resources must be identified from an early stage, with the qualities and quantities defined to address material flow. Furthermore, the study by Gorgolewski, (2019) examined two case studies on reuse. The first study was on the incorporation of salvaged resources for the Mountain Equipment Coop (MEC) retail store in Ottawa. The project required the deconstruction of the existing MEC store building and the reuse of the reclaimed components from the deconstructed inventory. Approximately 75% of the used-building stock weight was reused in the new structure, with further incorporation of used materials from other sources (Gorgolewski, 2008). The project required the design team to work for a significant amount of time compared to the typical design period of a normal project. It also required an alliance with structural engineers who had experience appraising insitu-resources to determine the potential and requirements for reuse. In addition, the design team had to source materials at the local material yards, local demolition hubs and reclaimed component suppliers for other parts of the structure; they had to ensure the quality of the resources being reused through testing and visual assessments (Gorgolewski, 2008).

Similarly, the second study on a new building at 740 rue Bel Air in Montreal, which had undergone deconstruction, had reclaimed steel resources which were also tested using X-ray imaging and chemical analysis (Gorgolewski, 2008). The tested steel joists reclaimed from the structure were reused in the new structure, and other salvaged components like cladding and bricks were reused in the structure, while some were used on other sites. Although the project was able to reuse or recycle a total of 9,000 m^3 of the reclaimed components, the structural engineers deemed the economic aspect of the project was not optimal. The engineers estimated that the costs of storing, refabricating and handling the reclaimed joists were more expensive than acquiring new ones.

Material reuse, though promising in balancing the economic and environmental impact of new buildings, is still significantly hindered by various technical, economic, and social factors. Studies on the barriers influencing the adoption of building material reuse have been explored by Rakhshan et al. (2020), Hosseini et al. (2015) and Iacovidou & Purnell (2016). The primary barriers identified are social, technical and economic barriers, weighted at 15%, 23% and 39%, respectively (Rakhshan et al., 2020). Labour intensity is a major economic factor influencing reuse due to some contributing processes such as the demolition cost of buildings for reuse purposes, the sorting cost for deconstructed materials, the cost of designing with reuse parts, the cost of finding reusable resources, storage of reclaimed resources, and the transport of reclaimed resources (Rakhshan et al., 2020; Gorgolewski & Morettin, 2008; Hosseini et al., 2015).

As discussed earlier in this section, the technical information uncertainty associated with material reuse is a significant barrier to its application. Existent aging building stocks are not designed for deconstruction, often limiting the information available to enable the reusability of salvaged components. Tests are needed to recertify reclaimed materials due to the uncertainty of how the material properties might have changed during the first service life. Furthermore, the lack of standardized processes and variety in RCMs affects the ease of introducing reclaimed components into new structures. Therefore, the potential to increase the feasibility of reusing reclaimed resources can be improved by guiding the process of reuse through the implementation of tools that standardize and streamline processes for salvaging resources, from the extraction stage to the reused stage (Gorgolewski, 2008).

2.4 Reuse of windows doors and wooden slats

The present study focuses on the use of windows, doors, and flooring resources, particularly wooden slats. In the context of windows, the operational performance of building entities is correlated with the emissions generated by a building, often as a result of its energy consumption, which can be impacted by the quality of windows, doors, and insulation (RDH Building Engineering Ltd, 2013). Essentially, buildings with better insulation and windows tend to perform more efficiently, using less energy for heating compared to those with less insulation. Apart from the insulation of the building, other entities within the building affect the operational performance, such as the window-to-wall ratio (WWR), which represents the ratio of an exterior wall surface area that is glazed (covered with glass) (Troup et al., 2019). The greater the number of windows relative to the building size, the higher the energy required for heating or cooling, depending on the climatic zone. However, the embodied energy of a window or door is based on the resources used for manufacturing and the overall energy invested in the installation process (Saadatian et al., 2021). A study by Arup (2022) explored how the embodied energy of windows in buildings is impacted by the frame type, glass quality, and number of glass panels. The complexity makes it challenging to assess the trade-off between embodied energy and operational energy, as these evaluations are highly dependent on various factors such as the building and window types, the resources used, and other window properties like reflectiveness and thermal performance. Consequently, decisions based on such estimations tend to be subjective in practice.

To address this complexity, previous studies have taken prescriptive approaches towards optimizing the selection of windows for different climatic zones. For instance, Saadatian et al. (2021) explored a combination of alternative glazing and framing options using a Pareto bi-objective optimization of cost and environmental impact. Although the study gives insight on the trade-offs between glazing and framing options and cost, it did not offer a comprehensive model that could be applied to different scenarios for assessing and comparing the characteristics of current windows in decision-making. Similarly, Salazar & Sowlati (2008) and Citherlet et al. (2000) explored life cycle assessments of windows with different frame types and properties. Likins-White et al. (2023) and Gustavsen et al. (2011) examined how different window frame profiles affect thermal performance and the impact on overall window unit performance. Asdrubali et al. (2021) reviewed existing studies to aggregate findings on the life cycle and performance of various window types, including

those framed with wood, PVC, and aluminum. Furthermore, the study by Litti et al. (2018) analyzed the deterioration rates of different types of window units, including aluminum, PVC, and timber-framed windows. The research provided a comprehensive 50-year timeline for the deterioration of each window type. The timber window showed the most significant loss of functionality at the 50-year mark, while aluminum plateaus after 50 years as the frame itself does not further deteriorate in comparison to wood and PVC, which continue to deteriorate over time.

In the case of wood, it is one of the highest valued extracted items from the construction processes. A study by (Guy & McLendon, n.d.) explores the practical aspects of salvaging wood from deconstructed buildings, offering critical insight into resource recovery processes, salvage value, and grading. It examines a series of deconstruction projects conducted between August 1999 and May 2000, focusing on structures built as early as 1915. These buildings, typically comprised of raised wood floor constructions with light wood framing and exterior cladding, presented varying levels of deterioration, most notably from water damage in kitchens, bathrooms, and roof areas. Both natural and human-made defects were identified during the visual inspection of the salvaged lumber. The human made defects were often due to dismantling techniques that included blunt force tools (e.g., sledgehammers), while other types of damage noted were knot, shake, wane, warp, slope of grain, twist, and termite damage. Termite damage was identified as the most detrimental to wood components, followed by human-induced impairments such as bolt holes and improper removal techniques.

2.5 Digital technologies for enabling circularity

The construction industry has made significant progress in recent years by integrating advanced digital tools to improve the accessibility of information related to resource management, especially for end-of-life management of resources (Byers et al., 2024). Some of the technological tools leveraged in the industry, include BIM, Geographic Information Systems (GIS), Material Passport, Internet of Things (IoT), LCA tools, Computer Vision, and Non-Destructive Testing (NDT) as summarized in Table 2-1.

Table 2-1: An overview of the digital technologies that enable circularity in the built environment.

Technology	Description
Material Passports (Buchholz & Lützkendorf, 2022; Çetin et al., 2023; Koppelaar et al., 2023; Paramatmuni & Cogswell, 2023)	A material passport is a collection of data describing the materials used in products or buildings. It provides information about the material origin, characteristics, production details, lifespan, quality, reuse potential, and environmental impact. Material passports can improve inventory management, inform deconstruction processes, shipping, and other aspects of reverse logistics for used building materials, allowing the adoption of circular practices like Design for Deconstruction (DfD), material reuse, recycling, and building adaptation. Notably, material passports are useful in obtaining data that can be used within different decision frameworks to enhance decision-making processes. Although the development of material passports is relatively new, it could potentially be instrumental in supplying the necessary information for the framework outlined in this paper.
Geographic Information Systems (GIS) (Akindele et al., 2023; Hussain, 2023; Tan et al., 2023)	GIS is a technology that captures and presents spatial data by integrating different data layers based on spatial location. It digitizes and visualizes abstract data, presenting it as geo-referenced map solutions through a design schema and functional components. As an end-of-life management tool, it is used to assess the recoverability of resources and quantify how much can be extracted from existing infrastructure. It gives a macro-level view of how resources can be quantified and tracked through the different processes. Moreover, the integration of GIS with BIM and other systems offers spatial solutions that facilitate sustainable construction practices. Combining BIM and GIS results in a unified data set for building projects and their surrounding areas.

Internet of Things (IoT)(Jia et al., 2019; Tang et al., 2019)	IoT's can be described as a network that connects sensors and actuators, allowing them to exchange data across various platforms via a unified framework. Each application has its own unique connection requirements between various technological tools like sensors, the cloud, and actuators or user interfaces. These tools encompass sensing, identification, and recognition technologies, along with necessary hardware, software, cloud platforms, communication technologies, networks, positioning technologies, and data processing systems. IoT's are basically automated frameworks that facilitate decision making processes.
Computer vision (Schlüter et al., 2018; Yeung et al., 2015; Zhong et al., 2019)	Computer vision is a multidisciplinary field that explores how computers can derive sophisticated understanding from digital images or videos. It offers detailed digital imagery and video content, such as the location and behavior of objects and site conditions, which helps professionals better manage construction projects. Computer vision enables the extraction of physical properties from resources retrieved from buildings, allowing the creation of digital replicas. The replicas facilitate simulations to test resource performance in various scenarios, integrating modeling with resource extraction from existing building inventories. Additionally, 3D scanning is considered a part of computer vision. It involves using cameras and lasers to capture three-dimensional data from the physical world. Technology helps computers to interpret and understand the shape and appearance of objects in three dimensions, which is a core aspect of computer vision. The process typically involves capturing detailed images from multiple angles and then using software to reconstruct them into a three-dimensional model.

Non-destructive testing (NDT) (Fujita & Kuki, 2016; Jaskowska-Lemańska & Sagan, 2019; Morales Conde et al., 2014)	Non-destructive and semi-destructive testing are techniques for evaluating the structural performance of buildings without significantly impacting the condition of the building. Non-destructive testing involves surface-level assessment of the mechanical properties of building resources, using methods like acoustic, electrical, radiological, ultrasonic, and electromagnetic testing techniques. Meanwhile, semi-destructive tests used to assess attributes like material properties, damage extent, and corrosion are typically carried out using small, extracted samples of the structure, ensuring the structural integrity of the infrastructure is not affected and can be easily repaired. Essentially, non-destructive testing, along with material passports and other digital tools, can significantly enhance the creation of new information for RCMs that have limited information available.
Building Information Modeling (BIM)(Akinade et al., 2017; Bosché et al., 2015; Cepurnaite et al., 2017)	BIM is a digital representation of physical and functional characteristics of a structure. It is a technology that offers synergy across construction, energy, and software industries. With the increasing adoption of BIM, its application has seen significant innovation in areas such as building design, 3D coordination, facility maintenance, cost estimation, and building performance analysis. BIM applications have expanded by developing and integrating various technologies, like the Internet of Things (IoT). Devices and systems encompassing Radio Frequency Identification (RFID) Tags, Application Programming Interface (API) solutions, scanners, and sensors are increasingly used in aggregation. These integrated systems are crucial in resource monitoring, event tracking, collaboration, communication, and performance evaluation.

Optimization Programming Language (OPL) (Aidonis et al., 2009; Sanchez et al., 2019; Venter, 2010)	Optimization refers to the process of making something as effective or functional as possible. In engineering, essential decisions regarding multiple factors with trade-offs are often made to enhance processes and obtain the very best from resources. Optimization tools assess various solutions in key sectors like logistics, manufacturing, transportation, scheduling, etc. It involves selecting the best option from a set of alternatives, based on specific criteria or conditions. Therefore, optimization algorithms are typically used to solve optimization problems with an objective function, decision variables, constraints and parameters. In mathematical terms, optimization seeks to find the maximum or minimum value of a function within a given set of constraints.
Life Cycle Assessment tools(Cabeza et al., 2014; Yeheyis et al., 2013)	LCA is a methodology used to evaluate the environmental impacts associated with all the stages of a product's life, from raw material extraction through materials processing, manufacturing, distribution, use, repair, and maintenance, to disposal or recycling. LCA helps to identify opportunities to improve the environmental performance of products at various points in their life cycle. However, LCA can vary in its scope and depth, with certain evaluations analyzing extensive networks to understand the macro-scale impacts of infrastructure, while others narrow down their focus to the materials used, examining the micro-scale environmental effects. Moreover, LCA studies can have different main objectives, with some aiming to analyze various environmental impact indicators such as Global Warming Potential (GWP), Acidification Potential (AP), Eutrophication Potential (EP), Human Toxicity Potential (HTP), Abiotic Depletion Potential (ADP), Ozone Layer Depletion Potential (ODP), and Terrestrial Ecotoxicity Potential (TEP) and

others (Aryan et al., 2023). Meanwhile, other studies could focus on the overall effects of the infrastructure (total GHG Emission). The boundaries considered in LCA can also vary, encompassing cradle to gate, cradle to practical completion, cradle to grave, and cradle to cradle (Masson, 2023).

Technological tools like NDT, Material Passports, and other digital tools enrich the available information, crucial for making informed decisions on RCMs. Table 2-1 provides an overview of the technologies and highlights various data points collectible through these technologies. Collectively, the tools aid assessors in selecting viable resources for construction projects, by improving the data available for decision-making processes and thereby fostering circularity.

This study incorporates and discusses only a few of these tools for simplicity in demonstrating the framework. The choice of tools discussed in this paper followed natural evolution, stemming from the field study. Despite the availability of various tools for enhancing integrated material sourcing, the frameworks only incorporate BIM, 3D scanning, OPL, and LCA tools.

The papers selected and discussed in the literature review section were chosen based on their application of tools for end-of-life resource management, aligning with the framework's focus on reintroducing resources into the building inventory. These papers applied technological tools in a similar capacity for managing end-of-life resources, focusing on the end-of-life stages such as sorting, transportation and end-of-life treatment (Banias et al., 2022). This selection was made to build upon existing research in end-of-life resource management using these tools and to explore new ways of reintegrating building material stock into infrastructure. The following sections give an overview of these technologies: their current applications in the construction industry, their intended application within the framework proposed in this paper, and the knowledge or research gaps being filled by that application.

2.6 BIM for circular engineering in the built environment

Building Information technology has substantially evolved, impacting the Architectural, Engineering, and Construction (AEC) sector (Meža et al., 2021). Building design involves multiple

stakeholders, including architects, engineers, contractors, and owners, who all influence design decisions. While BIM processes are well-established for new constructions, they are not yet widely applied in the maintenance, refurbishment, or deconstruction of existing buildings. This transformation has led to a shift from conventional 2D and 3D models to advanced BIM models. These BIM models now seamlessly integrate with state-of-the-art technological components like Virtual Reality (VR), Artificial Intelligence (AI), assisted management systems, and robotic-driven construction technology (Meža et al., 2021)

Chen & Nguyen (2016) and Ness et al. (2020) demonstrated the potential of aggregated systems featuring BIM. A notable application of aggregated systems featuring BIM was the creation of a cyber-physical data platform, which is designed to facilitate the sourcing of reusable components from deconstructed buildings. Ness et al. (2020) integrated the cloud BIM environment with Radio Frequency Identification (RFID) tags to establish an innovative data platform based on the Product Service System (PSS) model. The case study demonstrated the use of a 3D scanner to capture a proposed building for deconstruction. The scans were incorporated into a BIM model, enabling RFID tags to track the BIM materials by connecting with the cloud.

The studies by Ness et al. (2020) and Chen & Nguyen (2016) give insight into how BIM can be integrated with other technological devices to enhance its capabilities. Although previous studies have expanded on different methods of applying BIM, the research has yet to address the focus of this paper, which is the optimization of RCM procurement.

BIM models contain information necessary for sourcing various building components. They support the ability to model structures before acquiring resources and to adapt resources during the acquisition process to meet specifications. Given this depth of knowledge and information, identifying necessary components for building sites becomes more precise, and building schedules can then be used for sourcing. Therefore, BIM is used within this project to extract resource schedules for analysis and component sourcing. Through the BIM platform, RCMs can be assessed for integrability.

2.7 3D imaging systems

The use of 3D scanning technology has evolved in the built environment industry and can be applied across the building life cycle for building maintenance, construction monitoring, demolition

planning, and asset preservation (Zhang et al., 2022). 3D scanning systems use different technologies to achieve a 3D digital replication of objects or spaces virtually. The different types of imaging systems are:

Laser-based scanners: Laser scanning systems use a laser beam emitted by a laser projector to reconstruct a 3D image; the scanners can operate with a single sensor or multiple sensors. There are two main laser-based technologies: the laser triangulation system and the time-of-flight system (Bhatti et al., 2021).

Lidar: Light Detection and Ranging systems are commonly used for various applications, including autonomous vehicles, robotics, and 3D mapping. Lidar can measure the distance to objects with high precision, making it an important sensor for applications where highly accurate distance measurements are necessary (Rashdi et al., 2022).

Structured light scanners: A structured light system projects light with patterns onto an object to reconstruct the object using the deformation in the projected pattern. Typically, the emitting system emanates structured light toward the item being scanned, and the distorted lighting is reflected to the sensor, which acquires the image (Zhang et al., 2022).

Photogrammetry scanners: A photogrammetry system uses multiple captured images or recordings of an object or space to build a 3D image. Several software tools are specifically designed for photogrammetry, which can be used to process the images and extract the 3D information (Guerra et al., 2019). The software typically uses algorithms to identify common points in the overlapping regions of the photographs to reconstruct the 3D image.

Simultaneous Localization and Mapping (SLAM): The applications of 3D scanning can be seen in combination with robotic and drone systems. The technology frequently applied in this area is Simultaneous Localization and Mapping (SLAM), which allows a mobile robot or device to create a map of its environment while keeping track of its location within that map (Keitaanniemi et al., 2021). SLAM algorithms typically use a combination of sensors such as lasers, cameras, and inertial measurement units (IMUs) to gather data about the environment and the robot's own motion.

3D imaging systems have diverse applications within the built environment sector. The value of 3D scanning, in the context of this study, is in streamlining the acquisition of data concerning

components present at the RCM stores. Obtaining both the dimensions and the physical state of these components holds immense value, as it allows the evaluation of their compatibility with designs or structures before acquisition. The restores often lack comprehensive means of identification or existing digital replicas that can be used to depict components accurately and virtually. Hence, the ability to scan items upon arrival and automate the derivation of accurate dimensions and condition assessment is an asset.

2.8 Optimization

The applications of optimization tools vary in practice, and some examples are minimum or maximum flow, the spanning tree, transportation, transshipment, multicommodity flow, shortest path and other complex problems. These problems are also applicable in building and construction logistics. Brütting et al. (2018), Chen & Liao (2022), Demirel et al. (2016), Mollaei et al. (2023), and Sanchez et al. (2019) are among the various studies that have used optimization models in the built environment industry for decision-making processes.

Demirel et al. (2016) studied the use of mixed integer linear programming models for facilitating the reverse logistics process, focusing on the flow of resources at the end-of-life. They focused on the deconstruction phase to the transport phase, where resources are either deposited at landfills, recycling plants or disposal plants. Similarly, Chen & Liao (2022) proposed an optimization solution for a multi-depot vehicle routing problem. The study focused on optimizing construction demolition waste transport by considering time windows, vehicle capacity, vehicle routes, and transfer stations. Rocca et al. (2020) and Sanchez et al. (2019) also examined the use of optimization and machine learning algorithms to optimize decision-making for building deconstruction processes. Mollaei et al. (2023b) furthered the study in this field by extending beyond optimizing building deconstruction and focusing on understanding the value that could be derived from the structures themselves. Mollaei et al. (2023b), therefore, estimated the quantities of reusable, recyclable, and disposable options of in-situ building resources. A linear programming optimization methodology is applied in the study for a decision support model.

Optimization solvers are crucial for efficiently handling complex problems where manual calculation is impractical or impossible. There are different types of optimization solvers designed to tackle problems. For instance, linear programming solvers are designed to tackle problems with linear

objectives and constraints, and a standard algorithm for solving linear programming problems is the simplex method (Luenberger & Ye, 2021). Nonlinear programming solvers are used for problems where the objective function or any of the constraints are nonlinear. Integer Programming Solvers are used when the decision variables are required to be integers, while Mixed-Integer Programming (MIP) Solvers are for problems that involve both integer and continuous variables. Constraint programming solvers focus on finding solutions that satisfy a set of constraints without necessarily optimizing a particular objective function. While, Global optimization solvers are used to find the global optimum of a function, especially when the function may have multiple local optima that are not globally optimal. Some software packages that include optimization solvers are IBM's CPLEX, Gurobi, and MATLAB (Anand et al., 2017). In this paper, the IBM CPLEX solver is used. The Optimizer is renowned for handling large-scale optimization problems and is particularly effective for linear programming, MIP, and quadratic programming. It is also designed for integration with various applications, in the case of this study, the easy integration with Excel made it a great choice for the framework (IBM, n.d.).

These studies have demonstrated the broad potential of optimization programming in enhancing the efficiency of reverse logistics flows concerning resources. However, limited studies have demonstrated the feasibility of using optimization tools to incorporate used resources in new buildings. In one example, Brütting et al. (2018) focused on optimizing reuse through component matching, using the linear programming language to design a canopy with reclaimed steel pylons while minimizing resource wastage. The study assumed the state of the proposed pylons was optimal for application but notably stated the importance of mechanical and physical characteristics for application in a real-world situation. It demonstrated the applicability of optimization tools in the building industry, facilitating material reuse and reverse logistics processes and guiding decision-making across multiple stages. Despite these advancements, a comprehensive utilization of optimization programs in the integrated sourcing of reusable components from diverse sources remains unexplored.

2.9 Life Cycle Analysis

A material product's life cycle encompasses the journey through resource extraction, transportation, product development, utilization, and, ultimately, its end-of-life phase. Each product's creation and existence within the environment has an accounted impact, which

significantly hinges on the accumulated energy in the product's flow, development, and maintenance. Various materials sourced from the natural environment are refined and utilized in developing infrastructures with a complex mix of resources. So, over time, industries have devised tools to evaluate the environmental implications of resources accumulated within a structure. These tools differ across industries, particularly within construction, where aspects like life cycle costs, environmental impact, energy consumption, and more are gauged. Underlying models within the environmental impact assessment tools influence the results when assessing infrastructure, buildings, and other entities. For instance, impact calculations vary across jurisdictions due to regional codes, Environmental Product Declaration reports (EPD), and other factors.

For instance, Envest 2 functions as a building life-cycle design tool, exploring environmental and financial trade-offs during design while adhering to ISO 14040 standards. However, its analysis of use-phase impacts is limited. LISA, an Australian-developed tool, aids construction with freely available LCA decision support. While GaBi, a model from Germany's University of Stuttgart, follows a process-based approach factoring in unit Processes (Cabeza et al., 2014; Herrmann & Moltesen, 2015). Likewise, SimaPro follows a comparable process-based approach, but the main distinction from GaBi is its easier integration with Excel (Herrmann & Moltesen, 2015). Meanwhile, OpenLCA, is an open-source tool for comprehensive ecological, social, and economic impact assessments (Picardo et al., 2023). Finally, OneClick LCA incorporates data that encompasses energy usage, greenhouse gas emissions, water consumption, and other resource metrics (Besana & Tirelli, 2022). It calculates the environmental impacts of products, buildings, or systems across their entire life cycle using a collection of EPD's and other regional based information. Most of these systems yield CO2 equivalent values, measuring Global Warming Potential (GWP) and assessing climate impact. GWP is commonly used to evaluate the climate effects of various Green House Gases (GHG), allowing the evaluation of the effectiveness of various strategies by quantifying emissions, which is then used to measure the long-term warming impact of greenhouse gases in relation to carbon dioxide.

Integrating LCA tools into infrastructure planning and design is increasingly prevalent in construction and is gradually becoming a standard practice. Numerous studies employ these tools to gauge environmental impact before construction, enabling analysis of energy-saving measures and assessment of proposed infrastructure impacts. Opher et al. (2021) and Besana & Tirelli (2022)

both used the OneClick LCA tool for infrastructure LCA. Opher et al. (2021) discussed a Toronto case study on the refurbished Don Valley Brick Works' Kiln Building. The study quantified the embodied carbon from extraction to the installation stage using the OneClick LCA tool. It covered various components like raised floors, solar systems, curtain walls, mechanical rooms, doors, windows, roof layers, skylights, and more. The analysis concentrated on transportation, construction (A4 to A5), service life (B4 to B5), and waste disposal (C3 to C4), assuming a 60-year project lifespan for the impact calculations. Notably, the main life cycle phases examined through OneClick LCA were manufacturing (A3), material transport (A4), and installation (A5). Similarly, Besana & Tirelli (2022) employed the OneClick LCA tool in a Milan case study for a net zero carbon building. The OneClick LCA tool assessed the A1 to A5 modules, encompassing material production, supply, transport, and construction phases. These studies focused on using the OneClick LCA tool to assess material impacts, particularly in the early stages. It involved considering the product's transportation, manufacturing, and service life. The OneClick LCA tool's significance lies in its capacity for a comprehensive assessment.

2.10 Knowledge gap

Several studies have developed methodologies to minimize and manage construction waste destined for landfills. For example, Abdallah et al. (2021) created a multi-objective optimization framework to determine optimal waste-to-energy (WTE) management strategies for municipal solid waste. The model calculates energy production, carbon footprint, and financial profitability of various waste types processed at selected facilities. Meanwhile, Yazdani et al. (2021) evaluated 11 recycling facilities in Sydney, focusing on route planning optimization for construction and demolition waste collection across 30 different construction sites. The primary objective was to develop a decision-support tool that enhances the efficiency of waste collection in urban settings by integrating optimization and simulation techniques. Yeung et al. (2015) introduced a decision-support framework to aid stakeholders in identifying opportunities for structural steel reuse. The study developed an automated object recognition algorithm that detects cross sections of structural members and provides the necessary statistical parameters for conducting reliability analysis on reclaimed steel components. Sanchez et al. (2019) developed a decision-making framework (Sequential Disassembly Planning for Buildings (SDPB) method), for optimizing disassembly plans that enable the retrieval of specific components, applying cost and carbon

dioxide emissions as the primary objectives. Wang et al. (2022) proposed a life-cycle assessment (LCA) framework to evaluate and compare the environmental impacts associated with different disposal strategies like landfilling, reuse, and recycling. Similarly, Demirel et al. (2016) and Aidonis et al. (2009) assessed the use of mixed integer linear programming models for reverse logistics of end-of-life building components from the deconstruction phase to the transport phase where components are either deposited at landfills, recycling plants or disposal plants. The study by Chen & Liao, (2022) also proposed an optimization of the multi-depot vehicle routing problem with time windows for construction demolition waste recycling to optimize decisions considering time constraints, vehicle capacity, vehicle routes and transfer stations.

These studies set the foundation for this thesis by providing insight into well-developed areas of construction and demolition waste management while also highlighting opportunities that remain underexplored. For instance, most studies focus on the use of recovered materials alone, with an emphasis on optimizing extraction processes or applying salvaged components directly in new construction design. However, there is significant potential to balance the use of both new and used materials in new designs, and this thesis addresses that opportunity by advancing approaches for the integrated use of building material resources. Secondly, there is a lack of integration between real-world material data and the models developed in many of these studies. In most cases, optimization tools are built and tested within simulated environments, without being grounded in field-collected data, limiting their practical relevance. However, this thesis uses empirical data from the field as the groundwork for framework development to assess real-world scenarios.

Thirdly, there is a gap in how existing tools account for the different levels of materials in structures. While many studies target components or elements such as steel and concrete, they rarely consider how these interact within assemblies or how components influence the restoration and performance of an assembly. Therefore, this thesis broadens this understanding by examining how component relationships affect assembly performance. Finally, existing models often demonstrate limited adaptability. They are frequently designed as tailored solutions to specific problems, with little consideration of how they would function in a full-scale procurement process. The focus remains on the optimization formulation itself, without sufficient attention to how data is collected,

structured, and reintroduced into practical workflows, creating an isolated application of tools. Thus, this thesis proposes broader frameworks that embed optimization methods into procurement and material sourcing processes, ensuring their outputs can be connected to real project delivery contexts.

Based on these identified gaps, the thesis advances two key contributions. First, it introduces the Integrated Material Sourcing (IMS) framework, which incorporates BIM, 3D scanning, OPL, and LCA tools to support the assessment of RCMs(Chapter 3). Second, it develops the Assembly Restoration Framework (ARF), which enables comparative evaluations of restoration strategies within specified structural contexts (Chapter 4). Then the IMS framework is further extended to explore its adaptability for different materials and procurement criteria (Chapter 5). To ensure consistency of style and terminology with this thesis, minor revisions have been made to the following chapters (Chapter 3 and Chapter 4). Abstracts, however, remain unchanged from the published articles.

Chapter 3: Building Material Reuse: An Optimization Framework for Sourcing New and Reclaimed Building Materials

This chapter presents the development and application of the proposed framework, focusing on the procurement and evaluation of individual building components. It outlines how basic dimensional and material characteristics can be used to assess the suitability of reused components for reintegration into new projects. In the context of this chapter pertaining to the IMS discussion, windows are modelled as singular components, without disaggregation into sub-elements. This chapter is based on the following published article.

Olumo, A., & Haas, C. (2024). Building Material Reuse: An Optimization Framework for Sourcing New and Reclaimed Building Materials. Journal of Cleaner Production, 143892. <https://doi.org/10.1016/j.jclepro.2024.143892>

Abstract

The process of sourcing Reclaimed Construction Materials (RCMs) is predominantly manual and hindered by the limited digital presence of RCMs. However, the advancing technological landscape provides an opportunity to create a modular framework that can assess the value proposition of New Construction Materials (NCMs) and RCMs for a project before acquiring them. A field study in the Kitchener/Waterloo region inspired the development of a framework that has three underlying systems encompassing digital tools for data collection and analysis: (1) The Real Environment uses 3D scanners and a spreadsheet software, (2) The Model Environment uses Building Information Modelling (BIM) software and a Life Cycle Assessment (LCA) tool, and (3) The Core Engine uses an optimization program. Real-world data collected from RCM stores (The Habitat for Humanity) and NCM stores (The Home Depot) are used for a realistic demonstration of the framework. By practically applying the framework to source window and door components for a modelled multi-residential building design, an integrated selection of 35% RCMs and 65% NCMs was proposed for the building design. Furthermore, sensitivity analysis is also performed for validation. The framework may disrupt the ongoing building design practices that deem material reuse problematic

by enabling flexible sourcing of used and new building materials. A modular and iterative framework for facilitating reuse is thus contributed.

3.1 Introduction

The UNEP International Resource Panel 2020 postulates that residential building emissions from material cycles can be reduced, by at least 80 percent in 2050, by implementing continuous efficient resource strategies in the G7 and China (UNEP, 2020). In today's global context, where wildfires, climate change, and housing crises are becoming increasingly prevalent, reevaluating waste as a valuable resource for growth is not just a choice, but a necessity. The transition to a circular economy is paramount for optimizing resource usage, preserving our environmental history, and enhancing overall sustainability. While the circular economy concept is promising, implementing it effectively in the built environment industry requires more than theoretical understanding. Currently, discussions and actions around sustainable construction typically center on optimizing the operating energy efficiency of infrastructures, with limited focus on the virgin materials used in construction and the embodied energy they represent. While energy-efficient building design is often emphasized, it is also crucial to address the impact of resource extraction from the natural environment and extend the use of existing resources (UNEP, 2020).

Most resources produced from construction and demolition activities end up in landfills. However, some resources extracted and diverted from landfills can be found at reclaimed resource yards, restores and other secondhand stores where they can be repurchased for reuse, or other purposes (Olumo et al., 2022). The use of RCMs for new projects is hindered by the inadequate understanding of RCM extraction processes, variability in properties, reliability of the outcome of the extraction process, lack of confidence in the information provided for future use, and technical limitations with reusing the resources (Hosseini et al., 2015), (Rakhshan et al., 2020), and (Geldermans, 2016). However, some RCMs are still made available through the reverse logistics process.

Environmentally, reuse is typically more favorable than down cycling or recycling, as it generally avoids extensive reprocessing, which consumes additional resources and may result in increased environmental emissions. However, it is important to note that while reuse offers environmental benefits, it can also present challenges in terms of complexity and cost during the reverse logistics process. The reuse process can be capital-intensive and tasking in some situations (Vargas et al.,

2021). Social, economic, and environmental factors impact the end cost of RCMs. Efficiently managing the reverse logistics process involves careful consideration of these factors, with an emphasis on striking a balance between environmental sustainability and practicality. Direct reuse of RCMs accounts for less than 10% of current reverse logistics practices, which indicates a considerable portion of resources are either recycled, or downcycled (Pushpamali et al., 2019). Consequently, there is room for improvement in historical resource retention.

The reuse of RCMs is contingent upon the condition and origin of the resource. RCMs can be reused on-site or reclaimed from other locations as salvaged resources. Several authors have assessed the direct reuse of RCMs in construction (Rose & Stegemann, 2018; Brütting et al., 2019; Pongiglione & Calderini, 2014; Gorgolewski, 2008; Yeung et al., 2015). Yeung et al. (2015) compared the reuse and recycling of structural steel and found that the lifecycle impact advantages of reuse were clear, but reuse costs were higher than recycling in Canada. Rose & Stegemann. (2018) investigated the efficiency of circulating RCMs from demolition sites to ongoing construction sites within a 25km radius. The study found the process was labor-intensive and time-consuming. It was concluded that to address the challenges, early identification of demand for resources, with defined qualities and quantities, is crucial in tackling the resource flow challenges.

The Mountain Equipment Coop (MEC) retail store in Ottawa is an example of a direct reuse project that required the deconstruction of the existing building to rebuild a new structure. Approximately 75% of the used building stock weight from the deconstructed inventory was reused in the new structure, with further Incorporation of RCMs obtained from other sources (Gorgolewski, 2008). The study found that the project design process was time-consuming compared to the typical design period of a normal project. The challenges are the difficulty in sourcing RCMs as the design team had to visit various local salvage yards, demolition hubs, and reclaimed component suppliers for other structural parts, and the RCMs had to undergo testing to ensure their quality for reuse (Gorgolewski, 2008).

Although material reuse presents opportunities to balance the economic and environmental impact of new structures, as discussed earlier in the section, it still faces significant challenges stemming from technical, economic, and social factors. Particularly, the existing aging building stocks are not designed for deconstruction, often limiting the information available to enable the reusability of

reclaimed resources. Also, tests are necessary to recertify RCMs due to uncertainties about potential changes in material properties during their initial service life.

The lack of standardized processes and a diverse range of RCMs further complicates the integration of RCMs into new facilities. Although material reuse has a host of issues, one of the most significant issues is the negative perception toward the usage of RCMs in construction (Hosseini et al., 2015; Iacovidou & Purnell, 2016; Rakhshan et al., 2020). According to industry experts, the cautious approach to reusing RCMs in new builds is due to concerns about the quality, durability, or safety of the RCMs. However, overcoming reuse barriers requires changing perspectives. By aligning research with practical use, systems that identify, source, and integrate reusable resources can be explored. Thus, this research formalizes the sourcing of RCMs to scale their inclusion in new builds.

This paper posits that existing digitization tools, particularly BIM, 3D scanning, Optimization Programming Languages (OPL), and Life Cycle Assessment (LCA), can be incorporated into a system that facilitates an optimal acquisition of new and used building resources. In addition, implementing the framework for procurement from a regional supply network of RCMs and NCMs for a building could demonstrate the value of simultaneously using RCMs and NCMs. Therefore, the following research questions are addressed:

- (1) Can technologies such as BIM, 3D scanning, and optimization contribute to an optimized digitized sourcing process?
- (2) What benefits does the proposed framework bring to reusing RCMs, considering multiple variables that impact the end cost of reusing RCMs?

The approach to this study entails two stages: framework development and framework testing/application. The initial stage, framework development, required a field study to gain insight into the current situation in RCM sourcing. The field study, in combination with the literature study and technological resources, formed the basis for creating a comprehensive framework that analyzes the data collected in the field study and uses it to generate optimal sourcing recommendations for buildings.

The framework has three main structures: the model environment, the core engine, and the real environment. The three structures support the integration of information acquired using digitalization technologies. The current application of the framework in this paper is limited in scope

by the criteria applied in the case study, such as project location, building type, building component type, applied technology, and physical and mechanical characteristics.

Although the developed framework is structured for applicability across different types of industrial, residential, or commercial buildings, its application in this study is limited to residential buildings due to the component types assessed. Additionally, door and window resources are evaluated because of their non-load-bearing features, feasibility for current reuse, and defined physical characteristics. Also, this paper sets dimensions such as length and width as the basic matching criteria, considering only direct reuse of the resources without alteration. However, the complexity of matching and cost of refurbishment is evident in the types of resources presented at the Restores. The stores have resources with interesting shapes like arches and curves, which makes it challenging to use simple information for matching. Additionally, some of the window components are worn, suggesting that certain windows will require at least basic refurbishment.

Furthermore, the mechanical characteristics are not factored in the study, but the significance of efficient energy operation cannot be ignored in terms of building performance. It is necessary to examine the balance between embodied energy and its influence on operational efficiency, particularly for windows. While there is the possibility of exploring alternative technologies within the framework, this study limits the technological systems used for BIM, 3D scanning, LCA, and OPL. Moreover, the progression of technologies such as artificial intelligence, RFID tags, and other systems within the construction sector introduces a promising dimension to the comprehensive use of the framework. Since the framework is designed to incorporate various technologies, it can be adapted to use AI within its core engine for intelligent autonomous selection of composite components, utilizing environmental data to train and inform the framework's decision-making process.

Finally, the results from this study suggest that RCMs used in new projects alongside NCMs can be suitable and cost-effective. In fact, the sustained existence of RCM stores in North America (including those studied here) indicates that a market for these resources already exists (along with used lumber, masonry, tiles, and cabinetry), though it is generally undocumented in the academic literature. A market for reused structural steel has also emerged in Toronto, driven by the Toronto Green Building Mandate for reduction of embodied energy in new buildings, as described in a

meeting on October 10, 2023, at the WSP offices at 25 York Street in Toronto, where eight ongoing projects were identified. These findings emphasize the importance of establishing a well-functioning market for used resources with minimal factors hindering the flow of resources.

The following sections of this paper will explore the literature that underpins the technologies applied in the framework and discuss key papers relevant to the development of the framework. The sections further explain the methods for creating and implementing the framework, the outcomes derived from applying it and discuss the study's findings.

3.2 Research gap

There is yet to be an all-encompassing framework that defines the different stages or steps that could be taken in implementing different optimization tools given information from real-world data and matching it with information from design parameters. This paper takes a holistic approach to standardize the way in which different optimization tools can be used within a framework to match components to designs going beyond the distribution or transportation of resources but going further into reintroduction of reclaimed materials into new structures. Limited studies exist in terms of the reintroducing used materials into new structures as the current state of reuse is still developing and fairly unstructured.

The sourcing of RCMs, as discussed earlier, presents challenges. These challenges encompass factors like the difficulty in finding readily available materials, the limited information available during the material acquisition process, and the intricate and iterative design considerations when incorporating RCMs into designs before acquisition. While there are concerns about the structural integrity of RCMs, Gorgolewski's (2019) case study proposes that revalidating materials for reuse can occur post-acquisition. However, the current crude acquisition process hinders effective design using RCMs.

Additionally, the approach by Pongiglione & Calderini (2014) poses an insight into how to better fit reusable materials into new projects, what factors to consider, and how these materials would be integrated into projects without changing the dynamics of the design process in its entirety. Research is yet to assess RCM reuse on a greater scope, whereby the material functioning as part of an entire building or capital asset is assessed for its overall value to the asset before implementation. The highly fragmented reuse supply chain also influences stakeholders' decision

to consider reusing materials for projects. Although a few key players have successfully executed projects with reuse materials, it remains a minor practice. Therefore, an integrated sourcing approach could be beneficial to an evolving industry as inventory matures.

3.3 Methodology

The methodology in this study encompasses two stages. The first stage involves defining the problem and developing a framework. The second stage entails applying the framework to models of real-world situations supported by substantial real-world data collection to demonstrate its functionality and examine its strengths and weaknesses.

3.3.1 Framework development

To comprehend issues surrounding the acquisition of reusable materials for construction, two main stores, The Habitat Restore (one of many in the province) and Timeless Material Store in the Kitchener/Waterloo region were visited between January and December 2022; weekly visits were made from January to July 2022, and subsequent visits were made monthly to observe changes in RCM inventory. During the series of field discussions with the store managers, the limitations experienced by the store workers and the customers were detailed to understand the problems faced at these stores.

A common problem noted on online platforms used by these stores is the time-consuming nature of gathering and uploading information, only a limited number of RCMs are made available online, unlike New Construction Materials (NCMs). Moreover, the information presented online is not always usable in a meaningful way, nor is it timely, leading many customers to contact the store directly for specific like dimensions, which often cannot be accurately inferred from images alone. Alternatively, customers waste fuel, time, and money driving repeatedly to the stores to inspect stock in person. One obvious technical solution to this problem is to collect detailed physical attribute information about RCMs through 3D scanning and make it accessible online, allowing individuals to acquire more useful details about the products offered at the stores remotely. Through an iterative design prototyping process, field interactions led to a visualization of how the study could evolve. With additional literature study of the problems faced within the construction industry, the potential of the digitization systems became apparent through experimental practices, which involved using 3D scanning equipment of various precision and accuracy to scan RCMs found

at the Restores. The use of the systems inspired the development of the framework structure in this study.

3.3.2 Framework structure

This study develops and applies a methodological framework for integrated material sourcing; the framework consists of three underlying systems adaptable to various supply networks, materials classes, and construction sectors. The systems are: (1) the model environment, (2) the real environment and (3) the core engine. Figure 3-1 depicts the relationships within the framework.

Firstly, the model environment refers to the building design medium, where building design information is obtainable. Therefore, the data in the model environment is typically a digital representation of a prospective building that contains basic to detailed information on components needed. It contains information about buildings created digitally to meet real-world standards and is a source of component requirements. For instance, information like window opening requirements, building emissions standards, minimum strength, material type, design ratings and others can be acquired from the model environment to enable sourcing. In this study, Revit (a BIM tool) and OneClick (an LCA tool) are used for design and environmental information extraction. However, other design software can be used to define additional characteristics.

Secondly, the real environment refers to digital information of real-world product options, either new or used material options, whereby information about the available components from multiple sources can be obtained. Therefore, the real components' characteristics can be matched to the model components defined and required for the construction process. The data for the real environment can contain various information about the condition of existing components like location, material type, origin, size, strength, quality, rating and EPD. The digital tools used in the real environment for this study are 3D scanners.

Finally, the core of the decision-making platform is where the data from both the model environment and the real environment are collated, filtered and assessed in the optimization model. The core of the decision platform connects all the required information and optimizes resource selection based on the provided data. The data from the two connecting platforms are refined and organized, then components fitting the requirements within the model are evaluated to result in an optimal selection of components for a defined project. The following section will

discuss, in detail, the systems used for data collection, the data refinement process and the problems addressed in this study. Excel and CPLEX IDE are used for the data refinement and optimization process, respectively, in this study. Multiple systems can be added to the model and real environment to enrich the data acquired for processing in the core engine.

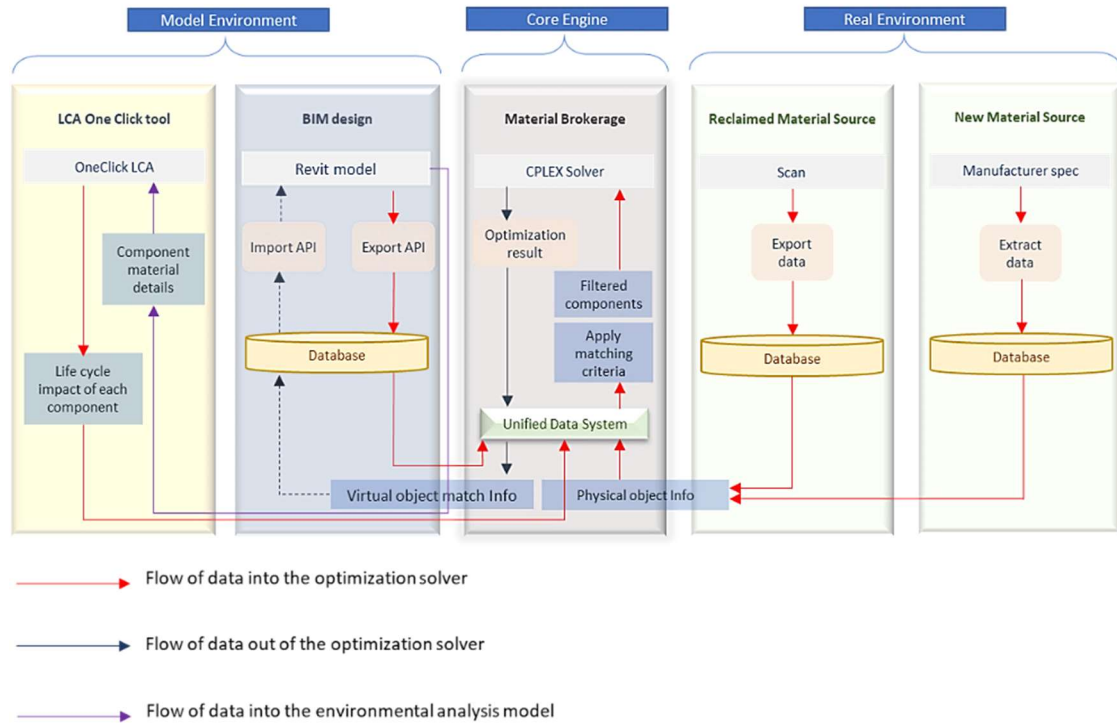


Figure 3-1: The proposed framework structure and flows

The developed framework in Figure 3-1 depicts the information flows between each system, and it shows how data is structured and related in the core engine, model environment, and real environment. The model environment includes the BIM design and OneClick LCA systems, where information on all the components and their requirements in the design is made available; they may change and evolve depending on design flexibility and stage of design. Other requirements like the operating energy impact and structural requirements could be added for completeness, depending on the class of the component and category of design. The real environment refers to component sources, including NCM and RCM stores, which provide available inventory data. Where possible, this includes known product dimensions and specifications. The core engine includes the component brokerage system, where the optimization tool is used to assess the optimal selection of components based on the minimization of cost and embodied energy objectives. Such multi-

objective optimization may include operating energy minimization, esthetic utility maximization, and other objectives in the future (through human-in-the-loop optimization procedures).

The framework structures how technological tools are used to extract real-world data, which is then matched with the data in building models. By considering the availability of resources that match the components in the design model and the cost of acquiring the resource, opportunities to reuse resources can be maximized. The process of using the framework involves entering information about available resources at different stores into an Excel spreadsheet. Next, the measurements of the building components are taken from the design model and also entered into the Excel spreadsheet. Then, the Excel data points are used to match components from the real environment and the model environment, ensuring the selected component align with the required size, and the optimization model is used to minimize the costs.”

In this study, Excel is used to process data, and the order of operation presented in Figure 3-1 is flexible and iterative; the flow directions must be followed, and at least one pass through all the red workflows must occur prior to a blue output workflow.

3.4 Framework Testing

3.4.1 Case Study and Functional Demonstration

To demonstrate how the developed framework can be adapted for various problems, how the data collected from the real and model environments are related, and how the optimization problem's objectives are defined, a case study is used. It serves also as a functional demonstration of the framework. Scenarios within the case are examined, highlighting the assumptions and limitations for each scenario. The first scenario (Scenario A) applies the framework to a cost-minimization problem for the filtered components. Filtered components are defined as those available at the sources that meet the selection constraints imposed by the design (in this case they are dimensional); they form the source components in a classical distribution optimization formulation. The second scenario (Scenario B) applies the framework to a cost and emissions minimization (multi-objective) problem for the filtered components. Since there are no constraints to use only NCMs or RCMs, the optimal selection is a mix of used and new components. Adding such constraints at various levels of design hierarchy is simple, if there is a need. In all the scenarios, the RCMs or NCMs considered are real-life component options identified in the region for this study.

3.4.2 Project Layout

The project is constrained to the region of Western Ontario, where nine RCM stores and eight NCM stores make up the 17 distribution nodes in the case study, along with five building positions which make up the five demand nodes. Figure 3-2 shows the position of the sources and destinations on the map. Note that components for all five building positions are not sourced simultaneously but independently.

3.4.3 Model environment data

The Revit software was used to develop a 3D building model for the analysis in the case study. The developed framework is used to determine the optimal window and door components selection for the multi-unit two-story building model in Figure 3-3.

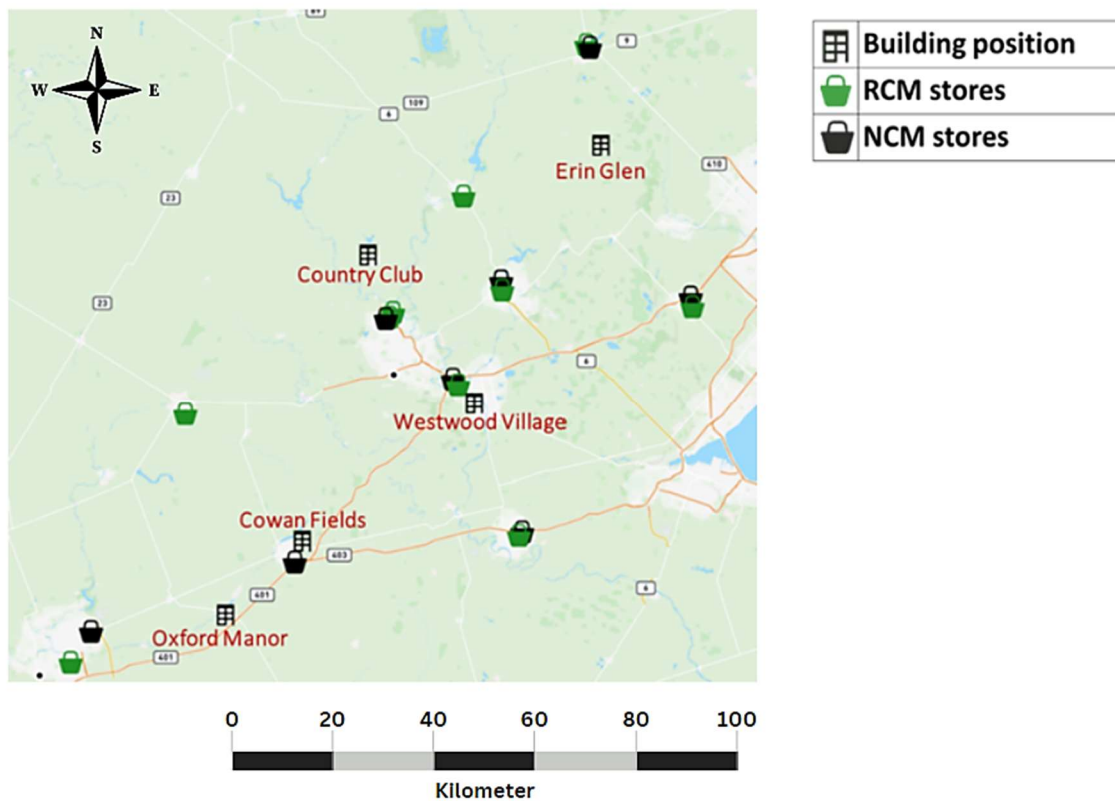


Figure 3-2: Map showing all the NCM stores, RCM stores, and building positions for the case study.

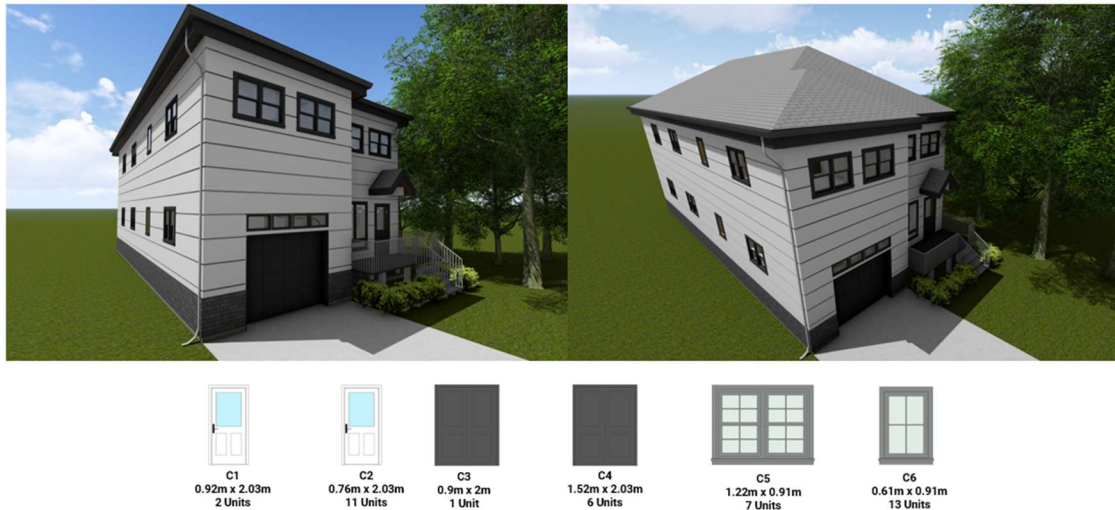


Figure 3-3: Building model designed in Revit for the case study

3.4.4 Real environment data

Real environment data includes component size, price, and location for new and used doors and windows. For used components, 3D scanning, point cloud analysis, and manual extraction of cost and dimensional properties from labels were used to collect data. For NCMs, data was collected from online purchase sites. Data on 593 doors and windows (NCMs and RCMs) were collected. The breakdown of the components collected is presented in Figure 3-4. Extraction of dimensional details (up to 2-4 mm accuracy) required the collection of scans of existing components from two RCM stores in the region of Kitchener-Waterloo. The scans of components including lumber, banisters, furniture, vanity units, and flooring were also collected from both stores. However, the focus was mainly on the window and door components. The scans are captured at the RCM stores, and the components are arranged to have both the width and height visible for the capturing process. The raw scan files are subsequently processed into point cloud files, and the dimensions are organized in an Excel sheet along with the cost and location for potential identification. Figure 3-5 shows some snippets of the RCM stores visited.

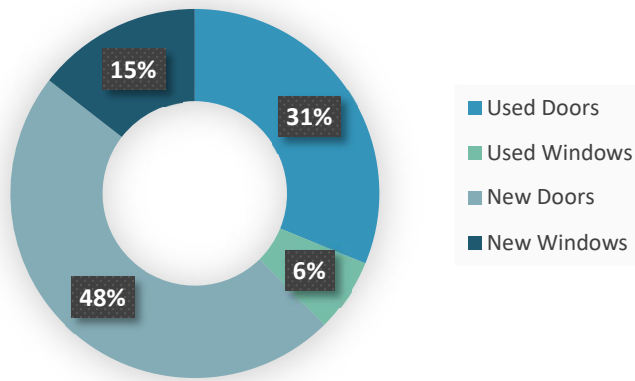


Figure 3-4: Collated component breakdown

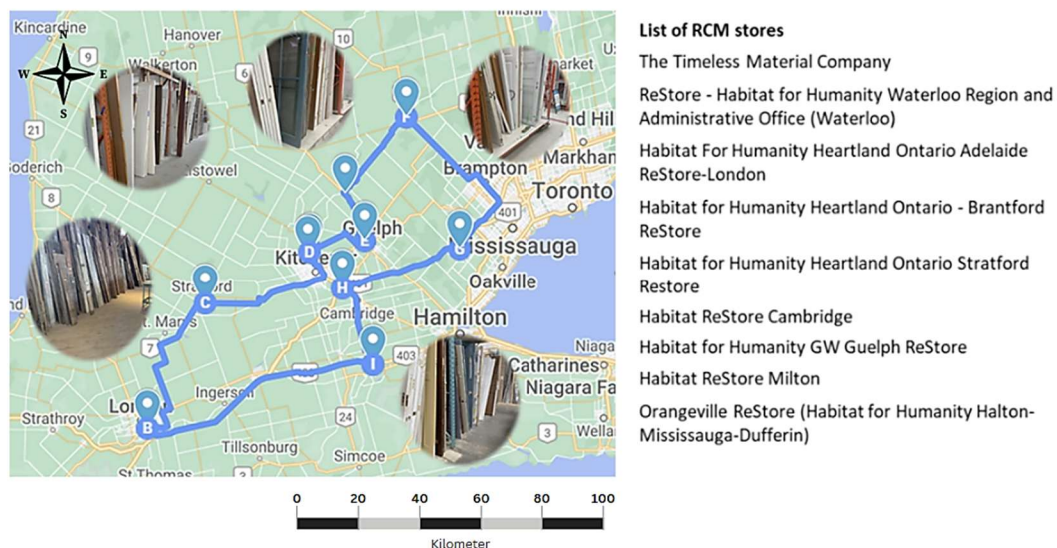


Figure 3-5: Map of the travel route for data collection from the RCM stores with snippets.

The three types of scanners used in this study to capture RCMs are shown in Figure 3-6: (1) the DotProduct3D scanner (DPI-8S), (2) the Faro Freestyle scanner (Freestyle 2), and (3) the iPad scanner (iPad-3rd gen). They are all portable handheld scanners, and they were used to capture components in a sheltered environment.

The freestyle scanner was used to capture 20 scan files, the Dotproduct3D scanner captured 40 scan files, and the iPad scanner captured 15 scans. A total of 50 scans are processed for the component database. The scans included 30 doors and 20 windows processed and manually dimensioned (automated alternatives were not used for this case study). Figure 3-7 depicts how

the dimensions of the doors and windows were collected using the measuring tools in the point cloud platform. The required data from the scans are the length and width of the captured door and window components. In the case study, the constraint applied to filter the components is the size, which must be within ± 30 millimeters of the design requirements. This is reasonable, according to EZ-Hang Door (2023) and Glenda et al. (2022). Additionally, the corresponding transportation costs of acquiring the components are calculated at a predetermined rate of \$0.60 per kilometer using Statista (2023) data on travel carbon footprint. Upon successfully applying the constraints, a filtered list providing a selection of components that meet the building models' requirements is generated. This selection of components is then entered into the optimization engine.



Figure 3-6: 3D scanning systems used at the RCM stores to scan components.

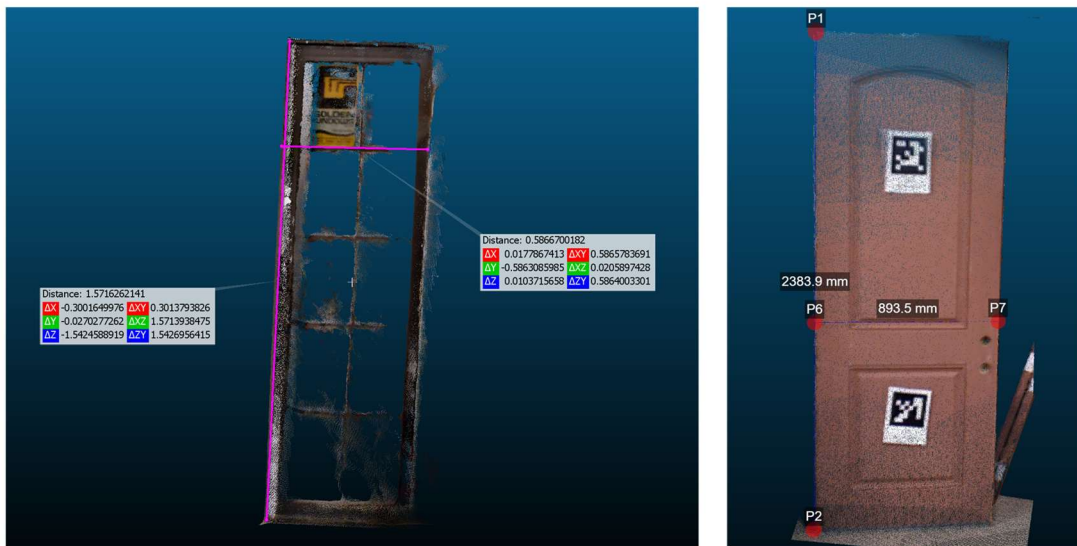
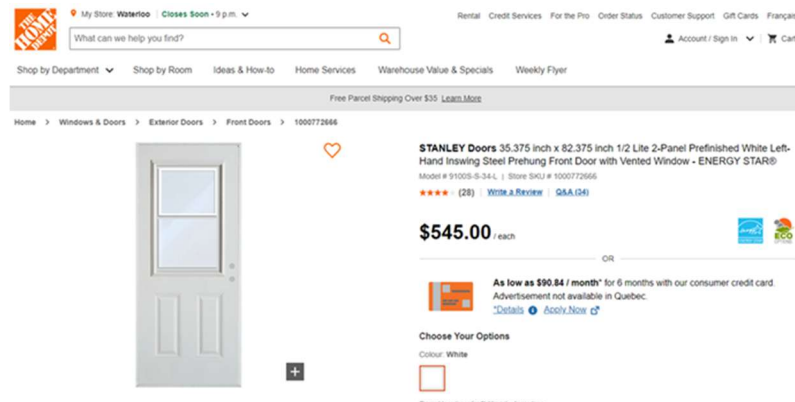


Figure 3-7: Dimension extraction method from 3D scans.

Home Depot websites are the data sources for information on newly available components. The websites showed varying sizes of components and had options for custom-made sizes. Figure 3-8 shows the information made available on the websites. Although information regarding NCMs was collected virtually, it was organized in an Excel spreadsheet, similar to how information regarding RCMs was arranged. In total, 282 data points were collected for NCM doors, and 85 were collected for NCM windows.



List of NCM stores

The Home Depot (Waterloo)
The Home Depot (Cambridge)
The Home Depot (London East)
The Home Depot (Woodstock)
The Home Depot (Milton)
The Home Depot (Brantford)
The Home Depot (Guelph)
The Home Depot (Orangeville)

Figure 3-8: Website layout for NCM data collection.

3.4.5 Framework structure for Scenario A

For the first scenario, Figure 3-9 depicts the flow of information through the framework. Firstly, the NCM and RCM information from the real environment is collected in the databases using the methods discussed earlier. Subsequently, the information is refined into a format where each item is organized using an ID, with associated details including location, width, height, and cost. These organized datasets are shown in Figure 3-9 form the foundational structure of analytical input tables. Concurrently, data regarding the dimensional attributes of the designed components is extracted from Revit. The categories of data extracted are the length, width, and quantity of components in the building model. Both sets of data, derived from the model and real-world environments, are then consolidated within the component brokerage platform in Excel, where specific criteria are used to identify components that meet the design requirements (i.e., length and width).

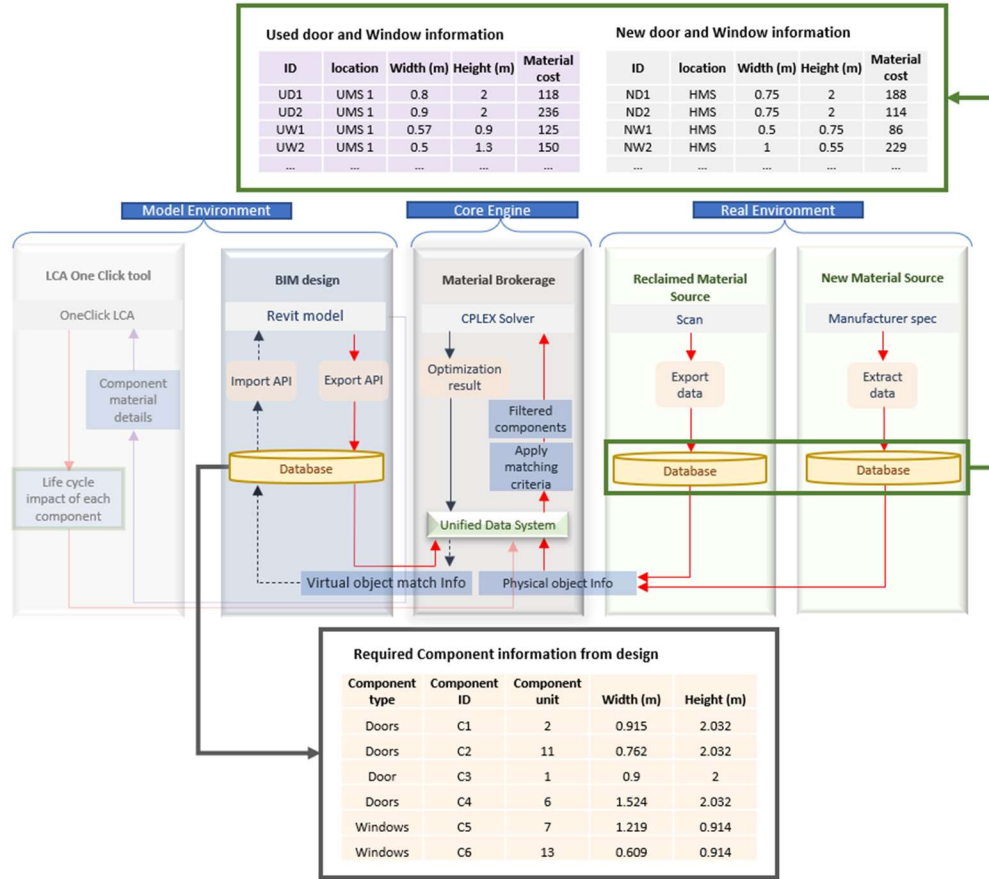


Figure 3-9: Data flow for scenario A with component information

3.4.6 Optimization parameters for Scenario A

The problem for the first scenario is the optimal selection of products based on their economic value (cost). Therefore, this study used the CPLEX tool to optimize the sourcing of door and window products by minimizing the total cost of the products sourced from multiple locations. Supply constraints did not make a solution infeasible. Situations where demand exceeds supply are beyond the scope of this study.

A transportation problem typically involves the transportation of components from an origin of n , where, $i=1,2,...,n$ to any destination m , where $j=1,2,...,m$. However, in this case, there is an additional factor of transporting multiple products p , where $k=1,2,...,p$ from an origin n to a location m . Hence, the program must minimize the entire cost of obtaining the components by determining the decision variables x_{ijk} based on the cost factors c_{ijk} and the demand and supply limits, d_{jk} and o_{ik} . The problem can be mathematically expressed in Table 3-1.

Table 3-1: Optimization model for scenario A

Indices		
<i>Sources, $i = 1, 2, \dots, n$</i>		
<i>Demands, $j = 1, 2, \dots, m$</i>		
<i>Products, $k = 1, 2, \dots, p$</i>		
Objective Function		
$\text{minimize } Z = \sum_{i=1}^n \sum_{j=1}^m \sum_{k=1}^p c_{ijk} \cdot x_{ijk}$		
Constraints		
<i>Demand satisfaction</i>	$\sum_{i=1}^n x_{ijk} \geq d_{jk}$	$j = 1, 2, \dots, m$ $k = 1, 2, \dots, p$
<i>Supply capacity</i>	$\sum_{j=1}^m x_{ijk} \leq o_{ik}$	$i = 1, 2, \dots, n$ $k = 1, 2, \dots, p$
<i>Non-negativity</i>	$x_{ijk} \geq 0$	$i = 1, 2, \dots, n$ $k = 1, 2, \dots, p$ $j = 1, 2, \dots, m$

3.4.7 Framework structure for Scenario B

The second scenario in this case study was a modification of the first scenario to include the embodied energy of the building components extracted from the building model. The embodied energy of each component (new and used) is obtained using OneClick LCA. Minimizing embodied energy is added as an objective, along with minimizing cost for a multi-objective optimization scenario. Figure 3-10 shows the added lifecycle impact values for each component using the OneClick LCA tool, illustrating how a system can be added to the model environment and connected to the other systems within the broader framework. For example, in future iterations, an operating energy calculator could be added to the model environment. The product emissions calculations during the life cycle stages are categorized from A to D in the standard modules. The assessment of new products in this case study was calculated using the modules for the product-to-construction process (A1 to A5 module of the standards). Although the emissions calculation for the new products encompassed all the stages between A1 and A5; the calculations for the RCMs did not encompass all the stages. Thus, the OneClick LCA tool excludes the impacts of the initial manufacturing process A1 to A3 for reused components, as these costs are already accounted for

as sunk costs in the first life cycle. In addition, the system did not consider impacts from the A5 module (the construction and installation process were not accounted for, because that was considered almost identical for new and used alternatives and therefore cancels out). The only module used in calculating the impact of reused components was transportation, replacement, and waste treatment of the component.

In particular, the OneClick LCA tool uses a functional unit based on the cubic meter or square meter of a component to calculate the associated impacts. In this case study, the building model from Revit was entered into the OneClick LCA tool. To verify consistency, the resource schedule in Revit was compared with the resource schedule in the LCA platform. The basic information for calculation were then entered e.g., the time period entered for the assessment was 60 years, a typical lifetime of a building (Bathurst, 2023), and the building area of the house was 230 square meter. The calculation for the building model adhered to the North American standard, using the assessment codes; EN 15978, EN 15804, ISO 14040 and ISO 14044. The frame type selected for the building is a timber frame structure, and all the impacts of the components were calculated in kilograms of CO2 emissions.

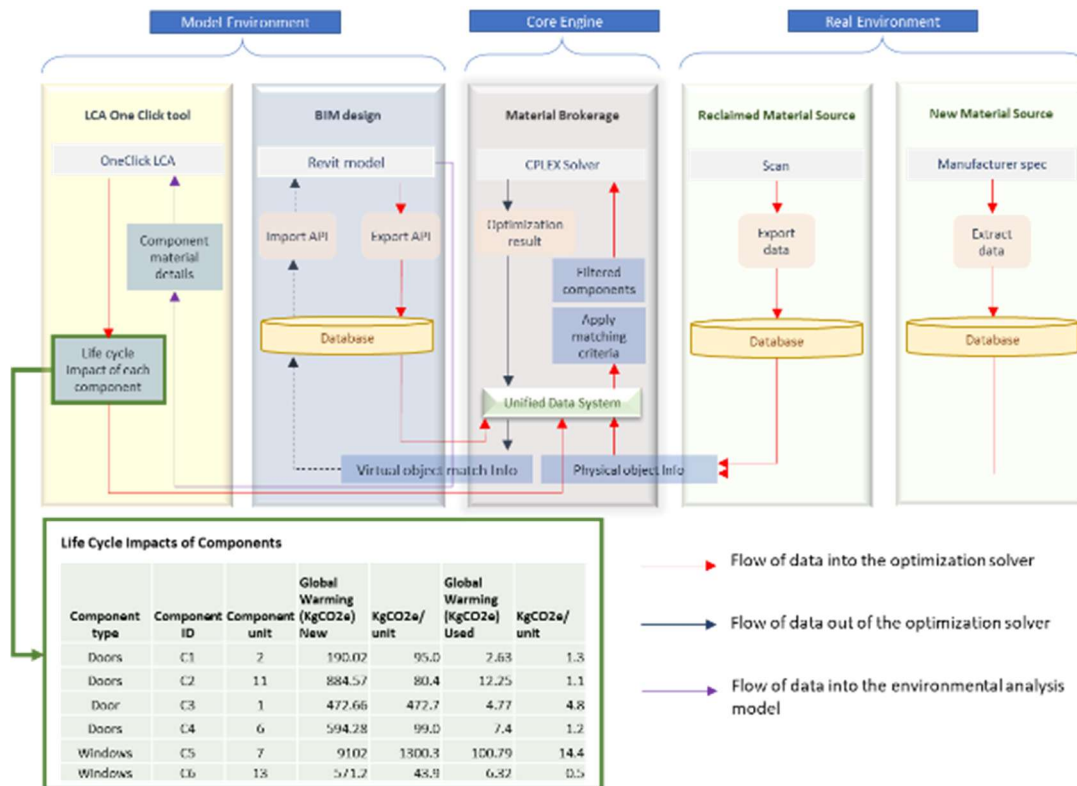


Figure 3-10: Data flow for scenario B showing the addition of information from OneClick LCA.

3.4.8 Optimization parameters for Scenario B

There are different methods of solving a multi-objective optimization problem; the weighting or constraint methods can be applied. However, for an integer programming problem, the weighting method is recommended (ReVelle et al., 2004). In this scenario, there are two objectives: (1) minimize the overall cost of obtaining the components, and (2) minimize the overall embodied energy of the components. The program must minimize the grand objective by determining the decision variables x_{ijk} based on the adjusted cost and embodied energy factors, where the weighting for the cost is gradually decreased at a 10% rate while the weight for the embodied energy is gradually increased at a 10% rate; wc_{ijk} and $(1-w)e_{ijk}$. The demand, d_{jk} and supply limits o_{ik} , detailed in Table 3-1 are consistent with scenario B, as presented in Table 3-2.

Table 3-2: Optimization model for scenario B

Indices		
Sources, $i = 1, 2, \dots, n$		
Demands, $j = 1, 2, \dots, m$		
Products, $k = 1, 2, \dots, p$		
Grand Objective		
$Z^G = [Z_1, Z_2, \dots, Z_r]$, $Z^G = wZ_1 + (1 - w)Z_2$		$0 \leq w \leq 1$
Objective Function		
$\text{minimize } Z^G = \sum_{i=1}^n \sum_{j=1}^m \sum_{k=1}^p (wc_{ijk} + (1 - w)e_{ijk}) x_{ijk}$		
Constraints		
Demand satisfaction	$\sum_{i=1}^n x_{ijk} \geq d_{jk}$	$j = 1, 2, \dots, m$ $k = 1, 2, \dots, p$
Supply capacity	$\sum_{j=1}^m x_{ijk} \leq o_{ik}$	$i = 1, 2, \dots, n$ $k = 1, 2, \dots, p$
Non-negativity	$x_{ijk} \geq 0$	$i = 1, 2, \dots, n$ $k = 1, 2, \dots, p$ $j = 1, 2, \dots, m$

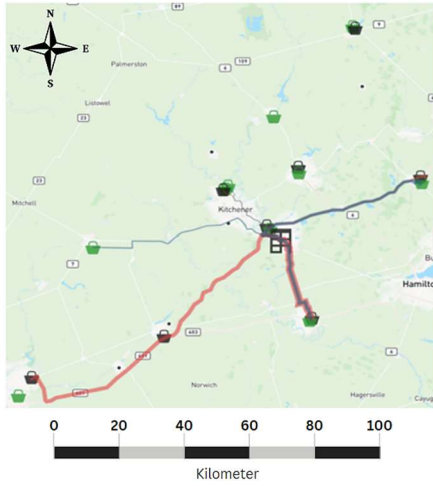
3.5 Results

3.5.1 Scenario A

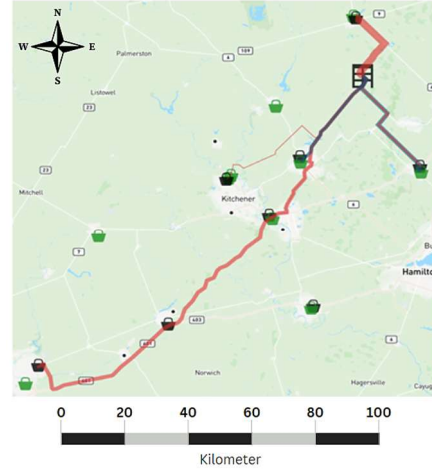
For each building location analyzed within the first scenario, the optimal component selection for all the locations was not the same. Figure 3-11 illustrates the component selection for all five building positions evaluated in this case study. Although there were variations in the components chosen for different building positions, these variances were not as pronounced across all the buildings. In fact, there were instances where similar items were selected for different structures. For example, components sourced from the London store were consistently present in most of the selections. Components from the London store were chosen for Country Club, Cowan Fields, and Oxford Manor. However, some unique situations arose where components sourced from places like Guelph Habitat for Humanity were exclusive to the Erin Glen community. Overall, there is variation in component selection for each building position.

The Erin Glen community was furthest away from the London Home Depot store, where components were consistently chosen based on their cost. Considering the distance between the Erin Glen community and the London Home Depot store, the cost of travel per unit possibly prompted the limited selection of the components from the London Home Depot store, resulting in the Erin Glen community choosing components from the closer Home Depot store at Orangeville. Surprisingly, these variations do not significantly impact the final cost of the components, as travel expenses do not substantially affect the overall sourcing costs. Notably, the lowest cost associated with sourcing is \$10,016, while the highest cost is \$10,629, as presented in Figure 3-11.

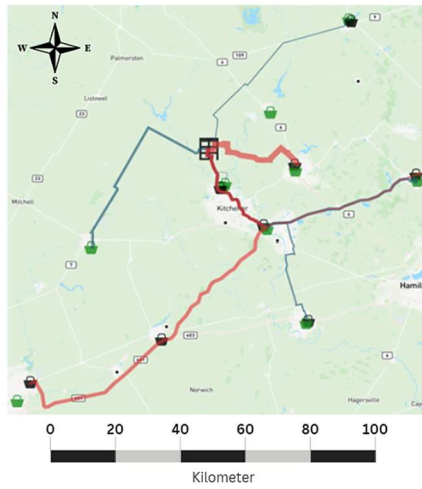
Another interesting finding is that the ratio of selected RCMs to NCMs remains consistent across all five locations, as seen in Figure 3-12. This consistency can likely be attributed to the fact that Home Depot locations tend to stock similar components, making it highly probable that the same components are selected from Home Depot in different areas for all the cases. The limited variation in selection suggests minimal differences in the types of components chosen, given the repetitive availability of these components at Home Depot stores (Notably, most items are priced exactly the same across all the NCM stores). Therefore, 15 components were selected from the RCMs, while the other 25 components were selected from the NCMs. The integrated sourcing based on the economic value of the components led to a 37% proposed use of RCMs alongside 63% of NCMs for all the building positions.



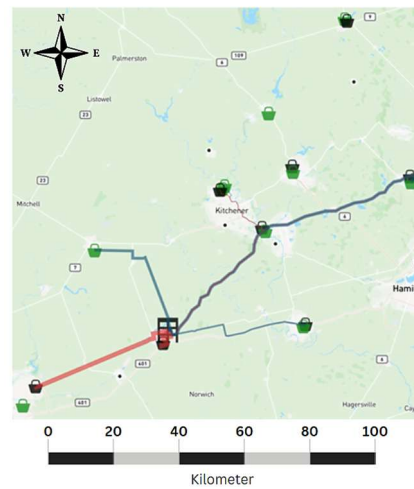
Westwood Village



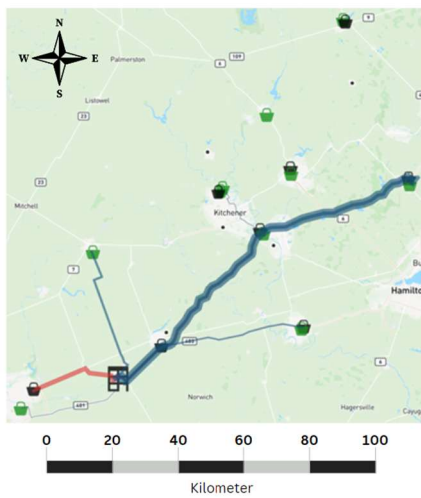
Erin Glen



Country Club



Cowan Fields



Oxford Manor

—	New Construction Materials (NCM) sources
—	Reclaimed Construction Materials (RCM) sources

Building Positions	Acronyms	Total cost of selected components
Country Club Estate	CCE	10629
Cowan Fields	CF	10016
Erin Glen Community	EGC	10500
Oxford Manor	OM	10162
Westwood Village	WV	10173

Figure 3-11: Distribution map results for each building position with total sourcing cost.



Figure 3-12: Component selection results for each building position, with supplementary information on the number of components selected from each store.

3.5.2 Scenario B

The multi-objective analysis exploring the trade-off between the embodied energy of the components and the cost of the components did not result in a significant change in the selection of components as the objective weights changed (Table 3-1). This rigidity can likely be attributed to two main factors: the constrained material inventory and the nonlinear correlation between cost and embodied energy.

The study collected 593 new and used construction resources for analysis. The framework was applied so that only components that satisfy the design constraints of the proposed building would be in the filtered inventory pool for selection through the optimization process. It limited the inventory pool to a much smaller number of resources. Figures 3-13 and 3-14 depict the distribution of new and used windows and doors (respectively) fitting the design model.

Additionally, there is a clear distinction in the embodied energy of new and used doors, but a wider variation in cost with some overlap for new and used doors. Generally, new materials tend to be

more expensive than the used ones and typically have higher embodied energy compared to the used materials. However, there are situations where the cost of used items could be just as high as new items, especially when sourcing quality antique doors. This results in a higher price for some materials with low embodied energy. The data is different for windows. It was expected that the size of the window would significantly influence both its embodied energy and cost. Bigger windows generally have higher embodied energy and cost.

There might be a trade-off between embodied energy and cost in situations with more options for window and door components, and with specific products of the same quality. Future studies will explore the correlation between embodied and operating energy to identify potential trade-offs between these parameters.

Table 3-3: multi-objective optimization results for Cowan fields in the case study

%Cost	%Embodied Energy	Cost		Embodied energy TMC	HH (Waterloo)	THD (Waterloo)	HH (London)	HH (Brantford)	HH (Stratford)	HH (Cambridge)	HH (Guelph)	HH (Milton)	HH (Orangeville)	HH (Fergus)	THD (Cambridge)	THD (London East)	THD (Woodstock)	THD (Milton)	THD (Brantford)	THD (Guelph)	THD (Orangeville)
100%	0%	10016	8163	1	0	1	0	3	5	0	0	6	0	0	1	8	13	2	0	0	0
90%	10%	10018	8163	1	0	1	0	3	5	0	0	6	0	0	1	8	15	0	0	0	0
80%	20%	10018	8163	1	0	1	0	3	5	0	0	6	0	0	1	8	15	0	0	0	0
70%	30%	10018	8163	1	0	1	0	3	5	0	0	6	0	0	1	8	15	0	0	0	0
60%	40%	10018	8163	1	0	1	0	3	5	0	0	6	0	0	1	8	15	0	0	0	0
50%	50%	10018	8163	1	0	1	0	3	5	0	0	6	0	0	1	8	15	0	0	0	0
40%	60%	10018	8163	1	0	1	0	3	5	0	0	6	0	0	1	8	15	0	0	0	0
30%	70%	10018	8163	1	0	1	0	3	5	0	0	6	0	0	1	8	15	0	0	0	0
20%	80%	10018	8163	1	0	1	0	3	5	0	0	6	0	0	1	8	15	0	0	0	0
10%	90%	10018	8163	1	0	1	0	3	5	0	0	6	0	0	1	8	15	0	0	0	0
0%	100%	14112	8163	2	0	3	0	0	0	0	2	6	0	5	3	14	5	0	0	0	0

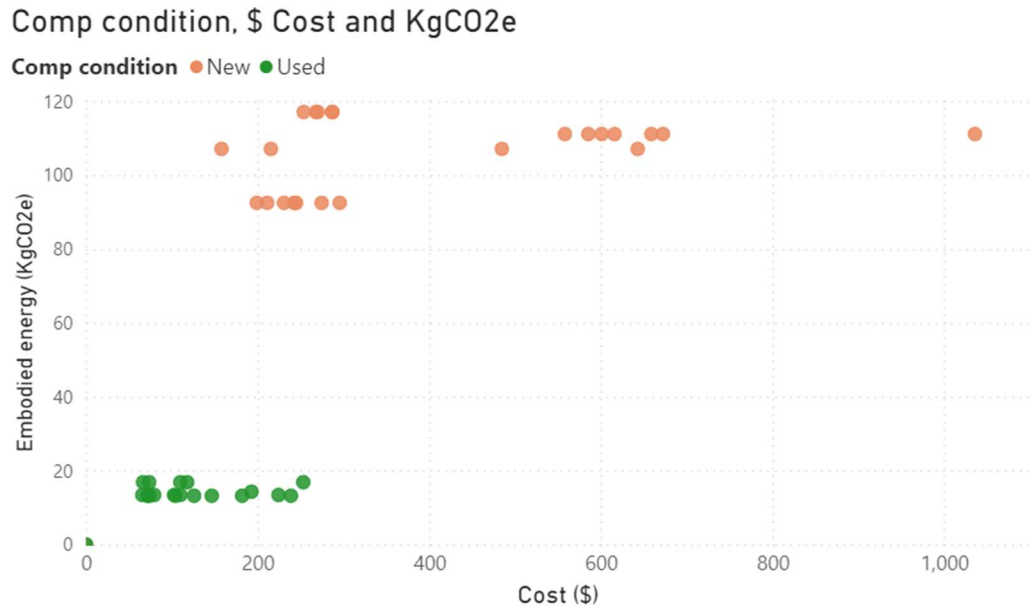


Figure 3-13: Window selection pool after applying dimensional constraints.

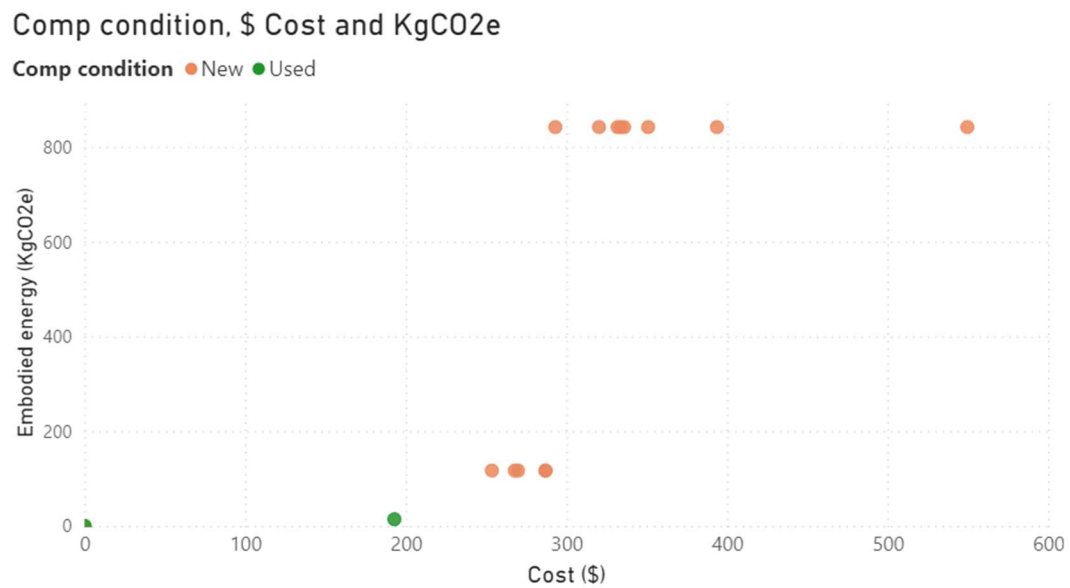


Figure 3-14: Door selection pool after applying dimensional constraints.

The study further explored the impact of scaling the prices of RCMs on the selection of NCMs for building models. The analysis was crucial because acquired RCMs often require refurbishment or upgrades, adding to their initial cost. Refining or preparing RCMs for reuse can be expensive, inflating the price of the original components. Therefore, the study explored how inflating the price of components step-wise from their original cost to three times the cost (i.e., a 100% to 300%

inflation) influenced decision-making. As anticipated, a higher price for RCMs led to a greater inclination towards selecting NCMs. It highlights the importance of reducing the cost of RCMs and minimizing expenses related to sourcing and refurbishment, making the process more economically viable (Figure 3-15).

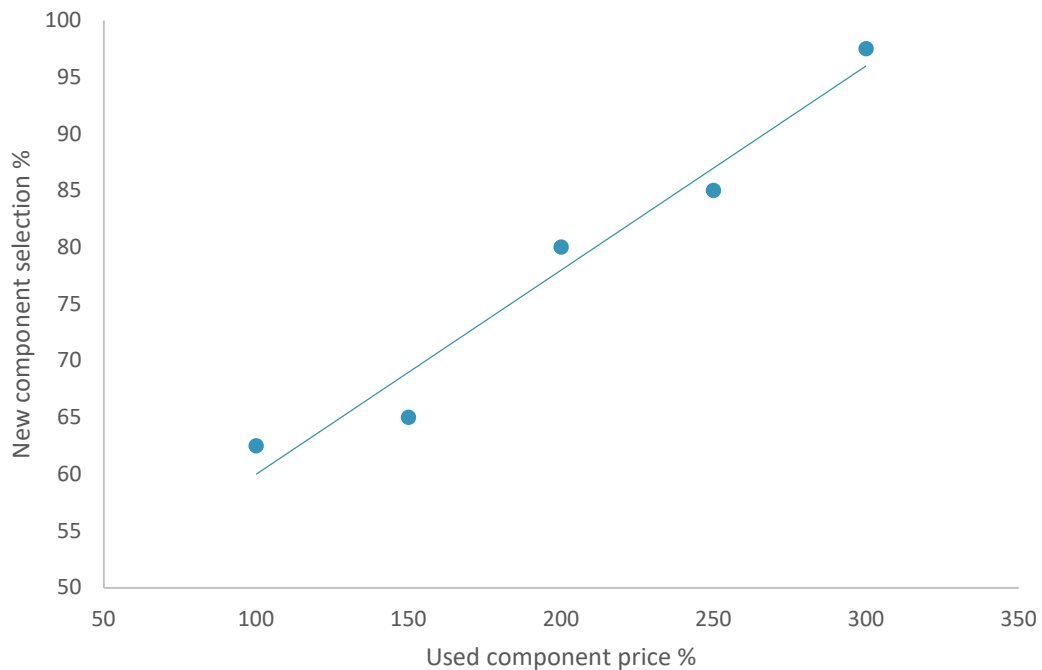


Figure 3-15: NCM selection as RCM price increases.

3.6 Analysis and Discussion

Notably, this preliminary study focused on selecting 40 components out of a pool of 403 filtered options and 593 collated components from the data source. The results from Scenario A demonstrated that considering both new and used sources for component options in construction projects could lower costs and reduce the reliance on new materials. Specifically, in this basic application of the framework, approximately 35% of used materials were viable for reuse in the case study, although various factors could influence component selection.

Additionally, the study explored the relationship between the cost and environmental impact of components in Scenario B. The addition of minimizing embodied energy as an objective did not significantly impact component selection for the case studied. It did, however, illustrate that reduced cost and environmental impact can go hand-in-hand in some situations. They are not

always a trade-off. However, in general there is a complex interplay between cost, environmental impact, and inventory maturity for a mixed new-and-used procurement strategy for building materials, as different material categories are considered and as operating energy, refurbishment costs, and inventory holding costs are considered. Having more resources available to source from may increase the chances of using more reclaimed items, underscoring the potential value of a digital material inventory system.

There is a growing trend in adopting modular construction and Design for Disassembly (DfD), with more construction modules being assembled by companies such as Pro Part Modular Construction and NRB Modular Construction (*Modular Construction Industry Blog*, 2024; *Prefabricated Buildings – ProPart Modular*, 2023). Pro Part Modular Construction demonstrated the value of DfD in the context of SKD Company, which needed to free up space for new equipment while maintaining its operations. To meet the demand, they relocated an existing two-story modular office complex, originally built in 1988, to another area within the facility. The modular design, featuring reusable partitions and bolt-together mezzanine structures, allowed the entire complex (including electrical, plumbing, HVAC, and sprinkler systems) to be quickly dismantled and reassembled in a new location.

The approach enabled SKD to efficiently reuse all the components with minimal disruption, showing the flexibility and sustainability benefits of modular construction. The modular office space was quickly operational again, highlighting how DfD allows for efficient relocation, modification, and reuse of building components. As a result, traditional construction methods are rapidly evolving to incorporate manufacturing processes that accelerate housing development. The Modular Building Institute reports over 500 homes worldwide identified as modular constructions, ranging from single-story buildings to 10-story hotels (*Modular Building Database*, 2024). This shift towards modular buildings and design for disassembly enhances future resource tracking, certification, and implementation of validation processes (Li et al., 2023; Munaro et al., 2020; Yang et al., 2024). Li et al. (2023) highlighted ongoing research focusing on the reuse of existing modules, which are already designed for construction and reuse processes. Daily explored options include rotating existing models in various orientations for secondary use. Additionally, innovative connections, particularly for timber modules, present opportunities to optimize component selection using the tool presented in this study.

Finally, the fundamental structure of the framework offers a platform to incorporate more criteria that contribute to the reusability of RCMs. As discussed in this study, the framework acts as an underlying structure that supports the simultaneous sourcing of new and RCMs for construction projects, promoting sustainable reuse practices while meeting building standards. While this study primarily examined optimal selection based on environmental and cost considerations, it is essential to account for additional factors such as projected lifetime and structural capacity. Therefore, adjusting multiple variables should be carefully considered when comparing components with complex characteristics. As new construction methods like panelized and modular construction gain traction, the availability of highly reusable materials is anticipated to increase in the coming years. These advanced materials will come equipped with readily accessible comprehensive information, allowing them to be easily assessed for viability in new projects using the underlying framework presented in this paper.

3.7 Conclusions and Recommendations

Based on the research, it can be concluded that using RCMs alongside NCMs in new projects can be a practical and economical choice. However, further investigation and evaluation are required to determine the efficiency of the RCM reverse logistics supply chain.

In addition, a framework for optimizing sourcing of new and reclaimed building materials has been developed, described here, and validated through functional demonstration in a case study and through limited sensitivity analysis. It incorporates data attained using existing technologies like 3D modeling, 3D scanning, optimization, and LCA tools, with the ability to implement other tools. Its defined relationships between a real environment, a model environment, and a core engine set a basis for further exploration into digital data requirements for component reuse. The application of the framework can evolve with practice to adapt to different building components, industry sectors, and economic regions with increased reuse material inventory. Emerging approaches to building design, such as design for deconstruction, computer vision, internet of things and material passports, will further enhance the reusability of reclaimed components. Digital data obtained from those systems will enhance the framework capability in the optimization of building component sourcing from new and used material sources. The selection of windows for the framework demonstration was optimized by considering the basic window dimensions. However, there is a performance standard for selecting windows that was not included for simplicity. Relying solely on

dimensions would not be sufficient in real-world scenarios where the infrastructure being considered is not an appendage to an existing infrastructure. It will be necessary to consider the trade-offs in energy between operational and embodied energy. Therefore, subsequent papers will explore how the mechanical characteristics influence window reuse.

Component types considered in this study are non-load bearing materials, windows and doors. Future research must extend to load bearing materials. Development and implementation of mechanical characteristics assessment tools such as non-destructive evaluation tests will be required. More automation is feasible and desirable for collecting and analyzing 3D scans and 2D images of used building components to characterize components in terms of dimensions, colors, exterior finish conditions, surface distress, and other relevant design features. Streamlined and automated digitalization workflows to populate inventory databases with such information are required. Each material category will require substantial research and development in these areas.

Use of the framework for optimization of building component selection under different scenarios was also demonstrated. Reusing components can be as advantageous as using new components. Broader applicability of the framework (and others referencing it) can be enhanced by further studies with more data, increased numbers of scenarios, and deployment of prototypes in practice.

Chapter 4: Assembly Restoration Framework for Modelling Circular Building Strategies

Expanding on the previous chapter, this chapter develops a framework for assembly level assessment. In contrast to the IMS framework, windows in the ARF framework are treated as assemblies composed of separable components, making it easier to assess how best to repair them. The ARF framework introduces additional complexity by considering interactions between components within an assembly and explores how restoration strategies can be evaluated holistically. This chapter is based on the following published article.

Olumo, A., Kapsis, C., & Haas, C. (2025). Assembly restoration framework for modeling circular building strategies. Resources, Conservation and Recycling, 220, 108331. <https://doi.org/10.1016/j.resconrec.2025.108331>

Abstract

Building renovations often focus on new building components, neglecting the potential of refurbished or reclaimed resources. This study develops a circular restoration framework to model different strategies for the end-of-life management of building assemblies. These strategies include: (1) Partial replacement – substituting parts of an old assembly with new parts, (2) Direct reuse—making no changes to the existing assembly, (3) Partial refurbishment – restoring old parts without undergoing a re-manufacturing process, and (4) Full replacement – purchasing a new assembly. The value of the framework is demonstrated through a window assembly example that assesses operation and embodied energy impacts of the different restoration strategies. The results show that integrated approaches, such as partial replacement and partial refurbishment, offer opportunities to mitigate tradeoff factors like embodied and operational energy. The Assembly Restoration Framework (ARF) facilitates comparative assessment of circular strategies, enhancing circular practices.

4.1 Introduction

Nonrenewable resources used today are resources that will not be available tomorrow, and for renewable resources, the threshold is set by the replenishment rate of the resource (Parrique et

al., 2019). Over two billion tons of municipal solid waste are produced annually worldwide, encompassing industrial, agricultural, healthcare, construction, and demolition waste (UNEP, 2024). However, only a small portion of the Construction and Demolition Waste (C&DW) materials are diverted from landfills (Rakhshan et al., 2020). The diverted C&DW materials are often distributed to secondary material stores, commonly referred to as ReStores. There are over 960 Habitat ReStores in the US and Canada, that stock RCMs, including kitchenettes, banisters, cabinetry, doors, flooring, skirting, windows, and others (Olumo et al., 2022). Thus, an informal market already exists for sourcing RCMs. However, there is a challenge in managing some RCMs that end up at ReStores, reintegrating them into the reverse logistics process for new buildings is complex (Gorgolewski, 2008). The RCMs have perceived residual value, yet current practices remain unsustainable. For instance, it is typically advised to service windows of a house every 20-25 years (Garvin & Blois-Brooke, 1995). It usually involves complete replacement of all windows in a dwelling. The unsustainable approach results in the wastage of valuable resources like glass that could otherwise be diverted from landfills (Martin et al., 2024). Although primary materials for glass, like silica sand, are abundant, environmental regulations, geopolitical tensions, and trade restrictions have contributed to price volatility and supply challenges. Similar disruptions and resource depletion issues affect the aluminum, crude oil, and timber industries. Thus, innovation in building resource management to ensure the sustainability of high-performance products is urgent, as the basic materials are essential not only for windows but also for many other building assemblies.

Building assemblies are a combination of various components that make up a functioning unit within a building system (Nassar et al., 2003). For example, external walls are composed of multiple components, including framing, insulation, and cladding. This study considers how components within assemblies might be selectively substituted or enhanced to improve overall performance. Appendix A illustrates the assemblies examined in previous studies (Huedo et al., 2016; Jiang et al., 2022; Nassar et al., 2003), highlighting the assembly addressed in this research, an example of a typical window assembly. Currently, there are a few existing methodologies for assessing the impact of different restoration strategies for building assemblies. Previous studies like Blomsma & Tennant (2020); Huedo et al. (2016); Nassar et al. (2003) introduced various analytical tools for optimizing the selection of building assemblies based on specific criteria. However, most of these methodologies tend to view each item as a discrete unit, evaluating assemblies as indivisible

structures that could not be deconstructed into components. As such, previous studies do not consider selective reuse or partial replacement of components within an assembly. The limited approach overlooks the potential for deconstructing assemblies to reuse parts in new configurations, which restricts their applicability.

Thus, the objective of this study is to develop a framework to evaluate various strategies for managing end-of-life assemblies after their initial period of use. This study examines the use of end-of-life windows by modeling the embodied and operational energy for various restoration strategies. The second objective of the study is to test the efficacy of the framework by analyzing and identifying the performance data on windows collected from ReStores in the Ontario region. The study assesses how data and resources facilitate the implementation of what are typically presented as environmentally preferable strategies, such as reuse or refurbishment. Consequently, this research addresses two main questions:

- How can the impact of different restoration strategies for building assemblies be modelled?
- What are the data gaps at ReStores that can be addressed to facilitate modelling of restoration strategies for building assemblies?

4.1.1.1 Scope

This study's focus on windows is motivated by several factors. Firstly, windows are basic modular building assemblies that allow for separation of a windowpane from its frame, which simplifies the replacement of parts i.e. (IGU and Frame). Secondly, unlike other construction assemblies and components diverted from landfills, such as structural steel and masonry units, operating energy is generally not factored when reusing those components. However, windows give unique insight into the trade-offs between operating energy, embodied energy, and cost. While operating and embodied energy are factors that are crucial in window selection, other considerations like visible transmittance (TVIS), solar heat gain coefficient (SHGC), thermal conductance (U-factor), compatibility with building style, window type, shape, and aesthetics also contribute to the selection of windows, but they are outside the scope of this analysis. Additionally, windows are not structural components requiring extensive load capacity calculations for refurbishment or reuse. Finally, Habitat ReStores readily supply windows, proving their real-world availability as secondhand resources; thus, windows are ideal examples.

4.1.2 Research Gap

Selecting a window restoration strategy for a dwelling can be challenging. Typically, the choice is seen as binary: either keep the window as is or replace it entirely. Less frequently discussed options are partial replacement or refurbishment of the components in the window assembly. When improving window performance, the conventional recommendation is to replace the entire window unit, potentially necessitating the replacement of all windows within a dwelling. A popularly cited reason for upgrading all the window units in a dwelling is that the upgrade of just one window can result in a mismatch with the aesthetics and performance of the other windows.

Although there are limited studies on different restoration options, Litti et al. (2018) made a significant contribution by assessing the life cycle energy savings from various window restoration strategies for a heritage building using Infrared Thermography (IRT) to find air leaks in the window assembly, identifying areas where sealants should be applied. The study evaluated six scenarios: a baseline model with unchanged windows, three levels of fenestration maintenance and restoration (including frame painting, draught proofing, indoor storm-glazing addition, and internal secondary glazing), IGU replacement, and complete window unit replacement. Although, the study assessed the current condition of a historical building's windows and explored options for their improvement; it does not offer a generalized and adaptable framework for individuals or businesses to make decisions about their own buildings. Economically, it often seems more beneficial to replace windows in bulk rather than repair individual ones, benefiting service providers. Still, there is a pressing need to shift this mindset to allow for the manufacturing of upgradable windows or retention of reusable windows. For example, a high-performance window frame designed for easy reinstallation of an IGU can promote reuse, extend their lifespan, and reduce the need for new production. Finally, this study enhances the decision-making process by introducing a framework that facilitates comparative assessments. It explores various options for restoring assemblies like windows, proposing a model to evaluate how different restoration strategies affect both the embodied and operational energy of windows, using a specific window as an example.

4.2 Research Methodology

A framework for building assembly restoration is developed in this study through an inductive research approach. An initial field investigation of ReStores across the Western Ontario region was conducted to observe the real-world conditions of RCMs at nine ReStores. The study identified

different assemblies, including doors, vanities, kitchenettes and windows. During the field investigation, it was noted that some assemblies had primary information that enabled analysis of their component (glass and frame). In this case, a typical window unit, commonly found in these stores, was chosen due to its reusability potential and the availability of information about its composition. The analysis focused on identifying the key components of window assemblies, evaluating their structural composition, and determining the factors that enable or limit their reusability. Based on these insights, the study developed a framework for assembly restoration, particularly for used assemblies. The framework is then tested and validated through an example, where different restoration options for a sample window unit are assessed. The tools used to assess operational and embodied energy include Excel, which calculates the operational energy for various installation strategies, and OpenLCA, used for quantifying the embodied energy of these strategies. These tools are dynamically used in the assessments, following the mathematical models developed for this study. The research method is presented in Figure 4-1.

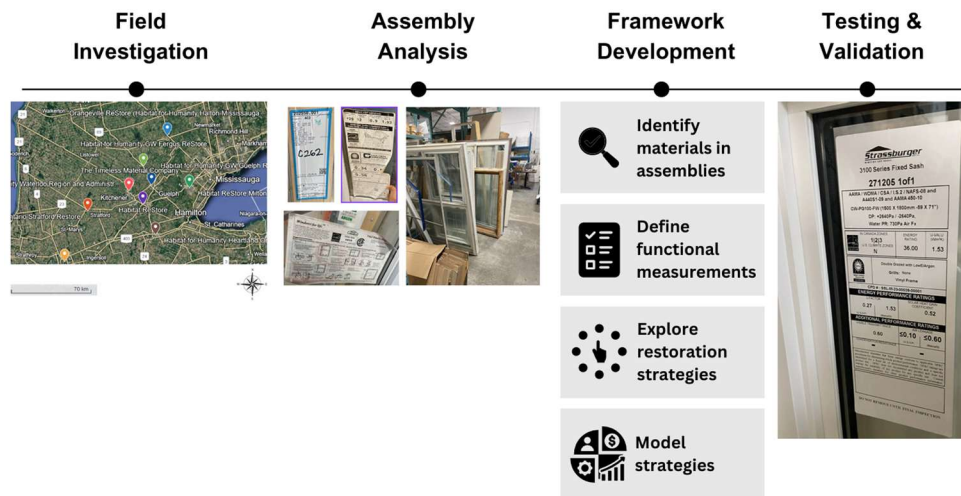


Figure 4-1: Research methodology

4.3 Proposed Framework

The proposed framework developed for evaluating different restoration strategies follows a sequential process of analysis to ensure a thorough assessment of viable restoration options. First, the components within the assembly are identified. Next, a functional measurement for the performance of that assembly is determined, identifying the key metrics necessary to assess the performance of each component. For instance, in the window example, the operational and

embodied energy is determined as the functional measurement, then the restoration strategies for each component type within the window assembly are examined. This involves examining potential options for replacing or refurbishing components. In the window example, four restoration options are identified:

- (1) Full replacement, the scenario of replacing the old unit with a new window unit (Scenario A).
- (2) Partial replacement, which entails purchasing a new Internal Glazing Unit (IGU) while maintaining the window frame (Scenario B).
- (3) Partial refurbishment, which involves restoring the IGU without undergoing a re-manufacturing process, while maintaining the frame (Scenario C).
- (4) Direct reuse, where no changes are made to an existing unit, leaving it as is (Scenario D).

Once the restoration strategies are defined, they are modelled for each component within the assembly, applying a mathematically defined function. For example, if the windowpane were to be replaced for an assembly, then the change in operational and embodied energy would be calculated to reflect the impact of changing the windowpane for that assembly. The process is repeated for all restoration strategies. Figure 4-2 illustrates the Assembly Restoration Framework (ARF) developed in this study to assess the different restoration strategies.

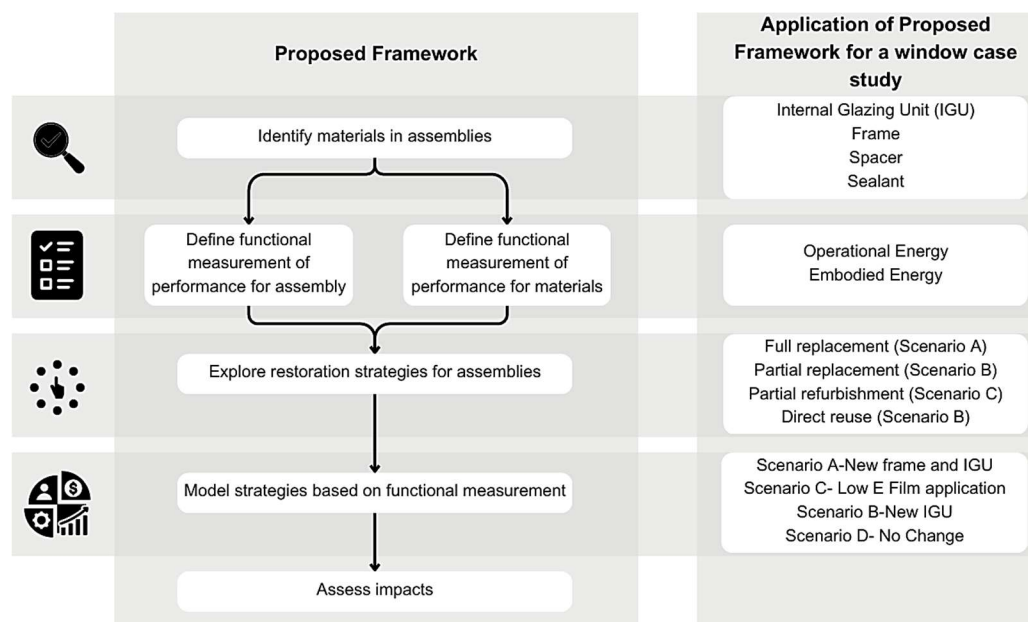


Figure 4-2: Assembly Restoration Framework (ARF)

To demonstrate the ARF's application, this study focuses on a window example. It considers a window installed in the early 2000s, which, after 25 years of use, is deemed less effective. The alternatives considered include restoring the existing window or replacing it with a salvaged window in good condition from the Habitat ReStore. The initial step in applying the ARF is to identify and evaluate other restorative options by determining the composition of the window assemblies involved.

4.3.1 Composition of the window assemblies

The original window is assumed to be a typical residential North American window from pre-2000, and the assembly composition is as follows:

- The IGU-to-frame ratio is 85% / 15%
- IGU (assuming 6mm glass/ 12 mm air cavity / 6 mm glass; NO low-e coating)
- U-value: $2.7 \text{ W/m}^2\text{K}$
- IGU SHGC: 0.7
- Frame (Vinyl)
- Frame U-value: $1.7 \text{ W/m}^2\text{K}$
- Window Overall U-value: $2.5 \text{ W/m}^2\text{K}$
- Window Overall SHGC: 0.6

The salvaged replacement window is a fixed sash window found at the Habitat ReStore in Waterloo.

Figure 4-3 shows the window data source, and the assembly composition is:

- Series: 3100 Series Fixed Sash
- Model Number: 271205 1of1
- Standards and Certifications: AAMA, WDMA, CSA, I.S.2, NAFS-08, A440S1-09....
- Performance Grade: CW-PG100-FW
- Design Pressure: +2640Pa / -2640Pa
- Water Penetration Resistance: 730Pa
- Dimensions: 1500 x 1800mm (59 x 71")
- Frame Material: Vinyl
- Energy Rating: 36.00
- U-Factor: $1.53 \text{ W/m}^2\text{K}$ (0.27 U.S.)

- Solar Heat Gain Coefficient: 0.52
- Visible Transmittance: 0.60
- Air Leakage: ≤ 0.10 (U.S.), ≤ 0.60 (Metric)
- Glazing: Double Glazed with LowE/Argon

The next step in applying ARF is to define the functional measurement of performance of the window assemblies.

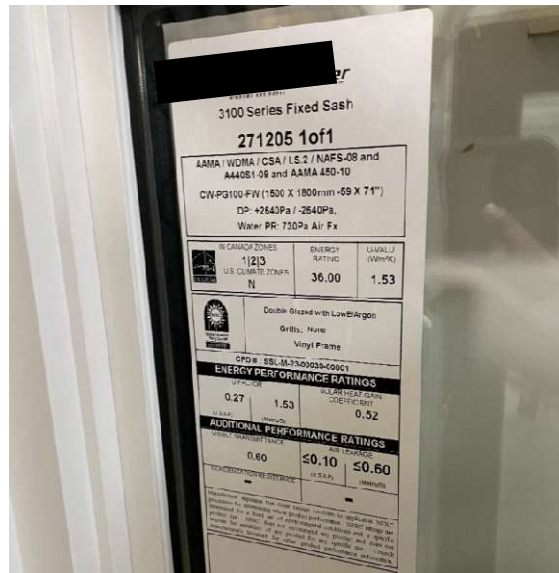


Figure 4-3: Replacement window data

4.3.2 Define the functional measurement of performance of the window assemblies

The functional measurement of performance for windows is the operating energy, the energy associated with the performance of the window in a building. However, it is not the only measurement of performance addressed in this study, the environmental impact of the window composition is also accounted for as a measure of performance, in this case the embodied energy of the window. Therefore, this assessment considers the operational and embodied energy impacts over a 50-year period. The analysis examines how the different improvement scenarios influence both the embodied and operational energy of the window units, considering an initial typical lifespan of 25 years and an extended use period of 25 years.

Given that the window assemblies have their U-value indicated, the information is used to determine the corresponding operational energy. The calculation draws data from the RDH Building Engineering Ltd. (2013) report, which presents the typical annual household energy consumption

(in megawatt-hours) and the approximate percentage attributable to various household performance factors (see Appendix J). Note that this is a benchmark house, and that use of such benchmarks is common in building construction productivity analysis and building materials recovery analysis. The table establishes a relationship between the U-value, the solar heat gain coefficient (SHC), and energy consumption across various Canadian locations, including Vancouver, Kelowna, Toronto, Montreal, Halifax, Prince Rupert, Ottawa, St. John's, Quebec City, Edmonton, among others. For this study, the values corresponding to Toronto are applied. The approach involves comparing the different windows assessed in the RDH Building Engineering Ltd (2013) report to find the windows closely matching the original window and the replacement window to estimate the operational energy associated with both assemblies. The next step in applying ARF is to determine the restoration strategies, considering the configurations of the assembly.

4.3.3 Explore restoration strategies

To understand the impact of different strategies on the energy efficiency of window components, it is essential to determine the parts of the window being analyzed. The study divides window assemblies into two main components: the frame, which encases the IGU, and the IGU, which includes windowpanes (typically two or three glass sheets), comprising the glass, spacer, and sealant (Citherlet et al., 2000; Likins-White et al., 2023). The IGU and the frame are the main parts that can be disassembled, and either refurbished, reused or replaced. This presents nine different variations of the window assembly when considering the restoration options considered in this study (reuse, refurbish, or replace with new):

1. Refurbish IGU + Refurbish Frame
- 2. Refurbish IGU + Reuse Frame**
3. Refurbish IGU + Replace Frame
4. Reuse IGU + Refurbish Frame
- 5. Reuse IGU + Reuse Frame**
6. Reuse IGU + Replace Frame
7. Replace IGU + Refurbish Frame
- 8. Replace IGU + Reuse Frame**
- 9. Replace IGU + Replace Frame**

Among the nine possible variations, this study focuses on variations 2, 5, 8, and 9, as replacing the frame without replacing the IGU is uncommon. Although, other studies could examine other variations according to the type of project. For instance, historic preservation may prioritize refurbishment and reuse over replacement. However, this study focuses on IGU restoration options since vinyl window frames typically contribute only 5% to 20% of the overall window unit performance, whereas improvements to the IGU can enhance window performance by more than 20% (Gustavsen et al., 2011; Litti et al., 2018). Figure 4-4 shows the different restoration strategies considered for the assessment in this study. The next step in applying the ARF is to model the strategies based on the functional measurements.

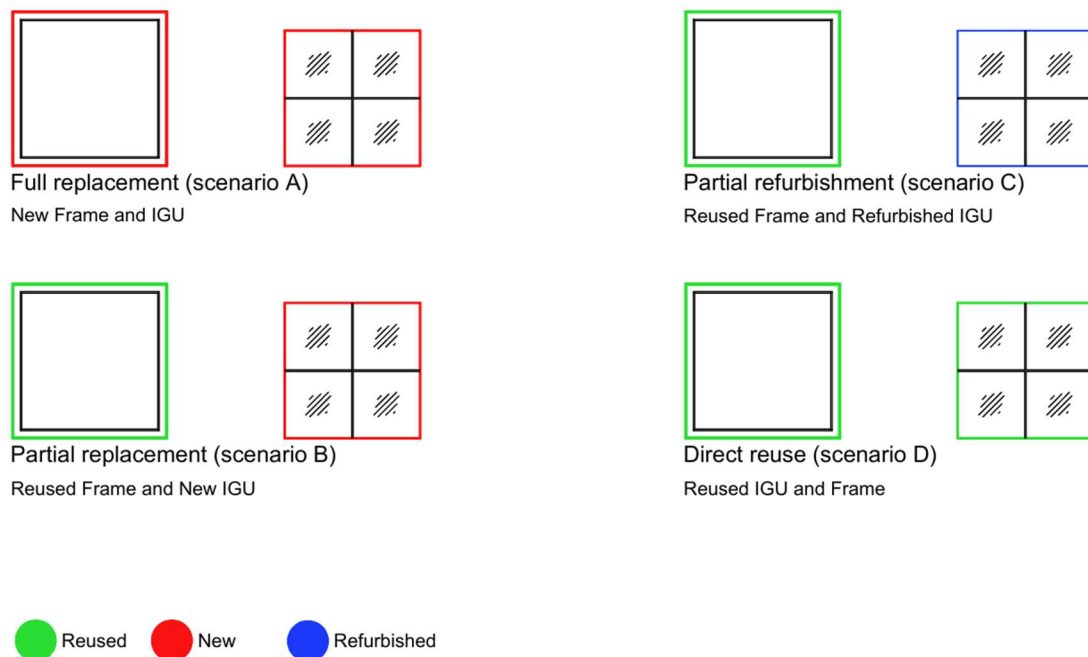


Figure 4-4: Window restoration strategies

4.3.4 Modelling Strategies for Operational Energy

The total operational energy accounts for the energy used from installation to 25 years, and any additional energy consumed beyond 25 years in the second lifespan of the window. Appendix B illustrates the operational energy for the strategies applied across these time periods, starting with the base operational energy. The base level refers to the energy expended by factors unrelated to the windows (the energy expended through other assemblies, e.g. roofing and walls) and is therefore excluded from the windows' performance evaluation. Subsequently, the incremental

operational energy specifically attributed to the windows can be calculated. During the initial lifetime of the windows, there is a gradual increase in operational energy for all window scenarios. The reason for the rise in operational energy can be attributed to the expected increase in energy consumption as window performance declines as a result of natural deterioration (e.g., failing gaskets and IGUs).

As a result, the operational energy of the initial window in this study returns to the base level and then increases again to a higher performance once it is replaced. Therefore, as depicted in Figure 4-4, full replacement (Scenario A) will result in an improvement in performance, while direct reuse (Scenario D) will result in a continuous deterioration over time. In the case of partial replacement (Scenario B), it is expected that the frame will remain unchanged while the IGU is replaced. Assuming the new IGU mirrors the performance of the old IGU, a marginal increase in operational energy will occur as a result of the frame's aging. However, partial replacement (Scenario B) and partial refurbishment (Scenario C) offer a range of outcomes. The replacement or restoration of the IGU could improve the IGU's performance beyond the original installation, match it, or slightly outperform the direct reuse (Scenario D). Thus, partial refurbishment (Scenario C) and partial replacement (Scenario B) impact could be between, full replacement (Scenario A) and direct reuse (Scenario D), varying with the improvement approach.

To mathematically formulate the operational energy of each restoration strategy, the following list of expressions are discussed in this section:

- Total operational energy (OpE_{Total}): Represents the energy consumption associated with the window over its lifecycle phases.
- Operational energy of the initial window ($OpE_{Original}$): The operational energy associated with the initial window.
- Operational energy of the new window (OpE_{new}): The operational energy associated with the new window.
- Operational energy of the IGU (OpE_{IGU}): Focuses on the energy specifically related to the window IGU.
- Deterioration factor (df): A multiplier reflecting the decrease in the window components' value or performance over time.

- Improvement factor (if): A multiplier indicating the potential increase in window performance or efficiency resulting from refurbishment activities.
- Operational energy of the frame (OpE_{frame}): Addresses the energy consumption attributed to the window frame.

Full replacement (Scenario A)

To calculate the operational energy for full replacement, the total operational energy is defined as the sum of the energy from the initial window unit and the energy from the subsequent window unit installed as a replacement. It is calculated over the initial and future life of the window. Equation 1 outlines the formula for full replacement.

$$OpE_{Total} = OpE_{original\ window} + OpE_{new\ window}$$

Equation 1

Partial replacement (Scenario B)

The operational energy for the partial replacement scenario is calculated as the sum of the operational energy from the original window, plus the operational energy for the replaced IGU, and the operational energy for the frame that is not replaced, adjusted by a deterioration factor. The deterioration factor is applied because the frame is not replaced and will remain as it is for its post-use life, reflecting its reduced performance over time. On the other hand, the operational energy for the IGU is entirely replaced, since the IGU is changed. Equation 2 outlines the formula for partial replacement.

$$OpE_{Total} = OpE_{original\ window} + (OpE_{new\ IGU} + (OpE_{frame} \times df))$$

Equation 2

Partial refurbishment (Scenario C)

For partial refurbishment, the total operational energy is calculated by starting with the operational energy of the original window, then adding the operational energy of the frame and IGU adjusted by a depreciating factor and subtracting the improvement factor. The deterioration factor accounts for the wear and tear on the IGU and frame over time, considered at the moment the IGU is replaced. The improvement factor represents enhancements made to the IGU through upgrades, such as applying low emissivity coating to the IGU, improving the IGU's air tightness, filling the IGU with inert gases like argon, or introducing thermally broken spacers within the IGU. These upgrades contribute to the improvement factor. The adjusted operational energy for the IGU is then added to the operational energy of the frame, which is not being replaced but is adjusted by its own deterioration factor to reflect its continued use beyond the original lifespan. Equation 3 outlines the formula for partial refurbishment.

$$OpE_{Total} = OpE_{original\ window} + (OpE_{IGU} \times (df - if)) + (OpE_{frame} \times df)$$

Equation 3

Direct reuse (Scenario D)

For the direct reuse of windows, the underlying assumption is that the original window will stay in place beyond its initial lifespan, extending into the post-use life. Consequently, the operational energy associated with the window will vary according to the specifics of the window itself during this extended period. The approach considers the operational energy for the window's initial lifecycle, followed by applying a deterioration factor to the operational energy for the post-use phase. Note, the deterioration factor is applied to the whole original window unit. Equation 4 outlines the formula for direct reuse.

$$OpE_{Total} = OpE_{original\ window} + (OpE_{original\ window} \times df)$$

Equation 4

4.3.5 Modelling Strategies for Embodied Energy

This research defines the scope of its life cycle assessment (LCA) by detailing how embodied energy is accounted for in the life cycle phases outlined in standards EN 15978 and EN 15804. Appendix C provides a breakdown of the relevant categories. In the product stage (A1-A3), the embodied energy of components within the original window assembly is estimated. As modifications are applied, the embodied energy of the added or altered ones is assessed and added to the initial embodied energy to get total embodied energy. The modifications are classified in EN standards under the B-stage life cycle phases, where B4 accounts for replacements and B5 for refurbishments.

To mathematically formulate the embodied energy of each restoration strategy, the following list of expressions are discussed in this section:

- Total Embodied Energy ($EmbE_{total}$): Represents the embodied energy associated with the window over its lifecycle phases.
- Embodied Energy of the initial window ($EmbE_{original\ window}$): The embodied energy associated with the initial window.
- Embodied Energy of the added resources ($EmbE_{improvement\ resources}$): The embodied energy associated with the materials used for refurbishment.
- Embodied Energy of the IGU ($EmbE_{new\ IGU}$): Focuses on the embodied energy specifically related to the new IGU.
- Embodied Energy of the new window unit ($EmbE_{new\ window}$): The embodied energy associated with the new window.

Full replacement (Scenario A)

For full replacement, the total embodied energy is calculated by adding the embodied energy of the original window to the embodied energy of the new window unit being installed. Equation 5 outlines the formula for full replacement.

$$Total\ Component\ EmbE = EmbE_{original\ window} + EmbE_{new\ window}$$

Equation 5

Partial replacement (Scenario B)

For partial replacement, the total embodied energy includes the embodied energy of the original window from its initial lifetime plus the embodied energy of the new IGU being used to replace the old IGU. Equation 6 outlines the formula for partial replacement.

$$Total\ Component\ EmbE = EmbE_{original\ window} + EmbE_{new\ IGU}$$

Equation 6

Partial refurbishment (Scenario C)

For partial refurbishment, the total embodied energy accounts for the embodied energy of the original window unit from its initial life cycle, plus the additional resources used to improve the initial window unit. Equation 7 outlines the formula for partial refurbishment.

$$Total\ Component\ EmbE = EmbE_{original\ window} + EmbE_{improvement\ resources}$$

Equation 7

Direct reuse (Scenario D)

For direct reuse, the total embodied energy is considered as the embodied energy from the initial lifetime plus zero, because the window unit is not changed. However, there are scenarios where a certain percentage of the initial embodied energy of an old unit is accounted for in the post-life (e.g. used window purchase). Equation 8 outlines the formula for direct reuse.

$$Total\ Component\ EmbE = EmbE_{original\ window} + 0$$

Equation 8

4.3.6 Assessing impacts

The final stage in the ARF tool's application is an impact assessment of each strategy. To assess the changes in operational and embodied energy, it is crucial to consider the modifications made for each scenario. Table 4-1 details the components in the window unit and the parameters used in this study for evaluating both embodied and operational energy for the window example. Additionally, Appendix D depicts the cross-section of the windows in this study.

Table 4-1: Components, description, and data sources for the windows in this study.

Components	Description	Data Sources
Window unit	To determine the window's weight, the window data label and data sheets of similar window sizes found on the Home Depot website was used (Appendix E). Additionally, an Environmental Product Declaration (EPD) for a similarly sized window was also used as a reference. Based on these references and data sheets, the total weight of the windows in this example is estimated to be 66 kg. Additionally, previous study suggests a double pane vinyl window frame can account for 5% to 20% of a vinyl window unit performance, while an improved IGU can result in an increase in window performance of up to 20%. Thus, this study assumes the window frame accounts for 20% of the operational energy and has a deterioration factor of 15% for its initial 25 years in use.	Appendix E, (Inline Fiberglass, 2021) (Gustavsen et al., 2011; Litti et al., 2018)
Glass Panes	The weight of a double pane (IGU) typically makes up about 65% to 80% of the total window unit weight, as reflected in the Environmental Product Declarations (EPDs) used as data sources. For the example, it is assumed that the glass accounts for approximately 70% of the total window weight.	(Inline Fiberglass, 2021; Qualitätsverband Kunststoffherzeugnisse e.V., 2016, 2017; Litti et al., 2018)
Aluminum Spacer	Insulating spacers can lower the total window U-value by 12%. These spacers can be made of metal or non-	(Van Den Bergh et al., 2013)

	metal materials. Metal spacers include options such as aluminum, galvanized steel, or stainless steel. Additionally, there are thermally improved metal spacers, which encompass U-shaped steel profiles, hybrid spacers, and thermally broken aluminum. For this study, a 12 mm aluminum spacer was used, corresponding to the window cross section.	
Argon gas	Windows typically contain argon, air, or krypton gases. According to the window data, the gaps in the windowpane contain argon gas. Using the area of the windowpane, the weight of the argon gas is estimated.	(Citherlet et al., 2000)
PVC frame	The weight of the PVC frame accounts for approximately 20% to 35% of the total window unit. For the purpose of this assessment, an approximate value of 30% is assumed.	(Inline Fiberglass, 2021; Qualitätsverband Kunststoffherzeugnisse e.V., 2016, 2017)
Low-E Film	The low-e film chosen for the partial refurbishment scenario is based on information from the Solar Gard document, which indicates an improvement range of 10% to 30% when applied to windows. Thus, using the EPD of the Low E film, a conservative 10% improvement factor is applied to only the partial refurbishment scenario, in which the embodied energy of the Low E Film is also used for the assessment in OpenLCA	(Curcija et al., 2017; Solar Gard, 2023)
PVC Stripping	Window stripping for PVC windows is typically made from PVC as well and can be replaced every 10 years, so the replacement of the stripping is factored in as additional PVC in OpenLCA. The weather-stripping data was sourced from a sample found on the Home Depot website, specifically in Appendix F. The data was used to determine the exact amount of weather stripping required for the base case window.	(Litti et al., 2018) Appendix F

4.3.7 Estimating operational energy

To calculate the operational energy for the base case analysis, the annual energy consumption is determined using the RDH Building Engineering Ltd (2013) report. The report provides an estimate of the total energy consumption for the entire window unit, which is then further divided into the energy attributed to the IGU and the energy attributed to the frame. Approximately 20% of the energy consumption is attributed to the frame performance, which is consistent with prior research. Furthermore, incorporating the data and information from Table 4-1, the impacts of each scenario can be determined using the mathematical models outlined for operational energy in equations 1, 2, 3, and 4.

4.3.8 Estimating embodied energy

For the embodied energy calculations, mathematical models from equations 5, 6, 7, and 8 were applied using the openLCA platform to assess the Global Warming Potential (GWP). In openLCA, it is necessary to define parameters such as the functional unit and the method of calculation, as there are various impact calculation models available. For this case, the CML V4.8 2016, ecoinvent 3.10 LCIA method, was used for impact calculations.

Additionally, it is necessary to define the material flows, which are based on existing datasets created by different contributing bodies. These datasets include those from the USEPA, USLCI, and other organizations, encompassing both open and paid databases. For this study, publicly available databases from key environmental agencies were used, containing information about the emissions attributed to various materials, allowing the selection of materials corresponding to the list in Table 4-1. However, the emissions attributed to the low-E film were directly entered into the openLCA platform using its Environmental Product Declaration (EPD), as shown in Appendix G.

The databases downloaded and used within the openLCA platform include USEPA, ECOINVENT, USLCI, ELCD, and NEEDS. All entries into the openLCA platform were quantified in kilograms for a unit of the window. Thus, the assessment's functional unit is a single window unit.

4.4 Results and Discussion

4.4.1 Result for the window example

This study developed a framework for evaluating restoration strategies for building assemblies, enabling the comparison of different approaches based on key performance criteria. The framework presents a workflow to assess strategies for building assemblies like windows to support informed decision-making. To show the application, a window assembly was selected as an example. The factors considered in the study are operational and embodied energy. The results of the four restoration strategies considered in this study are presented in Figure 4-5, which illustrates the impact of each strategy on both embodied and operational energy.

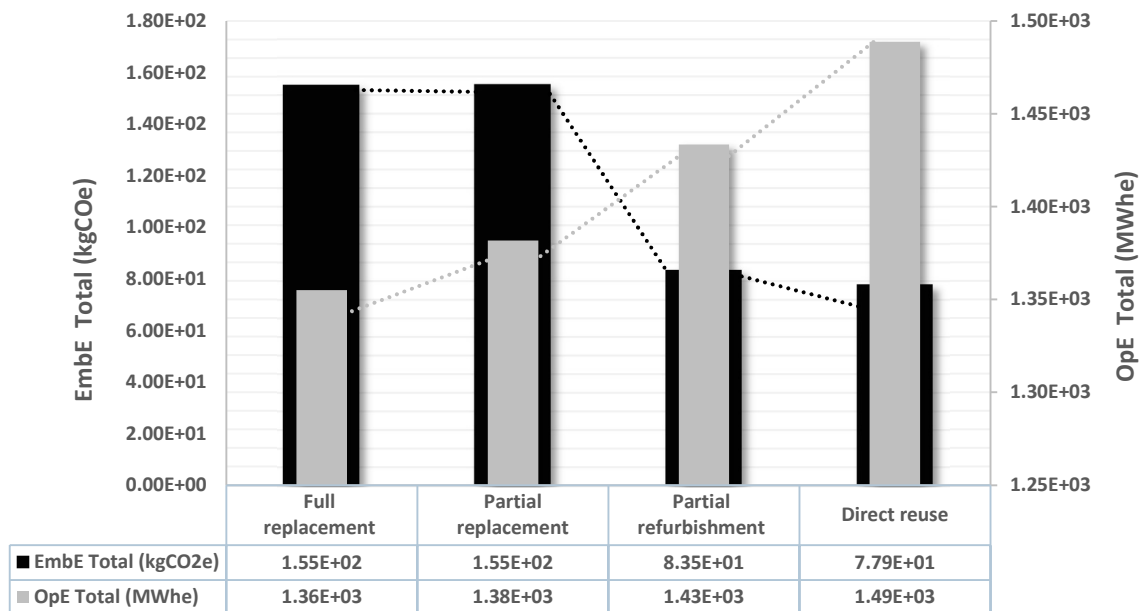


Figure 4-5: The total operational energy and embodied energy of the different strategies

The results show operational energy increases significantly for direct reuse (Scenario D) because of aging components and reduced efficiency. In contrast, full replacement (Scenario A) and partial refurbishment (Scenario C) have lower operational energy over time, reflecting improved performance from upgrades. However, the overall differences in operational energy across scenarios remain relatively small. Specifically, the gap between full replacement (Scenario A) and

partial replacement (Scenario B) is only 2%, while the difference between full replacement (Scenario A) and direct reuse (Scenario D) is approximately 10%. Similarly, partial refurbishment (Scenario C) reduces operational energy by about 5% compared to full replacement (Scenario A). Industry studies like Litti et al. (2018) found the replacement of a single pane timber window with full PVC window replacement reduced operational energy demand by 17%, in this study the replacement of an older PVC window, with a good state reclaimed PVC window yielded a 10% increase in performance.

While operational energy differences remain moderate, embodied energy varies significantly across restoration strategies due to differences in material use. However, this variation falls within an expected range, as demonstrated in a comprehensive study by Asdrubali et al. (2021), which estimated the embodied energy of aluminum, PVC, steel, and wooden framed windows. For double-paned PVC windows, the embodied energy (GWP) ranged between 40 and 90 kgCO₂eq, and in this study the PVC window has an embodied energy of 78 kgCO₂eq. As the window undergoes modifications under different restoration strategies, its embodied energy increases accordingly, depending on the materials and processes involved. As expected, full replacement (A) has 100% more embodied energy than direct reuse (D). Partial refurbishment (Scenario C) also significantly reduces embodied energy, it is about 85% lower than full replacement, since it involves minimal component replacement. Partial replacement (Scenario B) shows a much smaller reduction (only 2%) since most of the window assembly is still being replaced, aligning its embodied energy closely with full replacement.

The analysis confirms that partial replacement (B) and partial refurbishment (C) are between full replacement (A) and direct reuse (D) in terms of both operational and embodied energy. This suggests that refurbishment strategies effectively reduce embodied energy while maintaining reasonable operational efficiency. However, due to the large difference in scale between operational and embodied energy impacts, direct comparisons are not made between them since embodied energy is a onetime, upfront energy expenditure that happens only during material extraction, manufacturing, transportation, and installation. Meanwhile, operational energy is a continuous and long-term energy demand, occurring over the entire building's lifespan. Additionally, the analysis of materials that contributed to embodied energy reveals that flat glass and aluminum are the most significant contributors, while PVC, argon, and binders have minimal

impact. This is largely due to effective end-of-life resource management for PVC, which reduces its upstream embodied energy. Similarly, the application of Low-E film in partial window replacement did not significantly alter material contributions, indicating that such modifications have a negligible effect on overall embodied energy.

The results of the study show there are alternatives to full replacement strategies (Scenario A) which results in higher embodied energy, and direct reuse (Scenario D) which has minimal embodied energy impact, but can significantly compromise operational energy efficiency, leading to higher long-term energy consumption. Therefore, exploring options between partial replacement and partial refurbishment is crucial. However, it is important to note that the deterioration factor (df) and improvement factors (if) applied in this study are 15% and 10%, respectively. The values can be altered to explore how changes affect the operational energy calculations. Particularly, if the improvement factor significantly exceeds the deterioration factor, the window shows improved performance. Therefore, different strategies for enhancing the window can result in varied outcomes, especially in cases of partial refurbishment. These intermediary scenarios can help identify ways to enhance both embodied and operational energy, leading to better overall improvement scenarios for windows.

4.4.2 Assembly Restoration Framework (ARF) discussion

Extensive research has been conducted on window recycling and energy optimization, however, there remains a critical gap in understanding how to facilitate window restoration. The gap is emblematic of a broader challenge: the holistic study of reuse and refurbishment in construction, which lags due to its inherent complexity, industry fragmentation, and limited expertise. Unlike previous studies, such as Gustavsen et al. (2011), Litti et al. (2018), and Asdrubali et al. (2021), which primarily focus on whole-building energy modeling, life cycle embodied energy assessments, or optimizing window components for thermal performance, this study introduces a component-level restoration framework. Rather than treating windows as static components within a broader building system, this framework facilitates a component-level restoration approach that can be used in combination with other approaches, like building energy modeling and life cycle analysis.

The Assembly Restoration Framework (ARF) offers a decision-making tool for policymakers and industry professionals. The proposed framework develops a systematic workflow that begins with

identifying the composition of the assembly, followed by defining the functional measurement of performance for that assembly. Based on this, restoration strategies are explored, considering both component composition and performance criteria. These strategies are then modeled, and their impacts are assessed to provide a comprehensive evaluation of potential restoration outcomes. This structured approach allows for a more data-driven decision-making process, ensuring that restoration strategies are not only environmentally beneficial but also technically feasible. Unlike the decision-support frameworks in Yeung et al. (2015), which incorporated a technological tool, this study presents a framework designed for use alongside other technological tools that directly measure performance. The results from these tests can be integrated into the ARF tool for improved outcomes and assessments.

Furthermore, the application of the ARF tool can extend beyond use for window assemblies to other assemblies like doors, walls, flooring and others. Incorporating embodied energy into restoration planning, regulatory bodies can encourage sustainable refurbishment over full replacement where applicable, reducing waste and resource consumption. It can also be used to evaluate other parameters, including cost, allowing flexibility for building assemblies. In addition, the study focuses primarily on the embodied and operational energy of windows, but other factors also influence the selection and improvement scenarios for windows, such as transportation costs, service costs, and the expense of training service providers. These additional considerations are important for implementing environmentally friendly, economically viable, and operationally effective refurbishment scenarios. This study highlights that, while restoration strategies can extend the lifespan of windows, financial and labor-related barriers hinder their widespread adoption. Window refurbishment professionals often prioritize financially viable options over waste reduction due to the higher labor demands of dismantling, cleaning, and reassembling old windows. Compared to new installations, refurbishment can be more time-consuming and costly, reducing its appeal in the market. As a result, without incentives or policy interventions, window reuse remains an underutilized strategy.

Finally, the framework introduced in this study contributes to advancing sustainable circular practices by promoting reuse and refurbishment as viable alternatives to full replacement. However, widespread adoption of these strategies requires greater incentives, tools, and decision-support systems, like the ARF tool, to facilitate informed choices in circular construction. The ARF

tool could be implemented in nonprofit organizations, such as Habitat ReStores, to help customers compare restoration options and assess the feasibility of reusing existing window components. With the necessary tools, training, and infrastructure, assembly restoration techniques could become more accessible and widely adopted. Additionally, the establishment of new nonprofit initiatives and incentive programs could further encourage sustainable restoration practices, reduce waste while fostering economic opportunities in circular construction. Beyond nonprofit initiatives, the wider adoption of circular strategies could inspire the development of for-profit businesses that integrate restoration and reuse into their core models. By demonstrating the economic and environmental value of refurbishment, these businesses could help reshape the window sourcing industry, creating a more sustainable and resource-efficient marketplace.

4.5 Conclusion

In conclusion, this study introduced the Assembly Restoration Framework (ARF) as a structured approach for evaluating restoration strategies for building components, using windows as a demonstration. A structured approach was used to evaluate the operational and embodied energy of windows over 50 years, considering the following restoration strategies after 25 years. Full replacement (Scenario A), partial replacement (Scenario B), partial refurbishment (Scenario C), and direct reuse (Scenario D). The findings demonstrate that, while full replacement (Scenario A) results in the lowest operational energy, it has a significant embodied energy cost. Conversely, direct reuse (Scenario D) minimizes embodied energy but leads to higher long-term operational energy consumption. Partial replacement (Scenario B) and partial refurbishment (Scenario C) are intermediary solutions that balance both embodied and operational energy. Notably, partial refurbishment (Scenario C) reduces embodied energy by approximately 85% compared to full replacement (Scenario A). The application of low-E film significantly reduced the embodied energy without drastically compromising operational performance.

The contribution of this study is its demonstration of a component-level restoration analysis, distinguishing it from previous research focused solely on whole-building energy modeling, life cycle analysis, or thermal performance optimization. Unlike prior studies, the ARF tool is built on the insight gained from real-world data collected from stores that stock RCMs. This data highlights opportunities for developing structured frameworks to support the reverse logistics of used building assemblies, facilitating their reuse and refurbishment.

Ultimately, this study advances sustainable material management by demonstrating that restoration strategies can extend the lifecycle of building components, reducing waste, conserving resources, and lowering carbon footprints. Although this study used a window as an example to demonstrate the ARF framework, the framework can also apply to other building assemblies.

However, adapting the ARF framework to a new assembly requires model adjustments to align with that assembly's unique properties and evaluation criteria. For example, exterior building panels might be: (1) partially replaced, such as the connecting hardware, (2) directly reused, in such cases where the frame requires access and refurbishment but not the panels, (3) partially refurbished, where an insulating layer may be added or the exterior recoated, and (4) fully replaced, where for architectural or building performance reasons, the cost and additional embodied energy represented are justifiable. Future research could develop standardized datasets that combine both embodied energy and operational performance metrics, allowing for more refined restoration assessments. Additionally, expanding publicly accessible databases with precise window specifications, including U-values, frame materials, and expected durability, would significantly improve the applicability of restoration frameworks. Such advancements would support more data-driven decision-making in sustainable building practices.

Chapter 5: Evaluating a rebate policy mechanism designed for enhancing circular strategies in construction

Expanding on the previous chapter, this section applies the framework to full assemblies, such as windows or doors. It introduces additional complexity by considering interactions between components within an assembly and explores how restoration strategies can be evaluated holistically. This chapter is based on the following published article.

Olumo, A., & Haas, C. (2025). Modelling Circular Policy Strategies for Construction Material Sourcing: A Rebate-Based Demonstration. (Submitted)

Abstract

A major barrier to circular construction practice at scale is the disconnect between materials recovered from deconstruction and their reintegration into new building projects. This paper demonstrates how the Integrated Material Sourcing (IMS) Framework can be used to evaluate the influence of policy incentives on sustainable construction material sourcing decisions. The IMS Framework combines data from both building designs and real-world material inventories to optimize component selection for construction projects.

Using a fourplex case study, the IMS model optimizes selection of new or salvaged wood flooring based on cost, embodied energy, and perceived risk. A rebate mechanism is introduced as a sample policy scenario, in which cost-matching incentives are offered for salvaged material use, demonstrating how decision-making shifts under different policy conditions. Results reveal that high risk aversion significantly reduces the effectiveness of rebates, even when financial incentives are generous, in which case mandates might be a more effective policy tool. This study also reveals the gap in policies addressing reuse of materials. The application of the framework in this study gives policymakers and practitioners a versatile tool to simulate and stress-test circular strategies adapted to real construction scenarios.

Keywords: circular economy, policy mechanism, building resource optimization, salvaged construction materials, sustainable management, reverse logistics

5.1 Introduction

In Canada, only 16% of Construction, Renovation, and Demolition (CRD) waste is recycled or reused, despite estimates showing that up to 85% could be diverted from landfills (Lopoukhine, 2024). This presents opportunities for improvement in circular strategy implementation nationally and globally. Unfortunately, construction resources continue to exit the building lifecycle without reintegration, reinforcing the traditional "take-make-waste" approach (Lopoukhine, 2024). Salvaging resources is central to addressing the construction sector's contribution to environmental degradation. Implementing circular strategies could yield significant advantages, including greater use of salvaged resources, reduced carbon emissions, enhanced biodiversity, more robust supply chains, lower material costs, and economic growth fuelled by new industries and employment (Lopoukhine, 2024).

However, several barriers limit the widespread adoption of circular strategies, including lack of standardized recovered resources certifications, making their use more complex for designers and contractors (Dams et al., 2021; Byers et al., 2024). Construction processes still prioritize new resources, and regulatory frameworks often lag behind emerging reuse practices. Cultural perceptions further discourage reuse, associating salvaged resources with lower quality despite evidence of their durability and historical significance (Kapica et al., 2024). Previous studies highlight that addressing these barriers requires a shift in both policy and design practices. Dams et al. (2021) recommends incorporating disassembly and adaptability potential into early design phases to optimize resource recovery at the end of a product's life, while Kapica et al. (2024) emphasize the need for education, legal reforms, and certification systems to normalize reuse across construction sectors, and Lopoukhine (2024) underscores the economic and environmental gains achievable through targeted resource recovery strategies. These recommendations focus on strengthening the reverse logistics of building resources, aiming to reintegrate resources into new construction. However, there is a need to explore where resources exit and re-enter the system, and to identify real-world opportunities where policy interventions can shift construction waste flows toward salvage resource streams and new construction applications.

Circular strategies in construction aim to manage resources through three main interventions: slowing the resource loop, closing the resource loop, and narrowing the resource loop (Figure 1-1). Within each strategy, different types of interventions support the overall objective of maintaining

resources within the system. The first strategy, slowing the loop, focuses on designing and constructing resources to be durable, adaptable, and deconstructable (Ellen MacArthur Foundation, 2021). It improves the potential of resources to undergo refurbishment, recycling, or reuse later in their lifecycle. If resources are not built to be durable, adaptable, or easily deconstructed from the start, they are more likely to exit the system prematurely at the upstream level. Strengthening design and construction practices to prioritize durability and adaptability can avoid upstream resource exits and allow resources to remain active within their first lifecycle or transition smoothly into secondary cycles (Iacovidou & Purnell, 2016; Mollaei et al., 2023a).

The second strategy, closing the loop, involves applying interventions such as reuse, refurbishment, or recycling as resources approach the end of their initial use phase. These interventions prevent resources from exiting the system and instead allow them to take on new forms or functions while remaining within the resource stream (Ellen MacArthur Foundation, 2021). The third strategy, narrowing the loop, focuses on reducing the demand for virgin resources by reintegrating recovered resources into new construction processes. Resources that successfully go through extension strategies contribute to narrowing the loop by minimizing the need for newly extracted resources (Ellen MacArthur Foundation, 2021). However, even after extending resource use, downstream resource exits still occur. Salvaged resources that undergo deconstruction may not always re-enter construction projects. Some resources degrade during the transition phase due to a lack of proper maintenance, while others, although extracted, remain unsold at Reclaimed Construction Material (RCM) stores (Iacovidou & Purnell, 2016; Mollaei et al., 2023). In many cases, salvaged resources are recycled rather than treated as high-value assets that could be directly upgraded or reintroduced into new projects. These downstream losses highlight critical points where further interventions are needed to maximize the value and longevity of salvaged resources. With a clear understanding of resource loops, strategies and policies can be developed to target both upstream and downstream resource exits.

Historically, policy interventions have focused more heavily on upstream exits, with comparatively fewer measures aimed at downstream reintegration. Policies such as deconstruction mandates exemplify upstream interventions, aiming to prevent early resource loss by enabling resource extraction at the end of a building's service life (Mollaei et al., 2023a). In contrast, downstream interventions focus on promoting the reintegration of salvaged resources into new projects.

Mandating the use of a minimum percentage of reclaimed or recycled resources, such as the 10% recycled content requirement in new construction, serves as an example of a downstream-targeted policy (Emery et al., 2007). Recognizing how different policies influence resource flows provides critical insight into where interventions are currently effective and where further development is necessary. This study builds on these insights to assess how policies that target upstream or downstream interventions could be tested to enable circular strategy implementations.

From a methodological perspective, this study builds on a previously developed optimization framework for integrating RCMs into construction projects. While the earlier model primarily focused on cost and environmental considerations, the present study extends the framework by introducing risk factors and simulating the impact of rebate-based incentives. This adaptation aims to explore how policy mechanisms and uncertainty affect resource selection decisions in practical applications. Therefore, using empirical data on flooring components sourced from RCM stores, the study assesses resource selection outcomes across three categories: reclaimed, recycled, and new. Although the focus is on flooring, the methodology developed is adaptable to other building resources and decision factors.

The research questions addressed in this study are:

- (1) How do factors related to cost and perceived risk affect RCM selection in construction projects?
- (2) How can policy incentives, such as rebate programs, influence sourcing decisions to better support circular strategies?

Scope

The scope of this study is limited to flooring components, specifically reclaimed wooden flooring. Many building components can be found at RCM stores, ranging in type and size from kitchenettes, tiles, skirting boards, windows, and doors to structural framing elements and masonry (Olumo et al., 2022). This study focuses on salvaged wood flooring, readily available in Western Ontario RCM stores, because of its ubiquity in other stores of this type in North America and Europe. The analysis focuses on Timeless Material Store's flooring options, specifically recycled wooden slats and reclaimed wooden slats. The factors considered in this study includes cost, embodied energy, and risk perception. In contrast to prior studies that have primarily focused on tangible attributes such

as mechanical properties, structural performance, spatial constraints, and cost, this study introduces a mix of tangible and subjective parameters. It uses the Integrated Material Sourcing (IMS) framework, designed to optimize downstream sourcing decisions for resources in building projects. While other frameworks exist that target upstream circular strategies like deconstruction, salvage, or construction-phase planning. The IMS framework uniquely supports decision-making at the point of RCM procurement.

Finally, the study examines how policy instruments can influence the selection of environmentally preferable resources. A rebate-based incentive is modelled as a case study to explore this relationship. While other instruments, such as mandates or penalties, exist, this study focuses on rebate policies due to their non-coercive nature and relevance to real-world sustainability programs.

5.2 Research Methodology

This study adapts the Integrated Material Sourcing (IMS) framework to assess a rebate-based policy strategy aimed at facilitating the use of circular building components in new construction projects. The first step involves reviewing existing policies that support the secondary use of building resources and identifying the stages at which these policies influence resource retention. In doing so, the study distinguishes between upstream strategies and downstream strategies. To identify existing policies that have been implemented across various regions to support construction resource conservation, a systematic literature review using a structured search methodology was used to identify academic studies and papers discussing relevant policies on the webofscience platform. The goal was to capture a range of initiatives introduced by governments, institutions, and other organizations aimed at promoting the reuse, recycling, or conservation of construction resources. Beyond the academic literature, the study extended its search to include governmental reports and official websites, using the same search terms in the google browser. As a result, a wide array of relevant studies and real-world initiatives were uncovered.

Rebates, a downstream policy class, are the focus of this study. The IMS framework is applied to model the effects of a rebate on component selection at the end of life. The framework, originally developed to optimize (minimize) cost and embodied energy, is extended in this study to include an additional objective. While maintaining cost and embodied energy as objectives, the revised

model also incorporates perceived risk associated with using RCMs, and rebate-based incentives are introduced as a key variable. The objective function developed in this study, implements a multi-objective linear programming model. The model simultaneously minimizes cost, embodied energy, and risk, while also accounting for the maximization of potential rebates associated with different component sourcing decisions. To operationalize the model, real-world parameters were collected and input into an Excel-based interface connected to the IBM CPLEX optimization engine. The rebate parameter was scaled from \$0 up to approximately \$4,200 in \$100 increments across each defined risk magnitude, for each building unit in Figure 6 (FF_A, FF_B, SF_A, SF_B), allowing for a robust exploration of how rebate and risk interact to shape optimized procurement decisions.

Before discussing how perceived risk was modeled in this study, it is important to clarify how value perception is typically examined in relation to a resource. The assignment of value to resources by individuals or society is commonly studied through economic models designed to capture value assessment at scale. A widely used approach is the derivation of a utility function, which reflects the expected payoff associated with a decision to purchase a product. This utility function converts the monetary value of a choice into a psychological or perceived value for the decision-maker (ReVelle et al., 2004). Developing a utility function in this study would require an in-depth economic modeling approach that draws on data gathered through stakeholder engagement or canvassing to uncover how different individuals or groups perceive value in different types of resources, based on their priorities.

However, to simplify the approach in this study, perceived risk was modeled using a scaled system that assigns values to different resource categories: reclaimed, recycled, and new, on a scale from 1 to 7. This approach is informed by the study conducted by Khatri et al. (2025) on identifying consumer drivers for the adoption of recycled wood in construction. The study was carried out in Norway, where consumers were asked about the factors influencing their decision to use recycled wood in building new cabins or houses. Responses were gathered from 446 cabin owners and 467 house owners. A Likert scale ranging from 1 to 7 was used to assess perceived risk, with 1 indicating the lowest perceived risk and 7 the highest. In this study, RCMs were assigned a high-risk score (≈ 7), recycled components a moderate score (≈ 5), and new components a lower score (≈ 2). These base values were then scaled using a risk magnitude multiplier, with magnitudes set at 0, 0.2, 0.4, 0.6 and 0.8 to explore how increasing the perceived importance of risk influences component selection.

This approach enabled the study to simulate varying attitudes toward perceived risk. For instance, a risk magnitude of 0 represents a baseline case where perceived risk is not considered in decision-making, simulating an environment where RCMs are adopted without prejudice. In contrast, higher magnitudes simulate contexts where risk perceptions significantly deter the use of reclaimed or recycled resources, revealing how much stronger rebate incentives must be to overcome such barriers. The research methodology used in this study is shown in Figure 5-1.

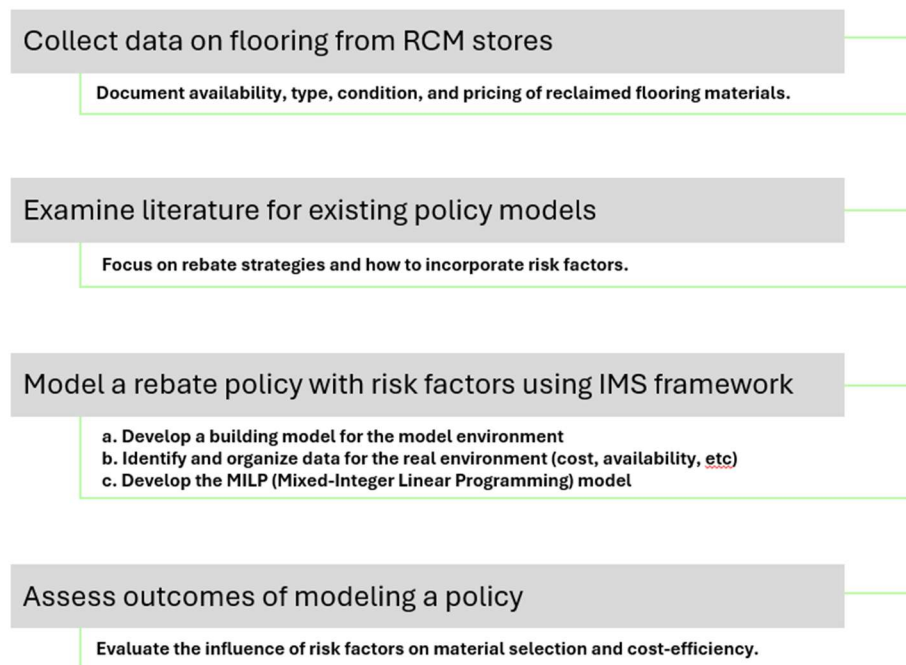


Figure 5-1: Workflow for Policy Assessment and Rebate Modeling Using the IMS Framework

5.2.1 Flooring Component Data

All component data used in this study, specifically for salvaged resources including reclaimed flooring and re-milled lumber used for flooring slats, were collected and documented from the Timeless Material Store. Information was recorded on both the general cost of salvaged resources and the specific pricing of flooring products. Re-milled lumber, typically labelled as such in-store, is repurposed into flooring slats and was categorized separately from directly reclaimed flooring. For new components, pricing and product information were extracted from the Home Depot website. The focus was on three flooring types: hardwood, redwood, and softwood. These same three categories were used to structure all data collected, ensuring consistency between reclaimed and

new component comparisons. Flooring data included complete product descriptions, cost per square foot, and a label indicating whether the component was salvaged, re-milled, or new.

A total of 19 flooring resources were compiled, new components were assumed to have the highest availability, set at 1,000 square meters, given they can be readily ordered online. For re-milled lumber, availability was conservatively estimated at 100 square meters based on a visual inspection of inventory at the Timeless Material Store. Reclaimed flooring availability was estimated at approximately 40 square meters, derived from 3D scans captured at the store. These scans provided dimensional data used to quantify available stock. Figure 5-2 and Figure 5-3 depict the resources found at the RCM stores, as well as examples from two other geographically disparate locations. Figure 5-4 illustrates the 3D scans used to estimate resource quantities.



Figure 5-2: Salvaged Flooring Resources at the Timeless Material Store, and stores in Pittsburgh PA and Gstaad Switzerland



Figure 5-3: Remilled/Recycled Flooring Resources at the Timeless Material Store

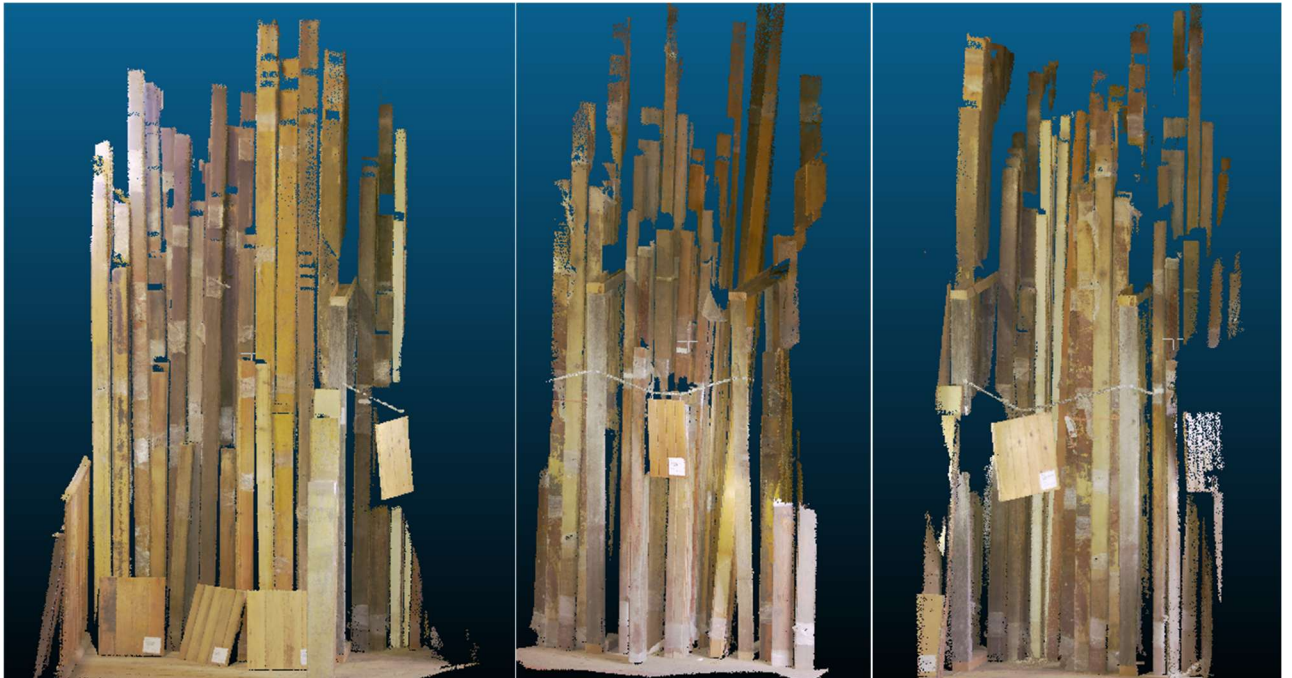


Figure 5-4: 3D Scans of Reclaimed Flooring Inventory

5.2.2 Policy Evaluation

A structured search strategy was employed to identify academic literature and relevant literature on policy drivers for salvaged components. The database and search engine used was Web of Science and Google chrome. The following steps were taken:

Search terms included:

- "policy drivers reclaimed building materials"
- "sustainable construction materials policy"
- "policies for reuse of salvaged materials in construction"
- "government incentives for salvaged or reclaimed materials"

In addition, Boolean combinations were used to broaden the search scope:

- ((reclaimed OR reused OR salvaged) AND construction AND materials) AND policy
- ((reclaimed OR reused OR salvaged) AND construction AND materials) AND sustainable AND policy
- ((reclaimed OR reused OR salvaged) AND construction AND materials) AND (government OR incentives OR tax OR subsidy OR rebate OR government support)

This yielded a total of 167 articles, which were then refined as follows:

- Removed 84 articles related to asphalt
- Manually filtered out 42 unrelated topics, such as textiles, batteries, water systems, and physics
- Semi-final dataset included 41 relevant articles after abstract review and relevance filtering
- Final dataset included 9 relevant research articles that clearly stated policy tools, and 11 other relevant sources (websites etc.) found that stated policy tools. However, only eight were applicable to this study, they are presented in Table 5-1.

The identified policies were then categorized based on the stage of resource flow they impact. Table 2 summarizes the identified policies along with their respective classification as upstream, downstream, or hybrid (including both upstream and downstream elements) strategies. Each entry includes the policy type, geographic context, policy mechanism (e.g., financial incentive, regulation), and the target resource or construction stage. These policies represent a range of

interventions from municipal deconstruction mandates (e.g., Portland’s Deconstruction Ordinance) to government-sponsored rebates (e.g., Toronto’s Development Charge Refund Program). Upstream labels indicate policies that influence the recovery and preservation of resources during demolition or disassembly phases (e.g., selective deconstruction ordinances, salvage mandates, design-for-disassembly requirements). Conversely, downstream labels indicate policies that promote the reuse or reintegration of salvaged resources in new construction (e.g., rebate programs, procurement incentives, material certification standards).

Table 5-1: Summary of Identified Policies and Associated Circular Strategy Classification

Country	Policy	Policy Strategy
USA (Oregon)	The City of Portland's Deconstruction Ordinance requires some homes to be deconstructed rather than demolished. If the building was built in 1940 or earlier, or designated as a historic resource, it requires structural deconstruction instead of mechanical demolition (Arbelaez et al., 2019).	Structural exemptions exist for structures not suitable for salvage. Code violations result in a \$500 fine for the first fine. Upstream
USA (Pittsburgh)	Pittsburgh's Zoning Performance Points is a scoring system used to evaluate the performance of individual properties within the city's zoning districts. It measures the property's conformance to the zoning code and assigns points based on various criteria such as land use, density, and design standards. The points are then used to determine the property's zoning compliance and inform decision-making for development projects, variances, and appeals. The provision is for projects that implement reuse obtain bonus points under Zoning performance (Lambert et al., 2024).	Developers earn bonus points for incorporating material reuse into their projects, which contributes to zoning compliance. Downstream

Canada (Victoria, BC)	Demolition permit applicants pay a refundable fee of \$19,500. This fee is refunded after the permit holder salvages the target amount of wood for reuse during their demolition. The target is aligned with the size of the house: 40 kilograms per square meter of above-ground floor area. Fulfilling the salvage target is generally achieved through deconstruction practices, or in some cases house moving. Permit holders must document and report the amount of wood salvaged and how it will be reused (Lambert et al., 2024).	Financial incentive of \$19,500 for wood quantity salvaged Upstream Downstream
Netherlands	The Dutch waste policy follows an integrated life-cycle approach, anchored by a strict landfill ban on construction, renovation, and demolition (CRD) waste. Additionally, the Netherlands imposes some of the highest landfill taxes and levies globally, averaging approximately \$162 per tonne, with rates varying based on volume, weight, and resource type (EEA, 2023).	Landfill taxes based on volume, weight and resource types deposited at landfills. Upstream
USA (Massachusetts)	The Massachusetts Waste Master Plan outlines the state's goals for reducing solid waste disposal over the next decade. A key strategy involves strict disposal bans that require facility operators to assess and manage waste types effectively. Facilities must demonstrate compliance by ensuring that banned resources are not sent to landfills or transfer stations. Instead, they are expected to separate and divert recyclable or reusable resources, such as asphalt, brick, drywall, concrete, and both treated and untreated wood (MassDEP, 2021).	Landfill Ban on some solid waste resources that can be recycled or reused. Upstream

Germany	Germany implemented a closed-loop recycling policy targeting the reuse of construction and demolition waste in structural concrete production. The approach is underpinned by national standards such as DIN 4226-100, which defines the allowable composition and quality of recycled aggregates used in concrete. Recycled resources are categorized under regulatory thresholds (Z0 to Z2) managed by the State Associations on Waste (LAGA) and Water Protection (LAWA). Only aggregates that meet specified pollutant limits (e.g., sulphates, heavy metals) can be reused in concrete (Weil et al., 2006).	To ensure compliance and maintain structural integrity, a maximum of 35 to 45% of recycled aggregate may be used in new concrete, depending on its classification. Although DIN standards are “voluntary” in name, they are mandatory in practice when referenced in building codes or contracts. Downstream
Canada (Vancouver, BC)	Vancouver’s Green Demolition Bylaw mandates that for single-family homes built before 1950, applicants must salvage at least 3.5 kg of reclaimed lumber per square foot of finished floor area during demolition. The application requires a one-page Wood Salvage Plan, a non-refundable administration fee of \$262.50 (as of 2024), and a refundable \$15,000 waste diversion deposit. The deposit is returned based on the quantity of wood successfully salvaged. Within 90 days after demolition, applicants must submit a Wood Salvage Compliance Report along with receipts and documentation to verify the salvaged resources (City of Vancouver, 2024).	The Bylaw requires a high percentage of demolition resources to be reused or recycled. Building resources reused or salvaged, instead of being recycled or discarded, are credited at five times their weight for the green demolition compliance requirement. Downstream Upstream

Canada (Toronto, ON)	The Toronto Development Charge Refund Program offers rebates for infrastructure projects that incorporate sustainable strategies, including the use of recycled or salvaged resources. The program is tiered, with rebates ranging from 25% to 50% based on sustainability goals, and involves several stages including consultation, compliance checks, and third-party evaluation (City of Toronto, 2017).	Financial incentives for projects incorporating sustainable strategies. The Old Mill Drive Centre, a mid-rise, multi-unit residential building, diverted 86% of construction waste.
		Upstream Downstream

5.3 Framework Application for Material Selection

The Integrated Material Sourcing (IMS) framework is structured around three main components: the real environment, the model environment, and the core engine. Figure 5-5 illustrates how the IMS framework is applied and adapted in this study to simulate complex, multi-dimensional decision-making scenarios in flooring component selection.

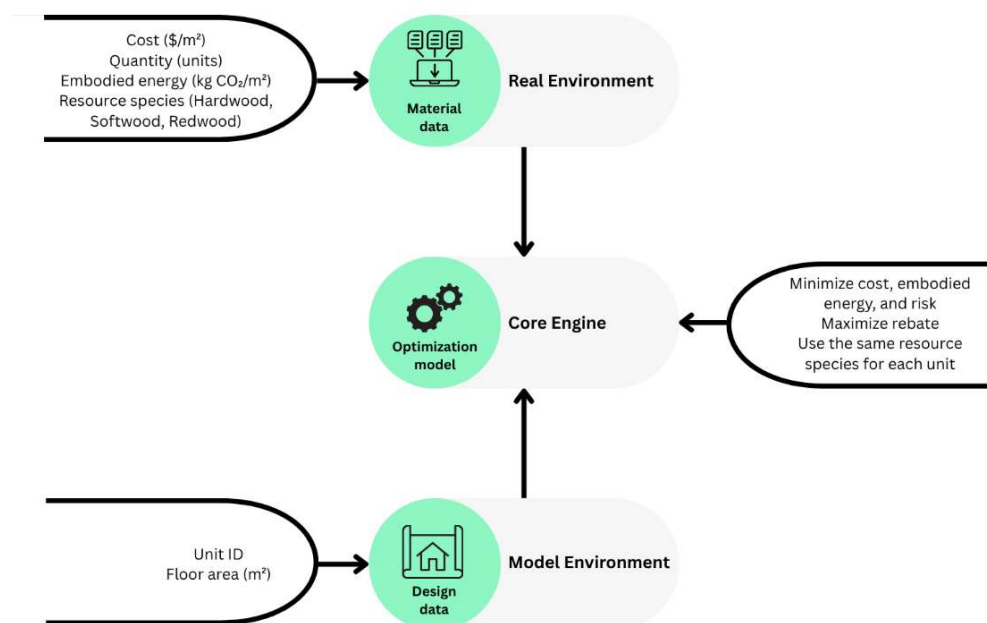


Figure 5-5: Structure of the IMS Framework

5.3.1 Real environment

The real environment includes the capture of real-world data from available resource suppliers. In this study, it includes detailed information about the components being considered, specifically, the cost, quantity, embodied energy, and wood species of various flooring types. The flooring data presented above was collected by the researchers, as previously discussed, and was subsequently input into an Excel spreadsheet for the optimization process. The only additional parameter that required calculation was the embodied energy, which was estimated using Environmental Product Declarations (EPDs) for North American wood products (Quebec Wood Export Bureau, 2020). The data used comes from North American EPD sources, allowing for a consistent estimation of embodied energy across both hardwood and softwood flooring types. These EPDs are based on the ASTM 20 standard, ensuring uniformity in the datasets. To maintain consistency, the same EPD sources were used for both hardwood and softwood components when estimating their embodied energy impacts. For this assessment, we focus on cradle-to-gate calculations, meaning the embodied energy was accounted for up until the flooring component is ready for use. The reason for this approach is that beyond the cradle-to-gate stage, such as installation, transportation, and end-of-life processes, there is little to no significant variation between different types of wood flooring. These later stages tend to have a similar impact regardless of whether the flooring is new, salvaged, or recycled. Similarly, we avoid the accounting debates around carbon capture for wood that are reflected in the different regimes used by such LCA tools as Tally and OneClick LCA. Since the choice of component is made before installation, the embodied energy is largely determined by the processes leading up to that point, making cradle-to-gate the most relevant boundary for this comparison.

To estimate the embodied energy for new, salvaged, and recycled wood flooring, the information from EPDs for new wood components was used as a reference. For the new flooring component, the values were taken directly from the EPD dataset, representing the full impact of raw material extraction, processing, and transportation. For the recycled wood component, it was assumed that 50% of the manufacturing impact from the new wood EPD would apply. This accounts for the additional processing required for recycling, such as reprocessing, refinishing, and repurposing the resource after extraction. For the salvaged wood component, a lower estimate of 25% of the new wood's manufacturing impact was used. The lower percentage reflects the fact that salvaged wood

undergoes minimal processing, usually limited to de-nailing, cleaning, and preparation for reuse. Unlike recycled wood, salvaged wood is not broken down and reprocessed, which significantly reduces its embodied energy.

5.3.2 Model environment

The model environment reflects the design-side requirements and constraints. It includes the parameters specified by the designer, such as the total flooring area to be covered, preferred resource types, and limits on embodied energy. For this study, a four-unit residential structure BIM (Building Information Model) with two units on each floor was designed in Revit thus serving as the information source for what is needed, where, and under what constraints. In this study, for functional demonstration, we focus on estimating the flooring area that must be covered and identifying the design specifications that guide component selection. Additionally, the specified requirement is that each unit must use a single type of wood flooring, either redwood, hardwood or softwood. Figure 5-6 depicts the model developed in Revit for this study.

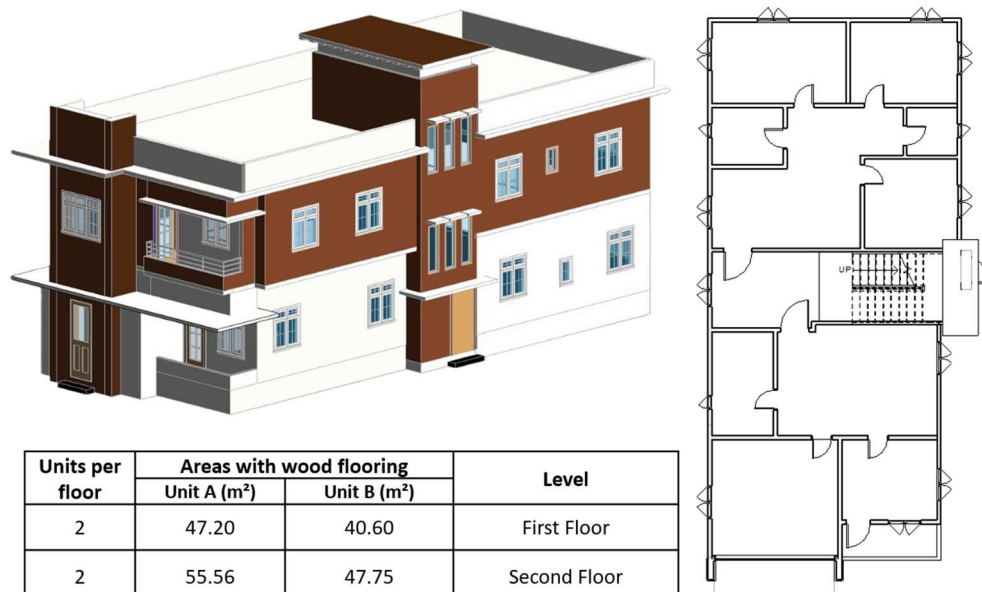


Figure 5-6: Modeled Residential Building Layout

5.3.3 Core Engine

The initial model presented in Olumo & Haas, (2024b) reflects a classic transportation problem, commonly used in operations research to determine the most cost-effective way to distribute products from multiple sources to multiple destinations. Its formulation was driven primarily by

cost minimization, with constraints ensuring supply and demand balance. The current model transforms the problem into a multi-resource allocation framework that reflects real-world sustainability considerations in construction or infrastructure planning. The objective function of the new model is designed to balance economic cost, environmental impact, perceived risk, and incentive-driven rebates, representing a more holistic and policy-sensitive optimization approach. The multi-objective function encourages selection of components that are energy efficient and low risk, promoting policy compliance by incorporating rebate logic, and rewarding units that meet rebate requirement. It provides flexibility through tunable parameters for cost, environment, and perceived risk (α, β , and γ), where $\alpha + \beta + \gamma = 1$. The objective is subject to several constraints, including area coverage, which ensures that each unit's total area is fully met by selected components. It enforces species consistency, meaning each unit must use a single type of wood flooring; for example, Unit A can use only hardwood or only softwood, but not a combination of both. Additionally, rebate constraints are included to ensure that the rebate amount a unit receives does not exceed the total cost of eligible components actually used, and the eligible components are reclaimed or recycled flooring. The following tables present the mathematical formulation used in the optimization model. Table 5-2 presents the parameters and indexes used in the optimization model. Table 5-3 lists the formulation of the optimization model.

Table 5-2: Parameters and Indexes used in the optimization model.

<i>Indexes</i>	
<i>Set of housing units, $u = 1, 2, \dots, U$</i>	
<i>Set of available flooring material resources, $i = 1, 2, \dots, I$</i>	
<i>Set of wood species (e.g., hardwood, softwood), $s = 1, 2, \dots, S$</i>	
<i>Parameters</i>	
<i>Unit cost of resource i (\$/m²)</i>	<i>cost_{i}</i>
<i>Embodied energy of resource i (kg CO₂/m²)</i>	<i>energy_{i}</i>
<i>Perceived risk factors associated with resource i</i>	<i>risk_{i}</i>
<i>Total flooring area to be covered in unit u (m²)</i>	<i>Area_{u}</i>
<i>Maximum quantity available for resource i (m²)</i>	<i>max available_{i}</i>
<i>Binary parameter: 1 if resource i qualifies for rebate; 0 otherwise</i>	<i>rebate eligible_{i}</i>
<i>Maximum rebate value allowed for unit u (\$)</i>	<i>rebate value_{u}</i>

Binary parameter: 1 if unit u qualifies for rebate; 0 otherwise	$rebate\ qualified_u$
Binary parameter: 1 if resource i belongs to species s ; 0 otherwise	n_{is}
Weight for cost in the objective function	α
Weight for embodied energy in the objective function	β
Weight for perceived risk in the objective function	γ

Table 5-3: Formulation of the optimization model

Objective Function

$$\text{minimize } \sum_{u \in \text{units}} \sum_{i \in \text{resources}} (\alpha \times \text{cost}_i + \beta \times \text{energy}_i + \gamma \times \text{risk}_i) \times x_{ui} - \sum_{u \in \text{units}} \text{rebate}_u$$

Constraints:

Each unit selects exactly one species.	$\sum_{s \in \text{species}} y_{us} \leq 1 \geq 0$	$\forall u \in \text{units}$
Total resource use must cover the full area of each unit.	$\sum_{i \in \text{resources}} x_{ui} \geq \text{Area}_u$	$\forall u \in \text{units}$
A unit can only use a resource if its species is selected.	$x_{ui} \leq \text{Area}_u \times \sum_{s \in \text{species}} y_{us} \times n_{is}$	$\forall u \in \text{units},$ $i \in \text{resources}$
Total allocation of each resource must not exceed its availability.	$\sum_{u \in \text{units}} x_{ui} \leq \text{max available}_i$	$\forall i \in \text{resources}$
Rebates are limited to the cost of eligible materials used.	$\text{rebate}_u \leq \sum_{i \in \text{resources}} \text{rebate eligible}_i \times \text{cost}_i \times x_{ui}$	$\forall u \in \text{units}$
Rebate amount is capped at the allowed value if the unit qualifies.	$\text{rebate}_u \leq \text{rebate value}_u \times \text{rebate qualified}_u$	$\forall u \in \text{units}$
A unit qualifies for rebate only if eligible material use meets or exceeds the rebate threshold.	$\sum_{i \in \text{resources}} \text{rebate eligible}_i \times \text{cost}_i \times x_{ui} \geq \text{rebate value}_u \times \text{rebate qualified}_u$	$\forall u \in \text{units}$
Non-Negativity Constraint	$x_{ui} \geq 0$	$\forall u, i$

5.4 Results and Discussion

This study sets out to assess how policy mechanisms like rebate-based incentives can influence the selection of salvaged building components. Using the IMS (Integrated Material Sourcing) framework, decision-making scenarios focused on how the selection of flooring components are assessed. The study aimed to answer two core questions: (1) how do cost and perceived risk affect the uptake of reclaimed components; and (2) to what extent can rebate programs influence sourcing behavior to promote circularity?

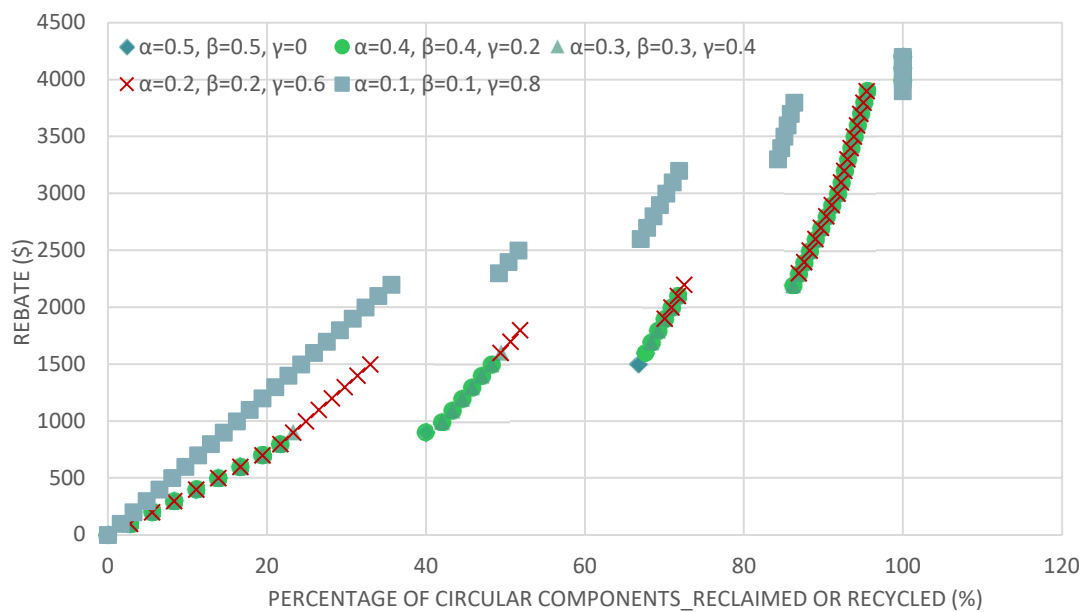


Figure 5-7: Relationship Between Rebate Magnitude and Percentage of Circular Component Selected at Varying Risk Levels

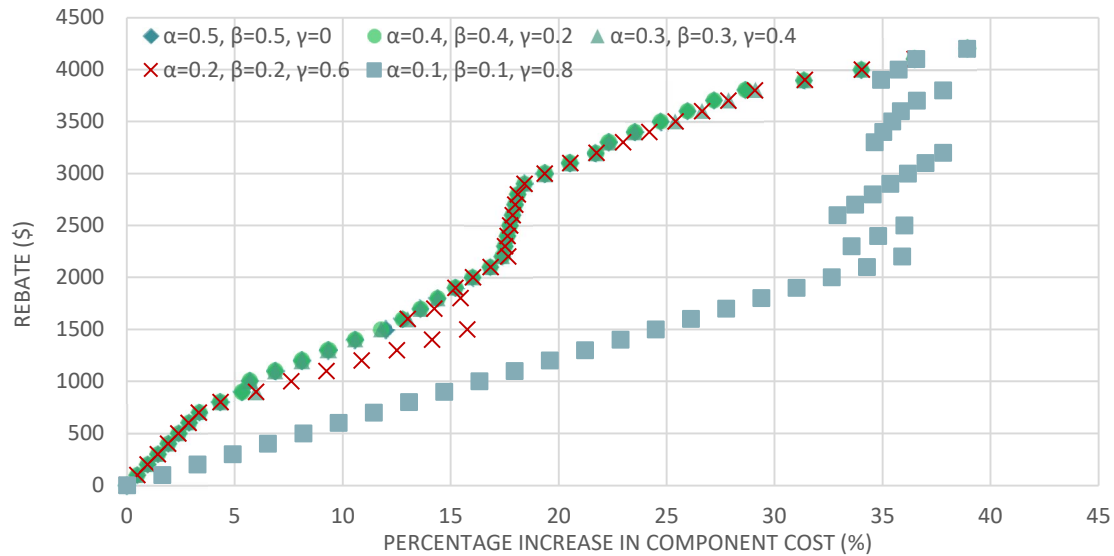


Figure 5-8: Component Cost Increase Relative to Rebate Magnitude Across Risk Scenarios

The analysis began with a base model in which the perceived risk magnitude was set to zero, it does not imply that rebates were absent, but rather that there was no negative perception associated with using reclaimed or recycled components. This simulated an environment where salvaged resources were perceived similarly to new resources in terms of trust, reliability, and performance. As expected, under this risk-neutral scenario, where $\alpha=0.5$, $\beta=0.5$, and $\gamma=0$, the selection of circular components (reclaimed or recycled) was higher and more responsive to available rebates, leading to a comparable increase in salvage component selection (Figure 5-7). Subsequent models introduced increasing levels of perceived risk (e.g., magnitudes 0.2, 0.4, 0.6 and 0.8) to examine how negative perceptions or uncertainties about component performance impacts resource selection. The results demonstrated that as perceived risk magnitude increased, the system required higher rebate values to maintain similar levels of reclaimed or recycled component selection. This aligns with real-world observations where higher levels of skepticism in a region or industry reduce the effectiveness of incentives unless they are scaled appropriately.

Figure 5-8 illustrates another important dimension of the model's behavior: the influence of resource availability on component selection outcomes. Initially, the relationship between rebate magnitude and the percentage of reclaimed or recycled components selected is relatively linear. At this stage, the model responds predictably; higher rebates lead to proportionally higher adoption of circular resources. However, as the available pool of RCMs shrinks, the trend shifts. The model

begins to require disproportionately higher rebates to continue increasing circular resource selection. This is particularly evident as the model approaches 100% selection of recycled or reclaimed components, where the rebate levels must rise to overcome scarcity and secure enough qualifying resources, so the data points start to scatter, breaking the linear trend it began with. The inflection point highlights a critical insight: resource availability directly constrains the effectiveness and affordability of rebate-based strategies. In environments with limited salvage or recycled resource stock, the rebate system becomes more expensive and less efficient, essentially forcing high-cost selection decisions to meet policy targets. Conversely, in contexts with a mature and diverse pool of circular resources, rebates can be applied more modestly and still achieve meaningful adoption. Therefore, policy design must consider the local availability and maturity of salvage resource markets when implementing financial incentives. Doing so helps avoid the need for aggressive subsidies and ensures that incentives align realistically with what the market can supply.

Table 5-4: Component Selection Breakdown for a \$2000 Rebate

Resource type	Species	$\alpha=0.5, \beta=0.5, \gamma=0$				$\alpha=0.4, \beta=0.4, \gamma=0.2$				$\alpha=0.3, \beta=0.3, \gamma=0.4$				$\alpha=0.2, \beta=0.2, \gamma=0.6$				$\alpha=0.1, \beta=0.1, \gamma=0.8$			
		Unit 1	Unit 2	Unit 3	Unit 4	Unit 1	Unit 2	Unit 3	Unit 4	Unit 1	Unit 2	Unit 3	Unit 4	Unit 1	Unit 2	Unit 3	Unit 4	Unit 1	Unit 2	Unit 3	Unit 4
Recycled	Hardwood	0.0	0.0	0.0	1.9	0.0	0.0	0.0	1.9	0.0	0.0	1.9	0.0	0.0	0.0	1.9	0.0	3.9	3.9	3.9	3.9
Recycled	Hardwood	0.0	0.0	0.0	1.9	0.0	0.0	0.0	1.9	0.0	0.0	1.9	0.0	0.0	0.0	1.9	0.0	3.9	3.9	3.9	3.9
Recycled	Hardwood	0.0	0.0	0.0	1.9	0.0	0.0	0.0	1.9	0.0	0.0	1.9	0.0	0.0	0.0	1.9	0.0	3.9	3.9	3.9	3.9
Recycled	Hardwood	0.0	0.0	0.0	1.9	0.0	0.0	0.0	1.9	0.0	0.0	1.9	0.0	0.0	0.0	1.9	0.0	3.9	3.9	3.9	3.9
Used	Hardwood	0.0	0.0	26.5	13.5	0.0	0.0	26.5	13.5	0.0	0.0	13.5	26.5	0.0	0.0	13.5	26.5	0.0	0.0	0.0	0.0
New	Hardwood	0.0	0.0	29.0	26.7	0.0	0.0	29.0	26.7	0.0	0.0	34.5	21.2	0.0	0.0	34.5	21.2	31.7	25.1	40.1	32.3
New	Hardwood	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
New	Hardwood	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
New	Hardwood	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Used	Redwood	0.0	40.0	0.0	0.0	0.0	40.0	0.0	0.0	0.0	40.0	0.0	0.0	0.0	40.0	0.0	0.0	0.0	0.0	0.0	0.0
Used	Redwood	0.0	0.3	0.0	0.0	0.0	0.3	0.0	0.0	0.0	0.3	0.0	0.0	0.0	0.3	0.0	0.0	0.0	0.0	0.0	0.0
Used	Redwood	0.0	0.3	0.0	0.0	0.0	0.3	0.0	0.0	0.0	0.3	0.0	0.0	0.0	0.3	0.0	0.0	0.0	0.0	0.0	0.0
Recycled	Softwood	7.2	0.0	0.0	0.0	47.2	0.0	0.0	0.0	47.2	0.0	0.0	0.0	47.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Recycled	Softwood	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Recycled	Softwood	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Recycled	Softwood	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Recycled	Softwood	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Used	Softwood	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Used	Softwood	40.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
% Recycled/Reclaimed Wood		70.9				70.9				70.9				70.9				32.4			

Table 5-5: Component Selection Breakdown for a \$3000 Rebate

Resource type	Species	$\alpha=0.5, \beta=0.5, \gamma=0$				$\alpha=0.4, \beta=0.4, \gamma=0.2$				$\alpha=0.3, \beta=0.3, \gamma=0.4$				$\alpha=0.2, \beta=0.2, \gamma=0.6$				$\alpha=0.1, \beta=0.1, \gamma=0.8$			
		Unit 1	Unit 2	Unit 3	Unit 4	Unit 1	Unit 2	Unit 3	Unit 4	Unit 1	Unit 2	Unit 3	Unit 4	Unit 1	Unit 2	Unit 3	Unit 4	Unit 1	Unit 2	Unit 3	Unit 4
Recycled	Hardwood	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	5.8	5.8
Recycled	Hardwood	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	5.8	5.8
Recycled	Hardwood	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	5.8	5.8
Recycled	Hardwood	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	5.8	5.8
Used	Hardwood	0.0	0.0	39.8	0.0	0.0	0.0	39.8	0.0	0.0	0.0	39.8	0.0	0.0	0.0	39.8	0.0	0.0	0.0	0.0	0.0
New	Hardwood	0.0	0.0	15.7	0.0	0.0	0.0	15.7	0.0	0.0	0.0	15.7	0.0	0.0	0.0	15.7	0.0	0.0	32.3	24.5	0.0
New	Hardwood	0.0	0.0	7	0.0	0.0	0.0	7	0.0	0.0	0.0	7	0.0	0.0	0.0	7	0.0	0.0	3	5	0.0
New	Hardwood	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
New	Hardwood	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Used	Redwood	0.0	37.9	0.0	0.0	0.0	37.9	0.0	0.0	0.0	37.9	0.0	0.0	0.0	37.9	0.0	0.0	0.0	0.0	0.0	0.0
Used	Redwood	0.0	1.3	0.0	0.0	0.0	1.3	0.0	0.0	0.0	1.3	0.0	0.0	0.0	1.3	0.0	0.0	0.0	0.0	0.0	0.0
Used	Redwood	0.0	1.3	0.0	0.0	0.0	1.3	0.0	0.0	0.0	1.3	0.0	0.0	0.0	1.3	0.0	0.0	0.0	0.0	0.0	0.0
Recycled	Softwood	47.2	0.0	0.0	7.8	47.2	0.0	0.0	8	47.2	0.0	0.0	8	47.2	0.0	0.0	8	47.2	47.2	40.6	0.0
Recycled	Softwood	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Recycled	Softwood	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Recycled	Softwood	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Used	Softwood	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Used	Softwood	0.0	0.0	0.0	40.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
% Recycled/Reclaimed Wood		91.8				91.8				91.8				91.8				70.2			

Table 5-6: Component Selection Breakdown for a \$4000 Rebate

Resource type	Species	$\alpha=0.5, \beta=0.5, \gamma=0$				$\alpha=0.4, \beta=0.4, \gamma=0.2$				$\alpha=0.3, \beta=0.3, \gamma=0.4$				$\alpha=0.2, \beta=0.2, \gamma=0.6$				$\alpha=0.1, \beta=0.1, \gamma=0.8$			
		Unit 1	Unit 2	Unit 3	Unit 4	Unit 1	Unit 2	Unit 3	Unit 4	Unit 1	Unit 2	Unit 3	Unit 4	Unit 1	Unit 2	Unit 3	Unit 4	Unit 1	Unit 2	Unit 3	Unit 4
Recycled	Hardwood	2.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Recycled	Hardwood	2.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Recycled	Hardwood	2.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Recycled	Hardwood	2.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Used	Hardwood	39.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
New	Hardwood	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
New	Hardwood	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
New	Hardwood	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
New	Hardwood	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Used	Redwood	0.0	0.0	0.0	36.6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Used	Redwood	0.0	0.0	0.0	5.6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Used	Redwood	0.0	0.0	0.0	5.6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Recycled	Softwood	0.0	0.0	15.6	0.0	10.2	0.0	55.6	34.3	29.6	0.0	36.2	34.3	29.6	0.0	55.6	14.9	10.2	0.0	55.6	34.3
Recycled	Softwood	0.0	0.0	0.0	0.0	8.8	15.9	0.0	6.7	8.8	15.9	0.0	6.7	8.8	15.9	0.0	6.7	18.5	15.9	0.0	6.7
Recycled	Softwood	0.0	0.0	0.0	0.0	8.8	15.9	0.0	6.7	8.8	15.9	0.0	6.7	8.8	15.9	0.0	6.7	18.5	15.9	0.0	6.7
Recycled	Softwood	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Recycled	Softwood	0.0	13.4	0.0	0.0	0.0	8.8	0.0	0.0	0.0	8.8	0.0	0.0	0.0	8.8	0.0	0.0	0.0	8.8	0.0	0.0
Used	Softwood	0.0	27.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Used	Softwood	0.0	0.0	40.0	0.0	19.4	0.0	0.0	0.0	0.0	0.0	19.4	0.0	0.0	0.0	0.0	19.4	0.0	0.0	0.0	0.0
% Recycled/Reclaimed Wood		100.0				100.0				100.0				100.0				100.0			

The study also examined the correlation between the percentage increase in component costs (due to risk aversion or circular component choices) and the size of the rebate increase. The results showed that, initially, increasing rebates led to proportional increases in salvaged component selection. However, the effectiveness of rebates varies depending on the perceived level of risk.

For example, at the point where a 65% increase in component cost is incurred (to accommodate salvaged materials), the resulting rebate differs significantly based on the risk magnitude. In low-risk scenarios (risk magnitude = 0), the rebate reaches approximately \$1200, whereas in high-risk scenarios (risk magnitude = 0.8), the rebate for the same cost increase is closer to \$2700. This demonstrates that higher perceived risk reduces the efficiency of rebates in encouraging salvage use. This pattern is further demonstrated in the results presented in Tables 5-4, 5-5, and 5-6, which show the outcomes of the optimization runs at rebate levels of 2000, 3000, and 4000 respectively. The purpose of presenting the breakdown of component selections for each building unit at these rebate levels was to observe how the selection of resources varied across different risk levels under a set rebate incentive. The outcomes illustrate that rebate incentives tend to promote more sustainable selection strategies, whereas risk on its own often leads to less sustainable outcomes. Together, these two factors help balance the selection process, resulting in solutions that maintain a degree of environmental sustainability while managing risk exposure. For instance, at the \$2000 rebate level, all risk scenarios resulted in a higher selection of new materials across the units. In contrast, at the \$3000 rebate level, there was a noticeable reduction in the use of new materials across all risk levels, with an increased presence of recycled components. By the time the rebate level increased to \$4000, where the incentive was strongest, the selection of new materials was virtually eliminated across all risk levels. Essentially, recycled materials became the dominant choice.

In executing the optimization runs, simulations were conducted in \$100 increments of rebate value to evaluate how varying financial incentives influenced component selection under different levels of perceived risk. It was observed that once the rebate value reached approximately \$4,000, the model consistently selected 100% reclaimed or recycled components, and no further changes in output were detected (Table 5-6). At this point, the

system had effectively reached saturation, and no additional runs were performed beyond this threshold. In total, 215 optimization runs were executed, capturing a diverse range of outcomes across combinations of rebate levels, risk magnitudes, and resource availability. Each iteration yielded a selection of optimized components.

Although, the results provide useful insight into how rebate structures and risk perceptions can shape sustainable sourcing decisions, it is important to note that a more robust model application test would require randomly varying both the availability of wood types and the demand across different building models, aligning with a standard Monte Carlo analysis framework. The current model is best viewed as an exploratory tool to illustrate underlying market mechanisms. For practical implementation in a specific market context, value ranges reflecting local conditions would need to be used to determine realistic and impactful rebate thresholds.

The results provide useful insights into policy design. In this study, rebates were modeled based on the market value of salvaged resources. If a unit incorporates \$1000 worth of reclaimed flooring, the same amount is reimbursed as a rebate. However, other models could link rebates to weight-based targets or specific resource types, such as wood. For example, as seen in the Lambert et al., (2024) The City of Victoria bylaw stated 40 kg of reclaimed wood must be accounted for through a documented salvage or circular plan. This suggests that future models could explore component-specific rebate mechanisms. Similarly, the City of Vancouver's policy combines a mandate for salvaging older housing stock with a fixed refundable charge at the permitting stage. While effective at achieving increased salvage rates, such a policy may not fully support projects operating at smaller scales or with limited reuse potential, an area where flexible, scaled rebate policies may offer more balanced and inclusive solutions. This situation presents an opportunity to utilize a model for evaluating optimal parameters to significantly increase salvage across various projects.

For rebate-based policies to be effective, they must consider the local social perception of salvage resource use. In regions or markets where circular resources are well accepted, smaller rebates can be impactful. Conversely, in risk-averse environments, rebates must be higher and paired with additional interventions, such as mandates, phased requirements, or performance-

based certifications. There are also practical implementation factors that were not captured in this study. Real-world deployment of the rebate policy strategies assessed in this study would involve significant financial and labor considerations. For example, to verify whether projects meet rebate eligibility thresholds, an auditing mechanism would be required, introducing both operational labor demands and administrative costs. These system-level logistics are vital to the success of any incentive-based program and must be considered in future modeling efforts.

A potential solution is to complement governmental strategies with nonprofit or industry-led partnerships. Nonprofit organizations could serve as independent auditing centers to verify salvaged resource usage, thereby enabling access to incentives while reducing the administrative burden on public agencies. This approach presents a promising opportunity for collaboration across sectors and could help streamline implementation by simplifying the compliance process for builders. Exploring such hybrid models could strengthen policy effectiveness and broaden adoption of RCMs in the construction industry.

While this study provides valuable insights into how rebate-based policies influence the selection of RCMs, there remain several important areas for future exploration to build a more holistic understanding of policy effectiveness and real-world applicability. Future research could account for behavioral and social dynamics in decision-making. Factors such as cultural resistance to reused resources, aesthetic preferences, and trust in the quality of salvaged resources can significantly impact component choices. Incorporating behavioral variables or qualitative data through interviews or surveys could reveal additional barriers or motivators influencing adoption.

5.5 Conclusion

In conclusion, the Integrated Material Sourcing (IMS) Framework has proven to be a valuable tool for analyzing how policy incentives like financial rebates can influence sourcing decisions in construction. As expected, the model showed that increasing rebate values led to greater selection of reclaimed and recycled components. However, perceived risk also impacted the influence of rebates, while a rebate of \$1,200 was enough to achieve a 65% reclaimed material selection under low-risk conditions, a much higher rebate of \$2,700 was needed to reach the same outcome under a high-risk condition. The results reveal that rebate-based models can

substantially increase the selection of reclaimed and recycled components, but the effectiveness of the incentive depends heavily on the perceived risk magnitude, suggesting that in environments where risk perception is high, rebates may not be the most effective strategy. In such cases, mandates or stricter regulations may be more appropriate than voluntary incentives. This insight helps support smarter policy design based on actual behavioral responses rather than assumptions about financial motivation alone.

The model focused more on risk in this study, while cost and embodied energy were held at equal weighting. Although all three objectives were considered, fully stress-testing every combination would require substantial computational resources. Still, this work lays a foundation for running more detailed and expansive simulations that examine how different combinations of objectives shift sourcing decisions. It is also important to acknowledge that factors like aesthetics were not included in this study, even though they play a real role in whether reclaimed materials are used. Future work could incorporate those softer, perception-based elements to create a more holistic tool. Also, since risk perception varies across countries and communities, the tool could be adapted to different contexts by incorporating local utility values and preferences. The study concludes that a decision-support system can effectively model both technical and socially driven factors like cost, embodied energy and risk. It also illustrates the value of simulation-based strategies in supporting circular policy design that is realistic and accounts for complex human behavior.

Chapter 6: Research Contribution and Conclusion

6.1 Thesis Summary

There is a disconnect in the uptake of salvaged resources within the construction industry. To address this issue, the study focused on salvaged resources that are collected and sold through Reclaimed Construction Material (RCM) stores, addressing the procurement gaps of RCMs, this thesis investigated the flow of RCMs, how they are stored, and how they are eventually reused. This led to an exploratory study beginning with fieldwork to document the types of resources extracted from buildings and their points of recovery. Using 3D scanning technology, the study captured detailed data about available resources, which were then used to build a comprehensive database. With a clear understanding of available resources, the study then explored their potential integration into new construction projects.

The goal of the study was to develop a method that would allow builders and designers to match their resource needs with components already available within a specific region. The proposed methodology did not mandate the exclusive use of RCMs in a new construction project; it explored a hybrid approach that integrates salvaged components with New Construction Materials (NCMs). By selecting compatible salvaged components, builders can achieve more sustainable outcomes while minimizing performance risks. This led to the development of the Integrated Material Sourcing (IMS) Framework.

The Integrated Material Sourcing (IMS) framework is an adaptable system designed to guide the selection of both NCMs and RCMs for specific construction projects. The framework is designed to match the supply of salvaged components with demand in active construction projects. It allows users to assess whether available RCMs can supplement NCMs, thereby reducing reliance on virgin resources and supporting circular material flows. It is structured to integrate data across the real environment, the model environment, and a core optimization engine.

- The real environment refers to inputs from salvage stores and storage sites where RCMs are located.
- The model environment reflects the design of the proposed new building or structure.

- The core engine integrates data from these two environments and performs optimization based on factors such as embodied carbon, transportation costs, and monetary cost.

The application of the IMS framework in this study has shown to be a valuable tool for supplementing NCMs with RCMs. As discussed in Chapter 3, for the window and door procurement, the framework recommended a mix of approximately 65% NCMs and 35% RCMs within the developed building model. The IMS framework was validated through a secondary use case involving flooring materials, where it incorporated perceived risk factors and rebate-based incentives to simulate real-world policy mechanisms. The results demonstrated the adaptability of the IMS model and its potential to inform policy as a decision-support tool for construction stakeholders. This study presents a fresh perspective on the efficient integration of RCMs on a greater scope, whereby the material functioning as part of an entire building or capital asset is assessed for its overall value to the structure before implementation.

As the development and implementation of the IMS framework evolved, a new opportunity emerged, extending the life of materials already in buildings, especially in cases where performance issues lead to premature removal. This insight led to the development of the Assembly Restoration Framework (ARF). ARF identifies opportunities for upgrading or partially restoring building assemblies rather than fully replacing them. ARF highlights that many building assemblies, such as windows, floors, and wall systems, can be deconstructed into salvageable components. For instance, window assemblies may be broken down into frames and glass panes, while floor systems can be separated into wooden slats and subfloors. ARF focuses on identifying opportunities for partial restoration or upgrades of building assemblies, rather than full replacement. The research explored windows as a primary example due to their composite nature (glass panes, frames, spacers, etc.) and the potential to improve thermal performance through methods like selective part replacement or the application of low-emissivity films. This framework helps assess whether replacement, refurbishment, or partial intervention is the most sustainable strategy, both in terms of embodied and operational energy.

The ARF framework mathematically models these restoration strategies for windows. It assesses both performance and embodied energy to identify viable reuse options. Through this modeling, the study explored nine potential restoration strategies and applied four in detail:

- Full replacement, where both the window frame and glass pane are replaced.
- Partial replacement, which involves replacing the glass panes while reusing the original frame.
- Partial refurbishment, where the frame is reused and the glass panes are refurbished.
- Direct reuse, which entails reusing both the frame and glass panes as-is.

The model helped identify the restoration options that could balance operational performance with embodied energy. The most promising opportunities lay between partial replacement and partial refurbishment, approaches that avoid the downsides of both extremes. On one end, direct reuse might lead to higher operational inefficiencies, while full replacement, although improving performance, results in greater resource consumption. Focusing on strategies like partial replacement and partial refurbishment provides a middle ground, where resources are not entirely discarded but restored and reintegrated, offering a more sustainable path forward.

In summary, the thesis expands our understanding of how to use tools and technologies to support procurement strategies for RCMs. It shows that it is both feasible and beneficial to integrate RCMs into new construction projects, thus contributing to the body of knowledge on procurement strategies for RCMs. It not only uses advanced tools and optimization techniques but also proposes actionable frameworks for integrating real-world and model data.

6.2 Limitations and Future Work

While this study identifies opportunities for improving the use of RCMs in new builds, it also highlights several limitations and areas for future research. One major limitation is the lack of infrastructure to support deconstruction within the construction industry. As global development accelerates in both developed and developing regions, the volume of construction waste grows. Yet, without systems in place to facilitate material recovery, valuable resources continue to exit the circular stream prematurely.

Despite these findings, key limitations remain in assessing the environmental impacts of material choices. As the Environmental Product Declaration (EPD) system continues to develop, and as life cycle assessment (LCA) tools evolve, particularly in the estimation of embodied energy, challenges remain. During the course of this study, it became evident that LCA methods and embodied energy calculation strategies vary significantly across tools. These differences arise from variations in how each tool defines system boundaries and which life cycle stages are considered. Life cycle inventories also contribute heavily to the inconsistencies in reported data. Moreover, regional differences in resource availability, production methods, and systems in place further complicate the reliability of comparative assessments. A general lack of transparency in resource data also remains a barrier. As discussed in Chapter 4, it would be highly beneficial to have a more unified system, one where the embodied energy of each component is clearly displayed on the manufacturer's label. This would significantly streamline procurement decisions and enable clearer comparisons between components based on their environmental impact. This study only addresses a fraction of the complex challenges surrounding construction waste. Site visits to various RCM stores exposed several systemic issues in reverse logistics. While these stores do not represent the full reuse and recovery supply chain, they offer insight into critical market gaps.

Quality Assurance: One significant challenge is the lack of standardized quality assurance procedures. Although widely discussed in the literature, quality assurance remains under-addressed in terms of practical implementation and standardization. However, the framework designed in this thesis offers a foundation for integrating quality assurance related data, such as mechanical properties (e.g., compressive strength, tensile capacity, fatigue behavior), to support decision-making.

Inventory Management: Poor inventory management further limits the use of RCMs. Most stores manage resources manually or with ad hoc systems, lacking any standardized practices. Addressing this issue will require integration of construction knowledge, systems development, and management strategies to track the flow of resources.

Procurement Challenges: This research partially addresses procurement inefficiencies by allowing RCMs to be sourced alongside NCMs. This dual-sourcing strategy improves the viability

of RCMs by reducing the risk associated with relying solely on secondhand components and enhancing the market appeal of RCMs. However, much more work remains to develop scalable procurement processes for widespread adoption.

Supply Constraints: Another gap is the unreliable supply of reclaimed resources. The current flow of materials into RCM stores is sparse and unregulated. Predictive modeling of the existing housing stock could help anticipate future availability, identify salvageable materials, and optimize routing toward reuse or resale.

Low Visibility of Resources: Although this study employs 3D scanning to capture and digitally replicate components, allowing for their optimized use, more needs to be done. An open, centralized platform is needed to map, classify, and display RCMs. This platform would provide key metadata (e.g., location, dimensions, condition) and improve accessibility for designers and contractors.

Finally, the fundamental structure of the frameworks developed in this thesis offers a platform to incorporate additional criteria that contribute to the reusability and successful integration of RCMs. As discussed in this study, the frameworks are suitable for the simultaneous sourcing of NCMs and RCMs for construction projects, promoting sustainable practices while meeting building standards and cost considerations. While this study primarily examined optimal selection, it is essential to account for additional factors such as projected lifespan and structural capacity. Therefore, adaptive models that compare components with complex characteristics should be considered when evaluating RCMs.

As new construction methods, such as modular systems, develop, the availability of highly reusable materials is anticipated to increase. Future work should focus on creating accessible, comprehensive information networks so that RCMs can be easily assessed for viability in new projects using the underlying frameworks developed in this thesis.

6.3 Concluding Remarks

This thesis concludes that integrating RCMs into new builds requires more than robust frameworks; it also demands infrastructural support, industry collaboration, and tools that improve visibility and access to salvage materials. The frameworks developed in this thesis are

built on real-world data, are adaptable to different use cases, and exemplify ongoing progress toward fully integrated systems that support RCM procurement. Currently, the RCM supply chain remains fragmented, and although a few organizations have successfully completed projects using RCMs, it remains a marginal practice. The Integrated Material Sourcing (IMS) framework and the Assembly Restoration Framework (ARF) developed through this research demonstrate that hybrid procurement of resources can be viable and meet performance, cost, and sustainability objectives.

The research emphasizes the value of real-world data. Canvassing the RCM stores provided insight into the types of RCMs being recovered, their availability, and the practical barriers to reuse. This information shaped both the problem definition and the model development. The study also demonstrated how integrating technologies such as 3D scanning, Building Information Modeling (BIM), Life Cycle Assessment (LCA), and Optimization Programming Language (OPL) can support circular decision-making. These technologies allowed for the parsing and linking of data across platforms to match available RCMs with design needs. This process provides a glimpse into the future potential of intelligent sourcing tools that recommend salvage components as supplements to new material procurement. The frameworks developed in this research represent early steps toward that possibility.

However, several limitations remain. There is no standardized platform for tracking the environmental performance or reuse potential of salvaged resources. Much of this data must be extracted from separate tools and methods, often requiring expertise and time. A more seamless process would involve attaching performance metadata to salvaged components, making them easier to assess and select. Another challenge is the maturity of materials being diverted from buildings. Many components do not reach RCM stores and instead end up in landfills. Low diversion rates limit both the available inventory and the potential for optimization. Even when salvaged resources do reach RCM stores, visibility remains a barrier. Some warehouses have significant inventory but limited means of cataloging or presenting it for potential reuse. In addition, storage and operational costs remain high, making it difficult for smaller organizations to scale reuse efforts.

Policy remains a critical lever. The rebate-based policy assessment discussed in Chapter 5 explored how financial incentives influence material selection. While current policy often targets landfill diversion, less attention is paid to incentivizing the actual reintegration of RCMs into new construction. Mandates or incentives must evolve to support downstream processes, including resource matching, component validation, and procurement. There is also limited policy support for developing platforms that support these activities. Greater collaboration between government and salvage centers could improve quality assurance practices and help inform standards for integrating salvaged materials into design and construction workflows.

Future research should explore how to better support reuse centers through technology, funding, and policy partnerships. Tools must be developed to assess component maturity, identify reuse potential at scale, and make this information readily available to designers and builders. Governmental platforms that encourage the use of validated RCMs, with performance-based guidelines and quality assurance systems, will be essential. Beyond the technical contributions, the most impactful insights came from engaging directly with people in the field. Speaking with staff at stores like Timeless Materials and Habitat for Humanity ReStore revealed the human dimensions of reuse: logistical challenges, value judgments, local knowledge, and informal systems that enable salvage to function. These experiences emphasized the importance of social factors in shaping reuse culture and highlighted the need to address reverse logistics from both technical and human perspectives.

As a researcher, this journey has contributed to both my technical and interpersonal growth. It has shown me that solving real-world problems depends not only on data and frameworks but also on meaningful engagement with stakeholders. The scope of circularity in construction is vast. While this research touches on one part of that landscape, it makes clear that reuse is a global issue with multiple layers, including material behavior, lifecycle data, tool integration, and cultural acceptance. The unbuilding process, for example, remains poorly understood and under-researched, yet it holds major potential for shaping salvage practices. If I were to start this research again, I would not take a different approach. Field engagement grounded the work in practical insights and helped define the real-world challenges. However, I would extend the study to new regions, recognizing that attitudes toward reuse vary significantly across contexts. The adaptability of the frameworks means they can be replicated in different cities or countries,

each revealing different constraints and opportunities. This realization is humbling and motivating.

Ultimately, this research has contributed meaningfully to the advancement of circular construction strategies on a global scale. As material inventories continue to grow and environmental pressures intensify, the need for intelligent, flexible, and people-centered reuse systems become urgent.

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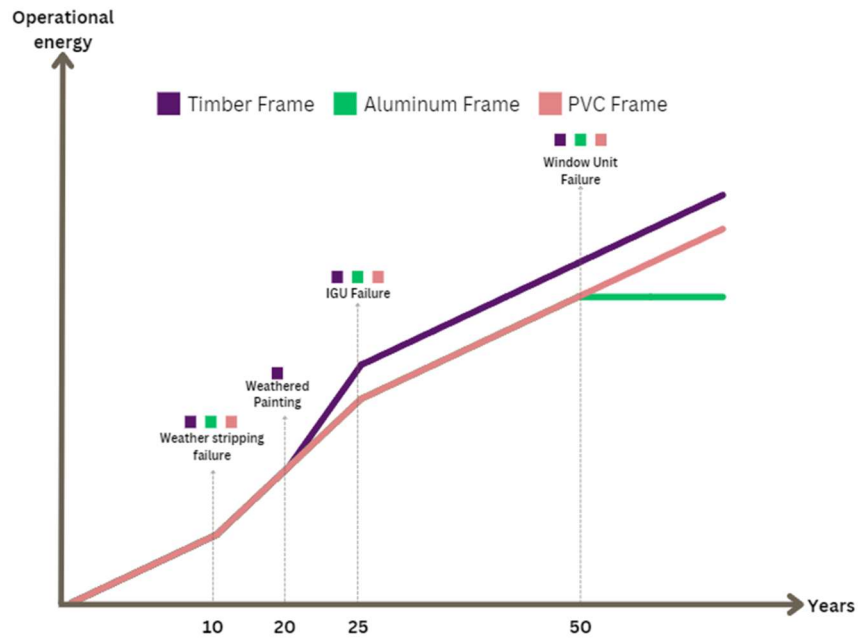
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Appendix A: Building assemblies' list

BUILDING COMPONENT	ASSEMBLIES	MATERIALS
WALLS	Interior Walls (Partitions)	Drywall, insulation, studs, and finishings.
	Exterior Walls	Structural framing, insulation, vapor barriers, sheathing, cladding, and finishes.
	Masonry Walls	Bricks, mortar, ties, reinforcing steel, and sometimes insulation and cladding layers.
FLOORS	Subfloor Assemblies	Floor joists, subfloor panels, and underlayment.
	Finished Floor Assemblies	Underlayment, adhesives, and finished material (tile, hardwood, carpet).
	Concrete Slab Floors	Reinforcing steel, vapor barriers, insulation, and finishing materials.
WINDOWS	Window Assemblies	Glazing, frame, sealants, spacer and weatherstripping.
	Curtain Wall Assemblies	Multiple panes, aluminum frames, spacers, sealants, and cladding.
DOORS	Exterior Door Assemblies	Door leaf, hinges, lockset, weatherstripping, frame, and threshold.
	Interior Door Assemblies	Door leaf, hinges, lockset or latch, and door frame.
STAIRS AND RAMPS CEILINGS	Stair Assemblies	Treads, risers, stringers, landings, handrails, and guardrails.
	Ramp Assemblies	Ramp surface, supporting, structure, handrails, and guardrails.
	Drop Ceiling Assemblies	Ceiling tiles, suspension grids, lighting fixtures, and acoustic insulation.
	Drywall Ceiling Assemblies	Drywall, furring strips, and finish coatings.

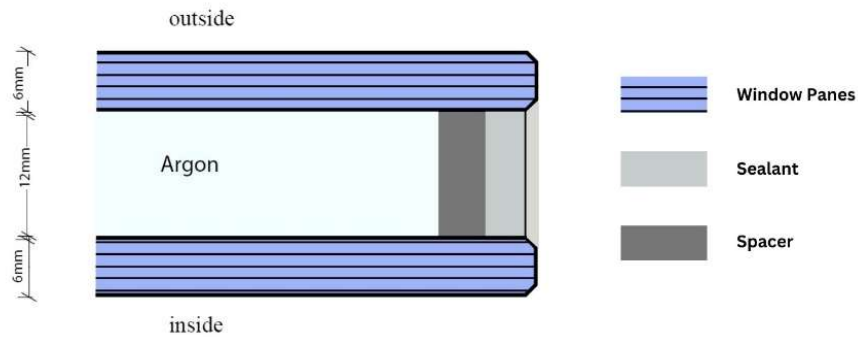
Appendix B: Deterioration of Timber, Aluminium and PVC Frames



Appendix C: Product life cycle stages

Product Stage (A1-A3)	Construction process stage (A4-A5)	Use Stage (B1-B7)	End of life Stage (C1-C4)	End of Life Stage (D)
A1. Raw material supply	A4. Transport	B1. Use	C1. De-construction demolition	Reuse, Recovery, and Recycling
A2. Transport	A5. Construction installation process	B2. Maintenance	C2. Transport	
A3. Manufacturing		B3. Repair	C3. Waste processing	
		B4. Replacement	C4. Disposal	
		B5. Refurbishment		
		B6. Operational energy use		
		B7. Operational water use		

Appendix D: Cross-section of the window unit



Appendix E: Product data for Window

7/3/24, 11:55 AM

JELD-WEN 71.5 in. x 59.5 in. V-4500 Bay Vinyl Window THDJW244000003 - The Home Depot

Product Depth (in.)	4.563 in
Product Height (in.)	59.5 in
Product Width (in.)	71.5 in
Rough Opening Height (in.)	60 in
Rough Opening Width (in.)	72 in
Width (in.) x Height (in.)	71.5 x 59.5

Details

Exterior Color/ Finish	White
Exterior Color/Finish Family	White
Features	Insect Screen, Integrated Nail Fin
Frame Material	Vinyl
Frame Type	Nail Fin
Glass Type	Low-E Glass
Glazing Type	Double-Pane
Grid Pattern	No Grid
Grille Type	No Grille
Hardware Color/Finish Family	White
Included	Grid, Screen
Interior Color/Finish Family	White
Lock Type	Lift Handle
Number of Grids	No Grid
Number of Locks	1
Product Weight (lb.)	132.41 lb
Returnable	90-Day
Solar Heat Gain Coefficient	0.33
U-Factor	0.33
Window Type	Other
Window Use Type	New Construction

Feedback

Warranty / Certifications

Energy Star Qualified	North-Central, Northern, South-Central, Southern
Manufacturer Warranty	Lifetime Limited

Appendix F: Product data for weather stripping

Specifications

Dimensions

Assembled Depth (in inches)	81	Assembled Height (in inches)	0.5
Assembled Weight (in lbs)	0.19	Assembled Width (in inches)	1.13
Packaged Depth (in inches)	81	Packaged Height (in inches)	0.5
Packaged Weight (in lbs)	0.19	Packaged Width (in inches)	1.12

Details

Application	Window	Colour	White
Country of Origin	US-United States	Length	81
Material	Vinyl		

Appendix G: EPD for low E film

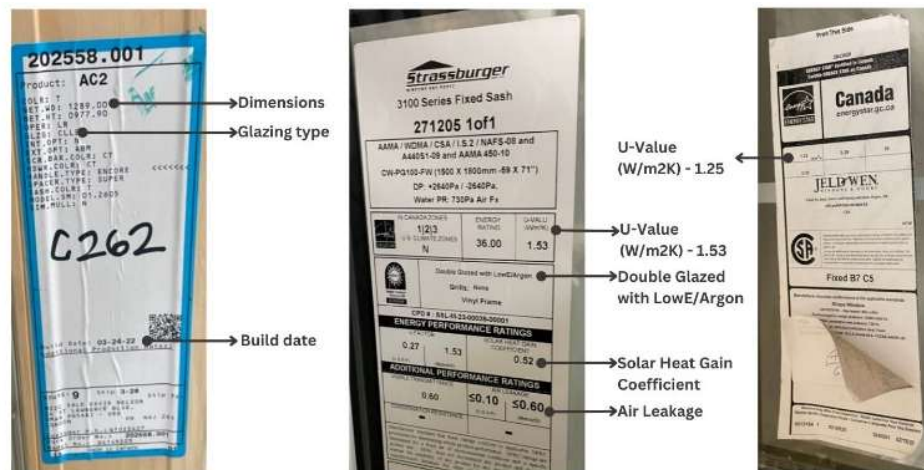
	Impacts Indicators	Product stage	Construction stage		Use stage							End of life stage				Reuse, Recovery Recycling
		A1 / A2 / A3	A4 Transport	A5 Installation	B1 Use	B2 Maintenance	B3 Repair	B4 Replacement	B5 Refurbishment	B6 Operational energy use	B7 Operational water use	C1 Deconstruction / demolition	C2 Transport	C3 Waste processing	C4 Disposal	D Reuse, recovery, recycling
	Climate Change [kg CO ₂ eq.]	5.63E+00	2.15E-01	3.31E-01	0	0	0	0	0	0	0	4.00E-04	1.20E-03	6.80E-03	1.31E-01	-1.32E-01
	Climate Change (fossil) [kg CO ₂ eq.]	5.63E+00	2.15E-01	3.07E-01	0	0	0	0	0	0	0	4.00E-04	1.20E-03	5.20E-03	1.31E-01	-1.31E-01
	Climate Change (biogenic) [kg CO ₂ eq.]	-9.20E-03	6.86E-05	1.70E-02	0	0	0	0	0	0	0	2.58E-06	5.36E-07	1.60E-03	7.49E-06	-1.00E-04
	Climate Change (land use change) [kg CO ₂ eq.]	1.90E-03	4.14E-05	7.30E-03	0	0	0	0	0	0	0	5.65E-07	4.44E-07	5.78E-06	7.37E-07	-4.36E-05
	Ozone depletion [kg CFC-11 eq.]	1.05E-06	4.80E-08	5.60E-08	0	0	0	0	0	0	0	2.50E-11	2.56E-10	6.55E-10	3.73E-10	-8.51E-09
	Acidification terrestrial and freshwater [Mole of H ⁺ eq.]	5.61E-02	1.50E+03	3.00E+03	0	0	0	0	0	0	0	1.79E-06	6.74E-06	2.63E-05	3.08E-05	-4.00E-04
	Eutrophication freshwater [kg P eq.]	1.84E-02	9.45E-07	9.00E-04	0	0	0	0	0	0	0	2.59E-08	1.17E-08	1.43E-07	2.92E-08	-2.28E-06
	Eutrophication freshwater [kg (PO ₄) ₃ eq.]	1.85E-02	2.90E-06	2.76E-03	0	0	0	0	0	0	0	7.94E-08	3.60E-08	4.39E-07	8.97E-08	-7.00E-06
	Eutrophication marine [kg N eq.]	2.08E-02	5.00E-04	1.10E-03	0	0	0	0	0	0	0	2.57E-07	2.38E-06	8.82E-06	2.29E-05	-7.39E-05
	Eutrophication terrestrial [Mole of N eq.]	2.42E-01	5.40E-03	1.27E-02	0	0	0	0	0	0	0	2.90E-06	2.62E-05	7.80E-05	1.00E-04	-8.00E-04
	Photochemical ozone formation - human health [kg NMVOC eq.]	5.71E-02	1.40E+03	3.00E+03	0	0	0	0	0	0	0	8.31E-07	7.47E-06	2.56E-05	3.89E-05	-3.00E-04
	Resource use, mineral and metals [kg Sb eq.] ¹	1.46E-02	1.76E+06	7.00E+04	0	0	0	0	0	0	0	1.09E-08	2.94E-08	1.07E-07	2.82E-08	-1.31E-06
	Resource use, energy carriers [MJ] ¹	9.09E+01	3.06E+00	4.78E+00	0	0	0	0	0	0	0	5.90E-03	1.78E-02	9.14E-02	3.50E-02	-2.61E+00
	Water scarcity [m ³ world equiv.] ¹	1.55E+00	7.80E-03	1.48E+01	0	0	0	0	0	0	0	4.33E-02	9.17E-05	1.60E-03	8.00E-04	-4.08E+02

¹ The results of this environmental impact indicator shall be used with care as the uncertainties of these results are high or as there is limited experience with the indicator.

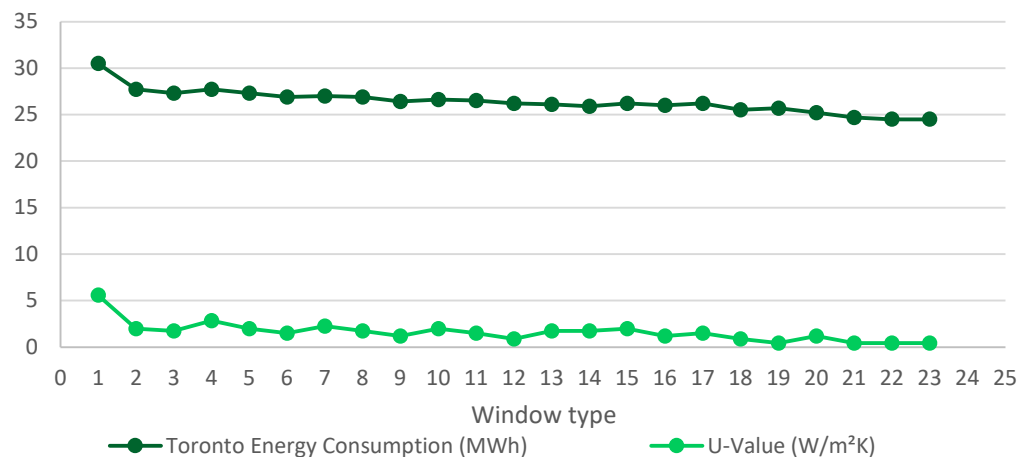
Appendix H: shows images from both Timeless and the Habitat ReStore.



Appendix I: Displays the labels found at the Habitat ReStores.



Appendix J: Window energy performance for Toronto.



Window energy performance for Toronto (RDH Building Engineering Ltd, 2013)