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TRANSITION TO A CIRCULAR ECONOMY IN OFF-SITE CONSTRUCTION SUPPLY CHAIN: PERSPECTIVES ON ECONOMIC VIABILITY

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ABSTRACT: The construction industry is among the most resource-intensive sectors, generating the highest levels of waste and emissions. Implementing Circular Economy (CE) principles offers a promising pathway toward a more sustainable built environment. However, a successful transition requires a robust assessment framework to support the development and adoption of CE strategies. Addressing this need, the present study evaluates the financial feasibility of integrating CE principles into the Modular and Off-site Construction (MOC) supply chain. Through system dynamics modeling, it examines material flows from end-of-life (EoL) buildings to MOC factories, identifying the key conditions necessary to maximize economic benefits. The research highlights the crucial roles of demolition contractors, recycling facilities, and secondary material markets in enhancing material recovery efficiency. A case study on a wood-frame panelized wall factory illustrates the model's utility, while the framework also demonstrating its potential applicability to other building types. Findings show that circular strategies can enhance profitability while reducing material waste and carbon emissions, even in the absence of government intervention. By detailing both profitable and non-profitable scenarios, this study provides valuable insights into various EoL scenarios and collaborative strategies among MOC supply chain stakeholders, including new players like deconstruction contractors. The proposed framework aims to guide decision-makers in simulating cost–benefit analyses of collaborative, CE-compliant scenarios, thereby facilitating the construction sector's transition to a CE.

1. INTRODUCTION AND RELATED STUDIES

The construction industry is one of the most resource-intensive and environmentally impactful sectors, accounting for approximately 50% of global material extraction, 39% of global CO_2 emissions, and 35% of landfill waste(Kamali et al. 2019; Vandervaeren et al. 2022). A significant portion of these materials turn into waste during the Construction, Renovation, and Demolition (CRD) phases of a building's lifecycle (Orenga Panizza and Nik-Bakht 2024). In Canada, CRD waste constitutes a major share of the solid waste stream, amounting to 4 million tonnes which is 12% of the total waste generated in the country (Environment and Climate Change Canada 2021). The large quantities of waste disposed of in landfills have become a major environmental concern. As a result, countries worldwide are seeking effective solutions to address this issue and minimize its environmental impact (Osmani and Villoria-Sáez 2019).

To address these challenges, Modular and Off-site construction (MOC) presents a promising alternative to traditional stick-built construction, offering significant reductions in waste generation and carbon emissions (Li et al. 2014; Zhang et al. 2024). By prefabricating building components in controlled indoor environments, MOC enhances productivity and minimizes environmental impact. However, despite these advantages, it largely relies on a linear economy model, following a “take, make, use, dispose” approach. This issue is becoming increasingly critical, particularly in countries like Canada, where a growing number of aging modular buildings reaching the end of their life cycle is driving widespread demolition and a substantial increase in waste generation. Therefore, it is essential to establish a circular business model encompassing the entire supply chain.

Construction supply chain management involves controlling the flow of materials, information, and operations from suppliers to end-users. Transitioning to a circular economy (CE) requires major process and structural changes, particularly in MOC, where multiple stages and dispersed stakeholders add complexity, making coordination essential (Zaalouk et al. 2023). In light of this complexity, recent research has increasingly explored barriers, enablers, and strategies for implementing circular practices across the construction supply chain. Key barriers include the fragmented nature of the supply chain, lack of transparency, inconsistent regulations, and limited stakeholder collaboration (Senaratne et al. 2023). These issues lead to inefficiencies in material reuse and recycling, compounded by low market demand for secondary materials, which prolongs material storage and creates logistical challenges (Giorgi et al. 2022). The traditional linear model, characterized by one-way material flow and siloed decision-making, impedes the systemic adoption of CE principles (Hosseini et al. 2015). In contrast, CE implementation, demands collaborative engagement among all stakeholders, including contractors, suppliers, recyclers, policymakers, and end-users, throughout the building lifecycle (Sudusinghe and Seuring 2022). Business model innovations, such as product-service systems, resource recovery models, and shared ownership, have proven effective in promoting closed-loop material flows (Jayakodi et al. 2024). Policy support also plays a crucial role, with financial incentives, carbon pricing mechanisms, and cap-and-trade systems providing essential drivers for CE adoption(Murray and Rivers 2015; Trochu et al. 2020). Although numerous studies in the manufacturing sector have examined pathways toward CE adoption, applying these strategies to the construction supply chain, particularly within MOC, remains at an early stage, largely due to the complex, dynamic, and project-specific nature of buildings, which diverges significantly from the standardized logic of manufacturing.

A critical yet often overlooked aspect of this transition is the end-of-life (EoL) stage. Despite MOC’s unique potential for transitioning to circularity through its capabilities for disassembly and reuse (Nik-Bakht et al. 2021), such potentials are not yet activated in the Canadian construction industry, due to several barriers. Firstly, MOC companies are hesitant to adopt circular practices without clear financial incentives, as sustainability is often seen as conflicting with profitability due to higher upfront costs, operational inefficiencies, or uncertain returns on investment (Abdelkafi and Täuscher 2016). Additionally, traditional demolition remains the dominant approach due to its efficiency, while deconstruction is often avoided due to higher costs, required labor, and uncertain market demand for recovered materials (Pantini and Rigamonti 2020; Van den Berg et al. 2020). As a result, valuable building components are frequently destroyed rather than recovered.

Unlike demolition, deconstruction facilitates material reuse and recycling, supports reverse logistics, and significantly reduces waste (Chileshe et al. 2018). However, its success depends on effectively reintegrating recovered materials into new production cycles. Manufacturers play a key role in this process by incorporating reclaimed materials from EoL buildings into their production lines, but, for these practices to be effective, stakeholders across the supply chain must maintain close and continuous collaboration (Riuttala et al. 2024). To achieve this, aligning diverse interests is essential, as changes in one area can create significant ripple effects throughout the supply chain.

Given these challenges, this study aims to evaluate the conditions under which a shift toward collaborative circular practices in the MOC supply chain can be achieved without compromising profitability for stakeholders. To this end, a cost-benefit analysis was conducted to evaluate the financial viability of CE practices under different scenarios. The assessment focuses on both a single manufacturing company and a demolition contractor, since both actors must adapt their investments and business strategies to align with circular practices. Understanding their economic conditions will provide valuable insights into the feasibility and impact of CE adoption on their businesses.

2. METHODOLOGY

This study adopts a three-stage research methodology (Figure 1) to evaluate the financial feasibility of various EoL scenarios within a collaborative MOC supply chain, ensuring profitability during the transition to a CE. The first stage examines existing linear processes from both the MOC factory and demolition contractor perspectives to establish a baseline for evaluating CE scenarios. This assessment of the status quo focuses on material flow, cost structures, and benefits associated with the linear approach. The baseline analysis not only provided a detailed understanding of existing supply chain dynamics but also served as a reference point for comparing alternative CE strategies in subsequent stages.

In the second stage, the take-back business model (Selvaraj and Chan 2024) was explored as a strategy to enhance circularity in the MOC supply chain by systematically returning recovered materials from deconstructed buildings for reintegration into production. At the EoL stage, materials follow three pathways: reuse after refurbishment, recycling, or landfill disposal. The reuse process begins with the recovery of building elements by demolition contractors. However, many existing buildings were not originally designed for deconstruction (Rakhshan et al. 2020), making recoverability a critical factor in determining material reuse and recycling potential. A key metric for assessing recoverability is the disassembly index, which classifies buildings into four levels based on ease of disassembly, influenced by connection types (Van den Berg et al. 2020), connection accessibility (Minunno et al. 2020), required tools and workforce for disassembly and moving components (O'Grady et al. 2021) among others. The index directly impacts material recovery rates, with Level 1 allowing for 100% recovery, while Level 4 permits only 5% (Franco 2019). However, not all recovered materials meet reuse standards (Akinade et al. 2015), as some deconstructed components fail to satisfy performance requirements (Diyamandoglu and Fortuna 2015). To address this, the study applies a reusability factor based on the methodology proposed by Akanbi et al. (2018) which assesses building material reusability using the Weibull reliability distribution, considering the age and life expectancy of building components (Akanbi et al. 2018).

The second pathway, recycling, refers to closed-loop recycling (upcycling), where recovered materials are remanufactured into the same product while maintaining their original function and quality. Lastly, non-reusable and non-recyclable materials are disposed of in landfills, contributing to CRD waste.

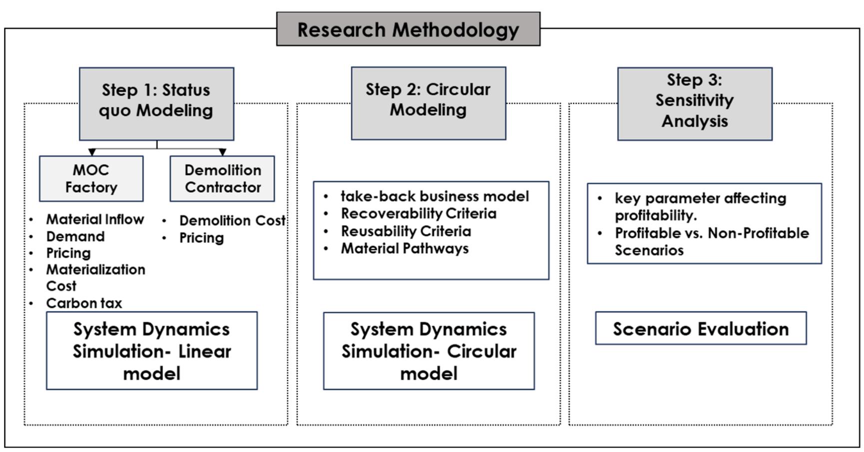


Figure 1- Research Methodology

Building on this framework, the potential for outsourcing material recovery and sorting tasks to a demolition contractor through long-term contractual agreements was assessed. This strategy leverages the contractor's expertise in deconstruction, ensuring efficiency while enabling the MOC manufacturer to focus on its primary production processes. To gain a clearer picture of investments in CE practices, system dynamics (SD) (Forrester 1997) was employed to capture the dynamic interactions related to material flow and profitability factors. Supply chain processes, particularly in a collaborative MOC environment, exhibit complex interdependencies that traditional static evaluation methods cannot fully capture (Guzzo et al. 2022). SD was selected in this study for its ability to model time-based flows and stakeholder interactions across the supply chain. By representing how system behavior changes over time, SD provides a more realistic and dynamic evaluation of potential future scenarios, making it a valuable tool for simulating real-world processes(Guzzo et al. 2022).

To apply this methodology in a practical context, it was tested through a case study, which is introduced in the Results section. The final stage involves sensitivity analysis to assess the impact of various parameters on the financial viability of CE adoption. Based on findings from the first two stages, this evaluation identifies key parameter interactions and critical profitability drivers. From the sensitivity analysis results, scenarios were evaluated and analyzed to distinguish between profitable and non-profitable cases for further assessment.

3. MODEL DEVELPMENT

As mentioned in the methodology section, the initial step is to analyze the existing linear processes. To achieve this, data from a wood-frame wall panel fabrication plant located in Edmonton, Alberta, Canada, serves as the basis for modeling the status quo scenario for manufacturer.

3.1 Status quo (linear model)

The SD modeling of the status quo was based on several key assumptions. First, all required starting materials for manufacturing were procured by the supplier, sourced entirely from virgin raw materials. Since historical production rates and corresponding material inflows were limited, a triangular distribution was applied to model the demand rate (Rojas 2017). Wall panels vary in size and are customized based on specific design parameters. However, for modeling purposes, an average panel size of 8.29 ft × 30.72 ft, derived from data provided by the industry partner, was used as a standardized reference. The model considered dimensional lumber, oriented strand board (OSB), and drywall as the primary materials, with their required quantities and corresponding weights calculated accordingly. The unit price of the panels was determined by adding a markup to the production costs obtained from (RSMeans 2024). An average markup of 10% was considered for both the manufacturer and the demolition contractor, consistent with industry standards (RSMeans 2024). Overhead and contingency costs, which remained constant across scenarios, were excluded from the analysis to focus solely on the impact of production cost variations on profit margins.

Regarding EoL processes, buildings reaching the end of their lifecycle were assumed to be demolished using traditional methods, with all resulting waste sent to landfills. Since no materials were recovered or recycled in this scenario, the total volume of demolition waste was assumed to be equal to the volume of materials originally used in the buildings' components. The revenue earned from the owner for demolition was calculated by adding a markup to the demolition cost, as obtained from (RSMeans 2024), along with disposal costs. Following the Treasury Board of Canada Secretariat's cost-benefit analysis guidelines (Secretariat 2022), a real discount rate of 7% was applied reflecting the time value of money, under stable prices and no inflation.

3.1.1 Numerical analysis

To evaluate the financial implications of this transition, this study employed incremental cost-benefit analysis. This method focused exclusively only on costs and benefits that differed between models while excluding constants. By isolating the incremental effects, this approach clarified the financial trade-offs and added value of circular practices. Specifically, it evaluated whether the additional investments in non-virgin materials were justified by the associated benefits. This comparative analysis considered only the cost elements that varied across different scenarios, as these factors determined the comparative performance of linear and circular models. In other words, the study evaluated revenues and partial costs to assess the financial outcomes of transitioning to circular practices. A full assessment of individual scenarios would require considering all associated costs, including constants.

The focus of this study was on the materialization stage, which referred to the process of transforming input materials into a product. In line with the principles of incremental cost-benefit analysis, procurement costs varied between virgin and non-virgin input materials, due to differences in sourcing and availability. When considering design costs, incorporating reclaimed materials adds complexity, often requiring over-dimensioning of components, which may lead to overdesigned structures. In addition, new designs should be done by considering inventory of the available materials from salvage (Gorgolewski 2008). Nevertheless, the literature suggests that the cost of designing using reused elements is not significantly higher than that of new ones (Dunant et al. 2018). As a result, this study assumed design costs were identical for virgin and non-virgin materials. Operational costs were standardized, as components sourced from non-virgin materials were restored to a “like-new” condition and were assumed to have fabrication costs equivalent to those of virgin materials. Carbon taxes, however, differed due to variations in emission factors, resulting in cost discrepancies between virgin and non-virgin materials. Table 1 provides a summary of part of the parameters used in the SD models, along with their corresponding sources.

Based on this modeling framework, a 30-year simulation under the linear model yielded a Net Present Value (NPV) of $29,433,800 for the manufacturer and $703,867 for the demolition contractor, establishing a baseline for comparison with CE scenarios.

Table 1: part of parameters considered in SD model

Item	**Amount**	**Unit**	**Reference**
Unit cost of landfilling	0.11	CAD/ kg	(GFL Environmental 2024)
Recycling tipping fee	0.09	CAD/ kg	(Ecco Recycling 2024)
Carbon tax rate	0.08	CAD/ kgCO_2	(EnergyRates 2024)
unit price - drywall	18.12	CAD/EA	(RSMeans 2024)
unit price - Lumber	1.44	CAD/ (ln. ft)	(RSMeans 2024)
unit price - OSB	18.7392	CAD/EA	(RSMeans 2024)
unit price of the panels	5.77	CAD/ft2	(RSMeans 2024)
Average life expectancy- Lumber	110	year	(Harvey 2001)
Average life expectancy- OSB	55	year	(Harvey 2001), (Jones 2023)
Average life expectancy- Drywall	60	year	(Economics Group of NAHB 2007)
Recycling efficiency- Lumber	0.88	ratio	(Pantini and Rigamonti 2020)
Recycling efficiency- OSB	0.6	ratio	(Wronka and Kowaluk 2022)
Recycling efficiency- Drywall	0.93	ratio	(Ndukwe and Yuan 2016)

3.2 Selective demolition, reuse, and recycling scenario

This section presents a SD model comprising two interconnected sub-systems. The first, the deconstruction sub-system (Figure 2-a), focuses on recovering components from EoL buildings and their subsequent steps for reuse or recycling. The second, the materialization sub-system (Figure 2-b), represents the manufacturing stage, where these recovered materials are utilized as input. By accounting for the costs and benefits associated with each sub-system and comparing the resulting NPV with linear models, the study evaluates and analyzes the financial implications for different scenarios.

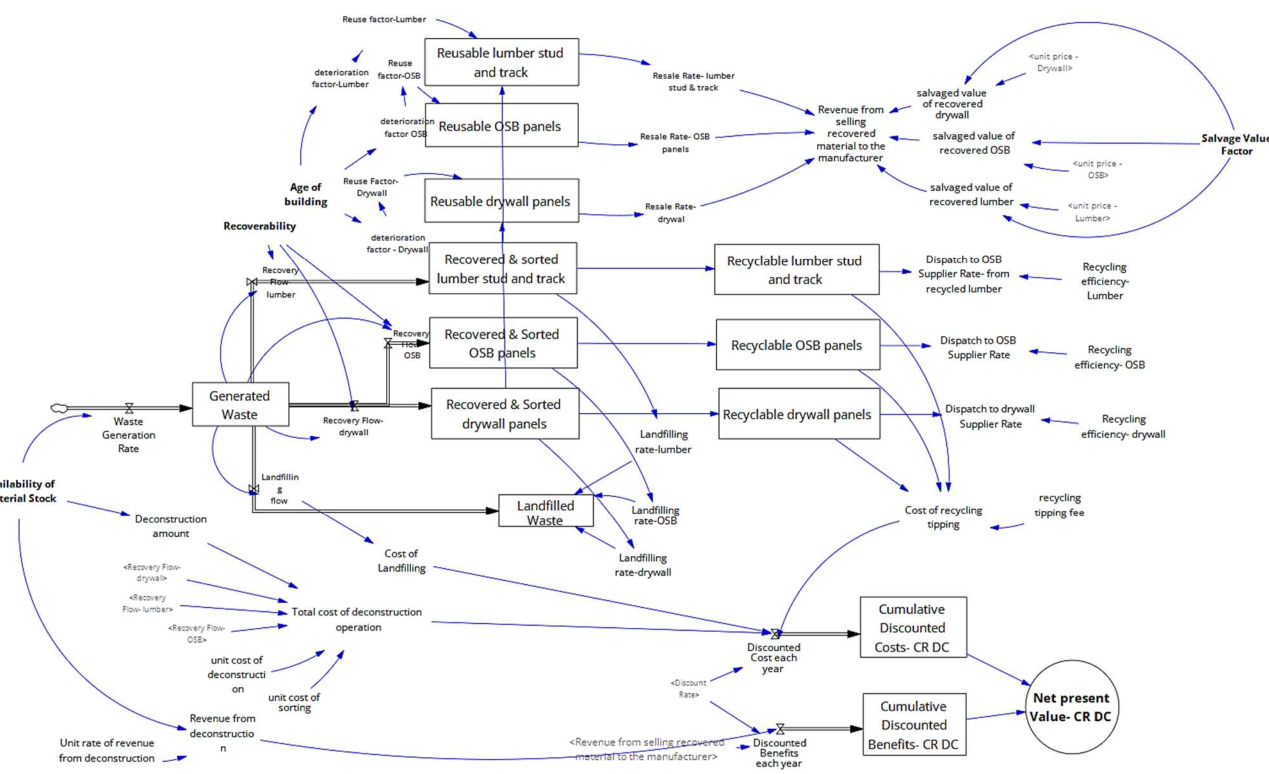
3.2.1 Model assumptions

Through long-term supply agreements between a demolition contractor and a manufacturer, salvaged building components from old structures can be returned to the manufacturer for potential reuse in the production line. In developing the SD model, several assumptions were made. The revenue earned by the manufacturer from selling products made from secondary materials was assumed to be the same as that of products made from virgin materials. After components were recovered, they were sent back to the supplier for refurbishment, minor repairs, testing, and recertification. The model assumes full acceptance of reusable materials, sufficient supplier capacity, and unlimited storage at both the manufacturing facility and supplier. Additionally, the study assumes that buildings operate under normal conditions, excluding early material failures such as decay or mechanical damage. Given the 30-year analysis period, only a single reuse cycle was modeled, with the age of components assumed to match the age of the buildings. Reusability was assessed based on the remaining useful life of the components, which must be at least 20 years to ensure they can serve at least one additional lifecycle in a new building. Otherwise, they are directed toward recycling. Moreover, recycling efficiency, defined as the yield of recycled material per unit of waste input, was accounted for, considering material losses during processing. Furthermore, the supplier has sufficient capacity to accept recycled materials from the recycling company to produce new components, with the price of these recycled components set at 85% of the retail value of new ones, reflecting typical market discounts offered to account for reduced production costs. Lastly, material transportation costs and logistics are excluded from the analysis.

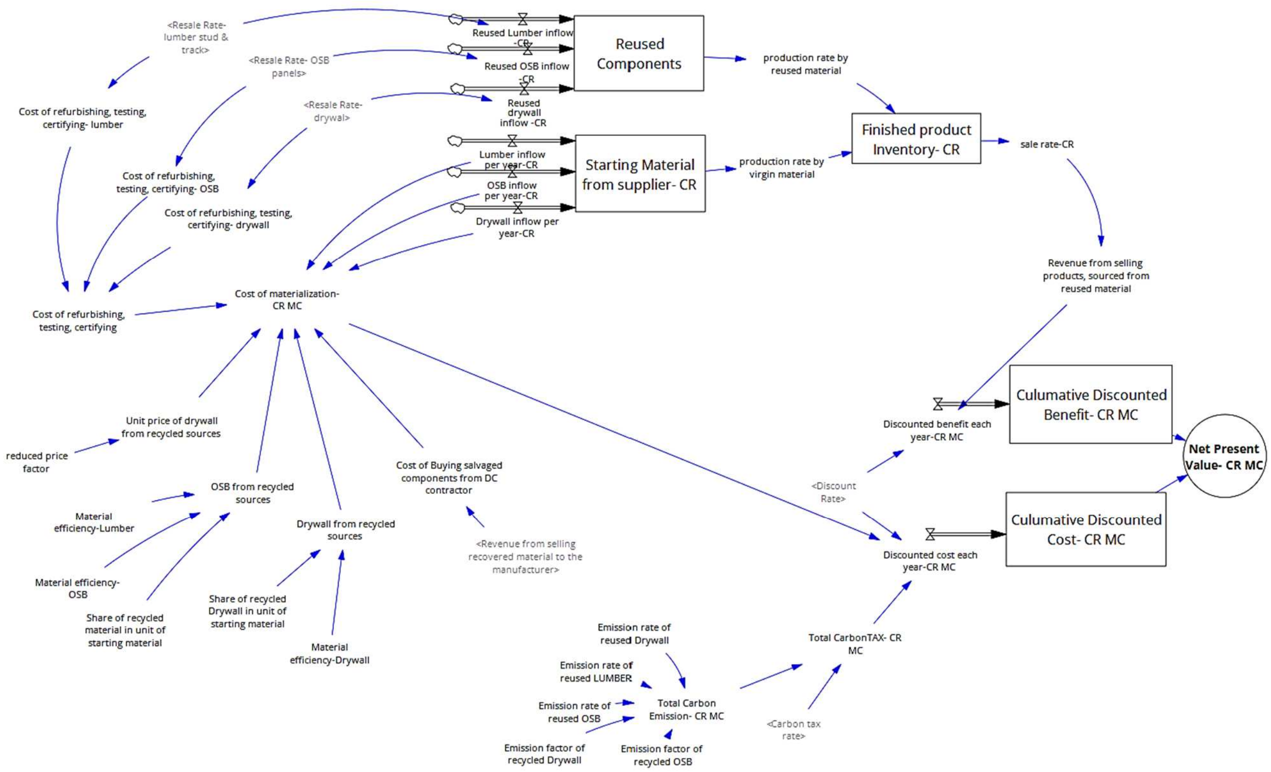
3.2.2 Numerical analysis

After considering model assumptions, stock-flow diagrams of two connected sub-systems were developed to quantify the total gain in NPV when transitioning both stakeholders from a linear economy to a circular framework (Figure 2). For the sake of visibility, some relationships and parameters were hidden to reduce complexity. Scenario analysis began by assigning various values to variables most susceptible to uncertainty. A reference configuration was first established, setting the salvage value at 30% of the retail price and all variables at their baseline values (age of the building stock: [45, 55) years, Recoverability: 2, Availability of Material from building Stock: 50% of factory's capacity). Sensitivity analysis followed, systematically varying those parameters. This process generated 48 unique combinations (4 × 4 × 3), enabling a comprehensive assessment of how these factors influence NPV and system performance.

In this study, "availability of material stock" refers to the proportion of the annual material inflow that can potentially be sourced from EoL buildings. Accordingly, the manufacturer's material inflow was determined by applying recoverability and reusability factors to this potential supply. Salvage value, treated as a decision variable, was analyzed across all combinations to assess its impact on NPV. Three key states were considered: the breakeven point, where the demolition contractor's NPV is neutral; the lower bound, ensuring the contractor's NPV aligns with a linear economy model; and the upper bound, where the manufacturer achieves a 10% NPV increase, reflecting the additional operational and logistical complexities required to make the circular model financially viable.



(a)



(b)

Figure 2- Stock and flow Diagram- Circular scenario, (a) Demolition contractor perspective (b)Manufacturer perspective

4. RESULT AND DISSCUSSION

This study highlights three main drivers of profitability in transitioning to a CE model: building age, material availability, and component recoverability. Among these, building age has the strongest influence, with newer buildings enabling higher NPV gains due to better material recovery. The availability of reusable materials and design for disassembly also play key roles in determining financial feasibility.

After running simulations for all 48 scenarios, those that failed to meet two key conditions were excluded. First, scenarios where the manufacturer's NPV did not increase by at least 10%, and second, those resulting in financial losses for the demolition contractor under deconstruction practices, were removed. The remaining 27 feasible scenarios were then ranked based on total NPV gain (ΔNPV), aggregating the benefits of transitioning to a CE model by combining the NPV improvements for both the manufacturer and the demolition contractor as a single entity. Table 2 summarizes the simulation results for the 27 feasible scenarios, organized in descending order based on ΔNPV.

Table 2: Simulation results

Scenario	Age of Building stock	Recoverability	Availability of Material Stock*	ΔNPV	Salvage Value**	
					Breakeven point	Acceptable range
S1	[25,35)	1	1	9,690,480	0.31207	[0.3539, 0.7535]
S2	[25,35)	2	1	8,020,500	0.23747	[0.2972, 0.728]
S3	[25,35)	1	0.75	7,566,940	0.31207	[0.368, 0.7341]
S4	[25,35)	Random	1	6,924,470	0.1847	[0.2573, 0.6666]
S5	[25,35)	2	0.75	6,141,470	0.23747	[0.3171, 0.679]

Scenario	Age of Building stock	Recoverability	Availability of Material Stock*	ΔNPV	Salvage Value**	
					Breakeven point	Acceptable range
S6	[25,35)	Random	0.75	5,217,850	0.1847	[0.2815, 0.594]
S7	[25,35)	1	0.5	5,199,600	0.31208	[0.3958, 0.664]
S8	[25,35)	3	1	4,887,500	--	[0.045, 0.43]
S9	[35,45)	1	1	4,283,800	0.57199	[0.6392, 0.7669]
S10	[35,45)	2	1	4,235,848	0.45234	[0.5483, 0.7235]
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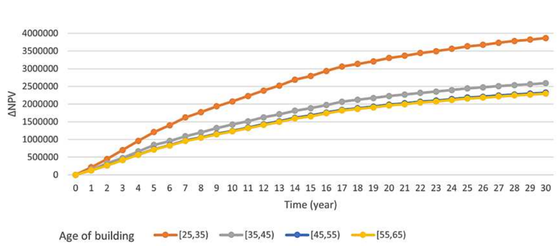
S25	[55,65)	2	0.75	3,033,720	0.5081	[0.649, 0.666]
S26	[45,55)	Random	0.75	2,955,770	0.4099	[0.58, 0.58]
S27	[45,55)	1	0.75	2,945,980	0.6337	[0.731, 0.731]

*Availability of material stock is expressed as a percentage of the factory's annual capacity.

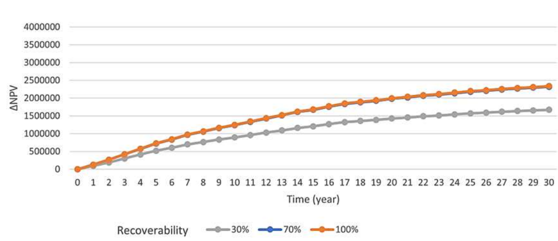
** Rates for salvage value are expressed as a percentage of the retail value of new materials.

To assess the impact of individual parameters, total NPV gain was analyzed over the simulation period using the reference configuration, varying one variable at a time while keeping others constant. The results show that building stock age is the most influential factor in NPV growth. Table 2 confirms this finding, with the top eight scenarios linked to the youngest buildings, while only 30% of older-building scenarios remain financially viable. As buildings age, demolition contractors face greater losses due to fewer reusable materials, mainly OSB and drywall, which have short life expectancies. The overlap in Figure 3(a) for the [45,55] and [55,65] age groups highlight this issue, as fewer materials meet the 20-year reuse threshold. Incorporating longer-lived materials could alter these findings, while renovation and retrofitting strategies offer promising directions for future research.

The availability of materials from the building stock is the second most influential factor. A larger material bank in urban areas enhances material recovery, boosting demolition contractor revenue and lowering manufacturing costs. Simulation results show that only 3 out of 16 scenarios assuming 50% material availability were financially viable. Material stock availability is also critical to ensuring a steady supply of reusable and recyclable materials. However, due to the lack of precise material inventory data in the study area, a simplified estimation method was used. Future research should incorporate more accurate material availability assessments.



(a)



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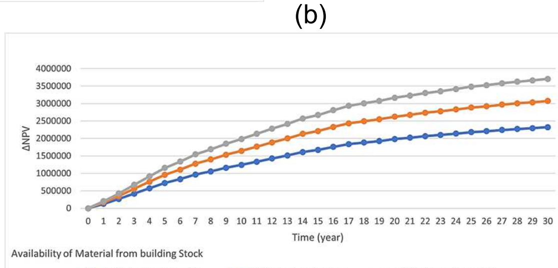

Figure 3: Impact of different factors on ΔNPV: (a) Age of building stock; (b) Recoverability; (c) Material Stock Availability.

Component recoverability is another key factor in profitability, highlighting the need to integrate deconstruction and disassembly strategies during the design phase. Using reversible connections, such as bolt-and-nut joints instead of adhesives or welded connections, facilitates efficient disassembly and minimizes damage, making reuse more viable. The age of the building also affects this case. With the baseline configuration set to the [45,55] age range, the reuse rate decreases significantly since the recovered materials are often unsuitable for reuse due to their low remaining usable life. Consequently, increasing recoverability from 70% to 100% has a limited impact on the total NPV gained.

5. CONCLUSIONS

This study explored the financial feasibility of transitioning the MOC industry toward a CE by integrating material recovery strategies and stakeholder collaboration. While MOC has significant potential for circularity, through standardized materials, ease of disassembly, and component reuse, uncertainties remain regarding the practical implementation of these strategies within the supply chain.

To enhance material recovery and align stakeholders' incentives, this study incorporated demolition contractors and recycling plants into the supply chain. It also explored a pathway for developing a secondary market for recovered materials, facilitating their reuse in new construction. This research fills a critical gap in MOC by highlighting stakeholder collaboration, an often-overlooked factor in circular transitions. Using system dynamics modeling, material flows from EoL buildings to MOC factories were analyzed, identifying conditions under which this transition can be financially viable in addition to gaining environmental targets. The study was applied to a wood-frame panelized wall factory, though the proposed model remains adaptable to various building types and construction scenarios.

Unlike many studies that assume government intervention, this research assessed financial viability without incentives, penalties, or adjusted landfill and recycling fees. This approach ensured a realistic evaluation of profitability under current market conditions. The simulation results revealed that certain CE-compliant strategies can be financially viable, though government support could further enhance their feasibility. By examining EoL strategies and their economic incentives, this study provides a practical foundation for advancing circularity in MOC.

While capturing key CE dynamics in the MOC supply chain, this study has limitations that future research should address. These include incorporating more accurate estimations of material and building component stocks, and addressing transportation and storage constraints, as supply chain spatial extent affects the logistics of reclaiming and transporting materials for reuse, recycling, and refurbishment. Additionally, future research should account for the profitability of other supply chain actors, such as suppliers and recycling plants, to provide a more comprehensive financial assessment of circular strategies.

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