A Decision-Making Framework for the Built Facilities' End-of-Life from Sustainability and Circular Economy Viewpoints

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Abstract for Masters

A Decision-Making Framework for the Built Facilities' End-of-Life from Sustainability and Circular Viewpoints

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The construction industry generates over a third of global waste, most of which is produced at the End-of-Life (EoL) stage of built facilities and disposed of in landfills. Existing decision-making models often focus on a limited range of EoL decisions and lack stakeholder diversity, leading to biased outcomes. This study develops an inclusive decision-making model for the EoL stage. It defines a framework of four EoL sub-phases, related decision problems, and alternatives based on a systematic literature review. A set of 25 criteria was compiled, validated through interviews with 25 stakeholders, and weighted using an Analytical Hierarchical Process (AHP) survey with 52 participants. The model was tested on a two-story, 59,360 SF resort facility in Ontario using data from reports, government sources, quantitative tools, and industry partners. Four scenarios were analyzed: Full Deconstruction, Partial Deconstruction, Full Demolition with landfill disposal, and Full Demolition with recycling. Full Deconstruction emerged as the optimal solution, outperforming Full Demolition with landfill disposal by ~40%. Regulations were identified as the most critical factor, followed by Environmental aspects, ranking higher than Economics—contrary to prior studies. These findings highlight the vital role of government regulations in driving sustainable practices. The resulting model provides robust guidance for decision-makers, addressing EoL complexities and promoting sustainability and circularity in the construction industry.

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Dedication

To my family, whose unwavering support and encouragement have been the foundation of all my achievements. Your sacrifices, love, and belief in me have been my greatest strength.

To my husband, for your endless patience, understanding, and motivation during this journey. Your presence by my side has been my anchor and my inspiration.

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Finally, to all those who strive for a more sustainable and equitable world, may this work contribute to the progress we all hope to see.

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List of Abbreviations

Abbreviation	**Description**
EoL	End-of-Life
AHP	Analytic Hierarchy Process
GHG	Greenhouse Gasses
CE	Circular Economy
CDW	Construction and Demolition Waste
MCDM	Multi-Criteria Decision-Making
LCA	Life Cycle Assessment
CI	Circular Index
BIM	Building Information Model
CR	Consistency Ratio
GTA	Great Toronto Area
OAT	One-at-a-time
GWP	Global Warming Potential

Chapter 1. Introduction

1.1 Motivation and Background

The construction industry has a substantial and far-reaching impact on the environment. Construction and building maintenance emissions together are responsible for about 39% of total global greenhouse gas (GHG) emissions (UN environment programme 2020) and nearly 35% of all waste in landfills around the globe (UN environment programme 2020). This impact is particularly acute in the EoL phase when building materials (and components) are mainly discarded and end up as waste (Purchase et al. 2022). Building entirely new buildings is oftentimes preferred to retrofit and material reuse, leading to significant resource extraction and energy consumption (Hu 2021). Moreover, the construction industry is the largest consumer of virgin materials (Orenga Panizza and Nik-Bakht 2024). The extraction of these non-renewable raw materials is resource-intensive. It consumes a substantial amount of water and energy, is associated with the polluting of air, soil, and water, and is further exacerbating climate change (Orenga Panizza and Nik-Bakht 2024). The impact of construction on the environment is massive and will continue increasing as more buildings and infrastructure are built for populations growing and/or forced to relocate as a result of climate disasters (Gomes et al. 2023).

In Canada, the construction industry is responsible for nearly 40% of material extraction (Allam and Nik-Bakht 2024). Unfortunately, these materials often become waste sooner than expected during the construction, renovation, and EoL stages. For instance, in 2010, the Canadian Construction and Demolition Waste (CDW) sector generated over 4 million tons of waste, with only 16% being diverted from landfills (CCME, 2019.). Most of those impacts can be attributed to the EoL stage, which contributes to more than half of the construction industry's waste streams (Akanbi et al. 2018). The impacts of the construction industry are not restricted to the environment but also affect the people and communities around EoL construction activities. Foremost among these impacts are health and safety concerns, as EoL construction activities may cause hazardous material exposure and noise pollution, which can lead to adverse health effects for both workers and residents (Cook et al. 2022; Purchase et al. 2022).

Addressing problems with the EoL stage of construction projects requires careful consideration of the two primary practices: demolition and deconstruction. Demolition involves the destruction of buildings with little consideration of material recovery, resulting in most waste being landfilled (Akinade et al. 2015). Unlike demolition, deconstruction involves the careful disassembly of buildings to recover materials for reuse, recycling, or repurposing (Akinade et al. 2015). Deconstruction not only reduces the volume of waste sent to landfills but also supports the principles of a Circular Economy (CE) by extending the lifecycle of building materials (Akinade et al. 2015).

In a linear construction model, buildings and infrastructure are constructed, used, and often demolished and disposed of (take-make-dispose) (Anastasiades et al. 2020). In contrast, CE in construction emphasizes preserving the value and extending the useful life of materials and structures (Nadazdi et al. 2022; Guerra and Leite 2021). To transform linear systems into circular ones, strategies such as deconstruction or partial deconstruction are needed to increase the reusability of materials and components (Allam and Nik-Bakht 2023a).

While CE may appear to be a solution to many waste management problems, its precise definition can be ambiguous (Velenturf and Purnell 2021). According to Velenturf & Purnell, 2021, CE should encompass more than just efforts to minimize resource exploitation and waste production (Velenturf and Purnell 2021). Environmentally, circular construction has the potential to minimize resource extraction, reduce waste generation, and lower GHG emissions by extending the life of assets and materials (Liu et al. 2021). Socially, it can lead to safer and healthier work environments, create job opportunities in refurbishment and material recovery, and engage local communities in more sustainable and collaborative construction practices (Purchase et al. 2022). In essence, circular construction represents a transformative paradigm that not only aligns with sustainability goals but also offers solutions to pressing environmental and social challenges within the construction industry. Therefore, effective decision-making is crucial to moving toward CE practices and enacting these changes in a sustainable way (Gomes et al. 2023).

A structured decision-making framework can help to standardize the process of evaluating and selecting the most appropriate EoL option for a given structure. The frameworks typically include a systematic evaluation of various factors such as economic, environmental, and social impacts, as well as the technical feasibility of different options. Using a structured framework can ensure that all relevant factors are considered and that decisions are made transparently and consistently. In addition, a structured framework can encourage the use of more environmentally friendly methods of demolition and disposal, enhancing CE (Gomes et al. 2023).

1.2 Problem Statement

The adoption of CE practices faces several barriers. Among those barriers, a prominent obstacle is the challenge of achieving a comprehensive understanding of the associated benefits and costs when comparing circular and linear systems (Ghisellini, Ripa, and Ulgiati 2018). In the pursuit of a more sustainable building industry, various decision-making frameworks and scoring systems have been proposed in research and practice. However, these approaches have mainly focused on the building design phase (Bueno et al. 2018; Hu 2019). They do not consider the full life cycle impacts, in particular, the EoL stage of materials, assets, or entire facilities. While green building design solutions are fundamental for sustainability improvement, the failure to account for long-term aspects like retrofitting, renovation, and potential demolition results in the oversight of significant EoL impacts. To incorporate the full EoL stage into this structured framework, it is crucial to understand the main struggles in the EoL stage, potential alternatives, and criteria that can incorporate sustainability to this decision process.

Additionally, these frameworks often inadequately address the challenge by omitting potential impacts, particularly social factors, and neglecting the inclusion of relevant stakeholders and affected individuals in decision-making processes (Gomes et al. 2023; Velenturf and Purnell 2021). This limitation can result in biased assessments and unreasonable recommendations, hindering the industry from making informed decisions that align with CE principles (Quéheille et al. 2022; Esther Aigwi et al. 2019). The inclusion of a wide range of stakeholders such as designers, contractors, owners, recycling and landfill facilities, demolition companies, and government representatives is needed (Gerding et al. 2021; Gomes et al. 2023). The introduction of those participants is crucial to successfully implementing sustainable CE since they are part of and responsible for the current linear status quo (Gomes et al. 2023).

Despite its substantial potential to address sustainability challenges, the decision-making process is still required. It is crucial to realize that a complete deconstruction and material reuse may not always be the optimal or practical solution for a built facility (Allam and Nik-Bakht 2024). Accordingly, the assumption that every building should be deconstructed instead of demolished is not universally accurate (Ghisellini et al. 2018). This decision should be made case by case, considering the best outcome regarding sustainability.

The current practice lacks a standardized and widely accepted framework that addresses the multiple stages of the EoL process in construction. Thus, there is a need for a framework that covers different decision problems and includes a diverse set of criteria. To achieve this, a structured decision-making framework is essential to help stakeholders make informative decisions throughout the EoL stage. Such frameworks should systematically evaluate economic, environmental, social impacts, and technical feasibility evaluated by multiple participants involved at the EoL stage.

1.3 Objectives

The primary goal of this study is to develop a Multi-Criteria Decision-Making (MCDM) model for the EoL stage of built facilities and incorporate input from a diverse range of stakeholders. This research aims to identify and articulate relevant attributes or criteria and evaluate available alternatives throughout the entire EoL stage. A key focus of the study is to incorporate comprehensive input from a diverse range of stakeholders and users across the construction industry. By doing so, the research seeks to provide owners and decision-makers with robust tools to make more informed, sustainable, and circular decisions during the EoL stage.

The model is designed to highlight and prioritize the most impactful decisions, reflecting the realities of the industry through the direct input of its participants. By integrating economic, environmental, social, and technical factors, and assigning community-driven weights to each, this study aims to offer a nuanced framework for decision-making that facilitates clearer evaluation of alternatives and supports a balanced approach to sustainability.

To achieve this overarching goal, the Research Objectives (RO) of this study are defined as:

- *Research Objective #1 (RO 1):* Identify key challenges and decision problems that need to be addressed during the EoL stage of built facilities through an extensive literature review.
- *Research Objective #2 (RO 2):* Develop a hierarchical tree of criteria that govern decision-making desirability by synthesizing insights from prior studies and incorporating input

from stakeholders. Stakeholder semi-structured interviews will validate this hierarchical structure to ensure its relevance and accuracy.

- *Research Objective #3 (RO 3):* Design and implement an online survey to collect and aggregate weights for each criterion, incorporating feedback from a diverse range of stakeholders and the broader community. The survey will be used to prioritize criteria based on the collective input of various participants.
- *Research Objective #4 (RO 4):* Evaluate the model's feasibility and effectiveness by applying it to a real-world Canadian construction project. This case study will test the model's practical application and assess its performance in a specific context.

1.4 Organization of the Thesis

Following the overview of the research's motivation, existing problems, and objectives provided in this chapter, the document is organized as follows: Chapter 2 presents the literature review; Chapter 3 introduces and explains the research methods of the model development; Chapter 4 details the results of the model development including the semi-structured interview and online survey; Chapter 5 covers the methods of model evaluation and case study; Chapter 6 presents the discussion and findings of the model evaluation process; and Chapter 7 concludes with final remarks.

Chapter 2. Literature Review

2.1 Main challenges at the EoL Stage

As this study aims to promote more sustainable and circular outcomes for built facilities, this section investigates the major challenges and considerations associated with the EoL stage. It reviews key decision problems and factors that impact the transition towards sustainable and circular practices in the management of built assets.

2.1.1 EoL Challenges

To initiate this research, a literature review was conducted to understand the main decision problems associated with the EoL stage of built facilities. While significant attention has been given to EoL considerations during the design phase, an area that is indeed crucial and worthy of focus, there remains a substantial gap concerning existing facilities. These structures, which did not benefit from early EoL planning, face unique challenges that require targeted solutions.

Recent studies have acknowledged the need for decision-making frameworks in addressing EoL challenges (Allam and Nik-Bakht 2023; Allam and Nik-Bakht 2023b; Allam et al. 2023; Panizza and Nik-Bakht 2024). However, many decision problems, such as whether to demolish or deconstruct a building, are often treated as separate issues. Some studies focus solely on deconstruction, demolition, or renovation decisions (Iodice et al. 2021; Abruzzini and Abrishami 2021; Baker et al. 2017) , while others concentrate on material disposal options like reuse, recycling, or landfilling (Nadazdi et al. 2022; Ding et al. 2018; Khoshand et al. 2020). It is crucial to approach all EoL decisions holistically rather than isolating specific aspects. Additional decisions, including facility selection, sorting systems, and material-level disposal options, also play an important role in circularity assessments (Hossain et al. 2017).

2.1.2 Literature Review Structure

A systematic literature analysis was conducted to establish a holistic set of related decision-making criteria, independent of the approach. Two databases, namely Google Scholar and Engineering Village, were used to screen pertinent studies. The search process involved predefined keywords such as “Circular economy”, “end-of-life”, “decision problems”, “construction”, “Life Cycle Assessment (LCA)”, “MCDM”, “Circularity Index (CI)”, “demolition”, “deconstruction”, "environmental", "social", and "regulations". This screening resulted in over 100 papers. Figure 1 illustrates the described process using a systematic approach.

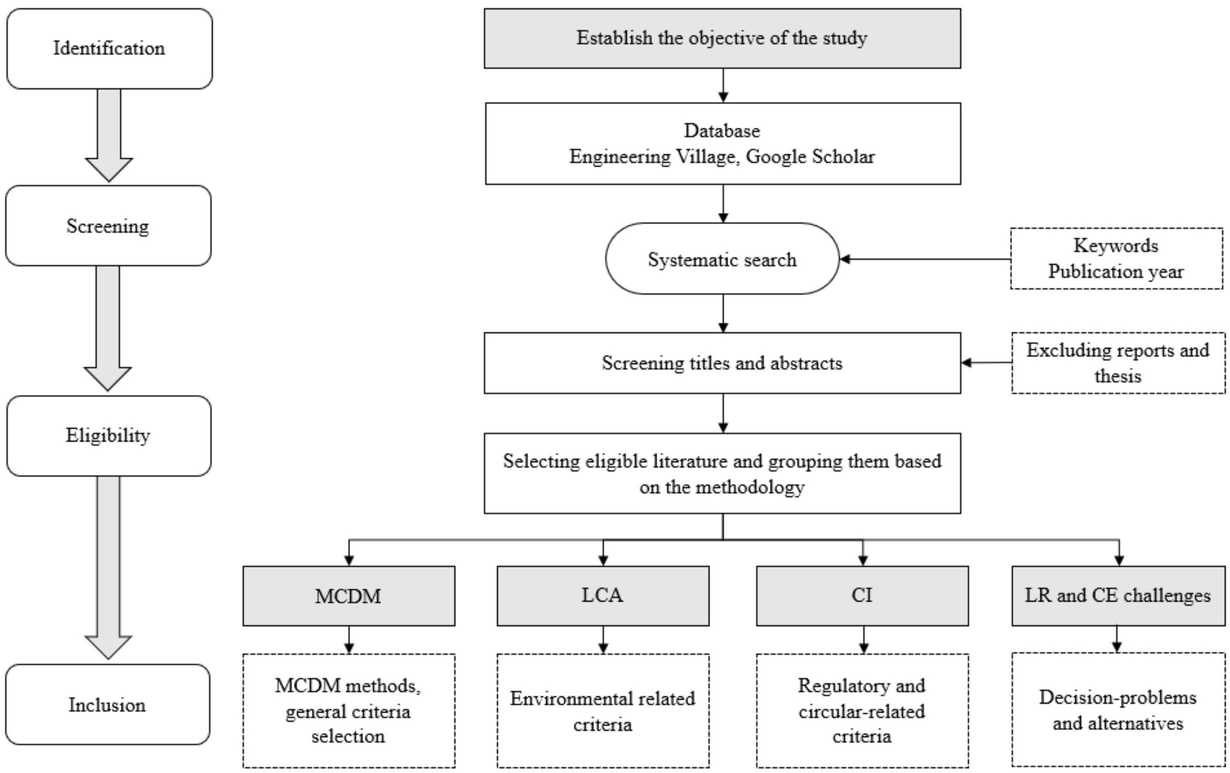


Figure 1 Literature Analysis Structure. Filtering, screening, and Selection

2.1.3 Construction Phase

To identify the main issues that can influence decision-making for a built facility, the author first identifies the process through the construction phases and, in more detail, the sub-phases of the EoL. The construction process is divided into 17 stages which are separated into 5 main groups (Serrano and Álvarez 2016; Abouhamad and Abu-Hamd 2021). A1-A3 covers the product stage, which includes raw material extraction, transportation, and manufacturing. A4-A5 pertains to the construction phase, encompassing the transport of materials and their installation on site. B1-B7 represents the use phase, involving the operational activities of the facility. C1-C4 corresponds to the EoL stage, addressing the facility's decommissioning, demolition, and post-use management. D includes external benefits and impacts beyond the system boundaries, such as reuse, recycling, and other sustainability considerations (Abouhamad and Abu-Hamd 2021).

The scope of this study falls within the C4 phase consisting of four EoL sub-phases as identified in the literature: (1) deconstruction/demolition, (2) transport, (3) waste processing, and (4) disposal (Vilches et al. 2017; Serrano and Álvarez 2016; Abouhamad and Abu-Hamd 2021). The Deconstruction/Demolition sub-phase involves the systematic dismantling or tearing down of the facility with deconstruction focused on carefully salvaging valuable materials and demolition on the more aggressive removal of the structure. In the Transport sub-phase, materials and waste are moved from the site to recycling centers, transfer stations, or other processing locations, ensuring efficient and safe handling. The Waste Processing sub-phase encompasses the sorting and preparation of materials for recycling, reuse, or energy recovery, aiming to maximize material recovery and reduce landfill waste. Finally, the Disposal sub-phase involves the responsible handling of non-recoverable waste, including the safe disposal of materials in landfills or through other approved methods to minimize environmental impact.

2.1.4 Decision Problems

To effectively address challenges specific to the EoL stage, a review was conducted to identify sub-phases of the EoL stage, problems specific to each sub-phase, and to understand how other studies analyze and address these problems. Traditional LCA methods often break EoL into four sub-phases: Destruction/Demolition, Transport, Waste Processing, and Disposal (Gomes et al. 2023). These stages were used in this study as a framework for the major decision problems in EoL and offer a good scaffolding upon which CE principles can be added to status quo construction practices.

For each one of these four sub-phases, related decision problems were identified. In the first sub-phase, “Deconstruction/Demolition,” the decision problem is to select which of these two choices is the best option for buildings reaching EoL (Esther Aigwi et al. 2019; Hasik et al. 2019). In the second sub-phase, “Transport”, the CDW disposal/recycling facility is selected. This includes decisions not only related to the transportation type and route but also the best available facility for the CDW, based on the options in the surrounding area and the typology of waste (Wang et al. 2021; Chen et al. 2018; Kang et al. 2022). In the third sub-phase, “Waste Processing”, sorting practices are selected, aiming to increase the rate of reuse and recycling of construction materials (Ding et al. 2021). In the last sub-phase “Disposal”, the final destination of construction materials and components is defined, whether that is a landfill (disposal), a recycling plant (recycle), or another construction site or storage facility (reuse) (Antunes et al. 2021; Mishra et al. 2019; Khoshand et al. 2020). Figure 2 illustrates the four sub-stages of the EoL phase according to this approach, in addition to the defined decision problems and possible alternatives.

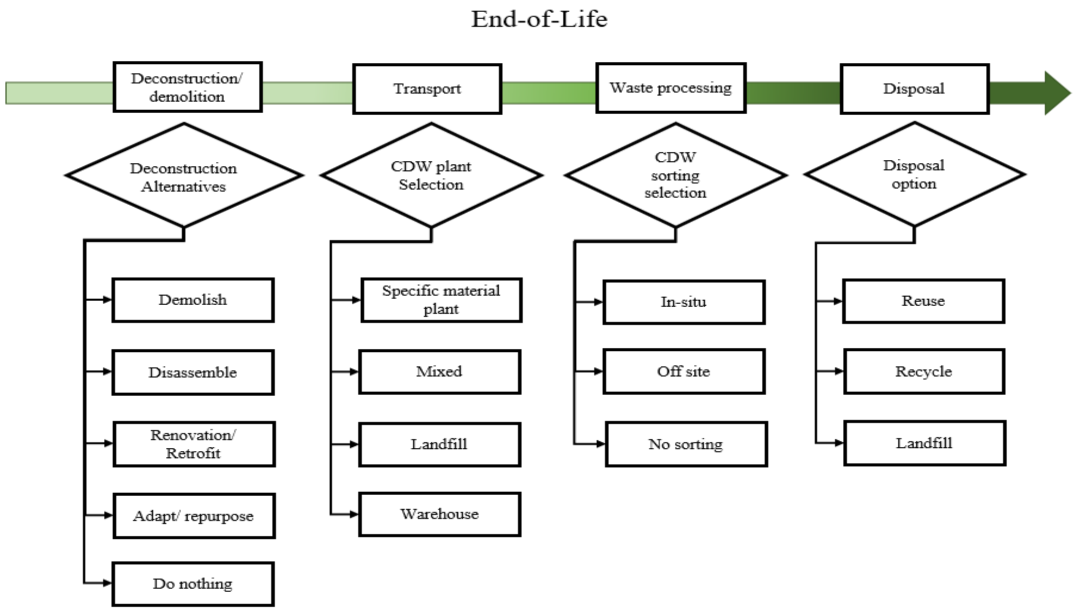


Figure 2 Decision problems and alternatives.

All the sub-phases and, consequently, the decision problems are highly interconnected. For example, the first three decision problems directly influence the last one, (i.e., “disposal”), which is the most detailed level of this decision-problem framework. The selection of demolition practices can perhaps increase or decrease the reusability and recyclability rate of construction materials’ disposal depending on chosen practices. Similarly, the same can be observed for in-site vs off-site sorting methods (Hossain et al. 2017)Facility selection is also highly related to the disposal sub-phase, where considering the available facilities in the region and selecting the best option can directly modify the disposal scenario.

2.2 Decision-Making and Impact Assessment for EoL

As this research focuses on identifying the most sustainable and circular alternatives for built facilities at the EoL stage, this section provides a comprehensive review of existing methods. The review aims to highlight the various approaches used to evaluate and compare environmental impacts, assess sustainability, and support decision-making in EoL scenarios. By examining these methods and tools, this section will lay the foundation for understanding how they can be applied to develop effective strategies for enhancing circularity and sustainability in construction practices by addressing specific decision problems.

The criteria used in solving these decision problems are inconsistent across the literature, particularly for social factors. Hence, an extensive review is necessary to create a comprehensive list of adaptable criteria applicable to various decision problems. In general, decision-making frameworks for EoL use two prevalent methods, LCA and MCDM. The decision-making criteria applied in each method tend to differ.

LCA primarily provides a detailed set of standardized environmental parameters but often overlooks socioeconomic impacts (Quéheille et al. 2022). In contrast, MCDM accommodates a diverse set of criteria, whether quantitative or qualitative, allowing for the inclusion of social, economic, or technical aspects (Garcia-Bernabeu et al. 2020). The integration of these assessment methods with Building Information Modeling (BIM) has been a notable trend to facilitate and enhance the data collection and assessment process (Figueiredo et al. 2021; Cheng et al. 2022; Bueno et al. 2018). Another valuable combination is the use of LCA to assess environmental impacts and MCDM for the remaining criteria, this combination facilitates the assessment of environmental-related factors and allows the inclusion of multiple stakeholders to assist in the criteria weighting process (Figueiredo et al. 2021).

2.2.1 Life Cycle Assessment

Another widely used method for evaluating the environmental impacts of buildings is LCA from raw material extraction to EoL disposal (Vilches et al. 2017; Di Maria et al. 2018). This method measures the potential environmental impacts associated with a product or service throughout its entire life cycle, as outlined in the ISO 14040:2006 and ISO 14044:2006 standards (Vilches et al. 2017). By examining each phase LCA provides valuable insights into resource use, emissions, and waste generation, guiding the development of more sustainable and environmentally friendly building practices. The LCA methodology uses information from databases to evaluate different alternatives. Some of the most used databases are: openLCA, Ecoinvent, Athena database, GaBi, and EPDs (Cheng et al. 2022).

Similar to the analysis done with the MCDM method Vitale et al., 2017 employed LCA to evaluate the environmental impacts associated with different stages of the EoL stage for built facilities, with a particular emphasis on demolition waste management (Vitale et al. 2017). Their analysis covers various stages including demolition, sorting, recycling, and disposal, and tracks the flow of materials to recycling, energy recovery, and final disposal. The study also compares environmental performances across different demolition scenarios (Vitale et al. 2017). The results highlight that selective demolition improves both the quality and quantity of materials available for resource recovery and safe disposal, while also shedding light on the environmental impacts associated with each stage of the waste management process.

Some LCA articles integrated information in these databases with BIM as a means of facilitating the LCA analysis (Cheng et al. 2022; Bueno et al. 2018; Jalaei and Jrade 2014). BIM has shown efficacy as a digital representation of the physical and functional characteristics of buildings, which can generate and store useful information that helps to address data availability problems for LCA studies. There are many ways to make this integration. The most popular practice is exporting the bill of quantity from the BIM environment. Other forms of integration involve developing new tools in BIM or using plugin tools such as Tally (Akbarnezhad et al. 2014).

2.2.2 Multi-Criteria Decision-Making Methods

Decision-making in construction involves navigating complex scenarios where multiple often conflicting factors must be balanced to ensure project success. MCDM is a vital tool in this context, helping to systematically evaluate and select the best alternatives by integrating various criteria and stakeholder preferences. To incorporate multiple stakeholders as decision-makers, various MCDM methods have been explored in previous literature, including the Analytic Hierarchy Process (AHP), Technique for Order Preference by Similarity to an Ideal Solution (TOPSIS), Preference Ranking Organization Method for Enrichment Evaluations (PROMETHEE), and Analytical Network Process (ANP). The advantages and limitations of each method must be considered in a case-specific manner when selecting an MCDM approach. AHP is a well-established, simple, and flexible approach that uses a pair-wise comparison to assign weights (T. L. Saaty 2008). It can handle complex decision structures and prioritize criteria, as long as there are no dependencies among them. Hence, AHP can be sensitive to changes in the input data. ANP is advantageous for capturing relationships among criteria but can become intricate as the decision structure grows (Ishizaka and Nemery 2013). PROMETHEE offers flexibility in modeling preferences and is conceptually straightforward, but it may be sensitive to certain parameter choices (Ishizaka and Nemery 2013). Lastly, TOPSIS is easy to understand and computationally efficient, yet it assumes linear relationships among criteria and may be sensitive to scaling issues (Ishizaka and Nemery 2013).

These methods are widely used in different phases of the construction industry and are enablers for aggregating CE composite indicators at a national scale. For example, Garcia-Bernabeu et al. (2020) aimed to create a CE composite indicator to evaluate the overall performance of EU countries in a unified manner, rather than addressing separate issues individually (Garcia-Bernabeu et al. 2020). Recognizing the need to integrate various CE dimensions into a single summary measure, the authors employed the TOPSIS method as part of their methodology to address this gap. Similarly, Stankovic´ Jelena J. et al., (2021) employed the PROMETHEE method in their study, covering seven years to analyze the CE development in the EU countries using 11 separate indicators (Stankovic´ Jelena J. et al. 2021). This approach aimed to create a CE composite index to evaluate those indicators collectively over the selected period.

In another example, Khoshand et al. (2020) went beyond environmental impacts by utilizing a Fuzzy AHP approach to create a framework encompassing 16 different criteria (Khoshand et al. 2020). Their criteria spanned environmental, social, technical, and economic dimensions (Khoshand et al. 2020). While this expansion of criteria addresses additional factors not often considered, some concerns regarding bias in MCDM models during rating processes have been raised. Their results showed that economic and social criteria received the highest and lowest importance levels, respectively; however, the study did not provide any information on the profiles of decision-makers participating in the process.

The lack of representativeness of diverse stakeholder groups was also identified by Chinda & Ammarapala (2016) (Chinda and Ammarapala 2016). They used AHP to analyze the outcome for four different scenarios i.e., reuse, remanufacturing, recycling, and landfill. The chosen participants for this study were four project managers, and two owners, excluding multiple stakeholders, directly and indirectly involved in the EoL of built facilities (Chinda and Ammarapala 2016).

Nadazdi et al. (2022) also identified some issues in the weight distribution due to the lack of diversity among the stakeholders (Nadazdi et al. 2022). In their study, they observed a shift in the importance of some criteria, based on different stakeholders' interests (Nadazdi et al. 2022). Participants in the pairwise comparison for an AHP approach must represent the diverse vested interests of decision-makers across all sub-phases of the EoL stage. Maintaining this representation is crucial to conducting a critical stakeholder analysis. The inclusion of participants with e.g. economic and environmental interests is as important as including roles, such as building owners, developers, legal representatives, design professionals, and local communities.

2.2.3 Criteria Selection

This review examines various assessments and measurements for making the most sustainable decisions at the EoL stage of built facilities. While different methodologies have been identified, it is also crucial to determine the parameters that guide these decisions. Key criteria need to be established to ensure that the main aspects of a sustainable CE are considered. The criteria are usually categorized into 'Main Criteria' and 'Sub-Criteria.' The main criteria represent broader categories, each branching into associated sub-criteria. For this study, all sub-criteria will be referred to as 'criteria,' while the term 'main criteria' will be retained to differentiate them from the subordinate levels.

A large number of references were reviewed to inform criteria selection. For clarity, these works are explained below, and citations are presented in Table 1. The first set of LCA-related papers focuses mainly on GHG emissions (Table 1). After that, the most frequent criteria presented are ‘Ozone Depletion,’ ‘Energy Consumption,’ ‘Photochemical Oxidant Formation,’ ‘Water Eutrophication,’ and ‘Water Consumption’ (Table 1). Therefore, those indicators can be considered the most significant criteria under the ‘Environment’ main criteria based on the LCA analysis within the selected literature. Even though an extended list of attributes is being considered in this group, it is reasonable to affirm that the LCA methodology alone is not sufficient to address the three (social, environmental, and economic) pillars of sustainability.

Table 1 Criteria used by LCA studies

Source	Antunes et al. 2021	Cheng et al. 2022	Xu et al. 2019	Joensuu et al. 2022	De Wolf et al. 2020	Bueno et al. 2018	Sanchez et al. 2018	L Eberhardt et al. 2019	Schlegl et al. 2019	Akbarnezhad et al. 2014	Jalaei et al. 2014	Robati et al. 2019
GHG (kgCO2eq)	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
ADP (f.f). (MJ)	✓								✓			
Ozone depletion (kg CFC-11 eq)						✓			✓		✓	
Smog potential (kg No_x eq)											✓	
Primary energy demand (MJ)							✓		✓	✓		
Fossil Fuel Consumption (kgce) or (MJ)		✓									✓	
Mineral Resource Consumption (kg)		✓										
Metal depletion (kg Fe eq)						✓						
Natural land transformation (M^2)						✓						
Terrestrial ecotoxicity (kg 1,4-DB eq)						✓						
Urban land occupation (m^2a)						✓						
Agriculture land occupation (m2a)						✓						
Acidification (moles of H+ eq)		✓									✓	
Photochemical oxidant formation (kg NMVOC)		✓				✓			✓			
Marine ecotoxicity (kg 1,4-DB eq)						✓						
Marine eutrophication (kg N-eq)						✓						
Freshwater eutrophication (kg P eq)		✓				✓			✓			
Freshwater ecotoxicity (kg 1,4-DB eq)						✓						
Freshwater consumption (m^3)		✓				✓			✓			
Timber consumption (m^3)		✓										
Particulate matter formation (kg PM10 eq)		✓				✓						
Human toxicity (kg 1,4-DB eq)						✓						
Ionizing radiation (kg U235 eq)						✓						
HH respiratory effects potential (kg PM2.5 eq)											✓	
Cost ($)										✓		
Lifetime (years)												✓

The criteria explored by this group of papers bring economics, social impact, technical details, and business environment into consideration. Table 2 shows the most frequently used or the most significant (importance attributed to the criteria by the study) criteria used for each publication in the group using MCDM methods. In the articles using this methodology, the most frequently used criteria are related to ‘Production Cost,’ ‘Revenues,’ ‘Pollution,’ ‘GHG,’ ‘Energy Consumption,’ ‘Worker’s Health,’ and ‘Job Creation.’ This frequency demonstrates a larger variety of criteria selection, which now includes economic and social indicators different than the LCA methodology. The LCA studies initially presented 33 criteria, and the MCDM used a total of 74. Those criteria, in many cases, are either the same or can be matched since having the same semantics.

Table 2 Criteria used by MCDM studies

Source		Lee et al. 2022	Khoshand et al., 2020	Alamerew et al 2019	Hasheminasab et al., 2022	Iodice et al., 2021	Nadazdi Ana et al., 2022	Chinda et al., 2015
Economic	Operational cost	✓	✓	✓	✓	✓	✓	✓
	Labor cost							✓
	Capital cost/ investment	✓	✓				✓	
	Landfill charges and tax							✓
	Revenues	✓		✓		✓	✓	
	Market demand			✓				
Environment	GHG	✓				✓	✓	
	Resources consumption	✓		✓		✓		
	Energy consumption	✓	✓		✓	✓		
	Pollution(air/soil/water)		✓		✓			
	Water consumption		✓		✓	✓		
	Land use					✓		
Social	Working hours and wages	✓						
	Worker’s health	✓	✓	✓		✓		
	Worker’s safety	✓	✓				✓	
	New job creation	✓	✓			✓	✓	
	Public acceptance	✓	✓					
	Public discomfort due to landfill presence					✓	✓	
Technical	Material sorting			✓				
	Availability of recovery facilities			✓				✓
	Material quality		✓	✓				
	Technical feasibility		✓					
CE	Green image site							✓
	Legislative pressure							✓
	Lifetime of products	✓				✓		✓
Legislation	Compliance with regulations			✓				
	Compliance with new legislation			✓				

To reduce the large set of environmental sub-criteria and make the model more feasible, this study only considered criteria that were used in at least 4 different studies between LCA and MCDM.

However, the other main criteria (i.e., social, economic etc.), did not include a set of criteria as extensive as the criteria under "environmental." For that reason, the inclusion threshold for these criteria was lowered to the presence in at least 3 articles.

For most criteria, their frequency was related to their significance to the model. The criteria 'Compliance with Legislation,' 'Market Demand,' and 'Public Acceptance to Reused Material,' on the other hand, were kept not for the frequency they appeared in the reviewed studies, but for their importance to the broader adoption of CE (Giorgi et al. 2022; Ghaffar et al. 2019; Nordbly 2019)

2.3 Gaps in the Literature

This review highlights several important gaps that need to be addressed. First, while individual aspects of EoL decisions, such as deconstruction, demolition, and material disposal, have been extensively studied, there is a notable lack of integrated approaches, i.e., approaches that consider these decisions as interconnected components of a comprehensive EoL strategy. Most studies focus on isolated issues rather than adopting a holistic view of the entire EoL process.

Additionally, there is a lack of consistency in the criteria used across different decision-making frameworks for EoL scenarios, particularly concerning social factors. Many frameworks do not incorporate a comprehensive set of criteria that address all relevant aspects of sustainability and circularity. A systematic approach to consolidating and evaluating criteria is needed to ensure that all pertinent factors are considered.

Moreover, studies using MCDM methods often suffer from insufficient stakeholder representation, leading to potential biases and incomplete decision-making outcomes. Research should focus on incorporating a diverse range of stakeholders to better reflect varied perspectives and interests.

Addressing these gaps will contribute to the development of more robust, practical, and holistic frameworks for managing the EoL of built facilities, ultimately supporting more sustainable and circular practices.

Chapter 3. Model Development Methodology

This chapter focuses on the methods used for the development and testing of the decision-making model. A high-level illustration, presented in Figure 3, provides an overview before delving into the details of each step.

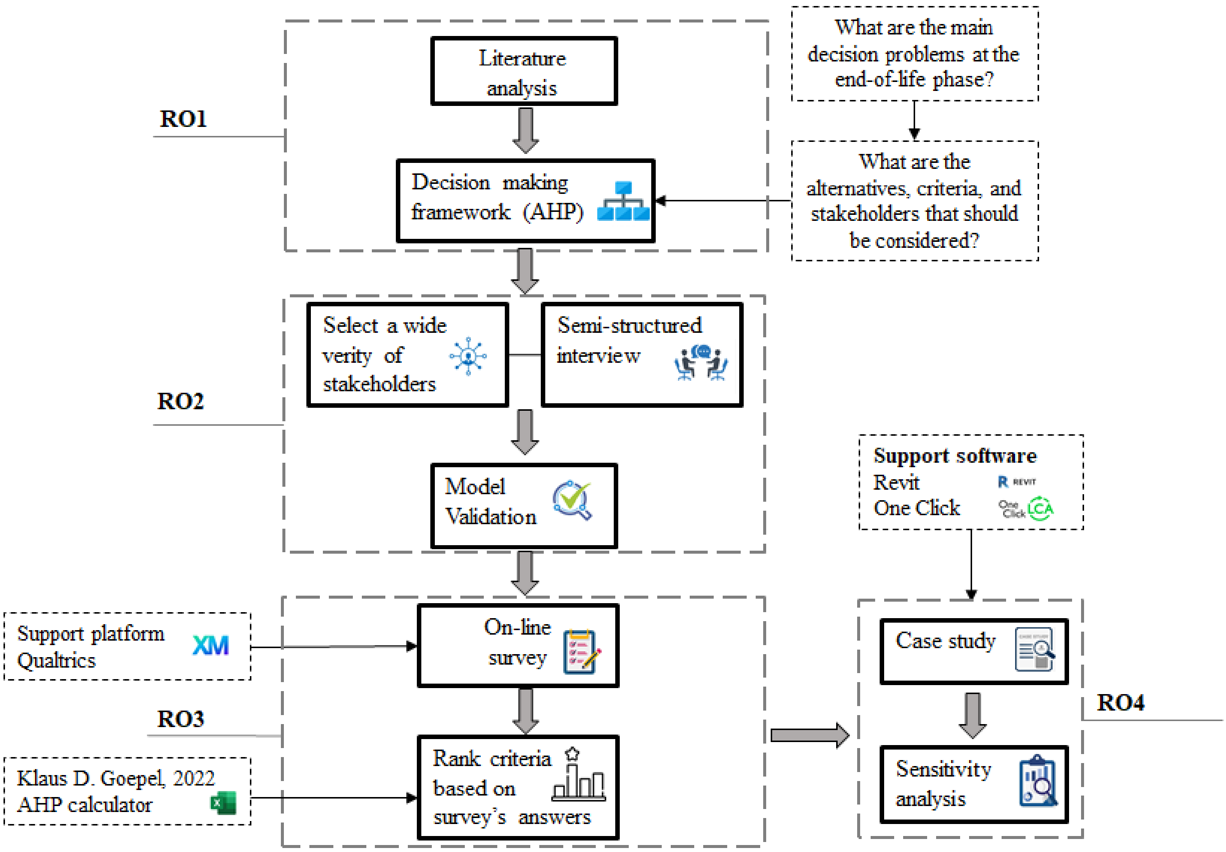


Figure 3 High-level methodology of this study

The study begins with a literature analysis, which forms the basis for developing the framework structure, representing RO1. This phase is divided into two stages: the first stage identifies the main issues to be addressed, referred to as decision problems, while the second stage evaluates the criteria necessary for making these decisions by summarizing parameters from similar studies.

The next step is to construct a structured framework. RO2 involves developing a hierarchical tree and validating this structure with insights from multiple experts through semi-structured interviews. After validation, the criteria need to be assigned weights. In RO3, a survey is designed and distributed to a diverse group of participants to gather input on these weights. The results are then aggregated to create a ranked list of criteria.

Finally, RO4 tests the model's feasibility through a case study. A sensitivity analysis is conducted to assess the model's robustness and ensure its reliability.

3.1 Model Development Methods

The model development follows a three-phase method to progress a comprehensive decision-making model for the EoL of built facilities. The phases include (1) development of the EoL decision-making framework (including decision makers/stakeholders to be involved) based on the literature; (2) model validation with the help of stakeholders; and (3) weighting the criteria through AHP, as depicted in Figure 4. Firstly, the literature analysis is used to identify the main categories of decision problems inherent to each EoL sub-phase and related decision criteria. Subsequently, the model is validated through semi-structured interviews with a diverse range of stakeholders involved in the EoL process. Finally, the criteria are weighted according to stakeholders' opinions, collected and processed through AHP, and conducted through surveys. Each phase is discussed in more detail in the following.

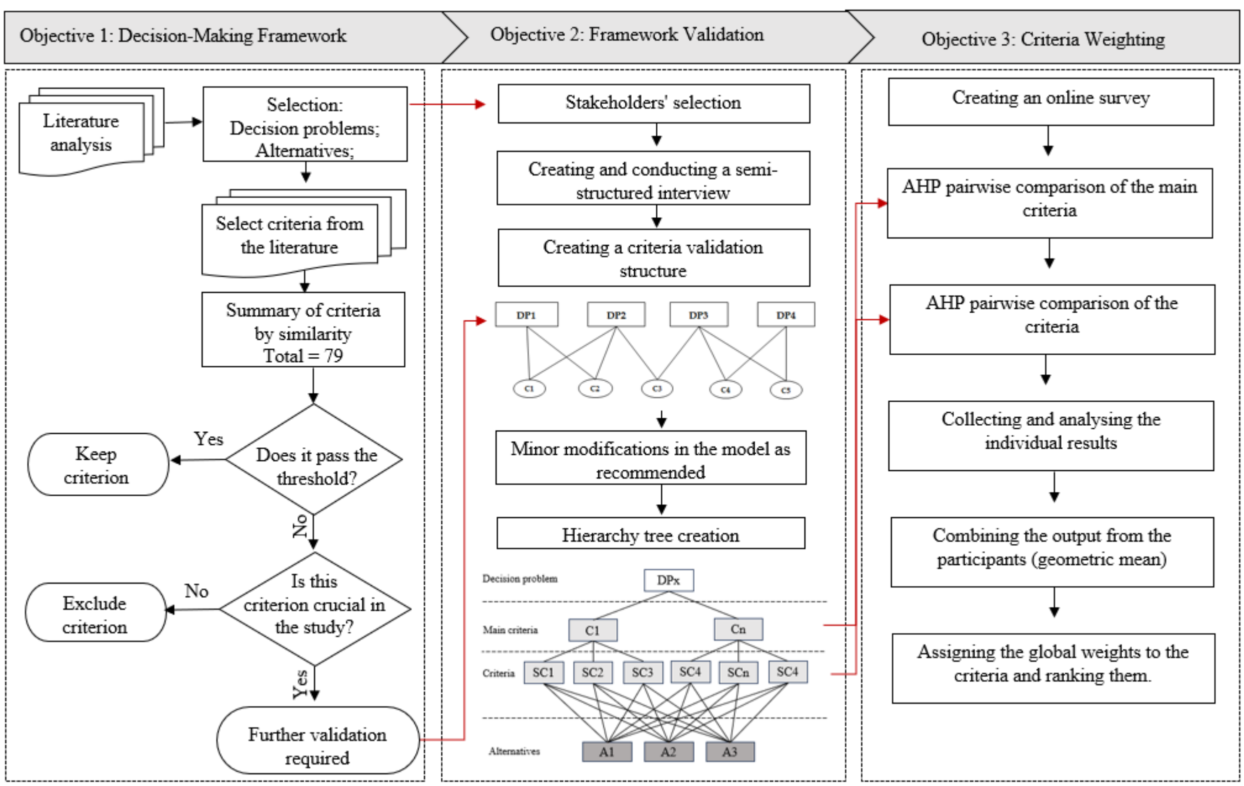


Figure 4 Model development high-level methodology

3.2 Decision-Making Framework

The hierarchical structure of the decision-making framework consists of decision problems, alternatives, main criteria, and criteria. The first step in establishing this hierarchy was identifying decision problems inherent in each EoL sub-phase. The literature revealed diverse groups of decision problems, initially evaluated independently (Stankovic´ Jelena J. et al. 2021). To adopt a holistic approach, the four subphases of the EoL (demolition/deconstruction, transport, waste processing, and disposal) were combined into one decision process: with four related decision problems: (1) choosing the deconstruction approach; (2) selecting the CDW disposal/recycling facility; (3) selecting the waste sorting practices; and (4) selecting the final destination for the construction materials. Subsequently, the alternatives were formulated by merging findings from various studies. The combination of alternatives across the literature ensured a systematic exploration of possibilities for each decision problem.

To compile the main criteria and criteria, a systematic literature review revealed 6 main criteria: environment, social, economic, regulations, material conditions, and site conditions. Under these main criteria, within the LCA and MCDM studies, 33 and 74 criteria were extracted respectively. After combining similar criteria, a condensed list of 26 criteria under LCA and 27 under MCDM was obtained. Due to the large number and the difficulty of working with 53 different criteria, criteria that appeared in at least three previous studies, or that were highlighted by previous studies to be important in the adoption of CE were selected (Alamerew and Brissaud 2019; Giorgi et al. 2022; Ghaffar et al. 2019)These important yet less frequent criteria include 'Green Image,' 'Market Demand,' and 'Space on Site.'

The criteria were selected mainly from the MCDM set due to its capacity to address different topics. The LCA set, however, provided standard measurements for the environmental criteria, which were employed in the model. Among the selected sets, some criteria such as 'GHG' from LCA or 'Operational cost' from MCDM sets, have been considered by all studies in their group. Therefore, those highly-conserved criteria were the most important to conserve. The remaining criteria were passed through a different selection process. To reduce the large set of environmental criteria and make the model more feasible, this study only considered criteria that were used in at least four different studies between LCA and MCDM. However, the other main criteria (i.e., social, economic, etc.), did not include as extensive a set of criteria as the criteria under 'Environmental.'

For that reason, the inclusion threshold for these criteria was lowered to the presence of at least three articles. For most criteria, their frequency was related to their significance to the model. The criteria ‘Compliance with Regulations,’ ‘Market Demand,’ and ‘Public Acceptance of Reused Material,’ on the other hand, were kept not for the frequency they appeared in the reviewed studies, but for their importance to the broader adoption of CE (Giorgi et al. 2022; Ghaffar et al. 2019; Nordbly 2019). Table 3 shows the final list of selected criteria with their sources.

Table 3 Summary of criteria applied in previous EoL studies.

Main Criteria	Criteria	Source
Environment	GHG emissions	(Nadazdi et al. 2022; Iodice et al. 2021; Lee et al. 2021; Antunes et al. 2021; Cheng et al. 2022; Xu et al. 2019; Joensuu et al. 2022)
	Energy consumption	(Schlegl et al. 2019; Akbarnezhad, Ong, and Chandra 2014; Khoshand et al. 2020; Hasheminasab et al. 2022; Iodice et al. 2021)
	Water consumption	(Khoshand et al. 2020; Hasheminasab et al. 2022; Iodice et al. 2021; Cheng et al. 2022; Bueno et al. 2018; Schlegl et al. 2019)
	Resources consumption	(Lee et al. 2021; Iodice et al. 2021; Cheng et al. 2022; Alamerew and Brissaud 2019)
Social	Public acceptance of reused material	(Giorgi et al. 2022; Ghaffar et al. 2019; Nordbly 2019; Lee et al. 2021; Alamerew and Brissaud 2019)
	Worker’s health and safety	(Lee et al. 2021; Khoshand et al. 2020; Alamerew and Brissaud 2019; Iodice et al. 2021; Nadazdi et al. 2022)
	Green image	(Chinda and Ammarapala 2016)
	Historical value	(Esther Aigwi et al. 2019)
	Networking among facilities	(Giorgi et al. 2022)
	Employment opportunities	(Lee et al. 2021; Khoshand et al. 2020; Iodice et al. 2021; Nadazdi et al. 2022)
Economic	Market demand	(Alamerew and Brissaud 2019)
	Fixed and variable costs	(Lee et al. 2021; Khoshand et al. 2020; Alamerew and Brissaud 2019; Hasheminasab et al. 2022; Iodice et al. 2021; Nadazdi et al. 2022; Chinda and Ammarapala 2016; Akbarnezhad, Ong, and Chandra 2014)
	Capital expenditure	
	Revenues	(Lee et al. 2021; Khoshand et al. 2020; Nadazdi et al. 2022)

		(Lee et al. 2021; Alamerew and Brissaud 2019; Iodice et al. 2021; Nadazdi et al. 2022)
Regulations	Compliance with regulations	(Liu et al. 2021; Giorgi et al. 2022; Ghaffar et al. 2019; Alamerew and Brissaud 2019)
	Incentives	(Ghaffar et al. 2019; Høibye and Sand 2018; Liu et al. 2021)
Site conditions	Space on site	(Chinda and Ammarapala 2016)
	Amount of waste	(Lee et al. 2021)
	Process time	(Lee et al. 2021; Chinda and Ammarapala 2016)
Material conditions	Material quality	(Khoshand et al. 2020; Alamerew and Brissaud 2019)
	Second life	(Lee et al. 2021; Iodice et al. 2021; Chinda and Ammarapala 2016; Robati et al. 2019)
	Hazardous	(Alamerew and Brissaud 2019; Bueno et al. 2018; Iodice et al. 2021; Purchase et al. 2022)
	Quality certification	(Alamerew and Brissaud 2019; Chinda and Ammarapala 2016)

Notably, the predominant criteria were 'GHG emissions,' 'Energy Consumption,' and 'Costs,' emphasizing their significance. Moreover, the less frequent main criteria were site and material conditions, followed by criteria under the umbrella of 'Social' (e.g., Historical value). These less-highlighted main criteria are critical factors that warrant attention given their potential to significantly influence the feasibility of projects and impact the lives of neighboring communities, and workers (Iodice et al. 2021; Purchase et al. 2022).

3.3 Framework Validation

To validate the framework semi-structured interviews were conducted with a diverse array of stakeholders to mitigate potential biases in the decision-making system (Ghisellini et al. 2018; Z. Chen et al. 2013). Key actors were identified across the EoL stage (Alamerew and Brissaud 2019; Gomes et al. 2023)including owners; developers; project managers; construction contractors; material suppliers; demolition and deconstruction companies; recycling, refurbishment, and sorting facilities; insurance professionals; building occupants; environmental specialists; policymakers; and researchers. To facilitate the analysis and selection of interviewees, these were divided into six groups: (1) Design; (2) Construction and Operation (3) EoL Services; (4)

Sustainability Specialists; (5) Insurance; and (6) the Public Community (referred to, as 'Community,' for short). The authors reached out to potential interviewees so that at least two people in each category would participate in the validation. A total of 25 video call interviews were conducted in this validation stage, yielding a cumulative recording of over 15 hours. The characteristics of the interviewees are summarized in Table 4.

Table 4 Framework Validation – Stakeholders Participants' Description

Stakeholder groups	Company Type	Role	Years of Experience	Sector	Location
Design	Design Company	Designer	4	Private	Québec
		Env. designer	10	Private	Québec
Construction & Operation	Building Development Company	Investor	7	Private	Québec
		Construction manager	2.5	Private	Québec
		Project Coordinator	2.5	Public	Québec
	Manufacture Company	Head, Sustainability & Public Affairs	30	Private	Ontario
	Educational facility	Facility Manager	12	Private	Québec
EoL Services	Sorting facility	Facility manager	3	CO-OP	British Columbia
	Refurbishment facility	Facility Manager	2	Private	British Columbia
	Demolition	General manager	15	Private	Alberta
	Demolition	Manager	10	Private	Ontario
	Government	Policy maker	10	Public	Québec
		Policy maker	2	Public	Québec
Sustainability Specialists	Consultant	Env. Specialist	5	Private	British Columbia
	Technological	CEO/ Researcher	5	Private	Ontario
	Academia	Env. Specialist	4	Non-profit	British Columbia
		Env. Specialist	8	Private	British Columbia
		Researcher	6	Academia	Ontario
Insurance	Insurance companies	Claims representative	52	Private	Alberta
		AVP Enterprise innovation	37	Private	Ontario
		Home product specialist	13	Private	Ontario
Community	Local community	(3) Occupants	-	-	Québec

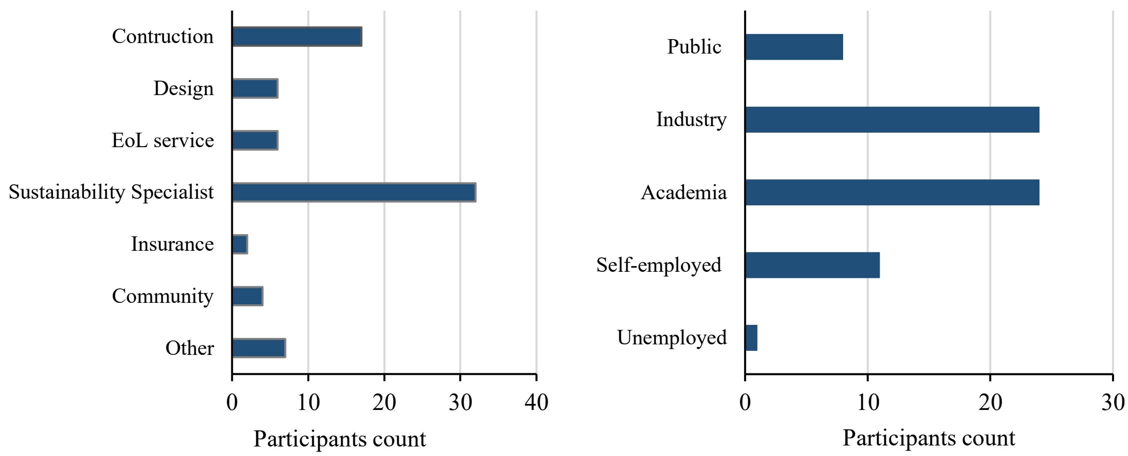
The interviews followed a carefully designed structure (Orenga Panizza and Nik-Bakht 2024; Ding et al. 2018; Hu 2019). Before interviewing the participants, various tests with colleagues were conducted to determine the average duration of the interview. Each interview began with participants being asked to describe their roles as stakeholders, their involvement and expertise in demolition/deconstruction, and reuse/recycling domains. Stakeholders were informed of the study's aim to include a diverse group, ensuring representation of their roles while maintaining confidentiality. Participants then received a concise presentation on the research, emphasizing the construction stages and focusing on the EoL. Each EoL phase and its related decision problem was explained.

After explaining the context, questions were asked to validate the framework in 3 steps, i.e., validation of (1) decision problems, (2) alternative solutions to each decision problem, and (3) criteria. In the first validation step, participants were presented with individual decision problems and were asked to discuss their pertinence to the EoL. Secondly, a list of alternatives for each decision problem was presented, and participants were asked to identify any missing options not accounted for by the study. In the third validation step, participants were shown all main criteria and criteria and asked to reflect on their importance to the decision problems. The full interview structure can be found in Appendix 1.

To ensure the interviews would be time efficient, instead of discussing the 23 criteria for every decision problem, they were discussed for at least two problems, chosen randomly for each participant. This ensured participants had ample opportunity to contemplate their relevance before excluding any criteria. Often, answers were not as clear as “keep it” or “remove it”. Thus, follow-up questions were regularly asked regarding their level of importance (on a 9-level Likert scale). Further discussion was also sought for the criteria that were less common in the literature. Additionally, participants were asked to suggest any criteria that might be missing in the framework.

3.3.1 Online Survey

The criteria weighting was conducted through an online survey built on the Qualtrics platform(“Qualtrics” 2005). Aiming to create a model of less bias, the survey was completely anonymous, allowing participants to share feedback more freely. To gather responses from a broad spectrum of stakeholders, the survey was actively promoted on professional online platforms, such as LinkedIn. The survey garnered a total of 52 valid responses, with 41 originating from Canada and 11 from various other countries, including Australia, Bahrain, Brazil, Norway, Singapore, and the USA. The participation of individuals from different backgrounds ensured representation from each of the previously selected stakeholder roles, as illustrated in Figure 5, which displays the distribution of survey participants. Furthermore, the survey sought to achieve a balanced representation across different sectors, recognizing that perspectives can vary based on one's industry involvement. Figure 5 (a) provides an overview of the participants' distribution by different identified roles related to the EoL stage; (b) participants' distribution across various sectors.



(a) Distribution of Participants by Role **(b) Distribution of Participants by Sector**

Figure 5 Survey Participants Distribution by Role and Sector

The survey initiation commenced with a concise introduction to the EoL stage, emphasizing its relevance to the specific decision problems under investigation. Each participant was subsequently allocated, at random, to one of the decision problems. To enhance participants' comprehension, a hypothetical scenario was presented, illustrating one of the problems. Participants were then invited to provide their insights regarding the relative importance of the “main criteria” associated with the assigned decision problem. Next, they were randomly assigned to a major criterion, to rate the importance of its criteria. Subsequently, participants were asked to rate their proficiency in the fields of demolition/deconstruction and reuse/recycling. Finally, there were questions about demographics, such as the participant's location, job title, and sector. The final weights for the main criteria and criteria were calculated based on the combination of all the participants through geometric mean. This aggregation was thoroughly inspected, ensuring that the combined result had a consistency rate under 10%, which is the recommended threshold (Saaty 2008).

3.3.2 Criteria Weighting

Judgment Scales

For the criteria weighting, the AHP was employed to determine the weights of the main criteria and criteria within the decision-making framework, which had been validated in the previous step. These weights were derived through a pairwise comparison matrix using a nine-point scale. This method allows for evaluating the relative importance of each criterion by assessing how much more or less significant one criterion is compared to another, as illustrated in Table 5.

Table 5 Level of importance, on a 1 – 9 scale, as recommended by Saaty (2008) for inputting values into the reciprocal matrix for criteria comparison

Intensity of relative importance	Definitions
1	Equal importance
3	Moderate importance
5	Essential or strong importance
7	Demonstrated importance
9	Extreme importance
2,4,6,8	Intermediate values between the two adjacent judgments

The Linear Scale, frequently used in AHP, is one of the most straightforward and widely adopted scales for comparing criteria or alternatives (Figueiredo et al. 2021; Semgalawe 2024; Chen et al. 2013). This scale operates on a direct 1 to 9 range, where each step signifies a consistent and equal increase in importance from one level to the next. The principle behind this scale is to assign a numerical value that reflects the relative importance of one criterion or alternative over another (Saaty 2008; Saaty 1987; Jiří and Kresta 2014).

Pairwise comparison matrix

This step allows decision-makers to evaluate how much more one criterion is preferred over another by conducting pairwise comparisons. Each element is compared against every other element, using a linear scale to express the intensity of preference.

The pairwise comparison matrix is structured in a square format, where both rows and columns represent the criteria or alternatives being compared. For each pair of elements, a value from the scale is assigned to indicate the relative importance of one element over the other. If element A is more important than element B, the corresponding cell in the matrix will contain a value from the scale that reflects this preference. Conversely, the reciprocal value will be placed in the cell where B is compared to A. Figure 6 illustrates a matrix constructed from survey participants’ responses, as prepared in Excel. Numbers 1 through 6 represent different main criteria.

1	Participant 1					
	1	2	3	4	5	6
1	1	1/9	9	9	1/9	9
2	9	1	9	1/9	1/9	9
3	1/9	1/9	1	1/9	1/9	9
4	1/9	9	9	1	1/9	9
5	9	9	9	9	1	9
6	1/9	1/9	1/9	1/9	1/9	1

Figure 6 Example of Pair-Wise Matrix from Participant Number 1

After building the pairwise comparison matrix, the next step is to normalize it. For each entry in the matrix, divide the value by the corresponding column sum. This transforms each entry into a normalized value that represents the proportion of the total importance assigned to that particular criterion. This step ensures that each column sums up to 1, representing the relative weight of each criterion within that column.

After normalization, it is critical to test the consistency ratio (CR) of the matrix. A low CR value indicates that the judgments are consistent. A low CR (less than 10%) suggests that the judgments are reliable and consistent. The CR is calculated using the formula, CR = CI/RI, where consistency index (CI), is, measured with the formula (1. 1). The Random Index (RI), is the average value that varies based on the order of the matrix, λ_{max} represents the maximum eigenvalue of matrix A (Saaty 2008; Saaty 1987).

$$CI = \frac{\lambda \max - n}{n - 1} \tag{1. 1}$$

To combine the opinions of multiple stakeholders, the geometric mean was applied (Krejcí and Stoklasa 2018). It is a valuable method for aggregating individual preferences into a collective decision. When multiple stakeholders provide their pairwise comparisons for the criteria, these individual judgments may vary. The geometric mean is used to synthesize these diverse inputs into a single set of priorities.

3.3.3 AHP Tools

Several decision-making AHP software tools are available, including Questfox, ChoiceResults, 123AHP, and Super Decisions (Ishizaka and Nemery 2013). In addition to these, AHP can also be implemented using Excel (Ishizaka and Nemery 2013). Goepel (2013) developed a free Excel tool that incorporates eight different judgment scales and allows the combination of inputs from multiple participants (Goepel 2013). This Excel tool served as the basis for the analysis in this study.

AHP was chosen for this study because it can combine diverse opinions without requiring stakeholders to agree on a single option. This flexibility is crucial in decision-making processes involving multiple participants with varying perspectives.

The decision to use Excel over other specialized AHP software tools was driven by several factors. First, Excel is widely accessible and user-friendly, making the use easy without the need for additional installations or subscriptions. Unlike other software tools, Excel's familiarity and simplicity allowed for more straightforward data handling and customization according to the study's specific needs. Additionally, the Excel-based tool provided the necessary flexibility to modify the input combination process, which was essential given the large number of responses received. However, modifications were necessary since the original tool could only combine up to 20 inputs, which was less than the number of responses received from the survey. By following the same mathematical logic, the table was adapted and used in stages: first to evaluate the main criteria, and then to assess each branch of the main criteria with the corresponding criteria.

Chapter 4. Model Development's Results and Discussion

This chapter investigates the contribution of each of the above-mentioned objectives. It begins by describing the validated decision-making model and outlining all the main criteria included in the framework. Following this, the criteria weighting process and details of the survey distribution are discussed.

4.1 Model Validation

To create a holistic framework for EoL decision-making a hierarchy was created relating the decision problems to alternatives, main criteria, and criteria, as discussed earlier. Based on a review of the literature, four EoL sub-phases were identified, each with a related decision problem. To assess the best alternative for each decision problem, previous studies generally employed criteria from the six main criteria, as shown in Table 3. The framework presented in Figure 6 is the output of the semi-structured interview with the 25 stakeholders. In addition to the 23 criteria collected from the literature, the interviewees recommended the inclusion of two additional criteria: Land value and Location. Land value was suggested to be an important economic criterion for deciding whether a building will be demolished and the land redeveloped. Location, as a site condition criterion, was also indicated to influence decisions because of potential site accessibility and traffic challenges.

Although environmental criteria were not considered the main priority in some EoL studies (Hasheminasab et al. 2022; Khoshand et al. 2020), the interviewed stakeholders unanimously recognized the significance of those criteria. Nevertheless, the lack of documentation and digital information for older buildings was suggested to be a barrier for current EoL practitioners to feasibly estimate these environmental impacts. Economic criteria were also found to be important for all stakeholder groups. Notably, the sustainability specialists stressed the need to raise landfill fees and establish regulations and incentives that make deconstruction and reuse financially advantageous for property owners and investors. Experts associated with EoL facilities expressed a strong interest in potential revenue generation and emphasized the importance of diversion to avoid landfill fees.

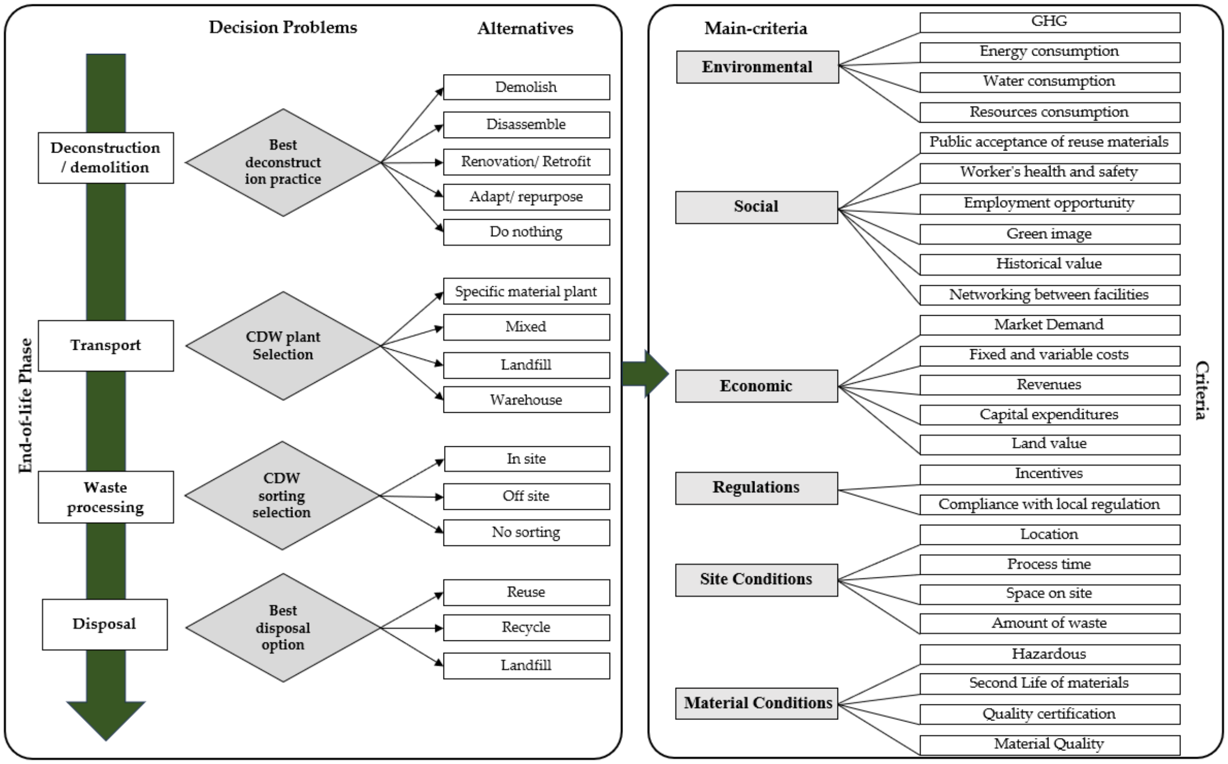


Figure 7. EoL Decision Framework: Decision Problems; Alternatives; Main criteria and criteria

Specific criteria, not commonly applied in previous studies, were also validated with the stakeholders, as shown in Figure 8. None of these criteria were unanimously selected to be removed from the framework, and only one criterion, i.e., 'Hazardous Materials,' was unanimously selected to be included in the framework. Furthermore, most participants agreed that historical value should be considered in EoL decisions, indicating the social motivation to maintain and not demolish certain facilities. Similarly, all stakeholder groups agreed land value, market demand, and amount of waste are important criteria, even if less common in the literature. Other criteria had mixed results, depending on the type of stakeholder group. For instance, 'Green image' was found to be important for construction, design, insurance, and sustainability professionals, but not for EoL service professionals or the community.

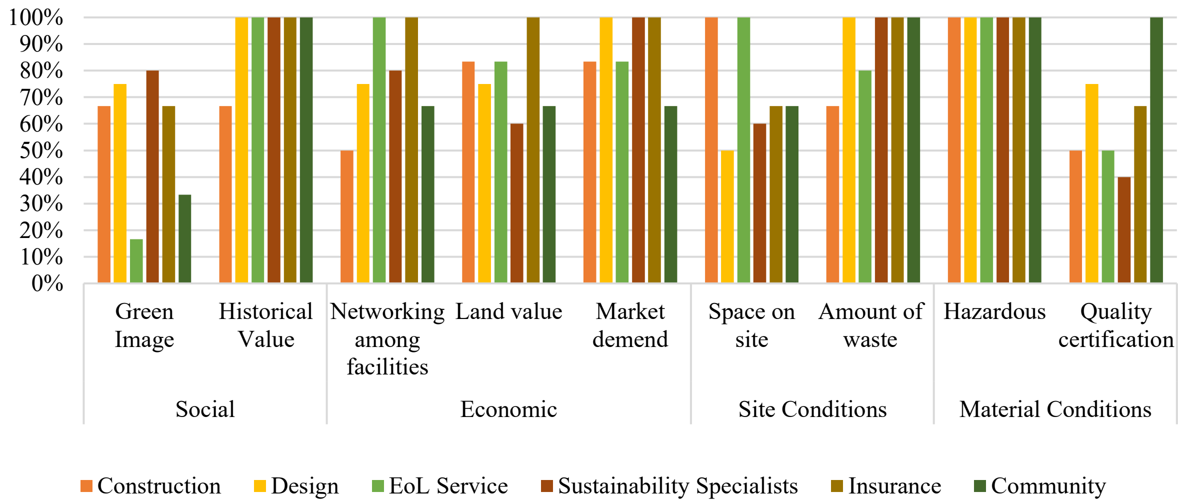


Figure 8. Criteria validation, percentage of criterion inclusion by the group of participants

4.2 Criteria Weighting

Like the validation interviewees, the 52 stakeholders engaged in criteria weighting found Regulations to be the most important main criteria, as shown Table 6. Compliance with regulations was also ranked as the most important criterion, as summarized in Table 7. Table 7 presents the criteria's local weight, i.e., weight within the relevant main criteria, and the global weight, i.e., overall weight among all main criteria. These findings shed light on the pivotal role of government participation and the formulation and expansion of regulations in advancing circularity in EoL.

Table 6.Main criteria weight distribution

Criteria	Weight	Priority
Regulations	0.222	1
Environmental	0.189	2
Economic	0.171	3
Social	0.145	4
Material conditions	0.144	5
Site conditions	0.129	6

In contrast to many other studies, ‘Economic’ criteria received a lower ranking than ‘Environmental’; likely due to the inclusion of diverse stakeholder groups in this study. Even though ‘Social’ criteria were rated fourth, its criteria ‘Worker's health and safety’ ranked third overall, as in Table 7. This highlights a significant concern for the well-being of workers involved in the EoL process. Similarly, ‘Material conditions’ was rated fifth, but its criteria ‘Hazardous materials' was rated second overall, also pointing to the importance of safety. Interestingly, 'Green image' emerged as the least important criterion, indicating that stakeholders prioritize environmental impacts over a perceived image, despite the importance of the image mentioned in the validation phase.

Table 7.Criteria, local and global weight distribution

Main Criteria	Criteria	Local Weight	Global weight	Priority
Environment	GHG emissions	12.54	2.4	16
	Energy consumption	32.61	6.2	4
	Water consumption	25.26	4.8	8
	Resources consumption	29.59	5.6	5
Social	Public acceptance of reused material	10.27	1.5	23
	Worker's health and safety	46.96	6.8	3
	Green image	6.79	1	25
	Historical value	14.95	2.2	18
	Networking among facilities	8.76	1.3	24
	Employment opportunities	12.28	1.8	11
Economic	Market demand	25.18	4.3	10
	Land value	14.07	2.4	15
	Fixed and variable costs	13.74	2.3	17
	Capital expenditure	19.56	3.3	12
	Revenues	27.45	4.7	9
Regulations	Compliance with regulations	76.80	1.7	1
	Incentives	23.20	5.1	6
Site conditions	Space on site	16.08	2.1	19
	Location	15.39	2	20
	Amount of waste	29.93	3.9	11
	Process time	38.60	5	7
Material conditions	Material quality	20.40	2.9	13
	Second life	12.10	1.7	22
	Hazardous	50.40	7.2	2
	Quality certification	17.10	2.5	14

Including multiple stakeholders at this scale in the decision process was a novelty of this study. The inclusion guarantees that participants with vested interests at the EoL stage (e.g. EoL Services, Insurance, Community, etc.) are not overlooked. Figure 9 shows the different weights provided by each group for each criterion. Most stakeholders prioritize regulation above all criteria aligning with the discussion from the semi-structured interviews. The results also show that construction, design, and insurance professionals still prioritize economics over environmental aspects. However, stakeholders who are most involved in or affected by the EoL stage (EoL services and community) value environmental aspects equally or more than economics. This disparity shows the difference in perspective between stakeholders involved in different EoL phases and the importance of including them in the decision process.

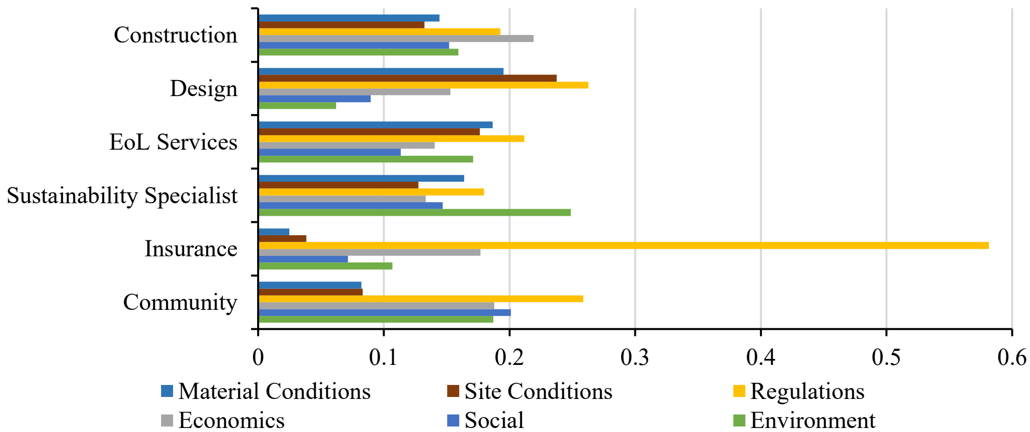


Figure 9 Level of importance of main criteria distributed by stakeholders' group.

Beyond recognizing the significance of each criterion for different stakeholder groups, it is crucial to consider the importance they attribute to each criterion throughout the EoL stages and their related decision problems. For the first and third decision problems, related to Demolition/Deconstruction and Waste Processing, respectively 'Regulation' stands out as the most important main criterion, as shown in Figure 10. For demolition/deconstruction decisions, this is likely due to the need to comply with local demolition regulations and obtain required permits. For waste processing, this is related to the need to meet existing regulations that often require some level of on-site sorting depending on the project size. In this third sub-phase, the least important main criteria were found to be 'Material Conditions' and 'Site Conditions.' Participants might have perceived that the condition of materials has less impact on sorting, as materials like scrap are often sorted on-site regardless of quality since they are sold by weight. While site conditions can facilitate on-site sorting, they are not viewed as critical barriers. Stakeholders during the semi-structured interviews acknowledged that difficult site conditions might complicate sorting but should not prevent it from happening.

In the second and fourth decision problems, related to Transportation and Disposal, respectively, 'Environment' was identified as the most important main criterion. This is likely due to the GHG emissions associated with transportation, and the direct environmental impacts of landfilling. It is also noteworthy that Economics was assigned a lower score in the disposal phase than in earlier phases, despite the potentially higher costs of landfill disposal. This discrepancy highlights a common focus on short-term costs in the construction industry, compared to long-term disposal costs and environmental impacts. This pattern underscores the challenge of integrating long-term sustainability into economic decision-making, emphasizing the need to consider both immediate and future costs in a more balanced manner.

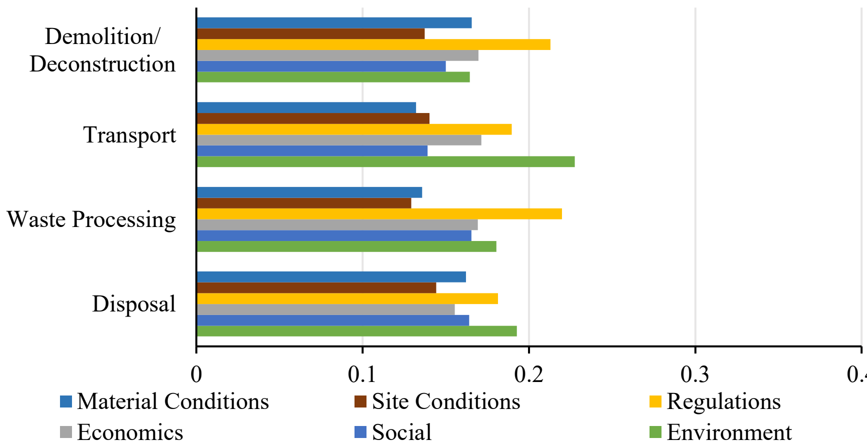


Figure 10. Level of importance of main criteria distributed by decision problems

'Site Conditions' consistently received the lowest score in all phases, except in Transportation where it was the second lowest. This main criterion not only includes criteria that were less common in literature, i.e., 'Space on Site' and 'Amount of Waste,' but also includes the criterion 'Location,' which was suggested by experts during the semi-structured interviews. The lack of widespread discussion and familiarity with these criteria may explain the consistently low weight of Site Conditions across decision problems. This gap highlights the need for better communication and education about site-specific issues in EoL decision-making processes.

Despite 'Social' criteria frequently being neglected in practice, it was never ranked the lowest importance among the EoL phases considered in the study. Herein, the inclusion of a diverse group of participants beyond those with profit-driven interests led to a relatively higher emphasis on social factors compared to other decision models. This suggests that social considerations may gain more prominence when the perspectives of a broader range of stakeholders are included. The lower weight assigned to 'Social' criteria in previous decision-making models underscores the need for greater advocacy and education to elevate their importance in industry practices.

Overall, these observations advance the understanding of the factors influencing EoL decisions for built facilities. They highlight the complexity of balancing 'regulatory, economic, environmental, material, and social considerations and the need for a more integrated approach to decision-making in the construction industry. While this study contributes a diverse perspective to the existing body of knowledge, it is generally constrained to Canadian practices, as the majority of respondents were from Canada. Another limitation is the inclusion of 25 criteria, which might pose a challenge for some stakeholders due to assessment difficulty. Nevertheless, the decision to include all criteria was based on expert input and literature findings, ensuring that stakeholders, even if they choose not to use all criteria, are aware of what has been deemed important by others.

Chapter 5. Model Implementation Methodology

This chapter focuses on the methods used to apply the model in a real case study. It begins with an overview of the case study, highlighting the project's key characteristics and relevance to the research objectives. Following this, the chapter explores the various scenarios considered in the analysis, detailing the specific conditions and assumptions that guide the evaluation process.

5.1 Case Study Evaluation

To test the practicality of the proposed model, we implemented it on a real case study. This process consists of five key steps:

1) Material Selection: For feasibility purposes, specific materials were selected for analysis rather than assessing every building component. This selection was made with the assistance of a professional demolition and deconstruction company.
2) Definition of EoL alternatives: Referred to as 'scenarios,' these alternatives represent possible outcomes for each decision problem defined in the model. Each alternative provides an option for the four main decision problems.
3) Data collection: This step outlines the sources and methods used to gather relevant data for the model.
4) Model evaluation: This phase includes data normalization, summation, and aggregation of data points according to each criterion's characteristics.
5) Sensitivity Analysis: This final step assesses each alternative's performance, evaluating how changes in criterion weight affect the final alternative rank to ensure robust decision-making.

5.1.1 Case Study Description

The selected building is situated near the Greater Toronto Area (GTA) in Ontario, Canada, primarily served as a resort. It features a two-story structure and a gross floor area of 59,360 SF. Timber, concrete, and concrete blocks are the primary construction materials, each used in specific subsystems. The structural framework is made of timber, and the floor system consists of wood slabs and joists. The foundation system is a slab-on-grade design using poured concrete, with over 20,000 square feet of concrete flooring. The wooden floor system covers more than 30,000 square feet. The building's framework includes wooden beams, pillars, and studs, with part of the wall system incorporating approximately 16,800 square feet of concrete block walls. This case study focuses specifically on these subsystems where timber, concrete, and concrete blocks play essential roles in the building's construction.

The resort was first opened as a hotel in the 1990s. Since then, it has undergone multiple renovations, amplified its capacity, and improved the property. These renovations resulted in an advantage over many other long-standing facilities due to the documentation of the modifications made. The building has drawings that allowed the owner to create a Revit model of the structures post-renovation. Figure 11 shows a schematic view of the building. This building was chosen for the case study due to its alignment with key evaluation criteria. In particular, its proximity to one of Canada's largest cities enhances access to recycling facilities and deconstruction alternatives. Additionally, the owner's interest in exploring options beyond demolition aligns with this study's objectives. The availability of detailed drawings and a Revit model also facilitates accurate material quantification, making it a suitable candidate for this analysis.

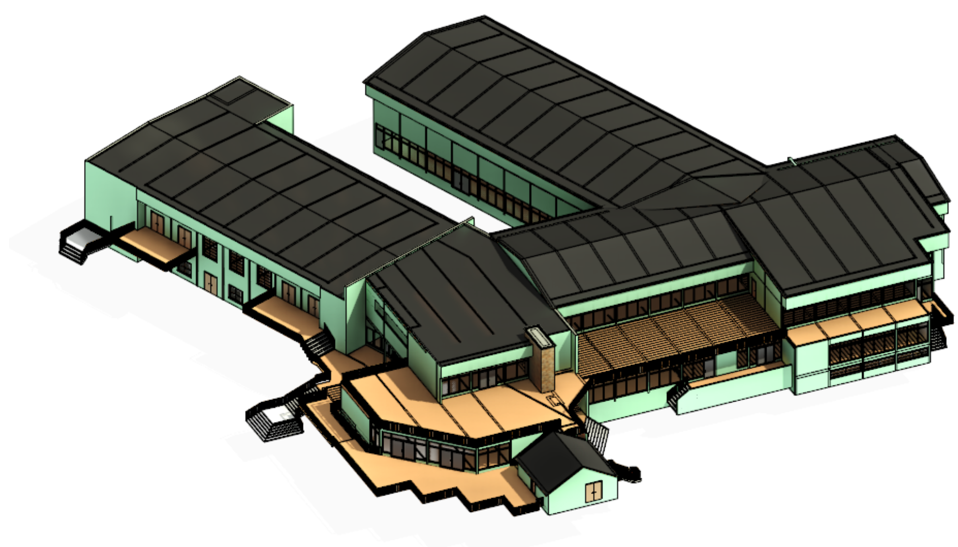


Figure 11 View of the case study's Revit Model

Using the model in Revit streamlined the material take-off process, making it easier and more accurate to quantify materials. The model, along with photos and reports provided by the owner, was crucial for gathering information on deconstruction, demolition, and partial demolition costs and revenues. Industry experts conducted a real-case evaluation of the cost and time for each proposed scenario. Additionally, photos of the building were sent to resellers to assess the potential salvage value of the building materials, particularly the timber.

5.1.2 Model Boundaries Definition

The goal of this step is to define feasible alternatives that address the various decision-making problems associated with the building's EoL phase. The model presents four distinct decision problems, and the objective is to identify alternatives that can be considered together. For example, this might include aligning reusable options with disassembly or ensuring waste is sent to specific facilities after sorting. To achieve this, two main inputs were required: first, understanding the owner's needs, and second, receiving guidance from industry experts (demolition/deconstruction manager) on effectively combining the possible alternatives.

The initial model included several EoL alternatives, such as Renovation/Retrofit, Adapt/Repurpose, Do Nothing, Demolish, and Disassemble. However, after discussions with the owner, it became clear that, due to the resort's multiple renovations, their primary intention was to remove the building. The owner's focus is on making an informed and sustainable decision, considering either demolition or disassembly. As a result, the other alternatives were excluded, narrowing the scope to these two options.

Demolition experts were consulted to ensure the chosen alternatives were feasible and realistic. A demolition management company based in the GTA with over 10 years of experience in demolition, deconstruction, and partial deconstruction projects provided valuable insights. An interview with one of their experts included discussions on project drawings and various deconstruction, demolition, and partial demolition alternatives. The company's feedback was instrumental in refining the model, offering a comprehensive view of feasible methods, salvageable materials, and the market demand for each service and material.

The company provided: (1) a list of removal options, including Full Deconstruction, Partial Deconstruction, and Full Demolition; (2) a combination of potential alternatives; (3) a list of materials with recycling potential; and (4) details on costs, time estimates, and crew sizes associated with each alternative. Additionally, while the company specializes in demolition, it also handles disassembly and partial disassembly, which is critical to the scope of this study. The information gathered offered a clearer understanding of the logistics involved in each method, including the time frames and crew requirements for demolishing, deconstructing, and sorting waste. Based on the expert consultation, the case study focuses on three main materials, concrete, concrete blocks, and timber, as these materials were integral to the building's construction and are commonly used in the Canadian construction sector. Concrete and timber are prevalent in both residential and commercial buildings, making them highly relevant for studies on EoL strategies. While their recycling rates may not be the highest, both materials present significant potential for reuse, repurposing, or downcycling, which aligns with the study's objectives of assessing sustainable EoL options.

Concrete, for instance, can often be crushed and reused as aggregate in new construction or road projects, reducing the need for virgin materials. Similarly, timber, particularly from structural elements, can be reclaimed for reuse in new construction or for creating value-added products such as furniture or flooring. Concrete blocks, while more challenging to recycle, can still be repurposed for non-structural applications or used in landscaping and site development. These materials were selected not only because they are integral to the building but also because they offer viable options for diversion from landfills through reuse, downcycling, or repurposing.

Moreover, the demolition and deconstruction industry in Canada has established methods for handling these materials, making them practical candidates for evaluating alternative EoL scenarios. Their selection also ensures that the case study is grounded in real-world conditions, where these materials are commonly found and their management is crucial for minimizing environmental impact. Four scenarios, which considered a group of alternatives for each decision problem developed in the model were considered. They are (1) Full Deconstruction, (2) Partial Deconstruction, (3) Full Demolition – Recycling, and (4) Full Demolition – Landfill.

In the Full Deconstruction scenario, the process involves careful disassembly of the wood structure and concrete blocks, along with machinery removal of the concrete slab. This approach requires a longer duration and larger crews. For the second decision problem, CDW plant selection, two options are considered: a warehouse for storing disassembled materials and a specific material plant for processing concrete into aggregates. The third decision problem, CDW sorting, is considered to be all in-situ, which takes longer but may reduce gate fees and additional charges for external sorting. For disposal, timber and concrete blocks are considered for reuse, while concrete is recycled.

In the Partial Deconstruction scenario, this alternative also considers two options for the first decision problem. Unlike the Full Deconstruction scenario, only the timber is disassembled. The concrete blocks are not considered for disassembly because they are more difficult to reuse in the market and require additional time for cleaning and separating from mortar. As a result, the concrete blocks and slabs are demolished. For the second decision problem, CDW plant selection, the timber is directed to a warehouse for storage, while the concrete blocks and slab are sent to a specific facility. The materials are sorted in situ, in the same manner as in the Full Deconstruction scenario. For disposal, the timber is reused, and the concrete and concrete blocks are recycled.

Two Full Demolition scenarios are considered: Scenario 3 – Demolition – Recycling and Scenario 4 – Demolition – Landfill. Both scenarios involve complete demolition of all selected materials, which requires a smaller crew and is faster compared to disassembly options. For the CDW plant selection, Scenario 3 sends all materials to a mixed waste plant for recycling, while Scenario 4 sends the materials to a landfill. There is no in-situ sorting considered for those scenarios, which saves time for the demolition crew. However, this time savings is offset by additional gate fees at the EoL facilities. For disposal, Scenario 3 recycles all materials, while Scenario 4 disposes of all materials in a landfill. Figure 12 shows the material distribution flow from each of those scenarios. Each scenario is represented by a color.

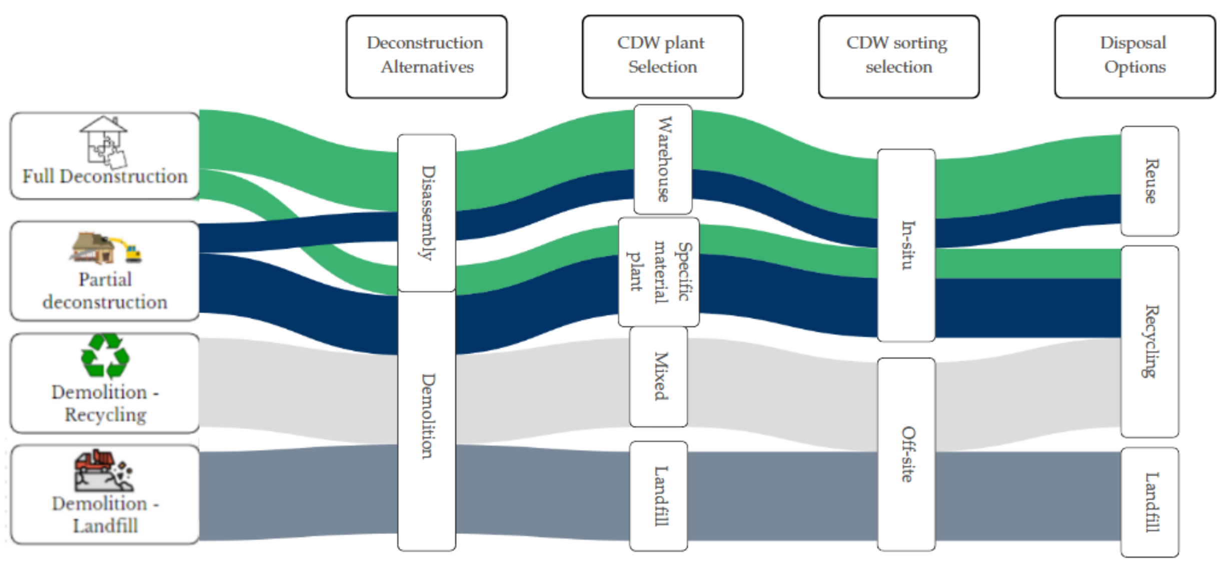


Figure 12 Material flow through the EoL phase

The developed model includes four decision problems, with each scenario offering one or more options under each decision problem, resulting in a group of alternatives to be evaluated collectively. With the assistance of the industry collaborator, four different scenarios were outlined as introduced in Figure 12, which illustrates the flow of materials through the EoL decision problems under each scenario. Additionally, different scenarios entail the placement of certain materials into certain waste streams. Table 8 describes in more detail which materials are considered in each of these scenarios for each method.

Table 8. Material Distribution Between Scenarios

Scenario		Disassembly & Reuse	Recycling	Landfilling
Scenario (1)	*Full Deconstruction*	T, B	C	N.A.
Scenario (2)	*Partial deconstruction*	T	B, C	N.A.
Scenario (3)	*Full demolition-recycling*	N.A.	T, B, C	N.A.
Scenario (4)	*Full demolition- landfill*	N.A.	N.A.	T, B, C

C: Concrete, B: Concrete Blocks, T: Timber structure

5.2 Model Evaluation Methods

This section provides an overview of the criteria selected for this case study, including a summary of all removed criteria and the rationale behind their exclusion. Additionally, it describes how each criterion was evaluated and assigned based on its role and impact within the study. This section also covers the aggregation methods applied, outlining the steps taken to consolidate results from each decision problem into a single, cohesive value that captures the overall impact. The normalization methods are also discussed, and finally, a sensitivity analysis is presented to examine the robustness of the findings and to determine the extent to which each criterion influences the overall outcome.

Certain criteria were excluded from this case study as they were not applicable based on the selected alternatives. The following criteria were removed: Historical Value, as the building does not hold any historical significance or heritage value; Land Value, since all alternatives would result in an empty plot of land; and Quality Certification, because none of the materials in the building are certified in any way. Additionally, Hazardous Materials were considered non-existent due to the lack of a detailed inspection. Material Quality was not assessed, as it would require further inspection post-removal; for this study, all deconstructed materials were assumed to be in good condition for reuse. Similarly, Second Life of Materials was not included, as it would require a specialist's inspection, which was not available for this case.

All of the remaining criteria were considered submitted to three categories. The first one divided the criteria into two groups: benefit and cost (Fiore et al. 2020). This separation allows for a clearer and more systematic evaluation of each criterion based on its impact on the overall decision-making goal. Dividing criteria into benefit and cost categories is essential to ensure that a higher overall score consistently indicates the best option. High values in Benefit criteria are desirable and contribute positively (e.g., 'Green Image,' 'Employment Opportunity,' 'Revenues'). In contrast, certain criteria, such as 'Energy Consumption,' 'Process Time,' or 'Costs,' are classified as Cost criteria due to their adverse impacts when values are high. Cost criteria are inversely proportional, meaning higher raw values result in lower scores after normalization, ensuring a balanced comparison across all criteria within the model. The second classification divides criteria into Quantitative, Qualitative, and Binary. This classification is straightforward: Quantitative criteria use numerical values, Qualitative criteria rely on subjective judgment, and Binary criteria give yes/no assessments. The last category includes Dynamic criteria. As defined in this study, represent criteria that are highly local and time-sensitive, with the ability to change frequently (Giorgi et al. 2022), which makes them imprecise and difficult to evaluate. These criteria— 'Public Acceptance of Reused Materials,' 'Market Demand,' and 'Networking Between Facilities' were selected based on input from experts participating in the validation of the decision model.

Given their variability, they were evaluated under hypothetical 'Status Quo - Linear' and 'Future – Circular' cases. The Future – Circular case represents a situation where circularity is well-established, with high acceptance of reused materials, strong connections between facilities, and high market demand. In contrast, the Status Quo – Linear case represents a situation where the acceptance of reused materials is low, there is no collaboration between facilities, and the market demand is minimal.

The next step is to determine a single representative value for each criterion, reflecting the combination of all decision problems within a given scenario. Each criterion was analyzed under each decision problem (i.e., deconstruction, sorting, transportation, and disposal). For example, 'GHG Emissions' were collected for each phase, and a summation of all these inputs provided one main result per criterion. While most criteria were aggregated through summation, some, like 'Location'—measured by the distance to EoL facilities—were averaged due to their nature.

Additionally, certain criteria were not considered in every decision problem because they were irrelevant, already considered as a whole, or not applicable. It is essential to note that all four scenarios were assessed consistently; if a criterion was omitted in one, it was omitted in all scenarios. Table 9 provides a list of criteria, indicating their assigned groups and the aggregation method applied to each in addition to the source of the data collection.

Table 9. Assessment and Measurement Methods Used per Criteria

Criteria	Benefit or Cost	Evaluation Approach	Unit	Aggregation method	Data Source
CO_2 e	COS	QT	Ton	Sum	OneClick
Energy Consumption	COS	QT	kWh	Sum	OneClick Reports
Water Consumption	COS	QT	m^3	Sum	DC Reports
Resources Consumption	COS	QT	Ton	Sum	Revit
Public Acceptance of Reused Material	BEN	DY	N.A.	N.A.	Dynamic
Worker's Health and Safety	BEN	QT	Number of accidents	Sum	Reports
Employment Opportunity	BEN	QT	Number of jobs	Sum	Reports
Green Image	BEN	QL	Low, medium, or high	Average	DC
Historical Value	N.A.	N.A.	N.A.	N.A.	N.A.
Networking Between Facilities	BEN	DY	N.A.	N.A.	Dynamic
Market Demand	BEN	DY	N.A.	N.A.	Dynamic
Fixed and Variable Cost	COS	QT	$	Sum	DC
Revenues	BEN	QT	$	Sum	IP
Capital Expenditures	COS	QT	$	Sum	IP
Land Value	N.A.	N.A.	N.A.	N.A.	N.A.
Incentives	BEN	BI	BI	BI	GD
Compliance with Regulation	BEN	BI	BI	BI	GD

Location (distance from EoL facilities)	COS	QT	Km	Average	Google Maps
Process Time	COS	QT	Days	Sum	DC
Space on Site	N.A.	N.A.	N.A.	N.A.	N.A.
Amount of Waste	COS	QT	Ton	Sum	Revit
Hazardous	N.A.	N.A.	N.A.	N.A.	N.A.
Second Life of Materials	N.A.	N.A.	N.A.	N.A.	N.A.
Quality Certification	N.A.	N.A.	N.A.	N.A.	N.A.
Material Quality	N.A.	N.A.	N.A.	N.A.	N.A.

COS: Cost, BEN: Benefit, QT: Quantitative, QL: Qualitative, BI: Binary, DC: Demolition Company, GD: Government Data, IP: Industry Partner

In AHP, data normalization is a critical step to ensure that the criteria and criteria values are comparable and within a standard range (Chen et al. 2013). This study used Linear Max as a Normalization method. The process required dividing the criteria into 'Benefits' and 'Cost' categories (Chen et al. 2013). For Benefit criteria, where higher values are preferred, the data is normalized by dividing each criterion value by the maximum value in the dataset. This method ensures that the highest value receives the highest score of 1, and all other values are scaled linearly.

For Cost criteria, where lower values are preferred, normalization is done in much the same way but the scaled value is subtracted from 1. This ensures that the worst alternative (the highest value for cost) is scaled to 0, and the best alternative (the lowest value) is scaled to 1. This normalization technique ensures that all criteria are on a comparable scale (0 to 1), allowing for an accurate aggregation of the results across decision problems.

5.3 Data Collection

The data needed for this assessment can be divided into three categories. The first one is the physical characteristics of the building to collect the amount and type of materials as well as the assembly information. This information is crucial for the building material take-off; this will guide the costs related to each service in addition to the environmental impacts. The second category is accounting for environmental assessment by quantifying the impact of each scenario. Software tools such as Revit and OneClick LCA were used to facilitate this process. The last category is collecting data from the external environment, including cost, revenues, regulations in place, and so on.

BIM, photos from a site inspection, and printed projects were used to collect the building's physical information. The combination of those data allowed a more complete understanding of the building. Since it was an old project, the BIM model was built later during one of the renovations. The BIM model was then used for material quantification; the material type was collected mostly from photos, assessment reports, and some printed projects.

To quantify the environmental impacts, a combination of the OneClick tool, Government reports, and partner input was needed. Based on the amount and type of materials identified from the previous step, the 'GHG Emissions' could be calculated. OneClick is a widely used tool that helps consultants, companies, and researchers calculate some environmental impacts (Lorna et al. 2024)The tool calculates the amount of 'GHG Emissions' for demolition, disassembly, and partial disassembly based on the building area and type.

Other impacts were calculated based on government reports and previous research; for example, the water use was calculated based on the number of workers estimated by the demolition company during the demolition process (including showering, cleaning, and cooking)(Korol and Dudina 2023). 'Energy Consumption' was converted from 'GHG Emissions'(Independent Statistics and Analysis 2023). Job opportunities were also based on reported job creations using different practices (reuse, landfill, etc.) (Tellus Institute with Sound Resource Management 2007). To assess 'Worker's Health and Safety' data was collected from a post-demolition/deconstruction phase since there are more reported cases at this stage (Oldendorf 2022).

The external environment data is extensive and complex to collect; however, it is essential since this data brings realistic options. This data collection includes costs from the demolition company who assisted us in this case, fees from recycling facilities and landfills, and potential material value (revenues) based on material type coming from second-hand facilities. Additional costs were calculated for the transport of the waste from the project site to the EoL facilities. Figure 13 describes the steps previously explained under methodology, highlighting the criteria removal and categorization in addition to the data collection and the tools and resources used. Among the criteria related to regulations, the most crucial criterion in this study is 'Incentives.' Due to the complexity of accounting for benefits such as carbon credits and the absence of a legal advisor on this project, 'Incentives' was treated as a binary criterion. Scenarios involving diversion options—Full Deconstruction, Partial Deconstruction, and Demolition – Recycling—were assigned a score of one, while Demolition – Landfill scored zero. This approach allows a simplified yet practical representation of 'Incentives,' emphasizing practices that support waste diversion.

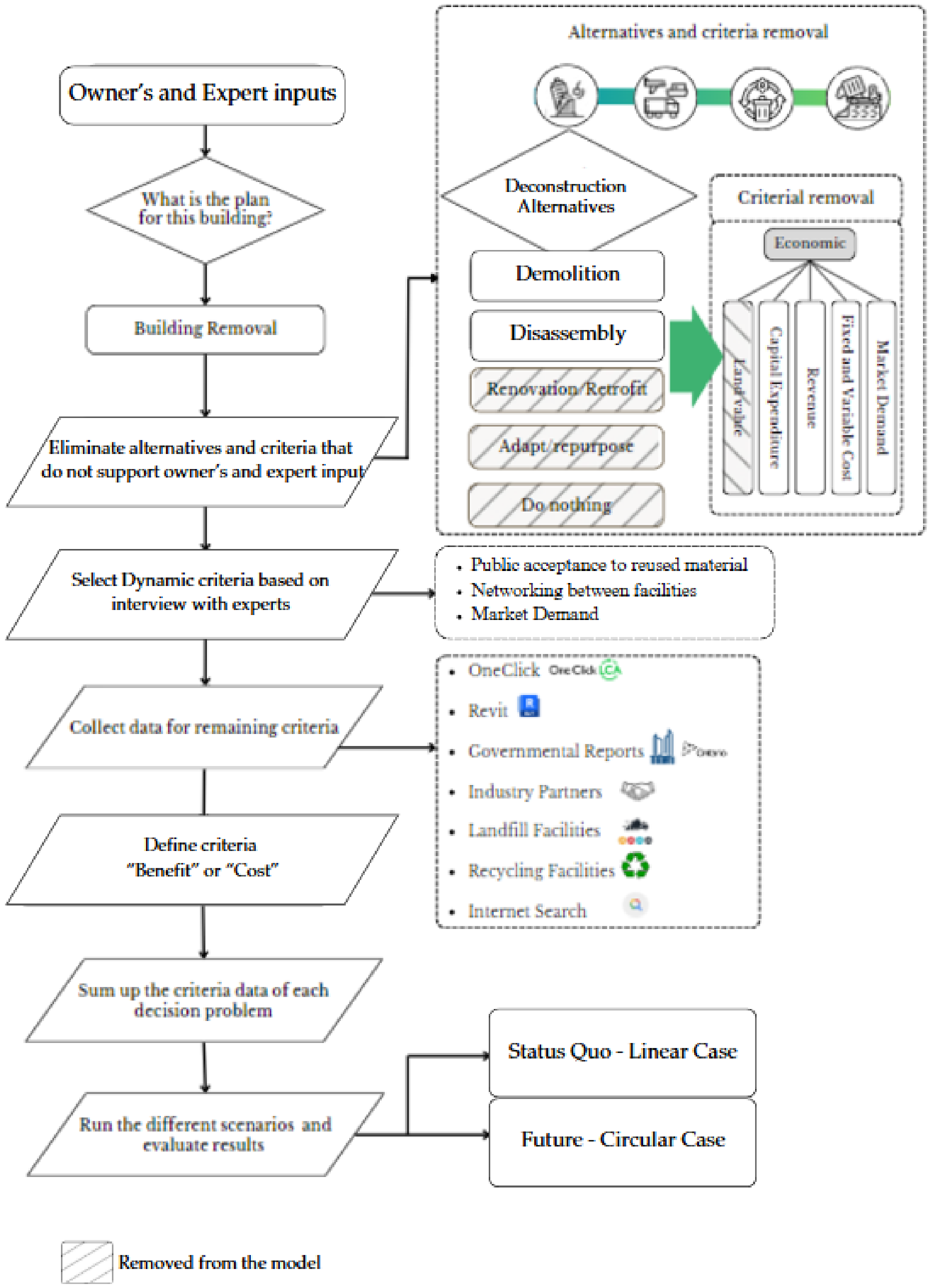


Figure 13 Methods of Criteria Definition, Removal, and Assessment

5.4 Evaluating Model Performance

After ensuring the values are comparable, each scenario's "Performance" score can be calculated. The normalized value of each criterion is multiplied by the weight assigned to that criterion, which was determined through the online survey. These weighted values are then summed, resulting in the overall performance score for each scenario. To verify the robustness of the model, considering the change in scenarios' ranks, a sensitivity analysis was conducted. Sensitivity analysis is a crucial component of the AHP as it provides insights into how changes in criteria weights influence the overall rankings of the alternatives. This analysis evaluates the robustness and stability of the AHP outcomes when/if the criteria weights are altered.

For this study was decided to use the one-at-a-time (OAT) technique (Chen et al. 2013). OAT is a common screening experiment that evaluates the impact of changing each chosen factor's values individually. The method consists of varying the criterion weight individually, while the others are kept constant, and observing the results in the alternative ranking. This method is methodologically simple, computationally inexpensive, and easy to develop (Chen et al. 2013). OAT's main limitation is that it does not account for potential interactions between the criteria, as each criterion is altered independently.

The initial set of weights derived from the pairwise comparisons in the AHP model was established as the baseline. Each criterion weight was then systematically varied by ±10%, OAT (Więckowski and Sałabun 2024) while keeping the other criteria weights constant. The chosen criteria will increase or decrease by 10%, and the remaining criteria will be adjusted proportionally based on their original weight. This range was chosen to provide a comprehensive assessment of the model's stability without introducing unrealistic weight variations(Więckowski and Sałabun 2024; Chen et al. 2013). This approach allowed for a clear understanding of the individual impact of each criterion on the overall ranking of the alternatives (Chen et al. 2013). For each variation, changes in the ranking of the alternatives were recorded to identify which criteria significantly impacted the rankings.

Chapter 6. Model Implementation's Results and Discussion

In this chapter, the implementation of the proposed model and the results of the case study are presented and analyzed. The discussion explores the performance of all evaluated scenarios across different decision problems, highlighting key insights into the relative strengths and weaknesses of each approach. By examining the implications of these results, this chapter aims to provide a deeper understanding of the factors influencing EoL decisions for built facilities, emphasizing the potential for circular strategies to address current industry challenges.

6.1 Model Results

As described in the methods section, two primary categorizations were applied to the criteria. The first categorization classified each criterion as either a Benefit or a Cost. After normalization, all results were scaled to ensure that higher values consistently indicate a more favorable impact on overall performance. The second categorization grouped the criteria into Quantitative, Qualitative, Binary, and Dynamic types. Given that the Dynamic criteria yield two different outcomes (the Status Quo – Linear and Future – Circular case).

The three Dynamic criteria were evaluated on a scale from 1 to 4, with 1 representing the lowest performance level and 4 representing the highest. In the Future – Circular case, Full Deconstruction was given the highest performance score (for the Dynamic criteria), followed by Partial Demolition, Demolition – Recycling, and Demolition – Landfill, in descending order. Conversely, in the Status Quo – Linear case, these ratings were inverted to reflect the least favorable circularity outcomes. Table 10 presents the aggregated values of each criterion across scenarios before normalization, along with the corresponding metrics used for each criterion.

Table 10 Raw values of criteria across scenarios and their corresponding metrics

Criteria	Unit	Full deconstruction	Partial deconstruction	Demolition Recycling	Demolition Landfill
CO2	Ton	202.46	266.16	320.20	284.70
Energy Consumption	kWh	891553.91	1204417.49	1425247.05	1397441.60
Water Consumption	Liters	61800.00	1204417.49	1425247.05	1397441.60
Resources Consumption	Ton	466.56	714.58	1377.63	1377.63
Public Acceptance of reused material	Dynamic	4 or 1	3 or 2	2 or 3	1 or 4

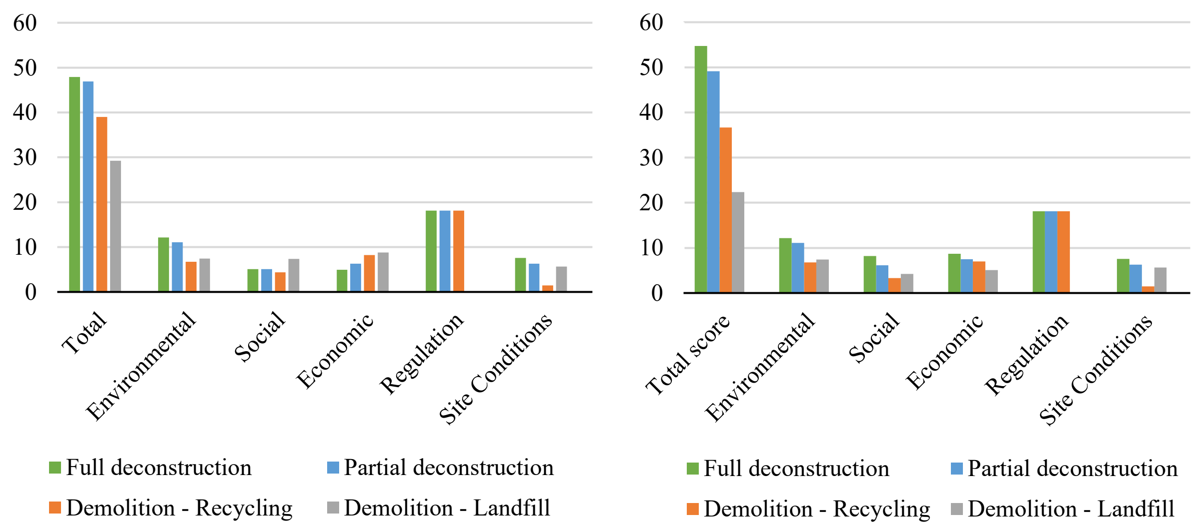
Worker's health and Safety	Accidents/ 100 full- time employees	3.20	3.20	3.20	2.20
Employment Opportunity	Jobs/1000 Ton	15.48	10.99	6.76	5.38
Green Image	Qualitative	4	3	2	1
Networking between facilities	Dynamic	4 or 1	3 or 2	2 or 3	1 or 4
Market Demand	Dynamic	4 or 1	3 or 2	2 or 3	1 or 4
Fixed and variable cost	$	397,306.04	377,405.12	469,271.16	623,530.90
Revenues	$	95,676.57	95,676.57	0	0
Capital expenditures	$	8,500.00	8,500.00	0	0
Incentives	Binary	1	1	1	0
Compliance with regulation	Binary	1	1	1	0
Location	Distance (km)	154.00	179.00	230.00	86.80
Process time	Weeks	13	10	8	2
Amount of waste	Ton	466.56	714.58	1377.63	1377.63

A notable variation in criterion values can be observed across the scenarios; however, drawing solid conclusions is difficult without considering the weights assigned to each criterion. To address this, Figure 14 will be presented (a) Status Quo – Linear case and (b) Future – Circular case, now integrating criterion weights to calculate an overall performance score for each scenario. By applying these weights, this approach allows a more holistic view of each scenario's effectiveness, ultimately enabling a clear scenario ranking.

Figure 14**Error! Reference source not found.** (a) shows the overall scores and breaks down scores by main criteria for each scenario under the Status Quo – Linear case, highlighting the ranking of preferred scenarios within this specific framework. In this case, two scenarios achieve almost the same score. They are Full deconstruction and Partial deconstruction. As seen in the breakdown scores, Full – Deconstruction has the highest score in ‘Environmental,’ and ‘Site Conditions.’ The same scores in ‘Regulations,’ similar scores in ‘Social,’ and the lowest score in ‘Economics.’ The lower scores are due to the Dynamic criteria that, in this case, prioritize the Demolition options.

When evaluating the Future – Circular Case the situation will be more favorable to the Deconstruction scenarios. Similarly, Figure 14 (b) presents an overall score and breaks down scores by the main criteria of all scenarios. For this situation, the best scenarios were in order: Full Deconstruction, Partial Deconstruction, Demolition – Recycling, and Demolition – Landfill.

Differently than the Status Quo – Linear, Full Deconstruction scores the highest in all the main criteria followed by Partial Deconstruction.



(a) Status Quo – Linear Case **(b) Future - Circular Case**

Figure 14 Scenarios Performance

The two Status Quo – Linear and Future-Circular cases show differences in overall scenario performance. In the Future – Circular case, Full Deconstruction ranks the highest with a slightly bigger difference from the second-best option (Partial Deconstruction), while in the Status Quo – Linear case, Full Deconstruction and Partial Deconstruction are basically tied at the top spot. In both cases, Demolition – Recycling follows closely behind, with a slightly smaller gap in the Status Quo – Linear case. Demolition – Landfill consistently ranks last, with a more significant gap compared to the other scenarios. This difference is primarily due to the regulatory criteria, which favor all scenarios except Demolition – Landfill.

Based on these results, a sensitivity analysis was conducted to test the robustness of the model. Two analyses were conducted, one for the Status Quo – Linear case and one for the Future – Circular case. The 'Baseline' represents the performance without any weight alteration. Then 10% is added or removed from each main criterion, while the other criteria have their weights changed proportionally from the original weight. The final performance can be compared to the 'Baseline.' This practice is repeated for all the main criteria. Figure 15 shows the comparison between the 'Baseline' of each alternative scenario and its variation for Status Quo - Linear.

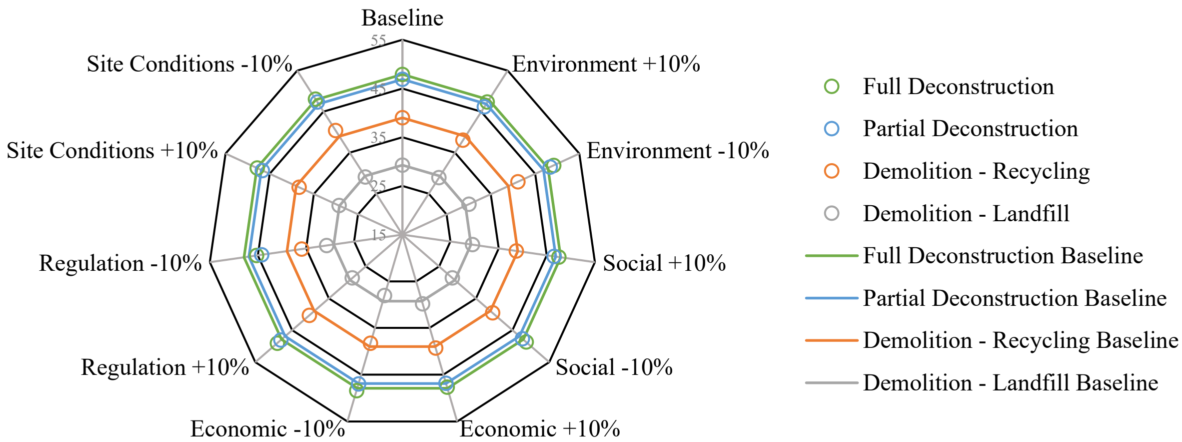


Figure 15 Status Quo – Linear – Sensitivity analysis comparative graph

Under the Status Quo – Linear case, Full Deconstruction and Partial Deconstruction have very close scores, 47.9 and 46.9, respectively. Despite this proximity, the model maintains the ranking priority of the four scenarios. The same analysis was done for the Future – Circular case. As shown in Figure 16. When there is a greater distinction between alternatives, the stability of each scenario's priority is clearer.

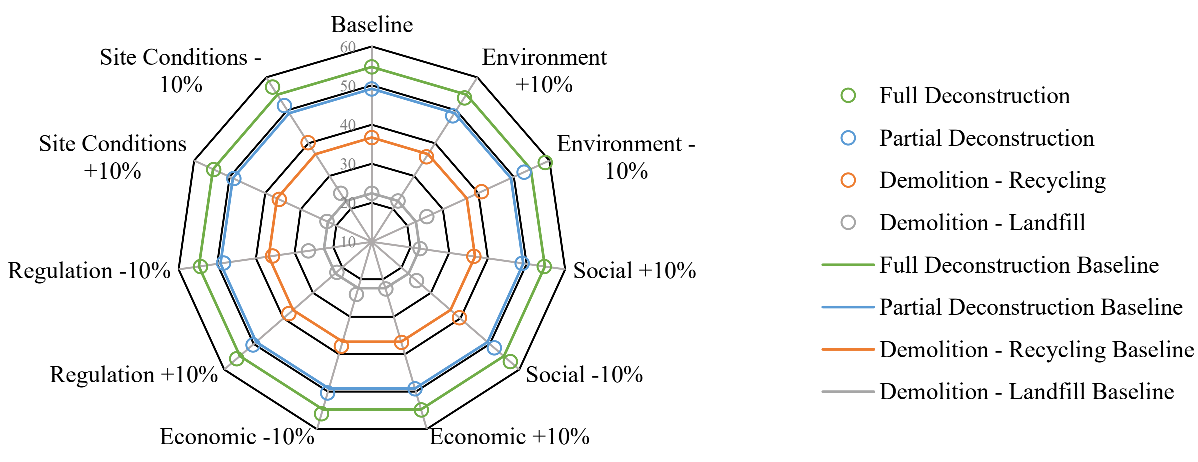


Figure 16 Future - Circular – Sensitivity analysis comparative graph

This analysis shows that, especially under the Canadian Status Quo, deciding on the EoL practices is still ambiguous. Two scenarios (Full Deconstruction and Partial Deconstruction) were virtually indistinguishable by the model under the Status Quo – Linear case. However, the other alternatives

(Demolition – Recycling and Demolition – Landfill) were consistently shown to be less desirable. Furthermore, stability was also observed under the future–circular case, where the rank priority of all scenarios remained consistent.

6.2 Model Evaluation Discussion

By looking at each criterion separately from the full scenario performance it can be observed in Table 10, that in the first criterion, 'GHG emission,' Demolition-landfill performed slightly better than Demolition – Recycling alternative. This might be due to the higher CO2e emissions of the recycling process that was considered by OneClick compared to landfill disposal, which may not consider long-term environmental impacts. Additionally, the 'Water Consumption' was higher for the Full Deconstruction scenario because the water considered in the process included the workers' use during the deconstruction/demolition process (for showers, cleaning, and other basic uses), which was deemed insignificant in other processes (NRC and CNRC 2022).

For 'Worker's Health and Safety,' the unit selected was the number of accidents. There is insufficient documentation and study of the best practices to avoid accidents on job sites for workers in deconstruction projects. These practices are still in development and have less historical precedent to draw upon. Based on this limitation, the only safety data used was regarding recycling practices vs landfill disposal, which are more widely reported (Alipour-Bashary et al. 2021).

Another significant point of interest for most stakeholders is the 'Cost' of each scenario. In this study, quotes from a demolition/deconstruction industry partner in Toronto were used to ensure the prices under consideration are realistic to the current market rates. While deconstruction costs are the highest, the summation of 'Costs' for the entire Partial Deconstruction and Full Deconstruction scenarios had the best performance.

When considering the overall cost, Partial Deconstruction comes as the cheapest (~\$310,000), followed by Full Deconstruction (~\$290,000), Demolition – Recycling (~\$460,000), and last Demolition – Landfill (~\$620,000). The high costs of Demolition – Landfills are primarily associated with the gate fees of landfills near GTA for CDW. The reduction in the price of both Deconstruction Scenarios comes from considerable revenue estimated by the sale of the timber used in the building. This estimation is also very sensitive to location and mainly market demand. A building should not expect to have this return as standard practice.

An additional cost was considered for the Deconstruction scenarios as ‘Capital Expenditure.’ Since extra research and assessment were done to analyze possible deconstruction and resale alternatives, a consultancy fee was added to those alternatives. Yet, even if the Deconstruction scenarios did not have any ‘Revenue’ from the material sale, the extra cost from ‘Capital Expenditure’ would not be significant enough to change the overall cost ranking.

The economic overall score, however, is not only based on those costs. It also includes the ‘Market Demand,’ which aim to reflect the complexity and instability of the market. Changing based on the practices established in a given location. In this study favoring Demolition scenarios on Status Quo – Linear and Deconstruction ones on Future – Circular.

The project's feasibility in meeting deadlines and sending CDW to their respective facilities is a crucial consideration for the technical team. As expected, more landfills are available than recycling facilities for CDW. The nearest landfill was approximately 80 km away while recycling facilities that accepted all CDW materials were situated over 200 km away. Surprisingly, a nearby facility, located about 150km away, was willing to sell reused material; however, this is not a universal reality for all projects due to the limited availability of such facilities (Shooshtarian et al. 2020).

The time required for the various processes in deconstruction/demolition and CDW sorting is a high priority when scheduling such a project. As expected, the Demolition – Landfill scenario is the quickest, with the estimation of less than one month to demolish and remove the waste, while Full Deconstruction takes over three months of work due to the careful handling required for the materials, as seen in Table 10. These insights support the idea that while deconstruction is achievable, it requires more extensive planning and preparation.

Within the regulatory criteria, ‘Incentives’ and ‘Compliance with Regulation’ carried substantial weight in the decision model. The criterion, ‘Compliance with Regulation,’ is modeled in this study as a binary variable due to the complexity of its assessment. In Ontario, as per the Ontario Environment Protect Act (Reg 103/9), at least 75% of the waste inevitably generated from construction activities shall be diverted from landfills (Ontario Regulation 103/94 2011). The Demolition – Landfill is the only scenario that will be non-compliant with these regulations.

While examining each criterion independently provides insights into each parameter's strengths and weaknesses, it is essential to consider the scenarios holistically to understand their overall impact and viability. The Status Quo—Linear case can be argued to reflect the current Canadian status quo practice more accurately. Under these conditions, the best options for the project, ranked by the decision model, would be inconclusive. Full Deconstruction and Partial Deconstruction are basically tied up, followed by Demolition—recycling and Demolition—landfill.

It is assumed in the Future – Circular case that circularity is well established in Canada. This assumption contrasts with the current Canadian status quo, which still requires significant development in this area (Lynch 2022; Allam and Nik-Bakht 2023). Under these conditions, the best options for the project based on the performance of the scenarios under the decision-making model would be Full Deconstruction, Partial Deconstruction, Demolition – Recycling, and Demolition – Landfill, respectively.

The Full Deconstruction and Partial Deconstruction alternatives represent a hybrid approach, combining disassembly for wood components with demolition for the concrete slab. These options also integrate a mix of reuse and recycling strategies, which are more achievable since in reality not all materials are suitable for reuse.

It is valid to remember that the selected scenarios were developed with the assistance of an industry partner, using the building assessment as a baseline for the decision-making model. However, additional scenarios can be tailored to the specific needs of each project.

The model's sensitivity analysis confirmed its robustness, showing stability even when criterion weights were adjusted for the sensitivity test. The sensitivity analysis confirmed that small changes in weights did not alter the ranking of alternatives, reinforcing the model’s reliability. This indicates that the model can accommodate additional scenarios without requiring recalibration. For instance, if a new scenario is introduced, the sum of scores across decision problems and multiplication of criterion weights ensures adaptability while preserving the model’s integrity.

The sensitivity analysis also highlights how the significance of criteria evolves across different decision problems, reflecting the distinct priorities of each phase. For example, in Demolition/Deconstruction, criteria such as ‘Regulation’ and ‘Economics’ tend to take precedence due to the emphasis on ‘Compliance with Regulations’ and cost efficiency. Conversely, in phases like Waste Processing or Disposal, ‘Environmental’ Impact and ‘Social’ Conditions become more critical, aligning with goals of sustainability and addressing community concerns.

Additionally, this decision-making model balances ‘Economic’, ‘Environmental’, ‘Social’, Regulations, ‘Site Conditions’ and ‘Material Conditions’, offering practical guidance for stakeholders. Some aspects, such as economic and environmental factors, are closer to implementation due to more available data and established benchmarks. In contrast, social criteria remain ambiguous, with high sensitivity to local contexts and limited data availability.

These findings show that landfill is the least favorable option when considering a holistic assessment, even under a reality not fully tailored for circularity. Those results demonstrate how regular decision practices do not consider the actual landfill cost (with all environmental and social impacts). These findings underscore the critical role of regulatory incentives and a well-connected infrastructure in promoting sustainable deconstruction practices.

If there were no incentives or regulations that prioritize the other alternatives, Demolition - landfill could have achieved the highest score. Ultimately, those results reveal an opportunity for policy and industry advancements to help shift Canada’s construction practices towards more circular, environmentally resilient approaches.

The main challenges must be addressed for a future circular case to be realized and for decision-makers and building owners to incentivize them better to adopt more deconstruction practices. The first is the broader use and certification of reused materials; the second is an improved regulatory and legal framework to incentivize this adoption properly; and the third is the proliferation and networking of waste processing centers that can accommodate these new waste streams.

This case study showed that dumping waste in a landfill was the most expensive option for this proposed project. Despite this cost, if it were legal and complied with regulations, it could be preferable under the Status Quo – Linear case to dump all construction waste in a landfill according to this decision model. The laws and regulations in the Toronto area appear to have been crafted to disincentivize the exclusive use of landfills by demolition companies. This will not be the case in every jurisdiction.

More access to information may be needed to increase the adoption of practices more closely align with a Future – Circular case. This study collected valuable data that is often not readily available to decision-makers. A further step to improve those decision processes would be creating an online platform where people could compare deconstruction and demolition costs and facilities where each type of CDW is acceptable, and gate fees associated with it. Educating people and making information available to show the financial advantages of deconstruction practices to decision-makers who might assume that costly, environmentally destructive practices are best for their needs.

Chapter 7. Concluding Remarks

Deconstruction and circularity in construction have recently garnered the attention of researchers and practitioners. A key barrier to greater adoption of circular practices in construction has been the complexity of making decisions that account for multiple types of benefits and costs. The present study contributes to the existing body of knowledge by developing a comprehensive and inclusive decision-making model. Unlike previous studies, the model considers all sub-phases of the facility EoL and includes the perspectives of diverse stakeholder groups involved in the EoL.

Based on a systematic literature review, the proposed model divides the EoL phase into four sub-phases: (1) deconstruction/demolition, (2) transport, (3) waste processing, and (4) disposal, each with a decision problem and related alternatives. To make these decisions, 23 criteria were compiled from the literature and organized into six main criteria: ‘Regulations,’ ‘Environmental,’ ‘Economic,’ ‘Social,’ ‘Material Conditions,’ and ‘Site Conditions.’ Validation of this framework with stakeholders led to adding two more criteria: ' Land Value’ and ‘Location.’ Stakeholders participated in the study to validate the framework and define the criteria weights. These stakeholders covered six groups: (1) Design; (2) Construction and Operation (3) EoL Services; (4) Sustainability Specialists; (5) Insurance; and (6) the Public Community.

Including these stakeholders provided insights into the different priorities of each group and the most essential criteria overall. In general, the stakeholders emphasized the importance of ‘Regulations.’ Not only was it rated as the most crucial main criterion, but the ‘Compliance with Regulations’ criterion was also rated as the most important overall. This underscores the importance of promoting the creation and extension of regulations within the construction sector. The second most important main criterion was ‘Environment,’ above ‘Economic’ considerations, rated third, different from many previous studies. The focus on the environment reflects the increasing urgency to address environmental concerns and climate change. Interestingly, economic criteria were only considered the most important for the construction professionals. Despite the ‘Material Conditions’ and ‘Social’ main criteria being rated less important, some of the criteria under those were considered highly important. The presence of ‘Hazardous Materials’ was the second most important criterion, and ‘Worker’s health and safety’ was third. Both point to the importance of safety in making EoL decisions.

The proposed decision-making model's limitation may be the breadth of criteria and stakeholders. The extensive set of criteria introduced could slow the decision-making process and complicate data collection. Nonetheless, this comprehensive approach provides a strong foundation for evaluating the trade-offs involved in EoL decisions. It highlights the critical role of regulatory and environmental priorities in advancing circular construction practices.

The second part of this study applied the proposed decision-making model to an actual case study, offering a practical examination of how EoL decisions unfold in a specific construction project. This phase focused on a resort building project near the GTA, Canada, which provided a representative context to test the model's applicability and explore potential EoL scenarios. The study examined the performance of various alternatives across the defined criteria, considering both 'Benefit' and 'Cost' aspects, and incorporated specialist input to generate realistic and actionable scenarios for decision-makers.

These findings highlight the importance of evaluating EoL scenarios holistically to address the nuances of decision-making in sustainable construction practices. The distinction between the Status Quo – Linear and Future – Circular cases underscores the significant impact of regulatory frameworks, public acceptance, and infrastructure availability on the feasibility and attractiveness of circular alternatives. While Full Deconstruction consistently emerges as the top performer under circular conditions, the ambiguous results in the Status Quo – Linear case reflect the challenges posed by current limitations in policy and infrastructure, where landfill and demolition options can occasionally align closely with deconstruction scenarios.

This case study also emphasizes the critical role of regulatory incentives and infrastructure development in driving more circular EoL practices. Expanding the certification and marketability of reused materials, improving legal frameworks to incentivize sustainable practices, and increasing the availability and connectivity of waste processing facilities are essential steps toward achieving circularity. Despite the economic and environmental benefits of deconstruction scenarios, significant barriers remain, including cost implications, extended project timelines, and logistical challenges associated with transporting materials to recycling or reuse facilities.

Ultimately, these results underscore the need for policy and industry advancements to shift Canada's construction sector toward more circular, environmentally resilient practices. By addressing the identified challenges and fostering greater access to information, decision-makers and building owners can be better equipped to adopt sustainable deconstruction methods that align with the principles of a Future – Circular case. This transition would reduce reliance on landfills and maximize resource efficiency, contributing to the broader goals of environmental and economic sustainability.

7.1 Contributions

The fundamental contribution of this research was to provide a broad decision-making model for the EoL stage of built facilities. To achieve this goal, the contributions of this project can be summarized as follows:

- Previous work tackled the different EoL stages as distinct issues, not addressing decision problems other than what is better to deconstruction or demolish. In response to this gap, the present thesis identified the most relevant decision problems throughout the EoL stage. Owners, designers, and architects can use these findings as a guide that can lead to a more sustainable decision.
- The literature review identified a disparity of preferences, often stemming from a lack of representativeness in stakeholder selection. Previous studies mainly included owners and construction managers as decision-makers. In addition to those decision-makers, this study included environmental specialists, policymakers, tenants, and professionals involved at the EoL stage, such as demolition managers and recycling facilities managers. The validated framework is now more inclusive, considering the perspectives of all stakeholders who play a meaningful role in the EoL stage.
- This thesis provides a significant contribution by analyzing a real-case scenario of a building in Ontario through comprehensive data collection and integration of tools such as OneClick, Revit, and governmental reports. The findings demonstrate that deconstruction options are more cost-effective than demolition, primarily due to the high gate fees for landfill disposal. Despite this, the persistence of demolition practices underscores the need for stronger regulatory frameworks. A key contribution of this work is the inclusion of regulation-related criteria in the decision-making process, addressing a critical gap in previous analyses and offering actionable insights for advancing sustainable practices in the construction industry.

7.2 Impacts

This research provides a deeper understanding of the key decisions required during the EoL stage of buildings and how they can accommodate more CE practices. By integrating insights from the literature and professionals actively working in the field, the model is more closely aligned with current industry needs than previous models. The decision model developed can facilitate the analysis of multiple scenarios, promoting greater awareness and encouraging a more circular approach to building lifecycles.

This research provides decision-makers with the tools to incorporate circular and sustainable parameters into their practices. It offers a structured model that can help owners and stakeholders make more informed decisions, fostering a more sustainable approach to the EoL stage of buildings.

7.3 Limitations

The limitations of this study are listed as follows:

- As circularity is still an emerging concept in the construction industry, comprehensive reports and benchmarks for comparing different scenarios are lacking. Consequently, several assumptions had to be made during the data collection. Some data could not be collected solely at the city level (Toronto). In some instances, country-level data and even U.S. sources, such as the Solid Waste Association of North America, were required to fill gaps in the data. However, this limitation is expected to diminish as circular awareness grows and more data is collected at broader scales.
- While this study aimed to validate the criteria for each of the four decision problems independently, there is also an assumption that all requirements are applicable across the different decision problems. This assumption may limit the precision of the model in addressing unique aspects of each sub-phase of EoL stages.
- The inclusion of diverse stakeholder perspectives and insights from the literature resulted in an extensive set of criteria. While this broad scope enriched the model, it also contributed to a longer and more complex data collection process.
- A significant portion of the anonymous survey responses came from individuals working in sustainability. While these participants may be more inclined to engage in studies like

this, their involvement could have influenced the weighting of criteria, potentially skewing the results towards a sustainability-focused perspective.

- Some criteria may exhibit correlations, leading to the potential for double counting similar impacts. This overlap could affect the accuracy of the analysis and the interpretation of results, highlighting the need for careful consideration when evaluating criteria interactions.
- Assessing the quality of materials requires specialized expertise and typically involves evaluating materials post-deconstruction or demolition. In this study, all wood and concrete blocks were assumed to be reusable, which does not reflect the reality of material conditions. This assumption may lead to overestimating the potential for material reuse and recycling.

7.4 Future Work

A list of recommendations for future work is proposed to advance this study and address the limitations mentioned above. However, these suggestions are not exhaustive and do not encompass all possible avenues for further research.

- As demonstrated in this study, not all criteria apply to every decision, and all the criteria have the same weight across decision problems. A question remains unanswered: Would the model have a different ranking priority if each decision problem had its own criteria weight? The addition of new criteria and more detailed decision problems should also be explored.
- Future studies should analyze the effect of including material assessment in the model. How critical is this main criterion compared to the other ones? This research could be integrated with studies on material evaluations to ensure that the potential for reuse and recycling is not overestimated. A comprehensive review of material quality would provide a more accurate understanding of what can be reused or recycled.
- Another relevant question is if the model would result in a different alternative if another MCDM method were used. Various methods should be explored and developed to minimize the correlations between criteria.
- Future work should also focus on developing a similar model that maintains or expands stakeholder diversity while requiring fewer inputs. This raises questions about whether

comparable results could be achieved with a smaller set of criteria and which criteria should prioritized in such a streamlined model.

- While this study incorporated input from individuals primarily across Canada to maintain a broad focus, specific projects would greatly benefit from gathering more localized input. Future investigators should utilize more advanced surveying methods to increase the amount of participation and make models that are better applicable to a particular municipality or region. This approach would ensure that the model better reflects the unique needs and characteristics of each location project.
- Additional case studies should be conducted to analyze how local regulations and the specific context of different cities influence the decision-making process. By examining similar buildings across various locations, this research would provide valuable insights into the impact of regional differences on EoL decisions.
- In this model, the ‘Regulations’ were considered the most important main criterion. Since it is very complex to quantify which incentives can be attributed to each scenario, future work should focus on regulatory criteria. Additional research could be done to answer questions regarding the true impact of regulations in a given location.

Reference

Abouhamad, Mona, and Metwally Abu-Hamd. 2021. "Life Cycle Assessment Framework for Embodied Environmental Impacts of Building Construction Systems." *Sustainability (Switzerland)* 13 (2): 1–21. https://doi.org/10.3390/su13020461.

Abruzzini, Aurora, and Sepehr Abrishami. 2021. "Integration of BIM and Advanced Digital Technologies to the End of Life Decision-Making Process: A Paradigm of Future Opportunities." *Journal of Engineering Design and Technology*.

Akanbi, Lukman A., Lukumon O. Oyedele, Olugbenga O. Akinade, Anuoluwapo O. Ajayi, Manuel Davila Delgado, Muhammad Bilal, and Sururah A. Bello. 2018. "Salvaging Building Materials in a Circular Economy: A BIM-Based Whole-Life Performance Estimator." *Resources, Conservation and Recycling* 129 (February):175–86. https://doi.org/10.1016/J.RESCONREC.2017.10.026.

Akbarnezhad, A., K. C.G. Ong, and L. R. Chandra. 2014. "Economic and Environmental Assessment of Deconstruction Strategies Using Building Information Modeling." *Automation in Construction* 37:131–44. https://doi.org/10.1016/j.autcon.2013.10.017.

Akinade, Olugbenga O., Lukumon O. Oyedele, Muhammad Bilal, Saheed O. Ajayi, Hakeem A. Owolabi, Hafiz A. Alaka, and Sururah A. Bello. 2015. "Waste Minimisation through Deconstruction: A BIM Based Deconstructability Assessment Score (BIM-DAS)." *Resources, Conservation and Recycling* 105 (December):167–76. https://doi.org/10.1016/j.resconrec.2015.10.018.

Alamerew, Yohannes A., and Daniel Brissaud. 2019. "Circular Economy Assessment Tool for End of Life Product Strategies." *Journal of Remanufacturing*.

Allam, A., and M. Nik-Bakht. 2024. "Supporting Circularity in Construction with Performance-Based Deconstruction." *Sustainable Production and Consumption* 45. https://www.sciencedirect.com/science/article/pii/S2352550923002968.

Allam, Amr, and Mazdak Nik-Bakht. 2023. "Barriers to Circularity in Construction: An Analysis of Experts' Perspectives." In *Proceedings of the 2023 European Conference on Computing* *in Construction and the 40th International CIB W78 Conference*. https://doi.org/10.35490/EC3.2023.234.

Allam, Amr, Rafaela Paniza, and Mazdak Nik-Bakht. 2023. “SWOT Analysis of Built Facilities’ Deconstruction Projects.” In *2023 CSCE International Conference, Joint with CRC 2023*. Moncton, NB.

Allam, Amr S., and Mazdak Nik-Bakht. 2023a. “From Demolition to Deconstruction of the Built Environment: A Synthesis of the Literature.” *Journal of Building Engineering*. Elsevier Ltd. https://doi.org/10.1016/j.jobe.2022.105679.

———. 2023b. “From Demolition to Deconstruction of the Built Environment: A Synthesis of the Literature.” *Journal of Building Engineering* 64 (April). https://doi.org/10.1016/J.JOBE.2022.105679.

———. 2024. “Supporting Circularity in Construction with Performance-Based Deconstruction.” *Sustainable Production and Consumption* 45 (March):1–14. https://doi.org/10.1016/j.spc.2023.12.021.

Allam, Amr S, and Mazdak Nik-Bakht. 2023. “BARRIERS TO CIRCULARITY IN CONSTRUCTION: AN ANALYSIS OF EXPERTS’ PERSPECTIVES.”

Anastasiades, K., J. Blom, M. Buyle, and A. Audenaert. 2020. “Translating the Circular Economy to Bridge Construction: Lessons Learnt from a Critical Literature Review.” *Renewable and Sustainable Energy Reviews*. Elsevier Ltd. https://doi.org/10.1016/j.rser.2019.109522.

Antunes, Ana, Ricardo Martins, José Dinis Silvestre, Ricardo Do Carmo, Hugo Costa, Eduardo Júlio, and Pedro Pedroso. 2021. “Environmental Impacts and Benefits of the End-of-Life of Building Materials: Database to Support Decision Making and Contribute to Circularity.” *Sustainability (Switzerland)* 13 (22). https://doi.org/10.3390/su132212659.

Baker, Hannah, Alice Moncaster, and Abir Al-Tabbaa. 2017. “Decision-Making for the Demolition or Adaptation of Buildings.” *Proceedings of the Institution of Civil Engineers: Forensic Engineering* 170 (3): 144–56. https://doi.org/10.1680/jfoen.16.00026.

Bueno, Cristiane, Lucas Melchiori Pereira, and Márcio Minto Fabricio. 2018. “Life Cycle Assessment and Environmental-Based Choices at the Early Design Stages: An Application

Using Building Information Modelling." *Architectural Engineering and Design Management* 14 (5): 332–46. https://doi.org/10.1080/17452007.2018.1458593.

Ccme. n.d. *GUIDE FOR IDENTIFYING, EVALUATING AND SELECTING POLICIES FOR INFLUENCING CONSTRUCTION, RENOVATION AND DEMOLITION WASTE MANAGEMENT*.

Chen, Jianguo, Chunxiang Hua, and Chenyu Liu. 2018. "Considerations for Better Construction and Demolition Waste Management: Identifying the Decision Behavior of Contractors and Government through a Game Theory Decision-Making Model." *Journal of Cleaner Production*, November.

Chen, Yun, Jia Yu, and Shahbaz Khan. 2013. "The Spatial Framework for Weight Sensitivity Analysis in AHP-Based Multi-Criteria Decision Making." *Environmental Modelling and Software* 48:129–40. https://doi.org/10.1016/j.envsoft.2013.06.010.

Chen, Zhen, M Asce, Arham B Abdullah, ; Chimay, J Anumba, F Asce, and Heng Li. 2013. "ANP Experiment for Demolition Plan Evaluation." https://doi.org/10.1061/(ASCE)CO.

Cheng, Baoquan, Kun Lu, Jianchang Li, Huihua Chen, Xiaowei Luo, and Muhammad Shafique. 2022. "Comprehensive Assessment of Embodied Environmental Impacts of Buildings Using Normalized Environmental Impact Factors." *Journal of Cleaner Production* 334 (February). https://doi.org/10.1016/j.jclepro.2021.130083.

Chinda, Thanwadee, and Veeris Ammarapala. 2016. "Decision-Making on Reverse Logistics in the Construction Industry." *Songklanakarin J. Sci. Technol*. Vol. 38. Khlong Luang. http://www.sjst.psu.ac.th.

Więckowski, Jakub, and Wojciech Sałabun. 2024. "Comparative Sensitivity Analysis in Composite Material Selection- Evaluating OAT and COMSAM Methods in Multi Criteria Decision Making." *Spectrum of Mechanical Engineering and Operational Research* 2:1–12.

Cook, Ed, Costas A. Velis, and Leon Black. 2022. "Construction and Demolition Waste Management: A Systematic Scoping Review of Risks to Occupational and Public Health." *Frontiers in Sustainability*. Frontiers Media S.A. https://doi.org/10.3389/frsus.2022.924926.

Ding, Zhikun, Rongsheng Liu, Yifei Wang, Vivian WY Tam, and Mingxue Ma. 2021. “An Agent-Based Model Approach for Urban Demolition Waste Quantification and a Management Framework for Stakeholders.” *Journal of Cleaner Production* 285 (February). https://doi.org/10.1016/j.jclepro.2020.124897.

Ding, Zhikun, Menglian Zhu, Zezhou Wu, Yanbin Fu, and Xia Liu. 2018. “Combining AHP-Entropy Approach with GIS for Construction Waste Landfill Selection—A Case Study of Shenzhen.” *International Journal of Environmental Research and Public Health* 15 (10). https://doi.org/10.3390/ijerph15102254.

Esther Aigwi, Itohan, Temitope Egbelakin, Jason Ingham, Robyn Phipps, and James Rotimi. 2019. “A Performance-Based Framework to Prioritise Underutilised Historical.” *Sustainable Cities and Society*, April.

Figueiredo, Karoline, Rodrigo Pierott, Ahmed W.A. Hammad, and Assed Haddad. 2021. “Sustainable Material Choice for Construction Projects: A Life Cycle Sustainability Assessment Framework Based on BIM and Fuzzy-AHP.” *Building and Environment* 196 (June). https://doi.org/10.1016/j.buildenv.2021.107805.

Fiore, Pierfrancesco, Giuseppe Donnarumma, Carmelo Falce, Emanuela D’andria, and Claudia Sicignano. 2020. “An AHP-Based Methodology for Decision Support in Integrated Interventions in School Buildings.” *Sustainability (Switzerland)* 12 (23): 1–20. https://doi.org/10.3390/su122310181.

Garcia-Bernabeu, Ana, Adolfo Hilario-Caballero, David Pla-Santamaria, and Francisco Salas-Molina. 2020. “A Process Oriented MCDM Approach to Construct a Circular Economy Composite Index.” *Sustainability (Switzerland)* 12 (2). https://doi.org/10.3390/su12020618.

Gerding, Ditte P., Hans Wamelink, and Els M. Leclercq. 2021. “Implementing Circularity in the Construction Process: A Case Study Examining the Reorganization of Multi-Actor Environment and the Decision-Making Process.” *Construction Management and Economics* 39 (7): 617–35. https://doi.org/10.1080/01446193.2021.1934885.

Ghaffar, Seyed Hamidreza, Matthew Burman, and Nuhu Braimah. 2019. “Pathways to Circular Construction: An Integrated Management of Construction and Demolition Waste for Resource Recovery.” *Journal of Cleaner Production*, October.

Ghisellini, Patrizia, Maddalena Ripa, and Sergio Ulgiati. 2018. "Exploring Environmental and Economic Costs and Benefits of a Circular Economy Approach to the Construction and Demolition Sector. A Literature Review." *Journal of Cleaner Production* 178 (March):618–43. https://doi.org/10.1016/j.jclepro.2017.11.207.

Giorgi, Serena, Monica Lavagna, Ke Wang, Mohamed Osmani, Gang Liu, and Andrea Campioli. 2022. "Drivers and Barriers towards Circular Economy in the Building Sector." *Journal of Cleaner Production*.

Goepel, Klaus D. 2013. "Implementing the Analytic Hierarchy Process as a Standard Method for Multi- Criteria Decision Making In Corporate Enterprises – A New AHP Excel Template with Multiple Inputs." In *Proceedings of the International Symposium on the Analytic Hierarchy Process*, 1–10.

Gomes, Julia, Rebecca Dziedzic, and Mazdak Nik-Bakht. 2023. "A Decision-Making Framework for the Built Facilities' End-of-Life from Sustainability and Circular Economy Viewpoints." In *Canadian Society for Civil Engineering*. Moncton.

Guerra, Beatriz C., and Fernanda Leite. 2021. "Circular Economy in the Construction Industry: An Overview of United States Stakeholders' Awareness, Major Challenges, and Enablers." *Resources, Conservation and Recycling* 170 (July). https://doi.org/10.1016/j.resconrec.2021.105617.

Hasheminasab, Hamidreza, Sarfaraz Hashemkhani Zolfani, Mohammadreza Kharrazi, and Dalia Streimikiene. 2022. "Combination of Sustainability and Circular Economy to Develop a Cleaner Building Industry." *Energy and Buildings* 258 (March). https://doi.org/10.1016/j.enbuild.2022.111838.

Hasik, Vaclav, Elizabeth Escott, Roderick Bates, Stephanie Carlisle, Billie Faircloth, and Melissa M. Bilec. 2019. "Comparative Whole-Building Life Cycle Assessment of Renovation and New Construction." *Building and Environment*, June.

Høibye, Linda, and Henrik Sand. 2018. *Circular Economy in the Nordic Construction Sector*. TemaNord. Nordic Council of Ministers. https://doi.org/10.6027/TN2018-517.

Hossain, Md Uzzal, Zezhou Wu, and Chi Sun Poon. 2017. "Comparative Environmental Evaluation of Construction Waste Management through Different Waste Sorting Systems in

Hong Kong." *Waste Management* 69 (November):325–35. https://doi.org/10.1016/j.wasman.2017.07.043.

Hu, Ming. 2019. "Building Impact Assessment—A Combined Life Cycle Assessment and Multicriteria Decision Analysis Framework." *Resources, Conservation and Recycling* 150.

Independent Statistics and Analysis. 2023. "How Much Carbon Dioxide Is Produced per Kilowatthour of U.S. Electricity Generation?" U.S. Energy Information Administration. December 2023.

Iodice, Silvia, Elena Garbarino, Maria Cerreta, and Davide Tonini. 2021. "Sustainability Assessment of Construction and Demolition Waste Management Applied to an Italian Case." *Waste Management* 128 (June):83–98. https://doi.org/10.1016/j.wasman.2021.04.031.

Ishizaka, Alessio., and Philippe. Nemery. 2013. *Multi-Criteria Decision Analysis : Methods and Software*.

Jalaei, Farzad, and Ahmad Jrade. 2014. "Integrating Building Information Modeling (BIM) and Energy Analysis Tools with Green Building Certification System to Conceptually Design Sustainable Buildings." *Journal of Information Technology in Construction* 19 (November):494–519. https://doi.org/10.1007/s12273-013-0120-0.

Jiří, Franek, and Aleš Kresta. 2014. "Judgment Scales and Consistency Measure in AHP." *Procedia Economics and Finance*, 164–73.

Joensuu, Tuomo, Roosa Leino, Jukka Heinonen, and Arto Saari. 2022. "Developing Buildings' Life Cycle Assessment in Circular Economy-Comparing Methods for Assessing Carbon Footprint of Reusable Components." *Sustainable Cities and Society* 77 (February). https://doi.org/10.1016/j.scs.2021.103499.

Kang, Kai, Svetlana Besklubova, Yaqi Dai, and Ray Y. Zhong. 2022. "Building Demolition Waste Management through Smart BIM: A Case Study in Hong Kong." *Waste Management* 143 (April):69–83. https://doi.org/10.1016/j.wasman.2022.02.027.

Khoshand, Afshin, Kimia Khanlari, Hamidreza Abbasianjahromi, and Milad Zoghi. 2020. "Construction and Demolition Waste Management: Fuzzy Analytic Hierarchy Process

Approach." *Waste Management and Research* 38 (7): 773–82. https://doi.org/10.1177/0734242X20910468.

Korol, Elena, and Anna Dudina. 2023. "Calculation of Fuel and Energy Resource Consumption during Building Demolition." In *E3S Web of Conferences*. Vol. 457. EDP Sciences. https://doi.org/10.1051/e3sconf/202345702056.

Krejcí, Jana, and Jan Stoklasa. 2018. "Aggregation in the Analytic Hierarchy Process Why Weighted." *Expert Systems With Applications* 114:97–106.

Kristyn Oldendorf. 2022. "Post-Collection and Maintenance Activities Contribute to Rise." Solid Waste Association of North America. 2022.

Lee, Sir Yee, Jiayao Hu, and Ming K. Lim. 2021. "Maximising the Circular Economy and Sustainability Outcomes: An End-of-Life Tyre Recycling Outlets Selection Model." *International Journal of Production Economics* 232 (February). https://doi.org/10.1016/j.ijpe.2020.107965.

Liu, Jingkuang, Piao Wu, Yuhan Jiang, and Xuetong Wang. 2021. "Explore Potential Barriers of Applying Circular Economy in Construction And." *Journal of Cleaner Production*.

Lorna, Dragonetti, Dimitra Papadaki, Cecilia Mazzoli, Alice Monacelli, Margarita-Niki Assimakopoulos, and Annarita Ferrante. 2024. "Circular Deep Renovation versus Demolition with Reconstruction: Environmental and Financial Evaluation to Support Decision Making in the Construction Sector." https://ssrn.com/abstract=4901962.

Lynch, Nicholas. 2022. "Unbuilding the City: Deconstruction and the Circular Economy in Vancouver." *Environment and Planning A* 54 (8): 1586–1603. https://doi.org/10.1177/0308518X221116891.

Maria, Andrea Di, Johan Eyckmans, and Karel Van Acker. 2018. "Downcycling versus Recycling of Construction and Demolition Waste: Combining LCA and LCC to Support Sustainable Policy Making." *Waste Management*, February.

Ming Hu. n.d. "Building Impact Assessment—A Combined Life Cycle Assessment and Multicriteria Decision Analysis Framework."

Mishra, Shraddha, Surya Prakash Singh, John Johansen, Yang Cheng, and Sami Farooq. 2019. “Evaluating Indicators for International Manufacturing Network under Circular Economy.” *Management Decision* 57 (4): 811–39. https://doi.org/10.1108/MD-05-2018-0565.

Nadazdi Ana, Naunovic Zorana, and Ivanisevic Nenad. 2022. “Circular Economy in Construction and Demolition Waste Management in the Western Balkans: A Sustainability Assessment Framework.” *Sustainability*.

NRC, and CNRC. 2022. *National Guidelines for Whole-Building Life Cycle Assessment*. National Research Council of Canada = Conseil national de recherches Canada.

Nordbly, Anne Sigrid. 2019. “Barriers and Opportunities to Reuse of Building Materials in the Norwegian Construction Sector.” *Conf. Earth and Environmental Science*.

Ontario Regulation 103/94. 2011. *Environment Protect Act*.

Orenga Panizza, Rafaela, and Mazdak Nik-Bakht. 2024. “Building Stock as a Future Supply of Second-Use Material – A Review of Urban Mining Methods.” *Waste Management Bulletin* 2 (2): 19–31. https://doi.org/10.1016/j.wmb.2024.03.001.

Panizza, R., and M. Nik-Bakht. 2024. “Building Stock as a Future Supply of Second-Use Material – a Review of Urban Mining Methods.” *Waste Management Bulletin* 2 (2): 19–31. https://doi.org/https://doi.org/10.1016/j.wmb.2024.03.001.

Purchase, Callun Keith, Dhafer Manna Al Zulayq, Bio Talakatoa O’brien, Matthew Joseph Kowalewski, Aydin Berenjian, Amir Hossein Tarighaleslami, and Mostafa Seifan. 2022. “Circular Economy of Construction and Demolition Waste: A Literature Review on Lessons, Challenges, and Benefits.” *Materials*. MDPI. https://doi.org/10.3390/ma15010076.

“Qualtrics.” 2005. 2005. https://www.qualtrics.com.

Quéheille, Eva, Anne Ventura, Nadia Saiyouri, and Franck Taillandier. 2022. “A Life Cycle Assessment Model of End-of-Life Scenarios for Building Deconstruction and Waste Management.” *Journal of Cleaner Production* 339 (March). https://doi.org/10.1016/j.jclepro.2022.130694.

Robati, Mehdi, Daniel Daly, and Georgios Kokogiannakis. 2019. “A Method of Uncertainty Analysis for Whole-Life Embodied Carbon Emissions (CO 2 -e) of Building Materials of a

Net-Zero Energy Building in Australia." *Journal of Cleaner Production* 225 (July):541–53. https://doi.org/10.1016/j.jclepro.2019.03.339.

Saaty, R W. 1987. "THE ANALYTIC HIERARCHY PROCESS-WHAT IT IS AND HOW IT IS USED." Vol. 9.

Saaty, Thomas L. 2008. "Decision Making with the Analytic Hierarchy Process." *Int. J. Services Sciences*. Vol. 1.

Schlegl, Friederike, Johannes Gantner, Rene Traunspurguer, and Stefan Albrecht. 2019. "LCA of Buildings in Germany: Proposal for a Future Benchmark Based on Existing Databases." *Energy & Buildings*.

Semgalawe, Nita. 2024. "Selection of P3 Delivery Methods for Sustainable Social Infrastructure Projects Using the Analytical Hierarchical Process."

Serrano, Antonio Ángel Rodríguez, and Santiago Porras Álvarez. 2016. "Life Cycle Assessment in Building: A Case Study on the Energy and Emissions Impact Related to the Choice of Housing Typologies and Construction Process in Spain." *Sustainability (Switzerland)* 8 (3). https://doi.org/10.3390/su8030287.

Shooshtarian, Salman, Savindi Caldera, Tayyab Maqsood, and Tim Ryley. 2020. "Using Recycled Construction and Demolition Waste Products: A Review of Stakeholders' Perceptions, Decisions, and Motivations." *Recycling*. MDPI AG. https://doi.org/10.3390/recycling5040031.

Stankovic´ Jelena J., Jankovic´-Milic Vesna, Marjanovic´ Ivana, and Janjic Jasmina. 2021. "An Integrated Approach of PCA and PROMETHEE in Spatial Assessment of Circular Economy Indicators." *Waste Management*.

Tellus Institute with Sound Resource Management. 2007. "More Jobs, Less Pollution: Growing the Recycling Economy in the U.S." www.bluegreenalliance.org.

UN environment programme. 2020. "2020 GLOBAL STATUS REPORT FOR BUILDINGS AND CONSTRUCTION." www.globalabc.org.

Velenturf, Anne P.M., and Phil Purnell. 2021. "Principles for a Sustainable Circular Economy." *Sustainable Production and Consumption*.

Vilches, Alberto, Antonio Garcia-Martinez, and Benito Sanchez-Montañes. 2017. "Life Cycle Assessment (LCA) of Building Refurbishment: A Literature Review." *Energy and Buildings*. Elsevier Ltd. https://doi.org/10.1016/j.enbuild.2016.11.042.

Vitale, Pierluca, Noemi Arena, Fabrizio Di Gregorio, and Umberto Arena. 2017. "Life Cycle Assessment of the End-of-Life Phase of a Residential Building." *Waste Management* 60 (February):311–21. https://doi.org/10.1016/j.wasman.2016.10.002.

Wang, Ting-Kwei, Zeqing Wu, and Chunyan Luo. 2021. "Multi-Participant Construction Waste Demolition and Transportation." *Resources, Conservation & Recycling*, March.

Xu, Jiuping, Yi Shi, Yachen Xie, and Siwei Zhao. 2019. "A BIM-Based Construction and Demolition Waste Information Management System for Greenhouse Gas Quantification and Reduction." *Journal of Cleaner Production* 229 (August):308–24. https://doi.org/10.1016/j.jclepro.2019.04.158.

Appendices

Appendix 1

Semi-structured interview questionnaire (explained in sections 3.2 and 3.3).

Model Validation /Semi-structured interview

An introduction is given to the participants:

The building and civil infrastructure sectors are producing massive quantities of construction and demolition waste, especially at the end-of-life stage. To this end, the goal of this interview is to validate a decision-making model that aims to consider the three pillars of sustainability and improve the circular economy.

Understanding the participants:

1–What is your experience with deconstruction and demolition?

2- What is your experience with the reuse and recycling process of construction materials?

Study questionnaire divided by decision problems:

Decision problem #1: Deconstruction/demolition

When the building reaches the EoL stage some decisions need to be made.

Q3–Considering that a building reached the end-of-life phase, what are the possible alternatives for the facility?

Q4–How should this decision be made, and what should be the considerations (criteria)?

Q5–Whom do you believe should be involved?

Decision problem #2: Transportation

Q6- Taking into consideration the selection of a facility (recycling plant, refurbish, or landfill) what should be the options for a building?

Q7–How should this decision be made, and what should be the considerations (criteria)?

Q8–Whom do you believe should be involved?

Decision problem #3: Waste Processing

Q9- Since sort ability is one of the biggest drivers of circularity, what are the available options we currently have (in-site sorting, off-site, no sorting)?

Q10–How should this decision be made, and what should be the considerations?

Q11–Whom do you believe should be involved?

Decision problem #4: Dispose

Q9- Looking at the most detailed level, what are the possible outcomes for the building materials?

Q10–How should this decision be made, and what should be the considerations?

Q11–Whom do you believe should be involved?

Under each decision-problem, the participants were also asked about two different criteria that were considered “unstable”. The criteria were repeated for two different decision problems since we wanted to evaluate it under different circumstances.

Demographic questions

Q12- Which of the following best describes you? (More than one alternative can be selected)

Choose from a list of stakeholders.

Q13- How many years of experience do you have in the selected industry?

Appendix 2

Online Survey (explained in section 3.2.3)

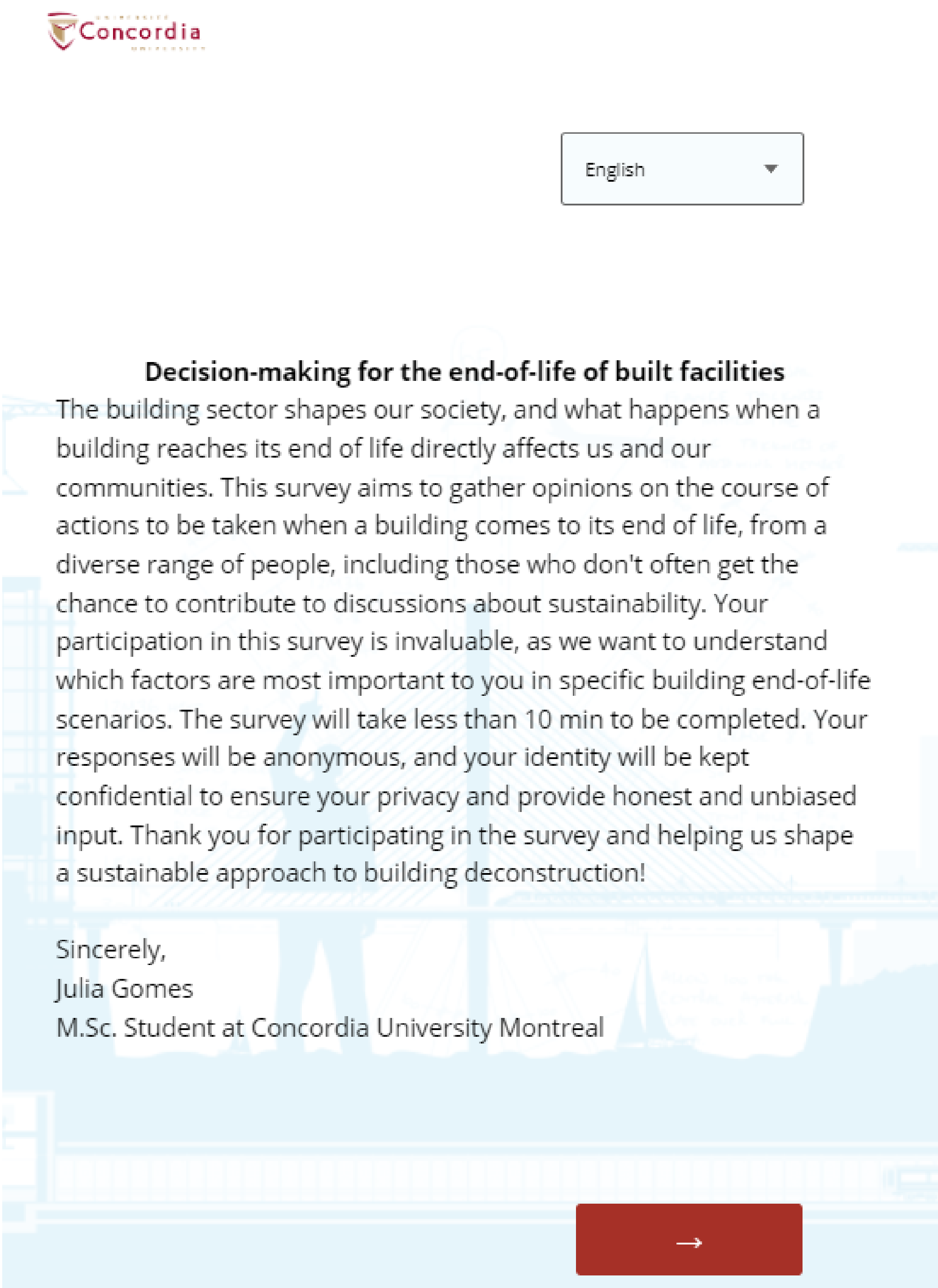


Figure 0.1: Image from the introduction of the survey on Qualtrics

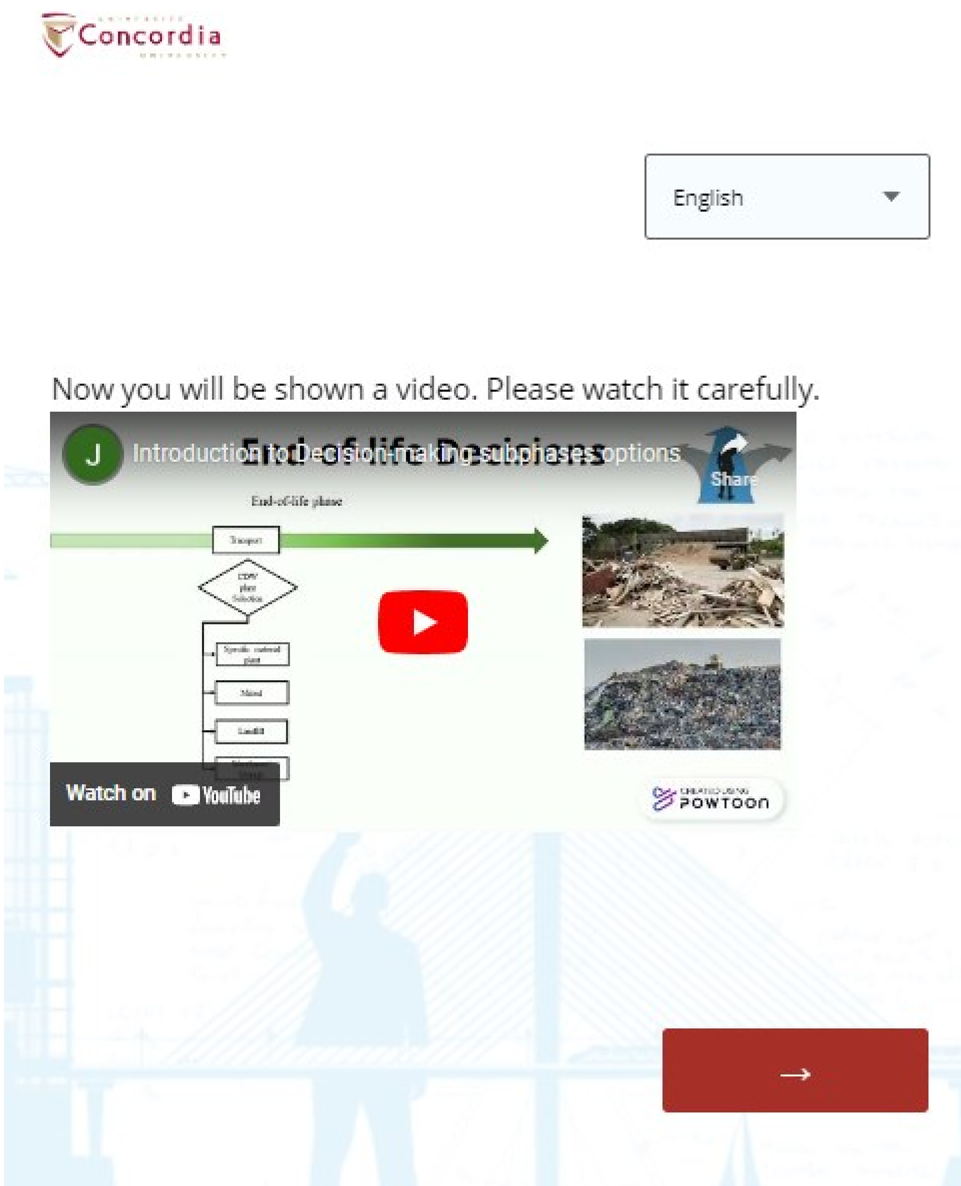


Figure A.2: Video explaining the EoL subphases to the participants

Sub-phases/ Decision problems introduction

Sub phase
#1 - Demolition/Deconstruction

Imagine a 50-year-old abandoned three-story apartment building located in Montreal, Canada. This building has remained vacant for over a decade. The following alternatives are under consideration:

- Demolition: Completely destroy the building.
- Disassemble: Carefully dismantle the building, salvaging materials.
- Renovation/Retrofit: Restore or upgrade the building.
- Adapt/Repurpose: Modify the building to serve a different function.
- Do Nothing: Leave the building as it is, not taking any immediate action.

To make the best decision I would like your help in defining the most important criteria in the next steps.

→

Figure A.3: Introduction of decision-problem number 1 (demolition/deconstruction)

Figure A.4: Introduction of decision-problem number 2 (waste processing)

Figure A.5: Introduction of decision-problem number 3 (transportation)

Sub phase
#4 - Disposal

A 50-year-old abandoned three-story apartment building is under renovation. During this process, construction waste/materials require further assessment to determine the best course of action. The available options are:

- Reuse: Find new purposes or applications for waste/materials.
- Downcycle: Convert the waste/materials into lower-grade products or materials.
- Recycle: Process the waste/materials to create new products or materials.
- Energy recovery: Convert the waste/materials into energy through methods like incineration.
- Landfill: Dispose of the waste/materials in a designated area without any processing.

To make the best decision I would like your help in defining the most important criteria in the next steps.

→

Figure A.6: Introduction of decision-problem number 4 (disposal)

Pairwise comparison explained

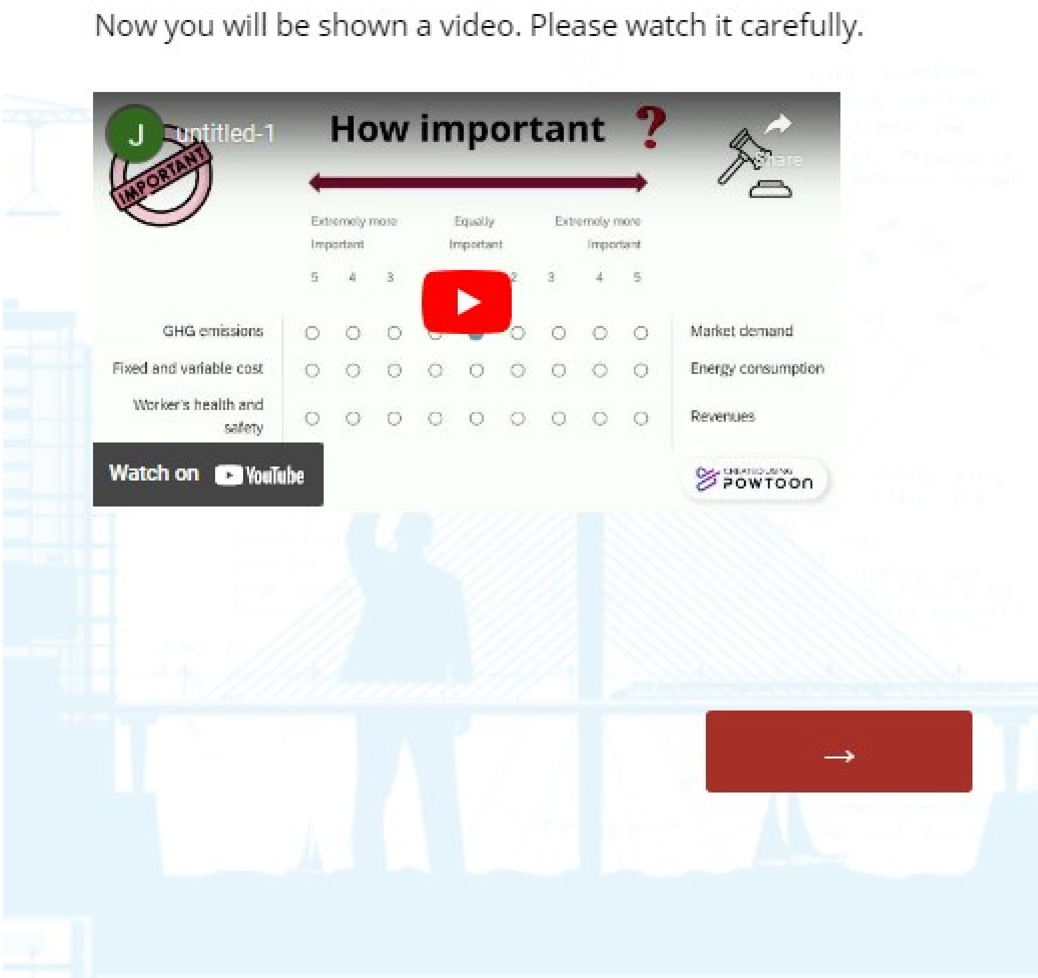


Figure A.7: Video explaining pairwise comparison and how to fill up the survey

<u>Main criteria assessment</u>

Assuming you are the main decision-maker. What is the relative importance of the high-level factors?
If you are using a mobile device, please rotate horizontally for better visualization.

	Extremely more important 5	4	3	2	Equally important 1	2	3	4	Extremely more important 5	
Environmental	○	○	○	○	○	○	○	○	○	Social
Environmental	○	○	○	○	○	○	○	○	○	Economics
Environmental	○	○	○	○	○	○	○	○	○	Regulations
Environmental	○	○	○	○	○	○	○	○	○	Site conditions
Environmental	○	○	○	○	○	○	○	○	○	Material conditions
Social	○	○	○	○	○	○	○	○	○	Economics
Social	○	○	○	○	○	○	○	○	○	Regulations
Social	○	○	○	○	○	○	○	○	○	Site conditions
Social	○	○	○	○	○	○	○	○	○	Material conditions
Economics	○	○	○	○	○	○	○	○	○	Regulations
Economics	○	○	○	○	○	○	○	○	○	Site conditions
Economics	○	○	○	○	○	○	○	○	○	Material conditions
Regulations	○	○	○	○	○	○	○	○	○	Site conditions
Regulations	○	○	○	○	○	○	○	○	○	Material conditions
Site conditions	○	○	○	○	○	○	○	○	○	Material conditions

Description of the main criteria

Environmental: Measurements of environmental impacts in each process.

Economics: Financial factors associated with each process.

Social: Social impacts and implications associated with the end of life (e.g., worker's safety, employment opportunity).

Material condition: Physical condition and properties of the used construction materials.

Site conditions: Physical characteristics and conditions of the site where the built facility is located.

Regulations: Regulatory requirements and compliance with applicable laws.

Figure A.8: Main criteria assessment

Criteria Assessment


Assuming you are the main decision-maker. What is the relative importance of the following factors?
If you are using a mobile device, please rotate horizontally for better visualization.

	Extremely more important 5	4	3	2	Equally important 1	2	3	4	Extremely more important 5	
Market Demand	○	○	○	○	○	○	○	○	○	Land Value
Market Demand	○	○	○	○	○	○	○	○	○	Fixed and variable cost
Market Demand	○	○	○	○	○	○	○	○	○	Revenues
Market Demand	○	○	○	○	○	○	○	○	○	Capital Expenditures
Land Value	○	○	○	○	○	○	○	○	○	Fixed and variable cost
Land Value	○	○	○	○	○	○	○	○	○	Revenues
Land Value	○	○	○	○	○	○	○	○	○	Capital Expenditures
Fixed and variable cost	○	○	○	○	○	○	○	○	○	Revenues
Fixed and variable cost	○	○	○	○	○	○	○	○	○	Capital Expenditures
Capital Expenditures	○	○	○	○	○	○	○	○	○	Revenues

Economics

Land Value ($): Consideration of the economic worth or potential of the land on which the built facility is located.

Revenues ($): Potential financial gains or income generation opportunities (material savage and resale, recycling and recovering, etc.).

Capital expenditure ($): Investment made by the company, this investment can be in property, plants, and equipment.

Fixed and variable costs ($): Summation of all the costs related to each of the operation options.

Market demand (qualitative): Possible market scenario in the region.

Figure A.9: Economics Criteria Assessment

Assuming you are the main decision-maker. What is the relative importance of the following factors?
If you are using a mobile device, please rotate horizontally for better visualization.

	Extremely more Important 5	4	3	2	Equally Important 1	2	3	4	Extremely more Important 5	
Public Acceptance or reused material	○	○	○	○	○	○	○	○	○	Worker's health and safety
Public Acceptance or reused material	○	○	○	○	○	○	○	○	○	Green image
Public Acceptance or reused material	○	○	○	○	○	○	○	○	○	Historical value
Public Acceptance or reused material	○	○	○	○	○	○	○	○	○	Networking between facilities
Public Acceptance or reused material	○	○	○	○	○	○	○	○	○	Employment opportunity
Worker's health and safety	○	○	○	○	○	○	○	○	○	Green image
Worker's health and safety	○	○	○	○	○	○	○	○	○	Historical value
Worker's health and safety	○	○	○	○	○	○	○	○	○	Networking between facilities
Worker's health and safety	○	○	○	○	○	○	○	○	○	Employment opportunity
Green image	○	○	○	○	○	○	○	○	○	Historical value
Green image	○	○	○	○	○	○	○	○	○	Networking between facilities
Green image	○	○	○	○	○	○	○	○	○	Employment opportunity
Historical value	○	○	○	○	○	○	○	○	○	Networking between facilities
Historical value	○	○	○	○	○	○	○	○	○	Employment opportunity
Networking between facilities	○	○	○	○	○	○	○	○	○	Employment opportunity

Social

Green image (qualitative): Reputation of a facility or organization regarding their environmentally responsible practice.

Networking between facilities (qualitative): Level of coordination, information sharing, and resource pooling between facilities or organizations.

Historical value (qualitative): Assessment and consideration of the historical, cultural, or architectural significance of the facility.

Worker's safety (number of accidents on the site): Health and well-being of the workers.

Employment opportunity (number of employees): Measures the increase of employment in the area due to the operations around the end of life of construction products.

Public discomfort due to landfill presence (qualitative): Well-being of people around landfill areas.

Figure A.10: Social Criteria Assessment

Assuming you are the main decision-maker. What is the relative importance of the following factors?
If you are using a mobile device, please rotate horizontally for better visualization.

	Extremely more Important 5	4	3	2	Equally Important 1	2	3	4	Extremely more Important 5	
GHG emissions	○	○	○	○	○	○	○	○	○	Energy consumption
GHG emissions	○	○	○	○	○	○	○	○	○	Water consumption
GHG emissions	○	○	○	○	○	○	○	○	○	Resources consumption
Energy consumption	○	○	○	○	○	○	○	○	○	Water consumption
Energy consumption	○	○	○	○	○	○	○	○	○	Resources consumption
Water consumption	○	○	○	○	○	○	○	○	○	Resources consumption
Compliance with local regulations	○	○	○	○	○	○	○	○	○	Incentives

Environmental

GHG emissions (CO_2e): Accounts for all the greenhouse gas emissions throughout the material's life cycle.

Energy consumption (kWh): Energy used during the material's life cycle.

Water consumption (m3): Water usage during the material's life cycle.

Resources consumption (kg): Consumption of natural resources.

Regulations

Compliance with regulation (binary): The agreement with demolition/recycling rates/circularity rules exists in different regions.

Incentives (binary): Financial, regulatory, or other types of incentives offered by the government.

Figure A.11: Environmental and Regulation Criteria Assessment

Assuming you are the main decision-maker. What is the relative importance of the following factors?
If you are using a mobile device, please rotate horizontally for better visualization.

	Extremely more Important 5	4	3	2	Equally Important 1	2	3	4	Extremely more Important 5	
Material quality	○	○	○	○	○	○	○	○	○	Second life of materials
Material quality	○	○	○	○	○	○	○	○	○	Hazardous
Material quality	○	○	○	○	○	○	○	○	○	Quality certification
Second life of materials	○	○	○	○	○	○	○	○	○	Hazardous
Second life of materials	○	○	○	○	○	○	○	○	○	Quality certification
Hazardous	○	○	○	○	○	○	○	○	○	Quality certification

Material conditions

Second life of materials (years): Performance to determine the material suitability for secondary applications.

Hazardous (binary): Presence of hazardous materials.

Quality certification (binary): The existence of a certificate that assesses the quality, performance, and suitability of materials.

Material quality *(*qualitative): Assessment of building materials and components quality conditions at the End-of-Life stage.

Figure A.12: Material Conditions Criteria Assessment


Assuming you are the main decision-maker. What is the relative importance of the following factors?
If you are using a mobile device, please rotate horizontally for better visualization.

	5	4	3	2	1	2	3	4	5	
	Extremely more Important				Equally Important				Extremely more Important	
Space in site	○	○	○	○	○	○	○	○	○	Location
Space in site	○	○	○	○	○	○	○	○	○	Amount of waste
Space in site	○	○	○	○	○	○	○	○	○	Process time
Location	○	○	○	○	○	○	○	○	○	Amount of waste
Location	○	○	○	○	○	○	○	○	○	Process time
Amount of waste	○	○	○	○	○	○	○	○	○	Process time

Site conditions

Space on-site (m^2): Available physical space within the site or property where the built facility is located.

Location (qualitative): Location of the site for logistics purposes (traffic, transportation, available facilities, etc.)

Process time (days): Evaluation of the time required for each process.

Amount of waste (kg): Assessing the waste produced to better direct it to its final destination.

Figure A.13: Site Conditions Criteria Assessment

Personal and demographic questions

How would you rate your level of experience with deconstruction and demolition?

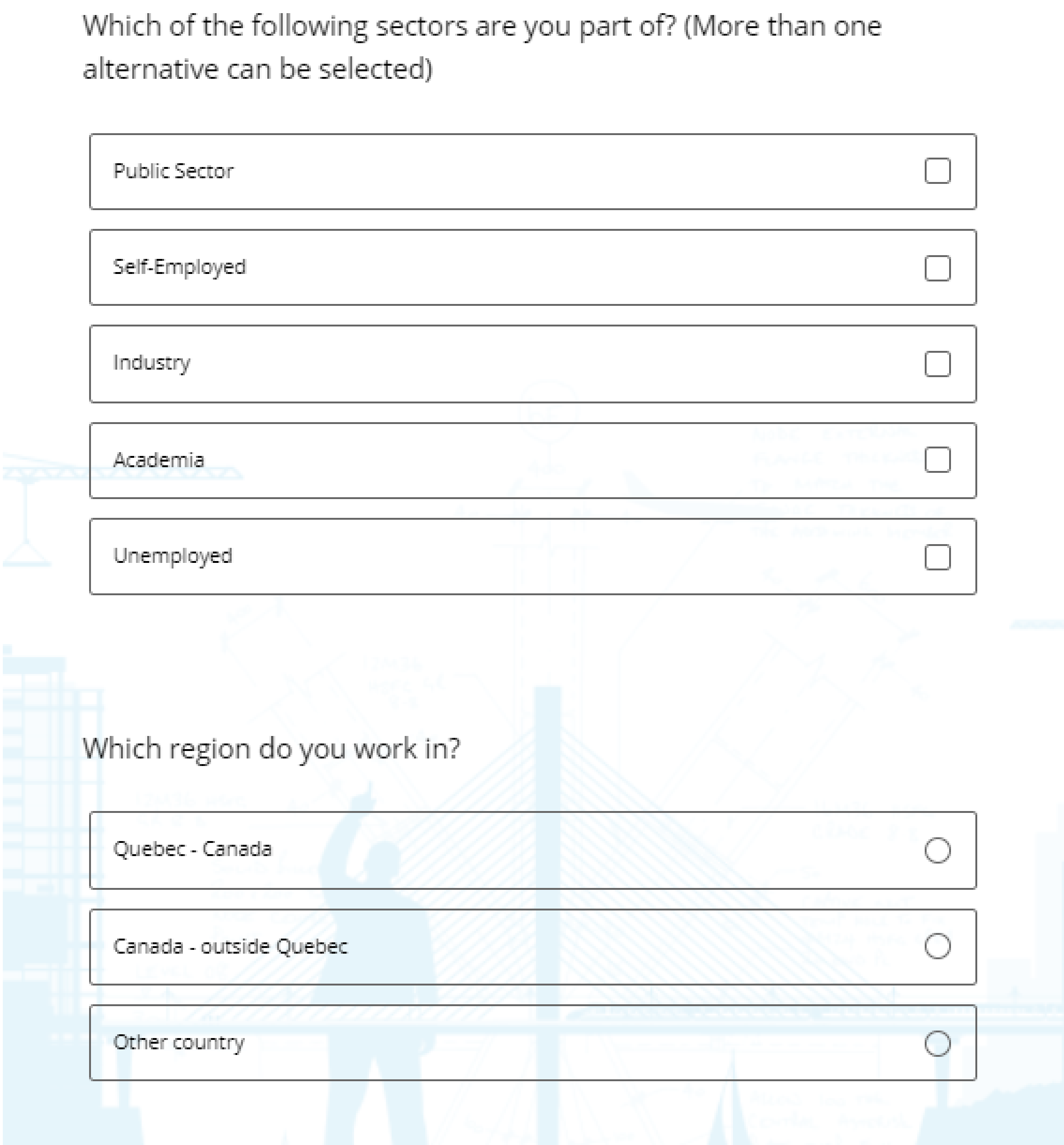
- No knowledge
- Basic knowledge
- Moderate knowledge
- Advanced knowledge

How would you rate your level of experience with the reuse and recycling of construction materials?

- No knowledge
- Basic knowledge
- Moderate knowledge
- Advanced knowledge

Thank you for answering the rating questions. The remaining are simple demographic questions, that will allow us to better understand the opinions of different stakeholder groups.

Figure A.14: Site Conditions Criteria Assessment

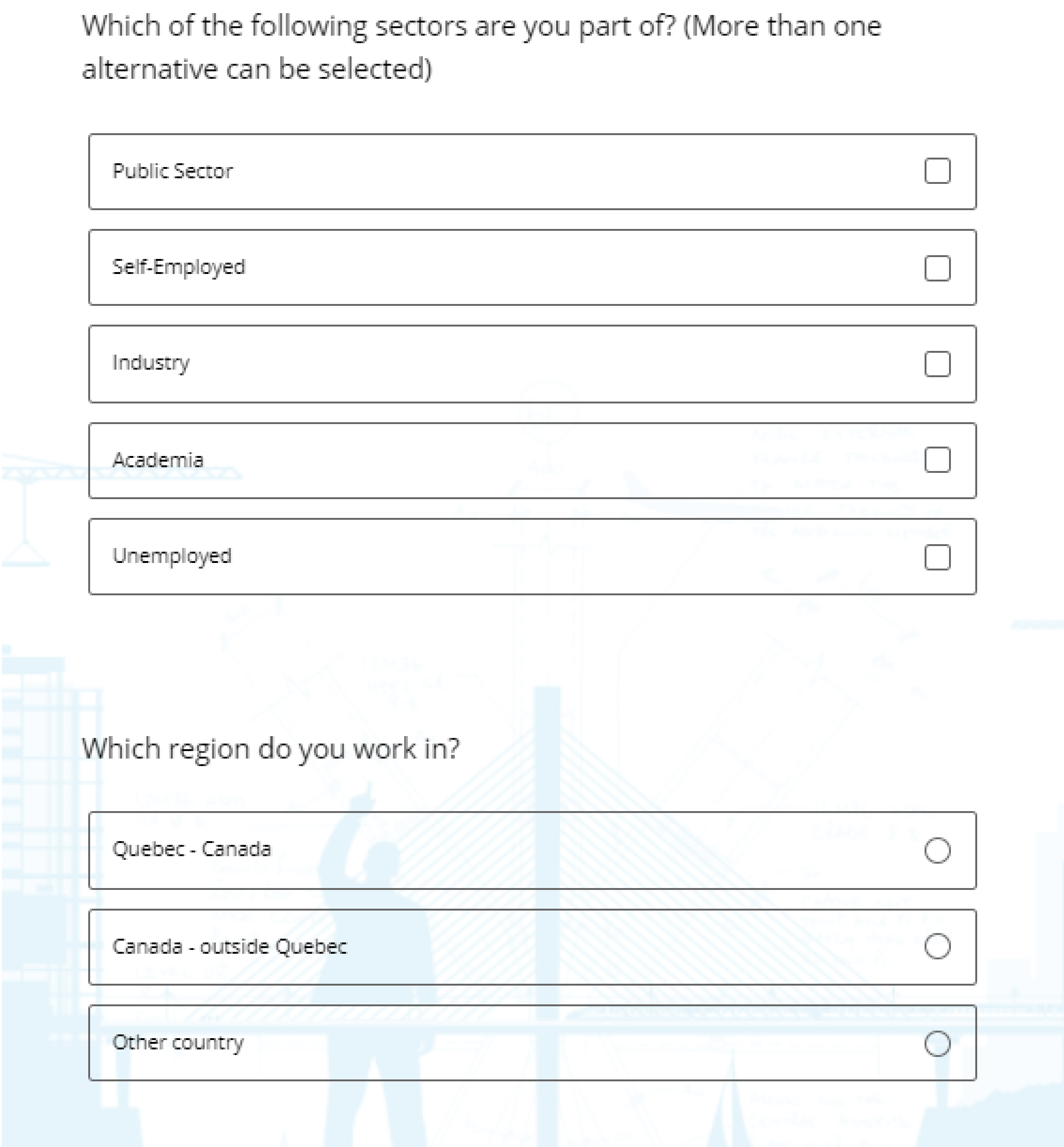

Which of the following sectors are you part of? (More than one alternative can be selected)

- Public Sector ☐
- Self-Employed ☐
- Industry ☐
- Academia ☐
- Unemployed ☐

Which region do you work in?

- Quebec - Canada ○
- Canada - outside Quebec ○
- Other country ○

Figure A.15: Demographic questions part 1



Which of the following sectors are you part of? (More than one alternative can be selected)

- [ ] Public Sector
- [ ] Self-Employed
- [ ] Industry
- [ ] Academia
- [ ] Unemployed

Which region do you work in?

- ○ Quebec - Canada
- ○ Canada - outside Quebec
- ○ Other country

Figure A.16: Demographic questions part 2

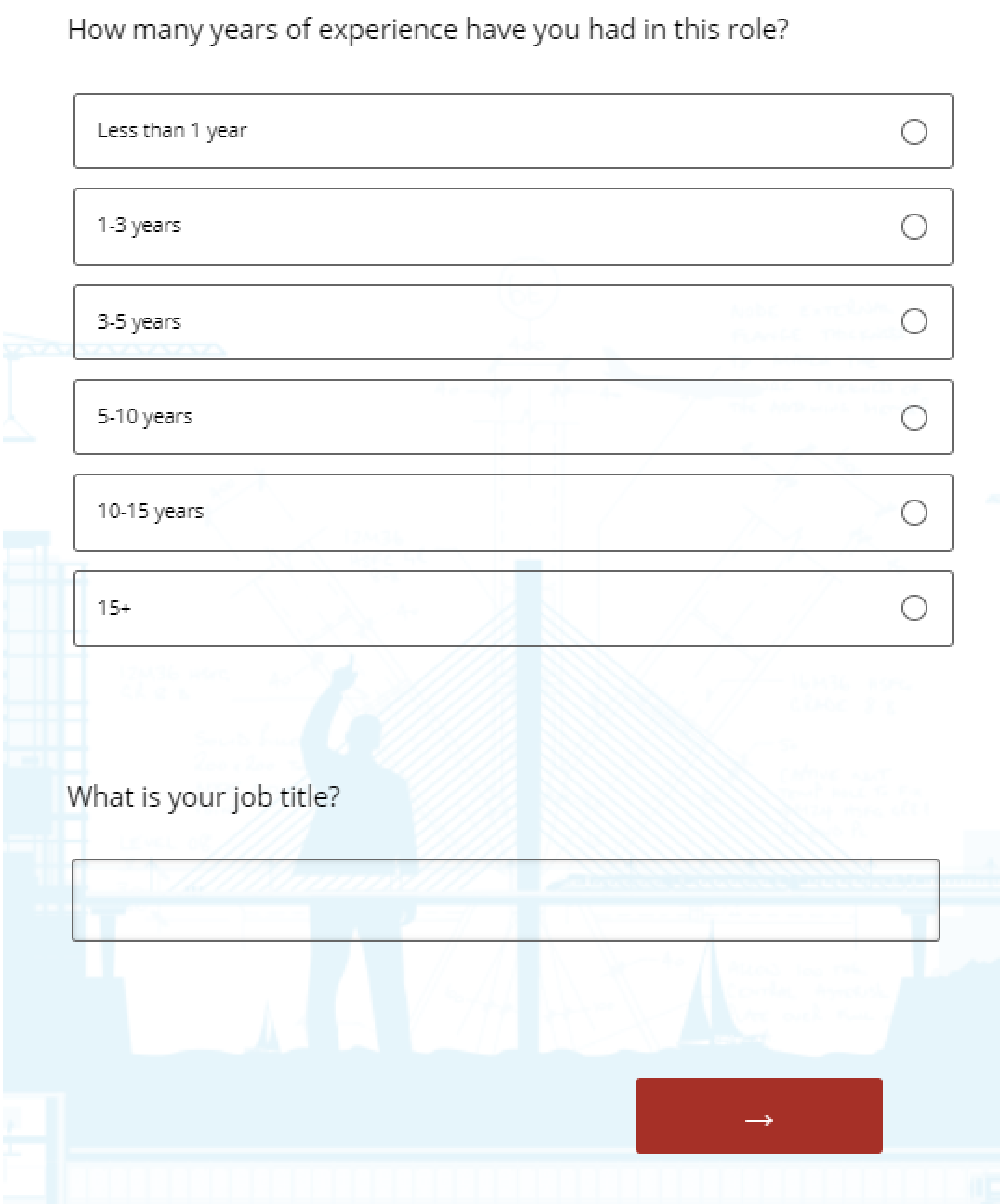
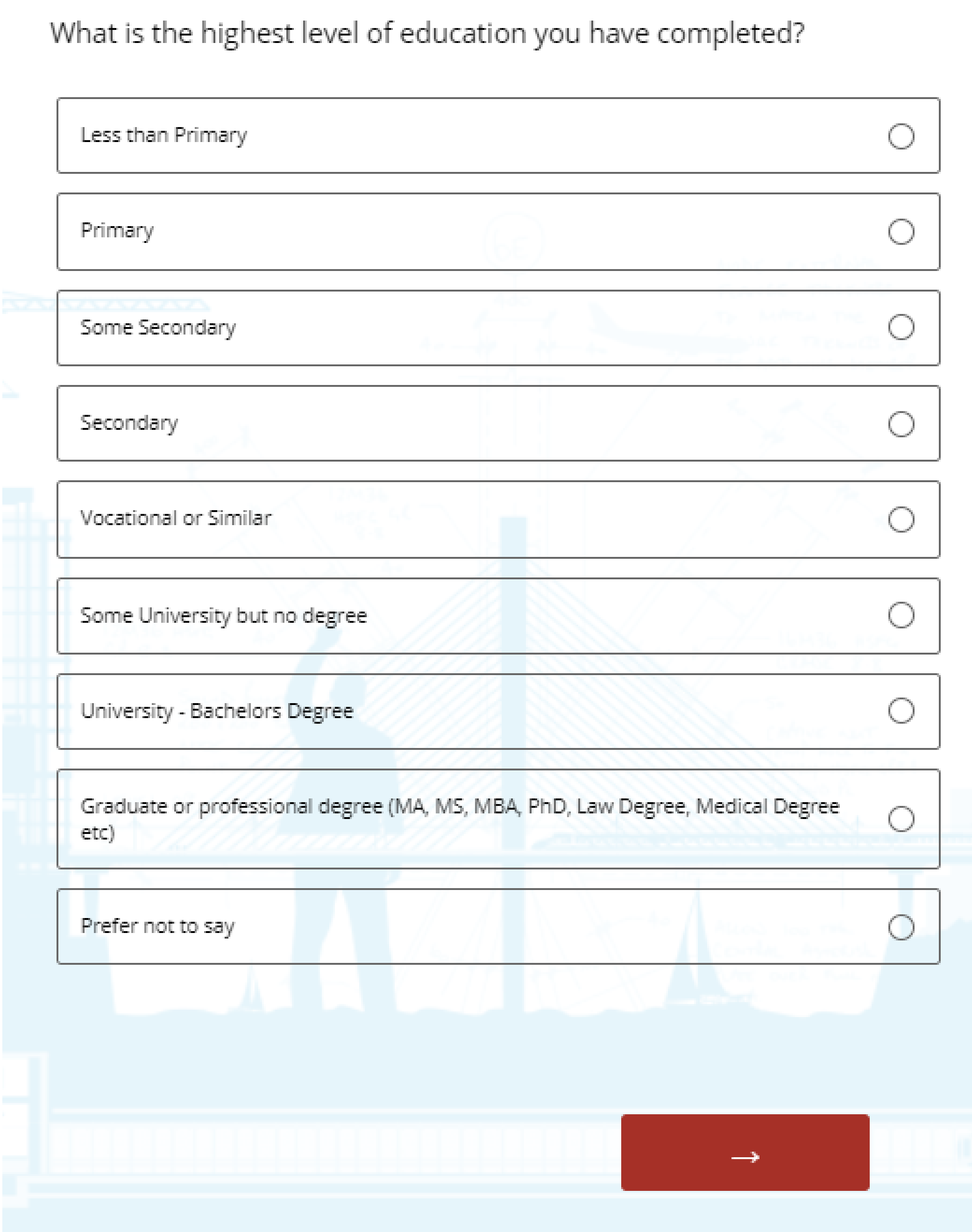


Figure A.17: Demographic questions part 3


What is the highest level of education you have completed?

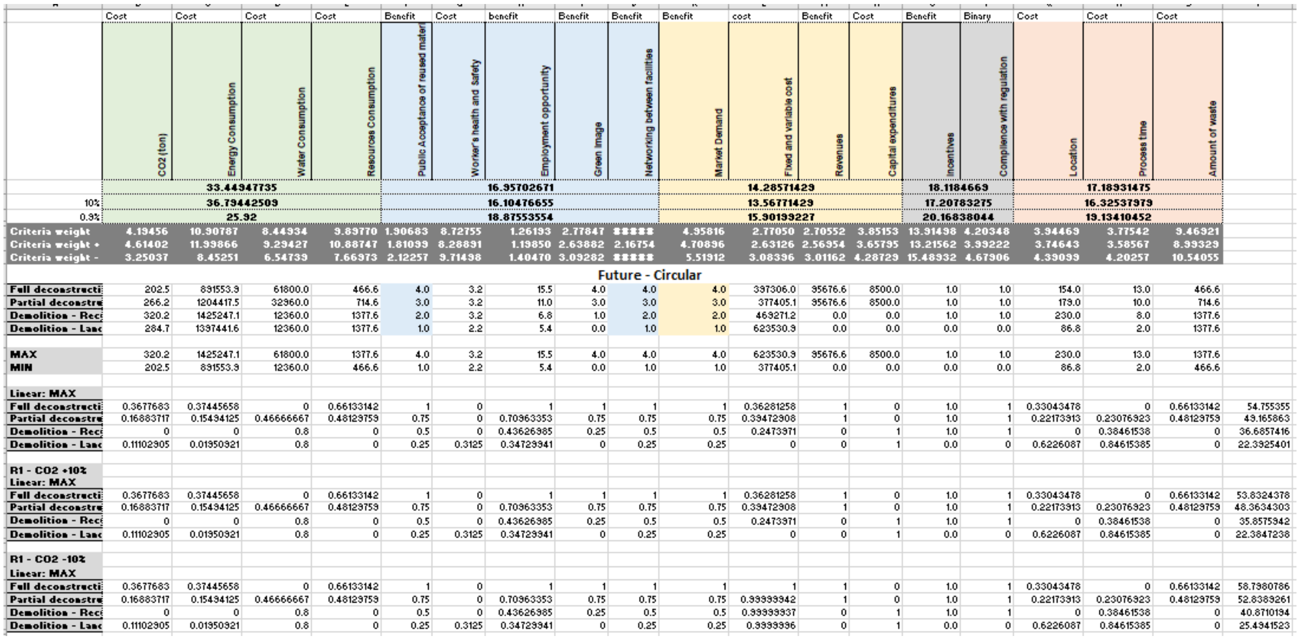
- Less than Primary
- Primary
- Some Secondary
- Secondary
- Vocational or Similar
- Some University but no degree
- University - Bachelors Degree
- Graduate or professional degree (MA, MS, MBA, PhD, Law Degree, Medical Degree etc)
- Prefer not to say

→

Figure A.18: Demographic questions part 4

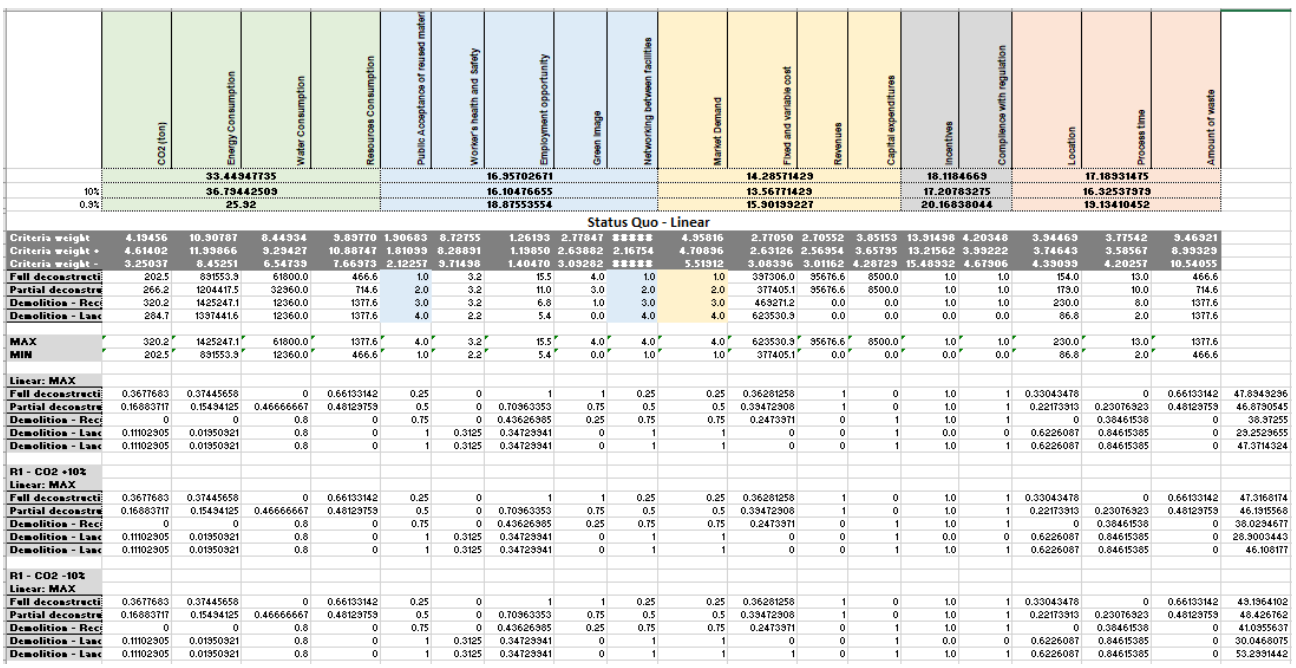
Appendix 3

Sensitivity Analysis (explained in section 4.4)



	Cost	Cost	Cost	Cost	Benefit	Cost	benefit	Benefit	Benefit	Benefit	cost	Benefit	Cost	Benefit	Binary	Cost	Cost	Cost	
	CO2 (ton)	Energy Consumption	Water Consumption	Resources Consumption	Public Acceptance of reused materi	Worker's health and Safety	Employment opportunity	Green image	Networking between facilities	Market Demand	Fixed and variable cost	Revenues	Capital expenditures	Incentives	Complience with regulation	Location	Process time	Amount of waste	
	33.44947735				16.95702671					14.28571429				18.1184669		17.18931475			
10%	36.79442509				16.10476655					13.56771429				17.20783275		16.32537979			
0.9%	25.92				18.87553554					15.90199227				20.16838044		19.13410452			
Criteria weight	4.19456	10.90787	8.44934	9.89770	1.90683	8.72755	1.26193	2.77847	#####	4.95816	2.77050	2.70552	3.85153	13.91498	4.20348	3.94469	3.77542	9.46921	
Criteria weight +	4.61402	11.99866	9.29427	10.88747	1.81099	8.28891	1.19850	2.63882	2.16754	4.70896	2.63126	2.56954	3.65795	13.21562	3.99222	3.74643	3.58567	8.99329	
Criteria weight -	3.25037	8.45251	6.54739	7.66973	2.12257	9.71498	1.40470	3.09282	#####	5.51912	3.08396	3.01162	4.28729	15.48932	4.67906	4.39099	4.20257	10.54055	
Future - Circular																			
Full deconstructi	202.5	891553.9	61800.0	466.6	4.0	3.2	15.5	4.0	4.0	4.0	397306.0	95676.6	8500.0	1.0	1.0	154.0	13.0	466.6	
Partial deconstru	266.2	1204417.5	32960.0	714.6	3.0	3.2	11.0	3.0	3.0	3.0	377405.1	95676.6	8500.0	1.0	1.0	179.0	10.0	714.6	
Demolition - Rec	320.2	1425247.1	12360.0	1377.6	2.0	3.2	6.8	1.0	2.0	2.0	469271.2	0.0	0.0	1.0	1.0	230.0	8.0	1377.6	
Demolition - Lanc	284.7	1397441.6	12360.0	1377.6	1.0	2.2	5.4	0.0	1.0	1.0	623530.9	0.0	0.0	0.0	0.0	86.8	2.0	1377.6	
MAX	320.2	1425247.1	61800.0	1377.6	4.0	3.2	15.5	4.0	4.0	4.0	623530.9	95676.6	8500.0	1.0	1.0	230.0	13.0	1377.6	
MIN	202.5	891553.9	12360.0	466.6	1.0	2.2	5.4	0.0	1.0	1.0	377405.1	0.0	0.0	0.0	0.0	86.8	2.0	466.6	
Linear: MAX																			
Full deconstructi	0.3677683	0.37445658	0	0.66133142	1	0	1	1	1	1	0.36281258	1	0	1.0	1	0.33043478	0	0.66133142	54.755355
Partial deconstru	0.16883717	0.15494125	0.46666667	0.48129759	0.75	0	0.70963353	0.75	0.75	0.75	0.39472908	1	0	1.0	1	0.22173913	0.23076923	0.48129759	49.165863
Demolition - Rec	0	0	0.8	0	0.5	0	0.43626985	0.25	0.5	0.5	0.2473971	0	1	1.0	1	0	0.38461538	0	36.6857416
Demolition - Lanc	0.11102905	0.01950921	0.8	0	0.25	0.3125	0.34729941	0	0.25	0.25	0	0	1	0.0	0	0.6226087	0.84615385	0	22.3925401
R1 - CO2 +10%																			
Linear: MAX																			
Full deconstructi	0.3677683	0.37445658	0	0.66133142	1	0	1	1	1	1	0.36281258	1	0	1.0	1	0.33043478	0	0.66133142	53.8324378
Partial deconstru	0.16883717	0.15494125	0.46666667	0.48129759	0.75	0	0.70963353	0.75	0.75	0.75	0.39472908	1	0	1.0	1	0.22173913	0.23076923	0.48129759	48.3634303
Demolition - Rec	0	0	0.8	0	0.5	0	0.43626985	0.25	0.5	0.5	0.2473971	0	1	1.0	1	0	0.38461538	0	35.8575942
Demolition - Lanc	0.11102905	0.01950921	0.8	0	0.25	0.3125	0.34729941	0	0.25	0.25	0	0	1	0.0	0	0.6226087	0.84615385	0	22.3847238
R1 - CO2 -10%																			
Linear: MAX																			
Full deconstructi	0.3677683	0.37445658	0	0.66133142	1	0	1	1	1	1	1	1	0	1.0	1	0.33043478	0	0.66133142	58.7980786
Partial deconstru	0.16883717	0.15494125	0.46666667	0.48129759	0.75	0	0.70963353	0.75	0.75	0.75	0.99999942	1	0	1.0	1	0.22173913	0.23076923	0.48129759	52.8389261
Demolition - Rec	0	0	0.8	0	0.5	0	0.43626985	0.25	0.5	0.5	0.99999937	0	1	1.0	1	0	0.38461538	0	40.8710194
Demolition - Lanc	0.11102905	0.01950921	0.8	0	0.25	0.3125	0.34729941	0	0.25	0.25	0.9999996	0	1	0.0	0	0.6226087	0.84615385	0	25.4941523

(a) Future - Circular



	CO2 (ton)	Energy Consumption	Water Consumption	Resources Consumption	Public Acceptance of reused materi	Worker's health and Safety	Employment opportunity	Green image	Networking between facilities	Market Demand	Fixed and variable cost	Revenues	Capital expenditures	Incentives	Complience with regulation	Location	Process time	Amount of waste	
	33.44947735				16.95702671					14.28571429				18.1184669		17.18931475			
10%	36.79442509				16.10476655					13.56771429				17.20783275		16.32537979			
0.9%	25.92				18.87553554					15.90199227				20.16838044		19.13410452			
Status Quo - Linear																			
Criteria weight	4.19456	10.90787	8.44934	9.89770	1.90683	8.72755	1.26193	2.77847	#####	4.95816	2.77050	2.70552	3.85153	13.91498	4.20348	3.94469	3.77542	9.46921	
Criteria weight +	4.61402	11.99866	9.29427	10.88747	1.81099	8.28891	1.19850	2.63882	2.16754	4.70896	2.63126	2.56954	3.65795	13.21562	3.99222	3.74643	3.58567	8.99329	
Criteria weight -	3.25037	8.45251	6.54739	7.66973	2.12257	9.71498	1.40470	3.09282	#####	5.51912	3.08396	3.01162	4.28729	15.48932	4.67906	4.39099	4.20257	10.54055	
Full deconstructi	202.5	891553.9	61800.0	466.6	1.0	3.2	15.5	4.0	1.0	1.0	397306.0	95676.6	8500.0	1.0	1.0	154.0	13.0	466.6	
Partial deconstru	266.2	1204417.5	32960.0	714.6	2.0	3.2	11.0	3.0	2.0	2.0	377405.1	95676.6	8500.0	1.0	1.0	179.0	10.0	714.6	
Demolition - Rec	320.2	1425247.1	12360.0	1377.6	3.0	3.2	6.8	1.0	3.0	3.0	469271.2	0.0	0.0	1.0	1.0	230.0	8.0	1377.6	
Demolition - Lanc	284.7	1397441.6	12360.0	1377.6	4.0	2.2	5.4	0.0	4.0	4.0	623530.9	0.0	0.0	0.0	0.0	86.8	2.0	1377.6	
MAX	320.2	1425247.1	61800.0	1377.6	4.0	3.2	15.5	4.0	4.0	4.0	623530.9	95676.6	8500.0	1.0	1.0	230.0	13.0	1377.6	
MIN	202.5	891553.9	12360.0	466.6	1.0	2.2	5.4	0.0	1.0	1.0	377405.1	0.0	0.0	0.0	0.0	86.8	2.0	466.6	
Linear: MAX																			
Full deconstructi	0.3677683	0.37445658	0	0.66133142	0.25	0	1	1	0.25	0.25	0.36281258	1	0	1.0	1	0.33043478	0	0.66133142	47.8949296
Partial deconstru	0.16883717	0.15494125	0.46666667	0.48129759	0.5	0	0.70963353	0.75	0.5	0.5	0.39472908	1	0	1.0	1	0.22173913	0.23076923	0.48129759	46.8790545
Demolition - Rec	0	0	0.8	0	0.75	0	0.43626985	0.25	0.75	0.75	0.2473971	0	1	1.0	1	0	0.38461538	0	38.97255
Demolition - Lanc	0.11102905	0.01950921	0.8	0	1	0.3125	0.34729941	0	1	1	0	0	1	0.0	0	0.6226087	0.84615385	0	29.2529655
Demolition - Lanc	0.11102905	0.01950921	0.8	0	1	0.3125	0.34729941	0	1	1	0	0	1	1.0	1	0.6226087	0.84615385	0	47.3714324
R1 - CO2 +10%																			
Linear: MAX																			
Full deconstructi	0.3677683	0.37445658	0	0.66133142	0.25	0	1	1	0.25	0.25	0.36281258	1	0	1.0	1	0.33043478	0	0.66133142	47.3168174
Partial deconstru	0.16883717	0.15494125	0.46666667	0.48129759	0.5	0	0.70963353	0.75	0.5	0.5	0.39472908	1	0	1.0	1	0.22173913	0.23076923	0.48129759	46.1915568
Demolition - Rec	0	0	0.8	0	0.75	0	0.43626985	0.25	0.75	0.75	0.2473971	0	1	1.0	1	0	0.38461538	0	38.0294677
Demolition - Lanc	0.11102905	0.01950921	0.8	0	1	0.3125	0.34729941	0	1	1	0	0	1	0.0	0	0.6226087	0.84615385	0	28.9003443
Demolition - Lanc	0.11102905	0.01950921	0.8	0	1	0.3125	0.34729941	0	1	1	0	0	1	1.0	1	0.6226087	0.84615385	0	46.108177
R1 - CO2 -10%																			
Linear: MAX																			
Full deconstructi	0.3677683	0.37445658	0	0.66133142	0.25	0	1	1	0.25	0.25	0.36281258	1	0	1.0	1	0.33043478	0	0.66133142	49.1964102
Partial deconstru	0.16883717	0.15494125	0.46666667	0.48129759	0.5	0	0.70963353	0.75	0.5	0.5	0.39472908	1	0	1.0	1	0.22173913	0.23076923	0.48129759	48.426762
Demolition - Rec	0	0	0.8	0	0.75	0	0.43626985	0.25	0.75	0.75	0.2473971	0	1	1.0	1	0	0.38461538	0	41.0955637
Demolition - Lanc	0.11102905	0.01950921	0.8	0	1	0.3125	0.34729941	0	1	1	0	0	1	0.0	0	0.6226087	0.84615385	0	30.0468075
Demolition - Lanc	0.11102905	0.01950921	0.8	0	1	0.3125	0.34729941	0	1	1	1	0	1	1.0	1	0.6226087	0.84615385	0	53.2991442

(b) Status Quo - Linear

Figure A.19: Sensitivity analysis of Environment main criteria (+/- 10%)

	Cost	Cost	Cost	Cost	Benefit	Cost	benefit	Benefit	Benefit	Benefit	cost	Benefit	Cost	Benefit	Binary	Cost	Cost	Cost	
	CO2 (ton)	Energy Consumption	Water Consumption	Resources Consumption	Public Acceptance of reused materi	Worker's health and Safety	Employment opportunity	Green image	Networking between facilities	Market Demand	Fixed and variable cost	Revenues	Capital expenditures	Incentives	Complience with regulation	Location	Process time	Amount of waste	
	33.44947735				16.95702671					14.28571429				18.1184669		17.18931475			
10%	32.76647247				18.65272938					13.99401429				17.74850592		16.83832613			
0.9%	34.9869888				13.14					14.9423598				18.9512856		17.9794248			
	12.54	32.61	25.26	29.59	11.2451	51.46865	7.44191144	16.38536	13.459	34.7070986	19.3935217	18.9387	26.96072	76.80	23.20	22.94848009	21.96375054	55.08776937	
Future - Circular																			
Criteria weight	4.19456	10.90787	8.44934	9.89770	1.90683	8.72755	1.26193	2.77847	#####	4.95816	2.77050	2.70552	3.85153	13.91498	4.20348	3.94469	3.77542	9.46921	
Criteria weight +	4.10892	10.68515	8.27681	9.69560	2.09751	9.60031	1.38812	3.05632	2.51047	4.85692	2.71393	#####	3.77289	13.63085	4.11765	3.86414	3.69833	9.27586	
Criteria weight -	4.38737	11.40926	8.83771	10.35265	1.47760	6.76298	0.97787	2.15304	1.76851	5.18606	2.89785	#####	4.02857	14.55459	4.39670	4.12600	3.94896	9.90446	
Full deconstructi	202.5	891553.9	61800.0	466.6	4.0	3.2	15.5	4.0	4.0	4.0	397306.0	95676.6	8500.0	1.0	1.0	154.0	13.0	466.6	
Partial deconstru	266.2	1204417.5	32960.0	714.6	3.0	3.2	11.0	3.0	3.0	3.0	377405.1	95676.6	8500.0	1.0	1.0	179.0	10.0	714.6	
Demolition - Rec	320.2	1425247.1	12360.0	1377.6	2.0	3.2	6.8	1.0	2.0	2.0	469271.2	0.0	0.0	1.0	1.0	230.0	8.0	1377.6	
Demolition - Lanc	284.7	1397441.6	12360.0	1377.6	1.0	2.2	5.4	0.0	1.0	1.0	623530.9	0.0	0.0	0.0	0.0	86.8	2.0	1377.6	
MAX	320.2	1425247.1	61800.0	1377.6	4.0	3.2	15.5	4.0	4.0	4.0	623530.9	95676.6	8500.0	1.0	1.0	230.0	13.0	1377.6	
MAX	320.2	1425247.1	32960.0	1377.6	3.0	3.2	11.0	3.0	3.0	3.0	623530.9	95676.6	8500.0	1.0	1.0	230.0	10.0	1377.6	
Linear: MAX																			
Full deconstructi	0.3677683	0.37445658	0	0.66133142	1	0	1	1	1	1	0.36281258	1	0	1.0	1	0.33043478	0	0.66133142	54.755355
Partial deconstru	0.16883717	0.15494125	0.46666667	0.48129759	0.75	0	0.70963353	0.75	0.75	0.75	0.39472908	1	0	1.0	1	0.22173913	0.23076923	0.48129759	49.165863
Demolition - Rec	0	0	0.8	0	0.5	0	0.43626985	0.25	0.5	0.5	0.2473971	0	1	1.0	1	0	0.38461538	0	36.6857416
Demolition - Lanc	0.11102905	0.01950921	0.8	0	0.25	0.3125	0.34729941	0	0.25	0.25	0	0	1	0.0	0	0.6226087	0.84615385	0	22.3925401
Demolition - Lanc	0.11102905	0.01950921	0.8	0	0.25	0.3125	0.34729941	0	0.25	0.25	0	0	1	1.0	1	0.6226087	0.84615385	0	40.511007
R1 - CO2 +10%																			
Linear: MAX																			
Full deconstructi	0.3677683	0.37445658	0	0.66133142	1	0	1	1	1	1	0.36281258	1	0	1.0	1	0.33043478	0	0.66133142	54.6282904
Partial deconstru	0.16883717	0.15494125	0.46666667	0.48129759	0.75	0	0.70963353	0.75	0.75	0.75	0.39472908	1	0	1.0	1	0.22173913	0.23076923	0.48129759	48.8990499
Demolition - Rec	0	0	0.8	0	0.5	0	0.43626985	0.25	0.5	0.5	0.2473971	0	1	1.0	1	0	0.38461538	0	36.3388183
Demolition - Lanc	0.11102905	0.01950921	0.8	0	0.25	0.3125	0.34729941	0	0.25	0.25	0	0	1	0.0	0	0.6226087	0.84615385	0	22.4426195
Demolition - Lanc	0.11102905	0.01950921	0.8	0	0.25	0.3125	0.34729941	0	0.25	0.25	0	0	1	1.0	1	0.6226087	0.84615385	0	40.1911255
R1 - CO2 -10%																			
Linear: MAX																			
Full deconstructi	0.3677683	0.37445658	0	0.66133142	1	0	1	1	1	1	1	1	0	1.0	1	0.33043478	0	0.66133142	56.8879448
Partial deconstru	0.16883717	0.15494125	0.46666667	0.48129759	0.75	0	0.70963353	0.75	0.75	0.75	0.99999942	1	0	1.0	1	0.22173913	0.23076923	0.48129759	51.5205287
Demolition - Rec	0	0	0.8	0	0.5	0	0.43626985	0.25	0.5	0.5	0.99999937	0	1	1.0	1	0	0.38461538	0	39.6476614
Demolition - Lanc	0.11102905	0.01950921	0.8	0	0.25	0.3125	0.34729941	0	0.25	0.25	0.9999996	0	1	0.0	0	0.6226087	0.84615385	0	25.1776965
Demolition - Lanc	0.11102905	0.01950921	0.8	0	0.25	0.3125	0.34729941	0	0.25	0.25	0	0	1	1.0	1	0.6226087	0.84615385	0	41.2311335

(a) Future - Circular

	Cost	Cost	Cost	Cost	Benefit	Cost	benefit	Benefit	Benefit	Benefit	cost	Benefit	Cost	Benefit	Binary	Cost	Cost	Cost	
	CO2 (ton)	Energy Consumption	Water Consumption	Resources Consumption	Public Acceptance of reused materi	Worker's health and Safety	Employment opportunity	Green image	Networking between facilities	Market Demand	Fixed and variable cost	Revenues	Capital expenditures	Incentives	Complience with regulation	Location	Process time	Amount of waste	
	33.44947735				16.95702671					14.28571429				18.1184669		17.18931475			
10%	32.76647247				18.65272938					13.99401429				17.74850592		16.83832613			
0.9%	34.9869888				13.14					14.9423598				18.9512856		17.9794248			
	12.54	32.61	25.26	29.59	11.2451	51.46865	7.44191144	16.38536	13.459	34.7070986	19.3935217	18.9387	26.96072	76.80	23.20	22.94848009	21.96375054	55.08776937	
Status Quo - Linear																			
Criteria weight	4.19456	10.90787	8.44934	9.89770	1.90683	8.72755	1.26193	2.77847	#####	4.95816	2.77050	2.70552	3.85153	13.91498	4.20348	3.94469	3.77542	9.46921	
Criteria weight +	4.10892	10.68515	8.27681	9.69560	2.09751	9.60031	1.38812	3.05632	2.51047	4.85692	2.71393	#####	3.77289	13.63085	4.11765	3.86414	3.69833	9.27586	
Criteria weight -	4.38737	11.40926	8.83771	10.35265	1.47760	6.76298	0.97787	2.15304	1.76851	5.18606	2.89785	#####	4.02857	14.55459	4.39670	4.12600	3.94896	9.90446	
Full deconstructi	202.5	891553.9	61800.0	466.6	4.0	3.2	15.5	4.0	4.0	4.0	397306.0	95676.6	8500.0	1.0	1.0	154.0	13.0	466.6	
Partial deconstru	266.2	1204417.5	32960.0	714.6	3.0	3.2	11.0	3.0	3.0	3.0	377405.1	95676.6	8500.0	1.0	1.0	179.0	10.0	714.6	
Demolition - Rec	320.2	1425247.1	12360.0	1377.6	2.0	3.2	6.8	1.0	2.0	2.0	469271.2	0.0	0.0	1.0	1.0	230.0	8.0	1377.6	
Demolition - Lanc	284.7	1397441.6	12360.0	1377.6	1.0	2.2	5.4	0.0	1.0	1.0	623530.9	0.0	0.0	0.0	0.0	86.8	2.0	1377.6	
MAX	320.2	1425247.1	61800.0	1377.6	4.0	3.2	15.5	4.0	4.0	4.0	623530.9	95676.6	8500.0	1.0	1.0	230.0	13.0	1377.6	
MAX	320.2	1425247.1	32960.0	1377.6	3.0	3.2	11.0	3.0	3.0	3.0	623530.9	95676.6	8500.0	1.0	1.0	230.0	10.0	1377.6	
Linear: MAX																			
Full deconstructi	0.3677683	0.37445658	0	0.66133142	0.25	0	1	1	0.25	0.25	0.36281258	1	0	1.0	1	0.33043478	0	0.66133142	47.8949296
Partial deconstru	0.16883717	0.15494125	0.46666667	0.48129759	0.5	0	0.70963353	0.75	0.5	0.5	0.39472908	1	0	1.0	1	0.22173913	0.23076923	0.48129759	46.8790545
Demolition - Rec	0	0	0.8	0	0.75	0	0.43626985	0.25	0.75	0.75	0.2473971	0	1	1.0	1	0	0.38461538	0	38.97255
Demolition - Lanc	0.11102905	0.01950921	0.8	0	1	0.3125	0.34729941	0	1	1	0	0	1	0.0	0	0.6226087	0.84615385	0	29.2529655
Demolition - Lanc	0.11102905	0.01950921	0.8	0	1	0.3125	0.34729941	0	1	1	0	0	1	1.0	1	0.6226087	0.84615385	0	47.3714324
R1 - CO2 +10%																			
Linear: MAX																			
Full deconstructi	0.3677683	0.37445658	0	0.66133142	0.25	0	1	1	0.25	0.25	0.36281258	1	0	1.0	1	0.33043478	0	0.66133142	47.5296146
Partial deconstru	0.16883717	0.15494125	0.46666667	0.48129759	0.5	0	0.70963353	0.75	0.5	0.5	0.39472908	1	0	1.0	1	0.22173913	0.23076923	0.48129759	46.5328246
Demolition - Rec	0	0	0.8	0	0.75	0	0.43626985	0.25	0.75	0.75	0.2473971	0	1	1.0	1	0	0.38461538	0	38.7050436
Demolition - Lanc	0.11102905	0.01950921	0.8	0	1	0.3125	0.34729941	0	1	1	0	0	1	0.0	0	0.6226087	0.84615385	0	29.5412953
Demolition - Lanc	0.11102905	0.01950921	0.8	0	1	0.3125	0.34729941	0	1	1	0	0	1	1.0	1	0.6226087	0.84615385	0	47.2898012
R1 - CO2 -10%																			
Linear: MAX																			
Full deconstructi	0.3677683	0.37445658	0	0.66133142	0.25	0	1	1	0.25	0.25	0.36281258	1	0	1.0	1	0.33043478	0	0.66133142	48.7173399
Partial deconstru	0.16883717	0.15494125	0.46666667	0.48129759	0.5	0	0.70963353	0.75	0.5	0.5	0.39472908	1	0	1.0	1	0.22173913	0.23076923	0.48129759	47.6585024
Demolition - Rec	0	0	0.8	0	0.75	0	0.43626985	0.25	0.75	0.75	0.2473971	0	1	1.0	1	0	0.38461538	0	39.5747769
Demolition - Lanc	0.11102905	0.01950921	0.8	0	1	0.3125	0.34729941	0	1	1	0	0	1	0.0	0	0.6226087	0.84615385	0	28.6039793
Demolition - Lanc	0.11102905	0.01950921	0.8	0	1	0.3125	0.34729941	0	1	1	0	0	1	1.0	1	0.6226087	0.84615385	0	47.5552649

(b) Status Quo - Linear

Figure A.20: Sensitivity analysis of Social main criteria (+/- 10%)

	CO2 (ton)	Energy Consumption	Water Consumption	Resources Consumption	Public Acceptance of reused mater	Worker's health and Safety	Employment opportunity	Green image	Networking between facilities	Market Demand	Fixed and variable cost	Revenues	Capital expenditures	Incentives	Complience with regulation	Location	Process time	Amount of waste	
	33.44947735				16.95702671					14.28571429				18.1184669		17.18931475			
10%	32.89198829				16.67441073					15.71428571				17.81649366		16.90282732			
0.9%	34.7043888				17.5931971					11.07				18.7982106		17.8341998			
	12.54	32.61	25.26	29.59	11.2451	51.46865	7.44191144	16.38536	13.459	34.7070986	19.3935217	18.9387	26.96072	76.80	23.20	22.94848009	21.96375054	55.08776937	
Future - Circular																			
Criteria weight	4.19456	10.90787	8.44934	9.89770	1.90683	8.72755	1.26193	2.77847	#####	4.95816	2.77050	2.70552	3.85153	13.91498	4.20348	3.94469	3.77542	9.46921	
Criteria weight +	4.12466	10.72608	8.30852	9.73274	1.87505	8.58209	1.24089	2.73216	2.24421	5.45397	3.04755	#####	4.23668	13.68307	4.13343	3.87894	3.71249	9.31139	
Criteria weight -	4.35193	11.31710	8.76633	10.26903	1.97837	9.05498	1.30927	2.88271	2.36787	3.84208	2.14686	2.09651	2.98455	14.43703	4.36118	4.09268	3.91706	9.82446	
Full deconstructi	202.5	891553.9	61800.0	466.6	4.0	3.2	15.5	4.0	4.0	4.0	397306.0	95676.6	8500.0	1.0	1.0	154.0	13.0	466.6	
Partial deconstru	266.2	1204417.5	32960.0	714.6	3.0	3.2	11.0	3.0	3.0	3.0	377405.1	95676.6	8500.0	1.0	1.0	179.0	10.0	714.6	
Demolition - Rec	320.2	1425247.1	12360.0	1377.6	2.0	3.2	6.8	1.0	2.0	2.0	469271.2	0.0	0.0	1.0	1.0	230.0	8.0	1377.6	
Demolition - Lanc	284.7	1397441.6	12360.0	1377.6	1.0	2.2	5.4	0.0	1.0	1.0	623530.9	0.0	0.0	0.0	0.0	86.8	2.0	1377.6	
MAX	320.2	1425247.1	61800.0	1377.6	4.0	3.2	15.5	4.0	4.0	4.0	623530.9	95676.6	8500.0	1.0	1.0	230.0	13.0	1377.6	
MAX	320.2	1425247.1	32960.0	1377.6	3.0	3.2	11.0	3.0	3.0	3.0	623530.9	95676.6	8500.0	1.0	1.0	230.0	10.0	1377.6	
Linear: MAX																			
Full deconstructi	0.3677683	0.37445658	0	0.66133142	1	0	1	1	1	1	0.36281258	1	0	1.0	1	0.33043478	0	0.66133142	54.755355
Partial deconstru	0.16883717	0.15494125	0.46666667	0.48129759	0.75	0	0.70963353	0.75	0.75	0.75	0.39472908	1	0	1.0	1	0.22173913	0.23076923	0.48129759	49.165863
Demolition - Rec	0	0	0.8	0	0.5	0	0.43626985	0.25	0.5	0.5	0.2473971	0	1	1.0	1	0	0.38461538	0	36.6857416
Demolition - Lanc	0.11102905	0.01950921	0.8	0	0.25	0.3125	0.34729941	0	0.25	0.25	0	0	1	0.0	0	0.6226087	0.84615385	0	22.3925401
Demolition - Lanc	0.11102905	0.01950921	0.8	0	0.25	0.3125	0.34729941	0	0.25	0.25	0	0	1	1.0	1	0.6226087	0.84615385	0	40.511007
R1 - CO2 +10%																			
Linear: MAX																			
Full deconstructi	0.3677683	0.37445658	0	0.66133142	1	0	1	1	1	1	0.36281258	1	0	1.0	1	0.33043478	0	0.66133142	54.8541351
Partial deconstru	0.16883717	0.15494125	0.46666667	0.48129759	0.75	0	0.70963353	0.75	0.75	0.75	0.39472908	1	0	1.0	1	0.22173913	0.23076923	0.48129759	49.2235043
Demolition - Rec	0	0	0.8	0	0.5	0	0.43626985	0.25	0.5	0.5	0.2473971	0	1	1.0	1	0	0.38461538	0	36.8928506
Demolition - Lanc	0.11102905	0.01950921	0.8	0	0.25	0.3125	0.34729941	0	0.25	0.25	0	0	1	0.0	0	0.6226087	0.84615385	0	22.6132904
Demolition - Lanc	0.11102905	0.01950921	0.8	0	0.25	0.3125	0.34729941	0	0.25	0.25	0	0	1	1.0	1	0.6226087	0.84615385	0	40.4297841
R1 - CO2 -10%																			
Linear: MAX																			
Full deconstructi	0.3677683	0.37445658	0	0.66133142	1	0	1	1	1	1	1	1	0	1.0	1	0.33043478	0	0.66133142	55.90096
Partial deconstru	0.16883717	0.15494125	0.46666667	0.48129759	0.75	0	0.70963353	0.75	0.75	0.75	0.99999942	1	0	1.0	1	0.22173913	0.23076923	0.48129759	50.3355493
Demolition - Rec	0	0	0.8	0	0.5	0	0.43626985	0.25	0.5	0.5	0.99999937	0	1	1.0	1	0	0.38461538	0	37.8352761
Demolition - Lanc	0.11102905	0.01950921	0.8	0	0.25	0.3125	0.34729941	0	0.25	0.25	0.9999996	0	1	0.0	0	0.6226087	0.84615385	0	24.0424949
Demolition - Lanc	0.11102905	0.01950921	0.8	0	0.25	0.3125	0.34729941	0	0.25	0.25	0	0	1	1.0	1	0.6226087	0.84615385	0	40.6938435

(a) Future – Circular

	CO2 (ton)	Energy Consumption	Water Consumption	Resources Consumption	Public Acceptance of reused materi	Worker's health and Safety	Employment opportunity	Green image	Networking between facilities	Market Demand	Fixed and variable cost	Revenues	Capital expenditures	Incentives	Complience with regulation	Location	Process time	Amount of waste	
	33.44947735				16.95702671					14.28571429				18.1184669		17.18931475			
10%	32.89198829				16.67441073					15.71428571				17.81649366		16.90282732			
0.9%	34.7043888				17.5931971					11.07				18.7982106		17.8341998			
Status Quo - Linear																			
Criteria weight	4.19456	10.90787	8.44934	9.89770	1.90683	8.72755	1.26193	2.77847	#####	4.95816	2.77050	2.70552	3.85153	13.91498	4.20348	3.94469	3.77542	9.46921	
Criteria weight +	4.10892	10.68515	8.27681	9.69560	2.09751	9.60031	1.38812	3.05632	2.51047	4.85692	2.71393	#####	3.77289	13.63085	4.11765	3.86414	3.69833	9.27586	
Criteria weight -	4.38737	11.40926	8.83771	10.35265	1.47760	6.76298	0.97787	2.15304	1.76851	5.18606	2.89785	#####	4.02857	14.55459	4.39670	4.12600	3.94896	9.90446	
Full deconstructi	202.5	891553.9	61800.0	466.6	1.0	3.2	15.5	4.0	1.0	1.0	397306.0	95676.6	8500.0	1.0	1.0	154.0	13.0	466.6	
Partial deconstru	266.2	1204417.5	32960.0	714.6	2.0	3.2	11.0	3.0	2.0	2.0	377405.1	95676.6	8500.0	1.0	1.0	179.0	10.0	714.6	
Demolition - Rec	320.2	1425247.1	12360.0	1377.6	3.0	3.2	6.8	1.0	3.0	3.0	469271.2	0.0	0.0	1.0	1.0	230.0	8.0	1377.6	
Demolition - Lanc	284.7	1397441.6	12360.0	1377.6	4.0	2.2	5.4	0.0	4.0	4.0	623530.9	0.0	0.0	0.0	0.0	86.8	2.0	1377.6	
Demolition - Lanc	284.7	1397441.6	12360.0	1377.6	4.0	2.2	5.4	0.0	4.0	4.0	623530.9	0.0	0.0	1.0	1.0	86.8	2.0	1377.6	
Linear: MAX																			
Full deconstructi	0.3677683	0.37445658	0	0.66133142	0.25	0	1	1	0.25	0.25	0.36281258	1	0	1.0	1	0.33043478	0	0.66133142	47.8949296
Partial deconstru	0.16883717	0.15494125	0.46666667	0.48129759	0.5	0	0.70963353	0.75	0.5	0.5	0.39472908	1	0	1.0	1	0.22173913	0.23076923	0.48129759	46.8790545
Demolition - Rec	0	0	0.8	0	0.75	0	0.43626985	0.25	0.75	0.75	0.2473971	0	1	1.0	1	0	0.38461538	0	38.97255
Demolition - Lanc	0.11102905	0.01950921	0.8	0	1	0.3125	0.34729941	0	1	1	0	0	1	0.0	0	0.6226087	0.84615385	0	29.2529655
Demolition - Lanc	0.11102905	0.01950921	0.8	0	1	0.3125	0.34729941	0	1	1	0	0	1	1.0	1	0.6226087	0.84615385	0	47.3714324
R1 - CO2 +10%																			
Linear: MAX																			
Full deconstructi	0.3677683	0.37445658	0	0.66133142	0.25	0	1	1	0.25	0.25	0.36281258	1	0	1.0	1	0.33043478	0	0.66133142	47.6742111
Partial deconstru	0.16883717	0.15494125	0.46666667	0.48129759	0.5	0	0.70963353	0.75	0.5	0.5	0.39472908	1	0	1.0	1	0.22173913	0.23076923	0.48129759	46.8301963
Demolition - Rec	0	0	0.8	0	0.75	0	0.43626985	0.25	0.75	0.75	0.2473971	0	1	1.0	1	0	0.38461538	0	39.2861586
Demolition - Lanc	0.11102905	0.01950921	0.8	0	1	0.3125	0.34729941	0	1	1	0	0	1	0.0	0	0.6226087	0.84615385	0	29.7932143
Demolition - Lanc	0.11102905	0.01950921	0.8	0	1	0.3125	0.34729941	0	1	1	0	0	1	1.0	1	0.6226087	0.84615385	0	47.609708
R1 - CO2 -10%																			
Linear: MAX																			
Full deconstructi	0.3677683	0.37445658	0	0.66133142	0.25	0	1	1	0.25	0.25	0.36281258	1	0	1.0	1	0.33043478	0	0.66133142	48.3917714
Partial deconstru	0.16883717	0.15494125	0.46666667	0.48129759	0.5	0	0.70963353	0.75	0.5	0.5	0.39472908	1	0	1.0	1	0.22173913	0.23076923	0.48129759	46.9890387
Demolition - Rec	0	0	0.8	0	0.75	0	0.43626985	0.25	0.75	0.75	0.2473971	0	1	1.0	1	0	0.38461538	0	38.2666204
Demolition - Lanc	0.11102905	0.01950921	0.8	0	1	0.3125	0.34729941	0	1	1	0	0	1	0.0	0	0.6226087	0.84615385	0	28.0368675
Demolition - Lanc	0.11102905	0.01950921	0.8	0	1	0.3125	0.34729941	0	1	1	0	0	1	1.0	1	0.6226087	0.84615385	0	46.8350781

(b) Status Quo - Linear

Figure A.21: Sensitivity analysis of Economics main criteria (+/- 10%)

	Cost	Cost	Cost	Cost	Benefit	Cost	benefit	Benefit	Benefit	Benefit	cost	Benefit	Cost	Benefit	Binary	Cost	Cost	Cost	
	CO2 (ton)	Energy Consumption	Water Consumption	Resources Consumption	Public Acceptance of reused materia	Worker's health and safety	Employment opportunity	Green image	Networking between facilities	Market Demand	Fixed and variable cost	Revenues	Capital expenditures	Incentives	Complience with regulation	Location	Process time	Amount of waste	
	33.44947735				16.95702671					14.28571429				18.1184669		17.18931475			
10%	32.7093207				16.58180841					13.96960571				19.93031359		16.80895647			
0.9%	35.1155808				17.8016486					14.9972793				14.04		18.0455068			
Future - Circular																			
Criteria weight	4.19456	10.90787	8.44934	9.89770	1.90683	8.72755	1.26193	2.77847	2.28225	4.95816	2.77050	2.70552	3.85153	13.91498	4.20348	3.94469	3.77542	9.46921	
Criteria weight + '	4.10175	10.66651	8.26237	9.67869	1.86464	8.53443	1.23400	2.71699	2.23175	4.84844	2.70920	2.64566	3.76631	15.30648	4.62383	3.85740	3.69188	9.25968	
Criteria weight - 1	4.40349	11.45119	8.87020	10.39070	2.00181	9.16227	1.32478	2.91686	2.39593	5.20512	2.90850	2.84028	4.04337	10.78272	3.25728	4.14117	3.96347	9.94087	
Full deconstructic	202.5	891553.9	61800.0	466.6	4.0	3.2	15.5	4.0	4.0	4.0	397306.0	95676.6	8500.0	1.0	1.0	154.0	13.0	466.6	
Partial deconstruc	266.2	1204417.5	32960.0	714.6	3.0	3.2	11.0	3.0	3.0	3.0	377405.1	95676.6	8500.0	1.0	1.0	179.0	10.0	714.6	
Demolition - Recy	320.2	1425247.1	12360.0	1377.6	2.0	3.2	6.8	1.0	2.0	2.0	469271.2	0.0	0.0	1.0	1.0	230.0	8.0	1377.6	
Demolition - Land	284.7	1397441.6	12360.0	1377.6	1.0	2.2	5.4	0.0	1.0	1.0	623530.9	0.0	0.0	0.0	0.0	86.8	2.0	1377.6	
MAX	320.2	1425247.1	61800.0	1377.6	4.0	3.2	15.5	4.0	4.0	4.0	623530.9	95676.6	8500.0	1.0	1.0	230.0	13.0	1377.6	
MIN	320.2	1425247.1	32960.0	1377.6	3.0	3.2	11.0	3.0	3.0	3.0	623530.9	95676.6	8500.0	1.0	1.0	230.0	10.0	1377.6	
Linear: MAX																			
Full deconstructic	0.367768298	0.374456584	0	0.661331417	1	0	1	1	1	1	0.362812583	1	0	1.0	1	0.330434783	0	0.661331417	54.755355
Partial deconstruc	0.168837166	0.154941253	0.466666667	0.481297591	0.75	0	0.709633531	0.75	0.75	0.75	0.39472908	1	0	1.0	1	0.22173913	0.230769231	0.481297591	49.16586301
Demolition - Recy	0	0	0.8	0	0.5	0	0.436269846	0.25	0.5	0.5	0.247397101	0	1	1.0	1	0	0.384615385	0	36.68574157
Demolition - Land	0.111029054	0.019509214	0.8	0	0.25	0.3125	0.34729941	0	0.25	0.25	0	0	1	0.0	0	0.622608696	0.846153846	0	22.39254006
Demolition - Land	0.111029054	0.019509214	0.8	0	0.25	0.3125	0.34729941	0	0.25	0.25	0	0	1	1.0	1	0.622608696	0.846153846	0	40.51100696
R1 - CO2 +10%																			
Linear: MAX																			
Full deconstructic	0.367768298	0.374456584	0	0.661331417	1	0	1	1	1	1	0.362812583	1	0	1.0	1	0.330434783	0	0.661331417	55.75651529
Partial deconstruc	0.168837166	0.154941253	0.466666667	0.481297591	0.75	0	0.709633531	0.75	0.75	0.75	0.39472908	1	0	1.0	1	0.22173913	0.230769231	0.481297591	50.29070533
Demolition - Recy	0	0	0.8	0	0.5	0	0.436269846	0.25	0.5	0.5	0.247397101	0	1	1.0	1	0	0.384615385	0	38.08673903
Demolition - Land	0.111029054	0.019509214	0.8	0	0.25	0.3125	0.34729941	0	0.25	0.25	0	0	1	0.0	0	0.622608696	0.846153846	0	21.89704689
Demolition - Land	0.111029054	0.019509214	0.8	0	0.25	0.3125	0.34729941	0	0.25	0.25	0	0	1	1.0	1	0.622608696	0.846153846	0	41.82736048
R1 - CO2 -10%																			
Linear: MAX																			
Full deconstructic	0.367768298	0.374456584	0	0.661331417	1	0	1	1	1	1	1	1	0	1.0	1	0.330434783	0	0.661331417	54.35501505
Partial deconstruc	0.168837166	0.154941253	0.466666667	0.481297591	0.75	0	0.709633531	0.75	0.75	0.75	0.999999418	1	0	1.0	1	0.22173913	0.230769231	0.481297591	48.39428212
Demolition - Recy	0	0	0.8	0	0.5	0	0.436269846	0.25	0.5	0.5	0.999999367	0	1	1.0	1	0	0.384615385	0	35.72104644
Demolition - Land	0.111029054	0.019509214	0.8	0	0.25	0.3125	0.34729941	0	0.25	0.25	0.999999603	0	1	0.0	0	0.622608696	0.846153846	0	26.41640189
Demolition - Land	0.111029054	0.019509214	0.8	0	0.25	0.3125	0.34729941	0	0.25	0.25	0	0	1	1.0	1	0.622608696	0.846153846	0	37.54790243

(a) Future – Circular

	Cost	Cost	Cost	Cost	Benefit	Cost	benefit	Benefit	Benefit	Benefit	cost	Benefit	Cost	Benefit	Binary	Cost	Cost	Cost	
	CO2 (ton)	Energy Consumption	Water Consumption	Resources Consumption	Public Acceptance of reused mater	Worker's health and safety	Employment opportunity	Green image	Networking between facilities	Market Demand	Fixed and variable cost	Revenues	Capital expenditures	Incentives	Complience with regulation	Location	Process time	Amount of waste	
	33.44947735				16.95702671					14.28571429				18.1184669		17.18931475			
10%	32.7093207				16.58180841					13.96960571				19.93031359		16.80895647			
0.9%	35.1155808				17.8016486					14.9972793				14.04		18.0455068			
Status Quo - Linear																			
Criteria weight	4.19456	10.90787	8.44934	9.89770	1.90683	8.72755	1.26193	2.77847	#####	4.95816	2.77050	2.70552	3.85153	13.91498	4.20348	3.94469	3.77542	9.46921	
Criteria weight +	4.10892	10.68515	8.27681	9.69560	2.09751	9.60031	1.38812	3.05632	2.51047	4.85692	2.71393	#####	3.77289	13.63085	4.11765	3.86414	3.69833	9.27586	
Criteria weight -	4.38737	11.40926	8.83771	10.35265	1.47760	6.76298	0.97787	2.15304	1.76851	5.18606	2.89785	#####	4.02857	14.55459	4.39670	4.12600	3.94896	9.90446	
Full deconstructi	202.5	891553.9	61800.0	466.6	1.0	3.2	15.5	4.0	1.0	1.0	397306.0	95676.6	8500.0	1.0	1.0	154.0	13.0	466.6	
Partial deconstre	266.2	1204417.5	32960.0	714.6	2.0	3.2	11.0	3.0	2.0	2.0	377405.1	95676.6	8500.0	1.0	1.0	179.0	10.0	714.6	
Demolition - Rec	320.2	1425247.1	12360.0	1377.6	3.0	3.2	6.8	1.0	3.0	3.0	469271.2	0.0	0.0	1.0	1.0	230.0	8.0	1377.6	
Demolition - Lanc	284.7	1397441.6	12360.0	1377.6	4.0	2.2	5.4	0.0	4.0	4.0	623530.9	0.0	0.0	0.0	0.0	86.8	2.0	1377.6	
Demolition - Lanc	284.7	1397441.6	12360.0	1377.6	4.0	2.2	5.4	0.0	4.0	4.0	623530.9	0.0	0.0	1.0	1.0	86.8	2.0	1377.6	
Linear: MAX																			
Full deconstructi	0.3677683	0.37445658	0	0.66133142	0.25	0	1	1	0.25	0.25	0.36281258	1	0	1.0	1	0.33043478	0	0.66133142	47.8949296
Partial deconstre	0.16883717	0.15494125	0.46666667	0.48129759	0.5	0	0.70963353	0.75	0.5	0.5	0.39472908	1	0	1.0	1	0.22173913	0.23076923	0.48129759	46.8790545
Demolition - Rec	0	0	0.8	0	0.75	0	0.43626985	0.25	0.75	0.75	0.2473971	0	1	1.0	1	0	0.38461538	0	38.97255
Demolition - Lanc	0.11102905	0.01950921	0.8	0	1	0.3125	0.34729941	0	1	1	0	0	1	0.0	0	0.6226087	0.84615385	0	29.2529655
Demolition - Lanc	0.11102905	0.01950921	0.8	0	1	0.3125	0.34729941	0	1	1	0	0	1	1.0	1	0.6226087	0.84615385	0	47.3714324
R1 - CO2 +10%																			
Linear: MAX																			
Full deconstructi	0.3677683	0.37445658	0	0.66133142	0.25	0	1	1	0.25	0.25	0.36281258	1	0	1.0	1	0.33043478	0	0.66133142	49.0478946
Partial deconstre	0.16883717	0.15494125	0.46666667	0.48129759	0.5	0	0.70963353	0.75	0.5	0.5	0.39472908	1	0	1.0	1	0.22173913	0.23076923	0.48129759	48.0544984
Demolition - Rec	0	0	0.8	0	0.75	0	0.43626985	0.25	0.75	0.75	0.2473971	0	1	1.0	1	0	0.38461538	0	40.3229459
Demolition - Lanc	0.11102905	0.01950921	0.8	0	1	0.3125	0.34729941	0	1	1	0	0	1	0.0	0	0.6226087	0.84615385	0	28.6056676
Demolition - Lanc	0.11102905	0.01950921	0.8	0	1	0.3125	0.34729941	0	1	1	0	0	1	1.0	1	0.6226087	0.84615385	0	48.5359812
R1 - CO2 -10%																			
Linear: MAX																			
Full deconstructi	0.3677683	0.37445658	0	0.66133142	0.25	0	1	1	0.25	0.25	0.36281258	1	0	1.0	1	0.33043478	0	0.66133142	45.2996149
Partial deconstre	0.16883717	0.15494125	0.46666667	0.48129759	0.5	0	0.70963353	0.75	0.5	0.5	0.39472908	1	0	1.0	1	0.22173913	0.23076923	0.48129759	44.2331396
Demolition - Rec	0	0	0.8	0	0.75	0	0.43626985	0.25	0.75	0.75	0.2473971	0	1	1.0	1	0	0.38461538	0	35.9328157
Demolition - Lanc	0.11102905	0.01950921	0.8	0	1	0.3125	0.34729941	0	1	1	0	0	1	0.0	0	0.6226087	0.84615385	0	30.7100426
Demolition - Lanc	0.11102905	0.01950921	0.8	0	1	0.3125	0.34729941	0	1	1	0	0	1	1.0	1	0.6226087	0.84615385	0	44.7500426

(b) Status Quo - Linear

Figure A.22: Sensitivity analysis of Regulations main criteria (+/- 10%)

	CO2 (ton)	Energy Consumption	Water Consumption	Resources Consumption	Public Acceptance of reused materia	Worker's health and Safety	Employment opportunity	Green image	Networking between facilities	Market Demand	Fixed and variable cost	Revenues	Capital expenditures	Incentives	Complience with regulation	Location	Process time	Amount of waste	
	Cost	Cost	Cost	Cost	Benefit	Cost	benefit	Benefit	Benefit	Benefit	cost	Benefit	Cost	Benefit	Binary	Cost	Cost	Cost	
	33.44947735				16.95702671					14.28571429				18.1184669		17.18931475			
10%	32.75515317				16.60504293					13.98918				17.74237463		18.90824623			
0.9%	35.01239904				17.74934118					14.95321209				18.96504948		13.32			
Future - Circular																			
Criteria weight	4.19456	10.90787	8.44934	9.89770	1.90683	8.72755	1.26193	2.77847	2.28225	4.95816	2.77050	2.70552	3.85153	13.91498	4.20348	3.94469	3.77542	9.46921	
Criteria weight +	4.10750	10.68146	8.27395	9.69225	1.86725	8.54639	1.23573	2.72080	2.23487	4.85524	2.71299	2.64936	3.77158	13.62614	4.11623	4.33916	4.15296	10.41613	
Criteria weight -	4.39055	11.41754	8.84413	10.36017	1.99593	9.13535	1.32089	2.90829	2.38889	5.18983	2.89995	2.83194	4.03149	14.56516	4.39989	3.05674	2.92557	7.33769	
Full deconstructio	202.5	891553.9	61800.0	466.6	4.0	3.2	15.5	4.0	4.0	4.0	397306.0	95676.6	8500.0	1.0	1.0	154.0	13.0	466.6	
Partial deconstru	266.2	1204417.5	32960.0	714.6	3.0	3.2	11.0	3.0	3.0	3.0	377405.1	95676.6	8500.0	1.0	1.0	179.0	10.0	714.6	
Demolition - Recy	320.2	1425247.1	12360.0	1377.6	2.0	3.2	6.8	1.0	2.0	2.0	469271.2	0.0	0.0	1.0	1.0	230.0	8.0	1377.6	
Demolition - Land	284.7	1397441.6	12360.0	1377.6	1.0	2.2	5.4	0.0	1.0	1.0	623530.9	0.0	0.0	0.0	0.0	86.8	2.0	1377.6	
MAX	320.2	1425247.1	61800.0	1377.6	4.0	3.2	15.5	4.0	4.0	4.0	623530.9	95676.6	8500.0	1.0	1.0	230.0	13.0	1377.6	
MIN	320.2	1425247.1	32960.0	1377.6	3.0	3.2	11.0	3.0	3.0	3.0	623530.9	95676.6	8500.0	1.0	1.0	230.0	10.0	1377.6	
Linear: MAX																			
Full deconstructio	0.367768298	0.374456584	0	0.661331417	1	0	1	1	1	1	0.362812583	1	0	1.0	1	0.330434783	0	0.661331417	54.755355
Partial deconstru	0.168837166	0.154941253	0.466666667	0.481297591	0.75	0	0.709633531	0.75	0.75	0.75	0.39472908	1	0	1.0	1	0.22173913	0.230769231	0.481297591	49.16586301
Demolition - Recy	0	0	0.8	0	0.5	0	0.436269846	0.25	0.5	0.5	0.247397101	0	1	1.0	1	0	0.384615385	0	36.68574157
Demolition - Land	0.111029054	0.019509214	0.8	0	0.25	0.3125	0.34729941	0	0.25	0.25	0	0	1	0.0	0	0.622608696	0.846153846	0	22.39254006
Demolition - Land	0.111029054	0.019509214	0.8	0	0.25	0.3125	0.34729941	0	0.25	0.25	0	0	1	1.0	1	0.622608696	0.846153846	0	40.51100696
R1 - CO2 +10%																			
Linear: MAX																			
Full deconstructio	0.367768298	0.374456584	0	0.661331417	1	0	1	1	1	1	0.362812583	1	0	1.0	1	0.330434783	0	0.661331417	54.53239622
Partial deconstru	0.168837166	0.154941253	0.466666667	0.481297591	0.75	0	0.709633531	0.75	0.75	0.75	0.39472908	1	0	1.0	1	0.22173913	0.230769231	0.481297591	48.90649572
Demolition - Recy	0	0	0.8	0	0.5	0	0.436269846	0.25	0.5	0.5	0.247397101	0	1	1.0	1	0	0.384615385	0	36.09959084
Demolition - Land	0.111029054	0.019509214	0.8	0	0.25	0.3125	0.34729941	0	0.25	0.25	0	0	1	0.0	0	0.622608696	0.846153846	0	22.61007859
Demolition - Land	0.111029054	0.019509214	0.8	0	0.25	0.3125	0.34729941	0	0.25	0.25	0	0	1	1.0	1	0.622608696	0.846153846	0	40.35245323
R1 - CO2 -10%																			
Linear: MAX																			
Full deconstructio	0.367768298	0.374456584	0	0.661331417	1	0	1	1	1	1	1	1	0	1.0	1	0.330434783	0	0.661331417	57.10504681
Partial deconstru	0.168837166	0.154941253	0.466666667	0.481297591	0.75	0	0.709633531	0.75	0.75	0.75	0.999999418	1	0	1.0	1	0.22173913	0.230769231	0.481297591	51.50495255
Demolition - Recy	0	0	0.8	0	0.5	0	0.436269846	0.25	0.5	0.5	0.999999367	0	1	1.0	1	0	0.384615385	0	40.18767699
Demolition - Land	0.111029054	0.019509214	0.8	0	0.25	0.3125	0.34729941	0	0.25	0.25	0.999999603	0	1	0.0	0	0.622608696	0.846153846	0	24.8028131
Demolition - Land	0.111029054	0.019509214	0.8	0	0.25	0.3125	0.34729941	0	0.25	0.25	0	0	1	1.0	1	0.622608696	0.846153846	0	40.8679093

(a) Future – Circular

	CO2 (ton)	Energy Consumption	Water Consumption	Resources Consumption	Public Acceptance of reused materi	Worker's health and Safety	Employment opportunity	Green image	Networking between facilities	Market Demand	Fixed and variable cost	Revenues	Capital expenditures	Incentives	Complience with regulation	Location	Process time	Amount of waste	
	Cost	Cost	Cost	Cost	Benefit	Cost	benefit	Benefit	Benefit	Benefit	cost	Benefit	Cost	Benefit	Binary	Cost	Cost	Cost	
	33.44947735				16.95702671					14.28571429				18.1184669		17.18931475			
10%	32.75515317				16.60504293					13.98918				17.74237463		18.90824623			
0.9%	35.01239904				17.74934118					14.95321209				18.96504948		13.32			
	12.54	32.61	25.26	29.59	11.2451	51.46865	7.44191144	16.38536	13.459	34.7070986	19.3935217	18.9387	26.96072	76.80	23.20	22.94848009	21.96375054	55.08776937	
Status Quo - Linear																			
Criteria weight	4.19456	10.90787	8.44934	9.89770	1.90683	8.72755	1.26193	2.77847	#####	4.95816	2.77050	2.70552	3.85153	13.91498	4.20348	3.94469	3.77542	9.46921	
Criteria weight +	4.10892	10.68515	8.27681	9.69560	2.09751	9.60031	1.38812	3.05632	2.51047	4.85692	2.71393	#####	3.77289	13.63085	4.11765	3.86414	3.69833	9.27586	
Criteria weight -	4.38737	11.40926	8.83771	10.35265	1.47760	6.76298	0.97787	2.15304	1.76851	5.18606	2.89785	#####	4.02857	14.55459	4.39670	4.12600	3.94896	9.90446	
Full deconstructi	202.5	891553.9	61800.0	466.6	1.0	3.2	15.5	4.0	1.0	1.0	397306.0	95676.6	8500.0	1.0	1.0	154.0	13.0	466.6	
Partial deconstru	266.2	1204417.5	32960.0	714.6	2.0	3.2	11.0	3.0	2.0	2.0	377405.1	95676.6	8500.0	1.0	1.0	179.0	10.0	714.6	
Demolition - Rec	320.2	1425247.1	12360.0	1377.6	3.0	3.2	6.8	1.0	3.0	3.0	469271.2	0.0	0.0	1.0	1.0	230.0	8.0	1377.6	
Demolition - Lan	284.7	1397441.6	12360.0	1377.6	4.0	2.2	5.4	0.0	4.0	4.0	623530.9	0.0	0.0	0.0	0.0	86.8	2.0	1377.6	
Demolition - Lan	284.7	1397441.6	12360.0	1377.6	4.0	2.2	5.4	0.0	4.0	4.0	623530.9	0.0	0.0	1.0	1.0	86.8	2.0	1377.6	
Linear: MAX																			
Full deconstructi	0.3677683	0.37445658	0	0.66133142	0.25	0	1	1	0.25	0.25	0.36281258	1	0	1.0	1	0.33043478	0	0.66133142	47.8949296
Partial deconstru	0.16883717	0.15494125	0.46666667	0.48129759	0.5	0	0.70963353	0.75	0.5	0.5	0.39472908	1	0	1.0	1	0.22173913	0.23076923	0.48129759	46.8790545
Demolition - Rec	0	0	0.8	0	0.75	0	0.43626985	0.25	0.75	0.75	0.2473971	0	1	1.0	1	0	0.38461538	0	38.97255
Demolition - Lan	0.11102905	0.01950921	0.8	0	1	0.3125	0.34729941	0	1	1	0	0	1	0.0	0	0.6226087	0.84615385	0	29.2529655
Demolition - Lan	0.11102905	0.01950921	0.8	0	1	0.3125	0.34729941	0	1	1	0	0	1	1.0	1	0.6226087	0.84615385	0	47.3714324
R1 - CO2 +10%																			
Linear: MAX																			
Full deconstructi	0.3677683	0.37445658	0	0.66133142	0.25	0	1	1	0.25	0.25	0.36281258	1	0	1.0	1	0.33043478	0	0.66133142	47.8143754
Partial deconstru	0.16883717	0.15494125	0.46666667	0.48129759	0.5	0	0.70963353	0.75	0.5	0.5	0.39472908	1	0	1.0	1	0.22173913	0.23076923	0.48129759	46.6671554
Demolition - Rec	0	0	0.8	0	0.75	0	0.43626985	0.25	0.75	0.75	0.2473971	0	1	1.0	1	0	0.38461538	0	38.3389311
Demolition - Lan	0.11102905	0.01950921	0.8	0	1	0.3125	0.34729941	0	1	1	0	0	1	0.0	0	0.6226087	0.84615385	0	29.3280994
Demolition - Lan	0.11102905	0.01950921	0.8	0	1	0.3125	0.34729941	0	1	1	0	0	1	1.0	1	0.6226087	0.84615385	0	47.0704741
R1 - CO2 -10%																			
Linear: MAX																			
Full deconstructi	0.3677683	0.37445658	0	0.66133142	0.25	0	1	1	0.25	0.25	0.36281258	1	0	1.0	1	0.33043478	0	0.66133142	48.0762546
Partial deconstru	0.16883717	0.15494125	0.46666667	0.48129759	0.5	0	0.70963353	0.75	0.5	0.5	0.39472908	1	0	1.0	1	0.22173913	0.23076923	0.48129759	47.3560369
Demolition - Rec	0	0	0.8	0	0.75	0	0.43626985	0.25	0.75	0.75	0.2473971	0	1	1.0	1	0	0.38461538	0	40.398824
Demolition - Lan	0.11102905	0.01950921	0.8	0	1	0.3125	0.34729941	0	1	1	0	0	1	0.0	0	0.6226087	0.84615385	0	29.0838376
Demolition - Lan	0.11102905	0.01950921	0.8	0	1	0.3125	0.34729941	0	1	1	0	0	1	1.0	1	0.6226087	0.84615385	0	48.048887

(b) Future – Circular

Figure A.23: Sensitivity analysis of Site Conditions main criteria (+/- 10%)