

Quantifying the Role of Government Support Policies for Circular Economy in Construction - Case of Recycled Concrete in Canada

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Abstract

Question: Under what conditions can a recycled concrete aggregate (RCA)-based Circular Economy Business Model (CEBM) achieve financial viability and price-competitiveness against a linear virgin Aggregate supply chain, and which policy levers most effectively enhance its competitiveness?

Purpose: This paper quantifies the economic feasibility of shifting from a linear concrete supply chain to an RCA-based CEBM and assesses how targeted government interventions affect profitability.

Research Method: A simulation-based approach integrates (i) a System Dynamics model of physical material flows for linear and circular pathways, (ii) discounted cash flow analysis, and (iii) a structured factorial scenario design to evaluate policy conditions.

Findings: Performance of the recovery/recycling is a key driver of circular viability. At moderate rates, RCA-based circular models are only selectively attractive and lack robustness across policies; high tipping fees can even raise RCA costs due to unavoidable residual disposal. At high rates ($\approx 95\%$), the circular configuration consistently achieves lower unit prices than the linear baseline for the same margin, with RCA becoming cost-competitive with virgin aggregate in multiple scenarios. Concessional financing reduces prices but does not change trends; carbon pricing primarily affects cement-related costs and offers only marginal relative benefits for circular concrete.

Limitations: The study is based on a hypothetical case study using parameterized costs and policy levels. While this approach allows for the isolation of key economic drivers, the results are sensitive to local market fluctuations, specific recovery performance, and varying contracting assumptions.

Implications: Policy packages should be performance-aligned: improving recovery and recycling capability is essential, while landfill pricing and financing tools should be designed to discourage avoidable disposal without unintentionally escalating costs for

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verified unrecoverable residuals. Relying on broad financial support alone is unlikely to deliver competitiveness.

Value for authors: This paper provides a transferable, decision-oriented modeling approach that connects material-flow dynamics to profitability and unit-price competitiveness, helping researchers and practitioners identify the operational thresholds and policy combinations needed to enable viable circular concrete business models.

Keywords: Circular Economy in Construction, Circular Economy Business Model, Recycled Concrete Aggregate, System Dynamics, Price on Carbon, Landfill Tipping Fee, Lean Disposal, Lean Salvage

Paper type: Full paper

Introduction

The Canadian construction sector is defined by a fundamental structural contradiction: it remains a vital engine of economic growth and infrastructure development, with a market value that reached CAD 222 billion in 2025 (Research and Markets, 2025), yet it ranks among the leading sources of environmental degradation, resource depletion, and waste (Orenga Panizza & Nik-Bakht, 2024). For decades, the industry has relied on a linear "take-make-use-dispose" model, extracting virgin materials, assembling them into buildings and infrastructure with finite service lives, and ultimately diverting much of the resulting debris to landfill (Allam & Nik-Bakht, 2023). Increasingly, this model is recognized not only as environmentally unsustainable, but also as a form of systemic value loss, as it prematurely discards materials and components that retain significant economic and functional potential (Blomsma & Brennan, 2017).

From a Lean Construction (LC) perspective, this value destruction becomes most evident at the end-of-life phase. Disposal activities represent a large Non-Value-Added (NVA) effort that consumes time, labor, and resources without creating stakeholder value, thereby compounding lifecycle inefficiencies. While traditional approaches focus on waste management of debris, LC employs tools such as Value Stream Mapping (VSM) to identify and eliminate NVA activities proactively, directing attention toward resource circulation and value retention (Zavaleta & Pablo, 2025).

These Lean principles of waste elimination and value optimization align closely with the Circular Economy (CE), which provides a broader regenerative framework for addressing the root causes of value loss embedded in linear end-of-life practices. CE aims to decouple economic activity from the consumption of finite resources by prioritizing value retention, keeping materials in use at their highest quality and utility for as long as possible (Ellen MacArthur Foundation, 2013). Transitioning to this framework requires shifting from destructive demolition toward deconstruction and disassembly, an economic strategy intended to ensure that the salvage value of recovered materials can offset the costs of recovery.

In Canada, the construction, demolition, and renovation (CDR) sector is estimated to generate approximately 4 million tonnes of waste annually, a substantial share of which is concrete (Environment and Climate Change Canada & Government of Canada, 2021). The scale of this opportunity is mirrored across North America; for instance, approximately 233.3 million metric tons of concrete are used annually for U.S. roadway construction alone (Iyer et al., 2024). If recovered and processed into recycled concrete aggregate (RCA), this stream could be transformed from a disposal burden into a high-value feedstock for new infrastructure.

However, a persistent value gap hinders meaningful progress toward circularity: despite the theoretical advantages of recycled materials such as RCA, their practical financial viability remains limited under current market conditions. This gap persists due to “linear lock-in”, a condition where low prices for virgin aggregates, comparatively low landfill tipping fees, and high capital expenditures (CapEx) for sorting, crushing, and recycling infrastructure challenge profitability for Circular Economy Business Models (CEBMs). At the same time, circular supply chains typically require higher operating costs tied to uncertain yields, contamination risk, and fragmented coordination between owners, deconstruction contractors, recyclers, and material suppliers.

In this context, government intervention is widely regarded as an essential catalyst bridging the value gap and making CEBMs economically competitive. This study categorizes such interventions into two complementary forms. First, financial support includes mechanisms such as carbon pricing, modifying landfill tipping fees, and direct subsidies designed to internalize environmental externalities and penalize linear practices. Second, market-structural support leverages the role of public agencies—such as Departments of Transportation (DOTs)—as front-end clients. Through strategic public procurement, agencies can bundle deconstruction and material supply responsibilities, adopt longer-term decision horizons, and design contracts that stabilize demand and mitigate investment risks.

Building on this framing, this study quantitatively evaluates government interventions' influence on the economic viability of value retention in an RCA-based CEBM in the Canadian context. Specifically, the research (i) investigates the feasibility of a profitable CEBM by determining the unit-price conditions under which sufficient incentives exist for supply chain actors to transition from linear to circular practices; and (ii) conducts a sensitivity analysis to compare the relative impact of three key financial levers—carbon pricing, landfill tipping fees, and direct financial incentives—on the CEBM unit price and profitability. By analyzing how these levers influence the CEBM unit price, this study identifies the most effective interventions for ensuring the economic viability of sustainable practices within the Canadian construction industry to support Lean-optimized resource circulation and sustainable practices.

Related Studies

The evolution of LC has shifted from a narrow focus on site-level productivity to a comprehensive framework for value creation and retention. By systematically eliminating NVA activities, specifically the seven wastes of overproduction, unnecessary transport, excess inventory, waiting, defects, over-processing, and motion, lean principles provide the essential foundation for integrating CE principles into the built environment (Alnajjar et al., 2025). This synergy is most evident in the emerging “Lean 5.0” paradigm, where digital technologies such as BIM (Building Information Modeling) and IoT (Internet of Things) are leveraged to minimize NVA activities while maximizing the recovery potential of materials through reuse and repurposing (Zavaleta & Pablo, 2025). Research indicates that unlike traditional, reactive waste management that addresses debris post-generation, a Lean-CE approach utilizes proactive tools like VSM to design out waste at the source (Salam & Gowda, 2025). This integration supports a circular flow where deconstruction is treated as a value-adding process, enabling high-value recovery rather than conventional downcycling (Nik-Bakht et al., 2021).

Within construction material loops, RCA is frequently studied as a high-volume pathway for operationalizing CE principles through the recovery of concrete from

construction and demolition activities (Tam et al., 2018). The environmental implications of this shift have been extensively documented through Life Cycle Assessment (LCA) studies (Tam et al., 2018; Y. Zhang et al., 2019). Overall, studies show that the environmental performance of RCA is impact-specific rather than universally better or worse. The most consistent advantage is resource conservation: replacing virgin aggregates with RCA directly reduces dependence on virgin quarrying, which translates into a major decrease in abiotic depletion potential (ADP) (often reported to be on the order of 95% lower, i.e., roughly a 20-fold difference) (Park et al., 2019). Beyond material substitution, RCA also provides a systemic benefit through waste diversion: diverting concrete from landfill reduces land occupation and inert waste management burdens and is frequently represented in LCA as an avoided-burden credit, the value of which depends on local landfill scarcity and is typically greater in dense urban regions (Jiménez et al., 2018).

By contrast, the global warming potential (GWP) response is highly variable. Crucially, aggregates are typically minor contributors to concrete's total GWP compared to the binder, so switching from virgin aggregates to RCA often yields only limited or uncertain GWP reductions. Cement production is commonly responsible for the dominant share of concrete impacts, often over 80% of GWP, meaning that the overall carbon outcome is strongly influenced by cement demand, rather than by aggregate substitution alone (H. Zhang et al., 2025). However, this does not diminish RCA's role in circularity; rather, it highlights that the primary environmental value of RCA lies in the drastic reductions of abiotic depletion (especially mineral resources) and landfill burden metrics that are often undervalued in carbon-centric policy frameworks.

Beyond environmental metrics, scholars have assessed the economic viability of this transition. While RCA supports environmental sustainability and preserves finite resources, the technical requirements for high-quality recovery create significant market friction (Makul et al., 2021; Tam et al., 2018). Comparative analyses show that the cost of processing materials to meet structural standards often exceeds the market price of virgin aggregates, particularly in regions where landfill tipping fees are low enough to make disposal the most profitable option (Makul, 2020). This "linear lock-in" is further reinforced by supply chain volatility and the high capital intensity of the required recycling infrastructure, which prevents many firms from achieving the scale necessary for competitive pricing (Dagilienė et al., 2021; Purchase et al., 2021).

To address these market imbalances, research into policy interventions suggests that a combination of carbon pricing and elevated tipping fees is necessary to internalize the environmental costs of value loss (Adabre et al., 2023). Within the Canadian context, these strategies are increasingly aligned with federal carbon frameworks designed to incentivize the recovery of secondary resources. Furthermore, public procurement strategies that bundle deconstruction with material supply are being explored to stabilize demand for recovered resources (De Angelis et al., 2018).

Despite well-documented environmental benefits and identified economic barriers, the literature reveals a notable gap: existing quantitative studies have rarely modeled the combined impact of targeted government interventions on profitability and competitiveness of CEBM in Canadian contexts, with a specific lack of detailed sensitivity analyses concerning RCA pricing under realistic high-recovery scenarios.

Methodology and Model Development

The research adopts a quantitative simulation approach to evaluate the economic feasibility of a circular supply chain, structured into three primary phases. First, material

flow modeling is conducted using System Dynamics (SD) (Forrester, 1997) to represent the physical system and establish a baseline scenario and a circular alternative. Second, an economic translation step converts simulated material volumes into time-indexed cashflows to evaluate profitability and unit-price conditions required for viability. Third, a policy scenario analysis quantifies how government intervention levers influence economic viability and competitiveness.

The methodology is applied to a hypothetical municipal bidding context for transportation infrastructure repair and renewal, with an emphasis on end-of-life concrete management, resource consumption, and embodied-carbon-related cost signals. Case-specific scope and parameter assumptions used to instantiate the model are defined in the following section.

Stage I: Material Flow Modeling

System Dynamics is used to represent material stocks and flows that govern end-of-life concrete management and aggregate supply. SD is well studied and is found effective in this context, as it captures the complexity of supply chains, maps the dynamic interactions among stakeholders, and enables the exploration of what-if scenarios. It also helps explain why certain outcomes occur in the system, which is essential for making informed decisions during the shift to circular practices (Guzzo et al., 2022). The model is implemented in Vensim® PLE (Ventana Systems Inc., 2025) over a 25-year decision horizon, consistent with long-term infrastructure contracting.

Figure 1 illustrates simplified block diagrams to compare the linear and circular processes to address the problem. In the linear configuration (Figure 1-a), virgin aggregates are extracted and combined with cement and water to produce concrete, which enters the stock of concrete structures through construction, while end-of-life concrete and associated residuals are routed to landfill. The model is then reconfigured into a circular alternative (Figure 1-b) by replacing demolition-oriented disposal with deconstruction, which enables the recovery of end-of-life concrete and its processing through a secondary recycling unit to produce RCA. In this circular configuration, RCA is looped back as a substitute input for virgin aggregates, subject to the assumed recovery and recycling constraints. The SD simulation generates annual time series of virgin aggregates demand, recovered concrete, recycled RCA output, and landfilled quantities, which provide the physical basis for the economic translation and policy analysis stages.

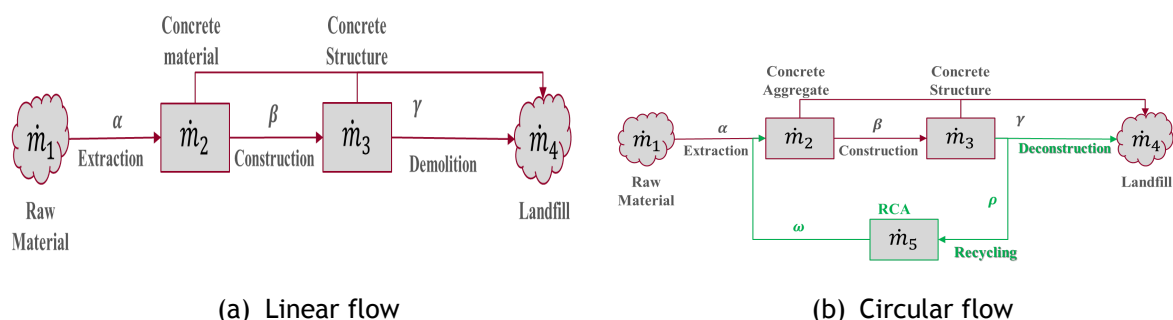


Figure 1: Conceptual models of material flow for the Linear and Circular production plans

Stage II: Economic Translation and NPV Analysis

In the second stage, the simulated physical flows are translated into stakeholder cashflows by applying unit cost and revenue parameters to the corresponding SD outputs. CapEx associated with enabling circular infrastructure are accounted for as investment terms consistent with the case assumptions. Economic feasibility is evaluated using standard discounted cashflow metrics over the decision horizon, with Net Present Value (NPV) used as the primary viability indicator. In addition, the analysis determines the implied unit bid price required for the circular alternative to maintain an acceptable profit margin under the defined contract structure.

Stage III: Policy Scenario Analysis

Finally, the model is used as an experimental platform to test how government interventions shift economic outcomes. Three policy levers are represented as exogenous parameters that modify cost or financing terms: (i) carbon pricing, (ii) landfill tipping fees, and (iii) direct financial incentives or loans. A structured scenario design is used to compare a circular baseline against policy-adjusted cases and to quantify the sensitivity of profitability and unit-price competitiveness to each lever. Results are reported as changes in NPV, required unit price, and the RCA to virgin aggregates price relationship under different policy settings.

Contextualization of the CEBM and Model Assumptions

Case context and contracting scope

To evaluate the proposed methodology, this study utilizes a hypothetical case example involving a municipal bid for transportation infrastructure repair and renewal. This case emphasizes demolition waste management and resource conservation at a municipal scale. The municipality is assumed to issue a bundled request for proposals (RFP) that combines (i) removal of end-of-life concrete from existing assets and (ii) supply of new concrete as a single integrated tender, structured as a long-term collaborative contract (25 years) rather than a project-based award. The annual scope includes supplying 135,000 metric tons of new concrete and removing approximately the same mass of installed concrete from structures such as bridges, tunnels, and curbsides. For simplicity, the procurement is modeled as a unit-price bid, where one price per ton of supplied concrete covers all relevant activities, including material supply, manufacturing, removal (demolition/deconstruction), transportation, and disposal.

Within this bundled arrangement, demolished concrete is assumed to be delivered to the recycling operation at zero purchase cost, since this remains financially attractive to the supplier as it avoids landfill tipping fees. The recycling operation is responsible for landfill charges associated with any fraction of incoming concrete that cannot be recycled due to contamination or processing losses. While the scenario is hypothetical, the underlying business model and cost assumptions are derived from an actual major concrete supplier operating in Canada. The base recovery rate for extracting reusable concrete through deconstruction is assumed to be 70%, with additional scenarios exploring the impact of higher recovery rates. All relevant cost parameters, along with production, deconstruction recovery, and recycling rates, are presented in Table 1.

Table 1: Parameters Considered in SD Model

Item	unit	Amount*	Reference
Landfill Tipping Fee	\$/ton	110	(Ottawa Valley Waste Recovery Centre, 2025)
Recycling cost	\$/ton	10	
Virgin Aggregate	\$/ton	30	Transportation cost from (RSMeans, 2024)
Cement	\$/ton	183	
Production rate	Fraction	0.9	
Rho (Recovery Rate)	Fraction	0.7	
Omega (Recycling Rate)	Fraction	0.75×0.6	
Cost of transportation - RCA	\$/ton	2	
Cost of demolition	\$/ton	100	
Cost of deconstruction		120	
Carbon tax rate			(Government of Canada- Environment and Climate Change Canada, 2023)

* Values of the items without a reference are taken from (or verified by) the industry partners

□ 0.75 is the aggregate coefficient

Technical and Financial Parameters

Several technical constraints govern the material conversion in the SD model. Normal-weight aggregates are assumed to comprise approximately 75% of the total concrete weight. This 0.75 coefficient is hard-coded into the model to convert concrete production quantities into required aggregate volumes. The concrete mix follows a standard 4:2:1 ratio of gravel, sand, and Portland cement, with a water-to-cement proportion of 0.5.

Operationally, the linear production model assumes a production rate $\beta = 0.9$, reflecting production losses/wastage in the manufacturing stage.

To maintain economic realism and reflect bidder behavior, the following assumptions are applied:

- **Profitability Threshold:** A minimum profit margin of 7% is assumed to reflect bidder participation thresholds (validated by the industry partner).
- **Discount Rate:** An annual interest rate of 10% is assumed, which is inclusive of inflation to represent the real interest rate.

Infrastructure Cost Estimation

CapEx for the concrete production line and the RCA processing facilities are estimated using the cost-capacity factor method, in which the cost of a new plant scales with capacity via a proration exponent:

$$C_B = C_A \left(\frac{Q_B}{Q_A} \right)^\alpha$$

where C_A and C_B are the costs of two similar plants, with the production capacities of Q_A and Q_B respectively, and α is the exponent, or proration factor. The value of the exponent typically lies between 0.5 and 0.85 for plants (Prasad et al., 2011).

Using two reference plants with capacities of 50,000 and 200,000 tons/year and capital costs of \$0.85M and \$2.5M, respectively, the proration exponent is calculated as $\alpha=0.78$.

$$C_{concrete} = 2,500,000 \left(\frac{150,000}{200,000} \right)^{0.78} = 1,997,505 \approx 2,000,000$$

To represent partial recycling, the model includes a small RCA plant with an annual capacity of 25,000 tons. The large-plant CapEx is first established from published unit capital intensity: establishing an aggregate recycling business requires \$4.40-\$8.80 per metric ton of annual capacity (U S Department of Interior & U S Geological Survey, 2000). Using the midpoint of this range, the CapEx of a 150,000 tons/year RCA facility is estimated as \$1,000,000.

Therefore, by assuming an operation factor of $\alpha=0.6$ (which according to AACEI, is recommended for processing units with unknown operation factor), the cost of a small unit (with an annual capacity of 25,000 tons) will be calculated as:

$$C_{SmallRCA Plant} = 1,000,000 \left(\frac{25,000}{150,000} \right)^{0.6} \approx \$350,000$$

In the full recycling configuration, the model evaluates a full-scale RCA processing unit with an annual capacity of 150,000 tons and an estimated CapEx of \$1,000,000 (based on the midpoint of the reported \$/capacity range).

Finally, the useful life of all processing facilities is set to 25 years, consistent with the contract horizon.

Government intervention policies and scenario parameterization

The intervention policies could play a crucial role in balancing these economic gaps. In the rest of this section, we provide a brief overview of the Canadian policies regarding the three interventions focused on by this paper. Then, the following sensitivity analysis quantifies the effectiveness of each intervention in improving CEBM feasibility.

Price on Carbon

Canada's carbon pricing framework plays a crucial role in influencing emissions-intensive industries, including concrete aggregate mining, through a combination of federal and provincial mechanisms. The Greenhouse Gas Pollution Pricing Act established a national carbon price, which started at \$10 per tonne of CO₂ equivalent in 2018 and is set to increase to \$170 per tonne by 2030 (Benjamin et al., 2022). This pricing structure applies to fossil fuels used across industries, including mining and construction. For large industrial emitters such as mining facilities, the Output-Based Pricing System (OBPS) provides an alternative to direct carbon taxation by setting sector-specific performance standards. Facilities that exceed their allocated emissions limits must pay a charge or submit credits, while those below the threshold can earn tradable credits,

effectively incentivizing emissions reductions while maintaining industry competitiveness (Withey et al., 2022). Canada's carbon pricing approach is dynamic and subject to periodic review. The annual carbon price increases, along with ongoing regulatory adjustments, ensure the system remains aligned with evolving climate commitments. Recent adjustments to the OBPS Regulations have sought to enhance industry compliance while mitigating competitiveness risks in sectors such as aggregate mining, construction, and heavy industry (Benjamin et al., 2022).

At a provincial level, carbon pricing strategies vary from one province to another. For example, British Columbia has maintained a carbon tax since 2008, which applies broadly to industries including mining and follows the federal benchmark, progressively increasing to \$170 per tonne by 2030. Other provinces, such as Ontario and Québec, have adopted cap-and-trade systems that set industry-specific emission limits and trading mechanisms to mitigate financial impacts on carbon-intensive sectors (Mascher, 2018). By integrating performance-based standards and credit-trading mechanisms, the OBPS structure balances economic feasibility with emission reduction goals, ensuring that mining and construction industries remain competitive while progressively reducing carbon footprints (Withey et al., 2022).

Tipping Fees

Landfill tipping fees for concrete waste in Canada vary significantly across municipalities, influenced by local policies, disposal capacities, and sustainability initiatives. Research indicates that concrete waste comprises approximately 10-16% of construction, renovation, and demolition waste streams in Canada. The diverted rate for concrete waste is estimated at 72.4%, primarily through recycling into aggregate for road base or new concrete production. However, the cost of processing recycled aggregate is often comparable to or higher than virgin aggregates due to contamination removal, processing, and storage costs, making disposal in landfills a more attractive option for some companies (Earle et al., 2014). Across different provinces, landfill fees for construction and demolition waste are structured to encourage recycling. For instance, Québec levies an additional \$22 per tonne on landfill tipping fees to fund waste diversion programs, while Manitoba imposes a \$10 per tonne surcharge, with 80% allocated to municipal recycling initiatives. Despite these policies, disposal remains an attractive alternative in some regions where landfill costs do not fully reflect the long-term environmental and social costs (Canada's Ecofiscal Commission, 2018).

A major barrier to concrete recycling in Canada is the perceived lower quality of recycled aggregate. Although it has been incorporated into Canadian construction standards such as CSA Standard A23.1, which acknowledges concrete as a fully reusable material, industry concerns remain regarding issues, such as durability and contamination. Additionally, transportation costs significantly impact the feasibility of recycling, as landfills are typically located closer to construction sites than specialized recycling facilities (Earle et al., 2014). These findings underscore the need for stronger policy measures, such as higher landfill tipping fees for concrete waste or subsidies for recycling infrastructure, to enhance the economic viability of recycled concrete while reducing the reliance on virgin aggregate sources. Table 2 shows some of the landfill costs across Canada.

Table 2: An overview of some landfill policies across Canada (as of January 2025)

Jurisdiction	Costs and regulations
British Columbia, Vancouver	Garbage, up to 1 ton: \$175/tonne Minimum and maximum fees applicable Transaction fee: \$5/load (included in minimum and maximum fees) 1 ~ 7.99 ton \$153/ton Maximum fee: \$1,021 (6640 kg and above) Transaction fee: \$5/load (included in maximum fee) more than 8 ton \$127/ton Transaction fee: \$5/load (included in maximum fee)
Kelowna	The Glenmore Landfill in Kelowna charges \$50 per tonne for clean concrete (uncontaminated material under 2 feet, such as sidewalks and tiles). Dirty concrete with minor contaminants like soil or rebar costs \$70 per tonne, while heavily contaminated materials are classified as garbage and charged at higher rates.
Alberta, Calgary	In 2025, Calgary's residential landfill rates include a \$25 flat fee for loads under 250 kg, while heavier loads (250 kg and over) are charged \$113 per tonne. Specific materials, such as yard waste, have a reduced rate of \$50 per tonne.
Ontario, Sudbury	The standard tipping fee for garbage is \$106 per tonne. Loads weighing 100 kg or less are subject to a flat rate of \$3.50. Additionally, a gate fee of \$5 applies to all entries, alongside the applicable tipping fees
Brantford	The Mohawk Street Landfill charges \$25 per tonne for non-reinforced concrete, asphalt, and brick rubble. A minimum load fee of \$10 applies to all loads weighing 150 kg or less.
Ottawa Valley Waste Recovery	For sorted construction and demolition waste, including concrete, the fee is \$110 per tonne, with a minimum fee of \$20 for loads under 175 kg.
Province of Québec	As of January 1, 2025, the Quebec government has set the charge for the disposal of residual materials at \$32.00 per metric ton. This fee is subject to an annual increase of \$2.00 per metric ton, aligning with the government's initiative to encourage waste diversion from landfills through recycling and recovery efforts

Loan Incentives

Canada has implemented a variety of federal and provincial financial programs to support businesses that contribute to a clean economy, offering incentives such as low-interest loans, investment tax credits, and targeted funding initiatives. At the federal level, the Canada Small Business Financing Program (CSBFP) provides loans of up to \$1 million to assist small businesses in financing sustainable projects, including clean technology adoption (Rana et al., 2021). Additionally, the Canada Growth Fund (CGF), with an allocation of \$15 billion, leverages financial tools such as carbon contracts for difference and concessional capital to attract private investment in low-carbon projects. The Clean Economy Investment Tax Credit further incentivizes businesses by reducing costs associated with renewable energy and carbon capture investments (Martin & Riordan, 2020). At the provincial level, Ontario offers tailored loan programs to support clean technology and sustainable start-ups, while Québec's Compétivert Program provides financial assistance to businesses integrating sustainable practices into their operations (Rana et al., 2021). Other financial instruments, such as green bonds and sustainability-linked loans, have also gained traction in Canada, enabling businesses to access lower-cost capital for environmentally friendly initiatives (Martin & Riordan, 2020). These targeted financial measures help overcome capital constraints, foster job creation in green industries, and accelerate Canada's transition towards a more sustainable economy.

Table 3 shows some of the available targeted financing options across Canada. Carbon-Accounting Scope and Boundaries.

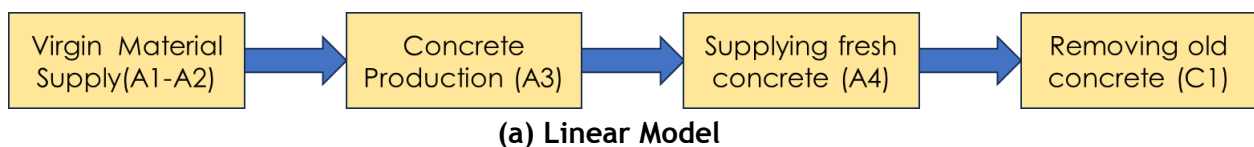
Table 3: Some key targeted financing options across Canada

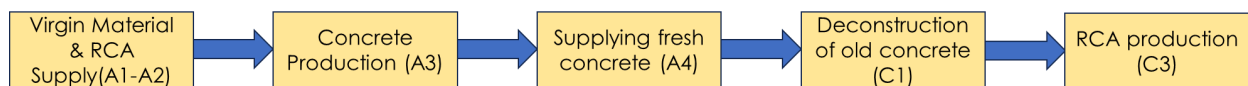
(a) Federal Government	
Canada Small Business Financing Program (CSBFP)	This program offers loans up to \$1 million to help small businesses purchase or improve land, buildings, and equipment. Interest rates are capped to ensure affordability, with a maximum of prime +3% for term loans and prime +5% for lines of credit.
Green Municipal Fund (GMF)	Provides low-interest loans and grants to support municipal sustainability projects (e.g., climate mitigation/adaptation, waste diversion, circular economy initiatives). Delivered by the Federation of Canadian Municipalities with support from the Government of Canada.
Clean Economy Investment Tax Credits (ITCs)	Federal government provides refundable tax credits to encourage capital investment in clean energy, hydrogen, and carbon capture technologies. These incentives aim to accelerate Canada's transition to a net-zero emissions economy by 2050.
(b) Provincial Governments	
Ontario	The Ontario's Clean Technology Loan Program supports clean energy start-ups and sustainable businesses through government-backed loans, venture capital funds, and private lenders, fostering the province's green economy.
Québec	Québec's Compétivert Program provides targeted financial assistance to businesses integrating clean technologies and eco-friendly practices, reinforcing the province's commitment to sustainability and circular economy initiatives

For scenario testing, financing is represented using discrete cases rather than a simple min-max interest range: CSBFP is treated as a “worst-case” debt option (high interest; 100% debt) and GMF as a “best-case” debt option (low interest; 100% debt). In addition, the Fonds économie circulaire (FEC) is modeled as a distinct blended-finance policy scenario (Québec circular economy framework) combining 35% debt at 10% interest (10-year term), a 20% non-repayable grant applied as a CapEx reduction, capturing the role of grant buffering in reducing effective capital burden (fondscl, 2025).

Carbon-accounting scope and boundaries

This study models the carbon implications of recycled concrete aggregate (RCA) using a recycled-content (cut-off) allocation approach (Steubing et al., 2016). Under this convention, upstream environmental burdens are attributed to the life cycle in which the recycled material is used, while the studied system does not receive avoided-burden credits for potential recycling at end-of-life. Accordingly, RCA enters the product system with zero upstream burden from its previous life (i.e., impacts from the original concrete production and its prior end-of-life treatment are not carried into the new concrete mix through RCA). The cut-off is therefore applied at the point where RCA becomes an input to concrete production.





(b) Circular Model (cut-off approach)

Figure 2: System boundary of the carbon-emission accounting framework

Figure 2 defines the system boundaries for the linear (a) and circular (b) configurations, respectively. Within these boundaries, the analysis includes virgin material supply (e.g., virgin aggregates and cement), concrete production, and delivery of concrete to site. End-of-life activities are represented through conventional demolition (linear case) or selective deconstruction (circular case), followed by disposal as applicable. While RCA is assigned zero upstream burden under the cut-off convention (RCA supply factor = 0), the processing required to convert recovered concrete into usable RCA is modeled explicitly through an RCA production process with its own carbon factor. This avoids double counting: upstream burdens are not attributed to RCA, while the energy/emissions associated with producing RCA are still captured within the system boundary. Table 4 summarizes the carbon footprint factors adopted for each modeled process.

Table 4: Carbon footprint factors for the processes included in the system boundary (cut-off approach)

Process	Carbon footprint factor (kgCO ₂ e/t)	Reference
Virgin Aggregates Supply	5.7 (kgCO ₂ e/t)	(Ecoinvent- Version 3.8, n.d.)
Cement Supply	900 (kgCO ₂ e/t)	(X. Li et al., 2022)
RCA Supply	0 (kgCO ₂ e/t)	cut-off method
Concrete Production	105 (kgCO ₂ e/t)	(X. Li et al., 2022)
Demolition (Conventional)	3 (kgCO ₂ e/t)	(Minunno et al., 2020)
Deconstruction (Selective Removal)	3 (kgCO ₂ e/t)	(Minunno et al., 2020)
RCA Production	4 (kgCO ₂ e/t)	(Ecoinvent- Version 3.8, n.d.)

Results

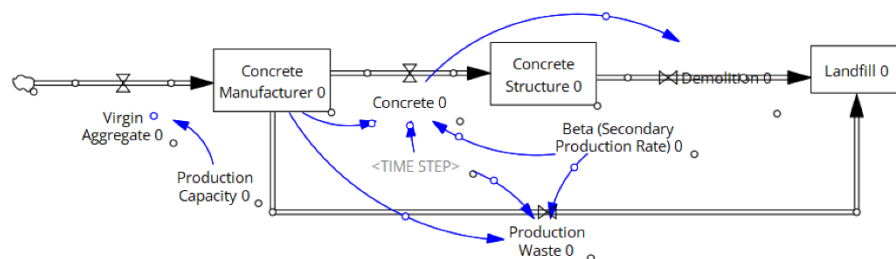
Scenario design and comparison logic

In the first step, a “take, make, use, and dispose” model is followed, aiming to identify the unit price to achieve the expected profit. The model is shown in Figure 3 (a). Since the quantity of demolished concrete is the same as the supplied concrete (less about 3% wastage), it was assumed that the same amount of material flows in and out of the concrete structure. A Production Rate of $\beta = 0.9$ sets the amount of waste from the production at 10%, and the plant’s production capacity is controlled by another parameter, i.e., Production Capacity (= 150,000 tons). As mentioned earlier, since the aggregate is assumed to comprise 75% of the concrete weight, the virgin aggregates extracted from the mine is estimated at 0.75 of the production capacities. After running the model, the material flow is recorded for an NPV analysis.

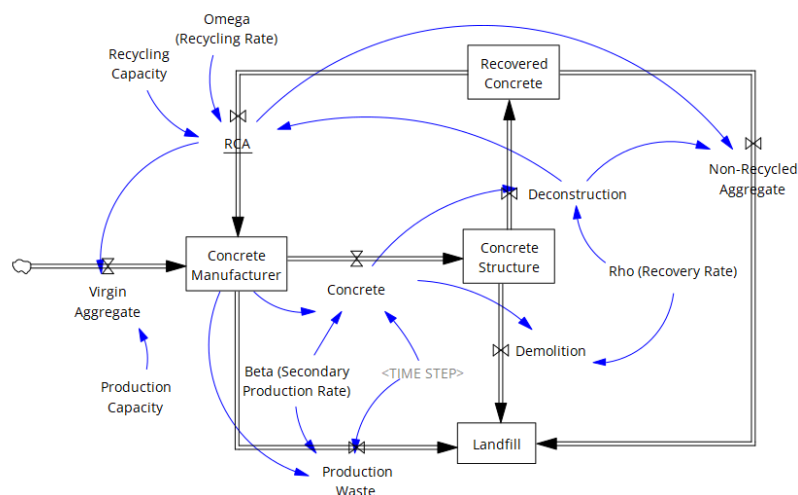
The cash-in and cash-outflows, covering the OpEx, CapEx, and revenue were calculated for each year, based on the unit costs and the amount of material flow. All CapEx calculations were based on historical data of similar plants, through the cost-capacity factor method, as will be explained in the next section. The revenue was calculated based on the amount of concrete supplied to the concrete structures, and the unit cost of the work (Uc) applied per ton of concrete supplied. After applying the actual market price for virgin aggregates, the minimum price per ton of concrete required to achieve a 7% profit margin, was estimated at CAD \$364.61/ton.

In the second step and given the comparatively large expenses associated with the raw material and disposal of demolished concrete (22% and 36% of the OpEx, respectively, as per our calculations), the idea of creating a secondary plant for recycling demolished concrete to extract RCA can be economically feasible. Two recycling configurations are evaluated under the same 25-year horizon:

- Partial recycling using a small RCA plant (capacity $Q_s = 25,000$ tons/year at CapEx = \$350,000), and
- Full recycling using a large RCA plant (capacity $Q_L = 150,000$ tons/year at CapEx = \$1,000,000).



Linear production



Circular production

Figure 3: Stock-flow diagram of the process

In practice, no major price differences are reported for virgin and recycled aggregates (as long as having the same mechanical properties). It is only mentioned in the

literature that in some cases the unit weight differences between the two types of aggregate may result in better volumetric prices for the RCA than virgin aggregates. For example, recycled CA6 is 15% lighter than virgin CA6, so one may receive up to 15% more volume per ton (or pay 15% less per ton) (Ozinga, 2025). Nevertheless, in this study, creating additional economic incentives for the concrete plant is one of the criteria; otherwise, it may be hard to justify the business plan for recycling.

As seen in Figure 3 (b), in the proposed circular model, concrete removal is performed through deconstruction rather than demolition, achieving a 70% recovery rate ($p = 0.7$), with the remaining 30% sent to landfills. Since landfill fees account for approximately 36% of operational expenses, transporting extracted concrete to the RCA unit—even at no cost—is financially beneficial. For the circular model to be competitive, RCA must be priced lower than virgin aggregates while maintaining positive NPV for both the RCA and concrete production units. While savings from landfill fees, input aggregates, and carbon taxes help offset deconstruction costs, the limited capacity of a small-scale RCA unit (25,000 tons/year) makes partial recycling financially unviable. Achieving a 7% profit margin for both the concrete manufacturer and the RCA plant would require a concrete price of \$366.64 per ton, which is higher than the linear model. Additionally, the RCA plant would need to sell at \$380.70 per ton, over 12 times the cost of virgin aggregates, rendering partial recycling economically infeasible. The capacity limitation also means that 69,500 tons per year of recovered concrete would still require landfilling, increasing tipping fee burdens for the RCA plant. This outcome is driven by the small unit's limited processing capacity, which leaves most end-of-life concrete to be landfilled; as a result, disposal costs dominate the circular cashflows and the implied RCA selling price becomes uncompetitive.

The full recovery scenario with the large RCA plant, with an annual capacity of 150,000 tons and a CapEx of \$1,000,000, was further evaluated.

Baseline 'A' (recovery 0.70, recycling 0.60)

Under Baseline 'A', the results showed that, despite a better performance than partial recycling; investment in the large plant for full recycling remains financially unviable. The minimum concrete price for a 7% profit margin was calculated to be \$346.20 per ton, and the minimum RCA price would need to be \$176 per ton. This required RCA price remains more than five times higher than the assumed virgin aggregates price, indicating that the circular option is not competitive under Baseline 'A'. One effective solution to improve the profitability of the circular model can be increasing the recovery and recycling rates.

Baseline 'B' (recovery & recycling 0.95)

Our industry partners have verified that these rates can exceed 95%, reaching up to 99%. However, even by applying a recovery and recycling rate of as high as 95% - 99%, the price of RCA required to achieve a 7% profit margin will be \$66.32/ton, which is still higher than virgin aggregates. It is worth mentioning that considering the coefficient of 0.75 for the weight of aggregates in concrete, even with a 100% recovery rate from deconstruction and a 100% recycling rate, the maximum possible amount of extractable RCA will be $0.75(135,000) = 101,250$ tons. Hence, under these assumptions, the RCA available for use will not exceed 101,250 tons per year. However, to achieve full production capacity and eliminate the need for virgin aggregates, an additional inflow of old concrete from external sources shall be incorporated into the model.

Scenario analysis

For each baseline state, a sensitivity analysis was performed to examine the impact of key variables. This resulted in 45 unique scenario combinations per baseline (90 in total), derived from a factorial design ($3 \times 3 \times 5$) by systematically varying the price on carbon, the tipping fee, and the government financial assistance, as detailed in Table 5.

From these three variables, two (price on carbon and tipping fees) are among government's levers to control the emissions (and indirectly the market), and the loan type is the only option over which the owner/contractor can define moves, even though the terms of those financial aids are also being controlled by the government.

Table 5: Variables of the sensitivity analysis

Variable	Reference Value	Values for Sensitivity Testing
Price on Carbon	80 \$/tCO _{2e}	0 170
Tipping Fee	110 \$/ton	20 175
Government financial assistant	N.A.	CSBFP GMF CSBFP & FEC GMF & FEC

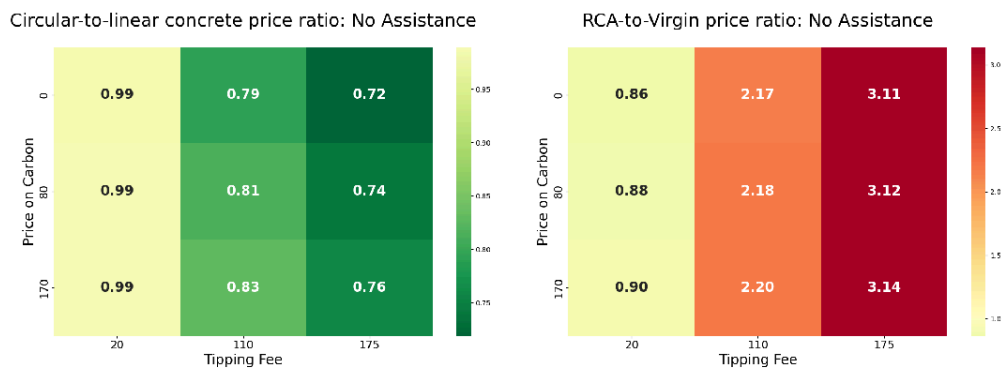
The scenario extreme analysis results (Table 6) for Baseline 'A' reveal a clear trade-off under this baseline. When tipping fees are high, the circular pathway achieves its strongest concrete price performance (circular-to-linear ratio down to 0.89) because disposal becomes costly in the linear system, making the linear option less attractive. However, the same condition produces the worst RCA price outcomes (RCA-to-virgin ratio up to ~8.8), since recovery and process efficiency are not sufficient to minimize residual disposal, RCA prices can increase sharply.

Table 6: Baseline A best- and worst-case price ratios (circular-to-linear concrete; RCA-to-virgin aggregate)

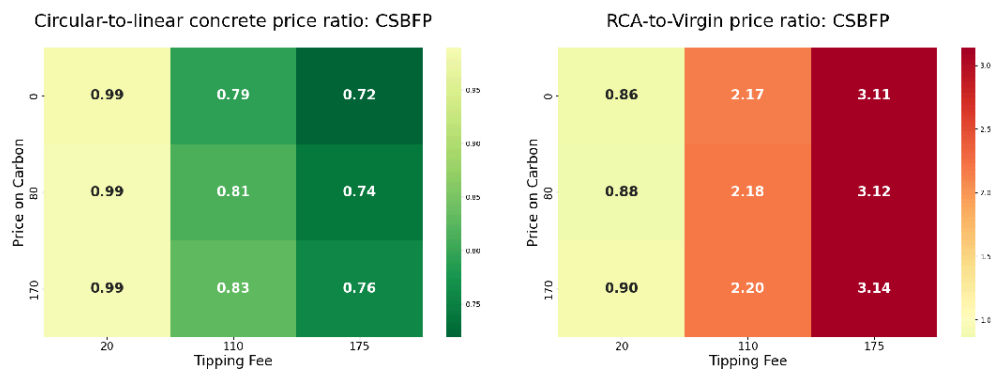
Scenario	Tipping Fee	Government financial assistant	Price on Carbon	Circular to Linear Concrete Price	RCA to virgin price
Best-Case Scenario for Concrete Price	175	GMF & FEC	0	0.89	8.36
Worst-Case Scenario for Concrete Price	20	-	170	1.04	1.85
Best-Case Scenario for RCA Price	20	GMF & FEC	0	1.02	1.6
Worst-Case Scenario for RCA Price	175	-	170	0.93	8.8

The scenario analysis results for Baseline ‘B’ (45 policy combinations) are illustrated in Figure 4, showing Circular to linear concrete price ratio (Figure 4-a) and RCA to virgin aggregate unit price ratio (Figure 4-b). A ratio greater than 1 indicates the circular option requires a higher unit price than the linear baseline (i.e., it is less competitive), whereas a ratio below 1 indicates the circular option is more competitive. Because Baseline ‘A’ remained economically unviable across all examined policy scenarios, its results are not visualized here.

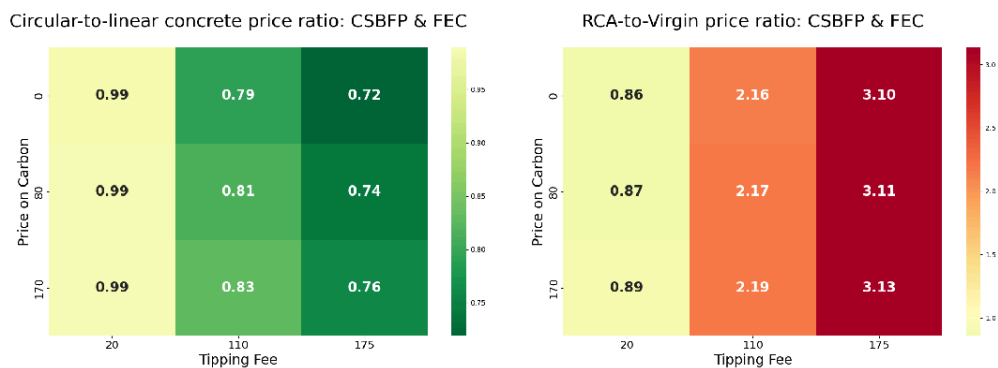
Here it must be emphasized that this study evaluates price competitiveness and financial viability rather than full lifecycle societal cost, (which would require broader environmental external factors).



(i) no loan



(ii) CSBFP



(iii) CSBFP & FEC

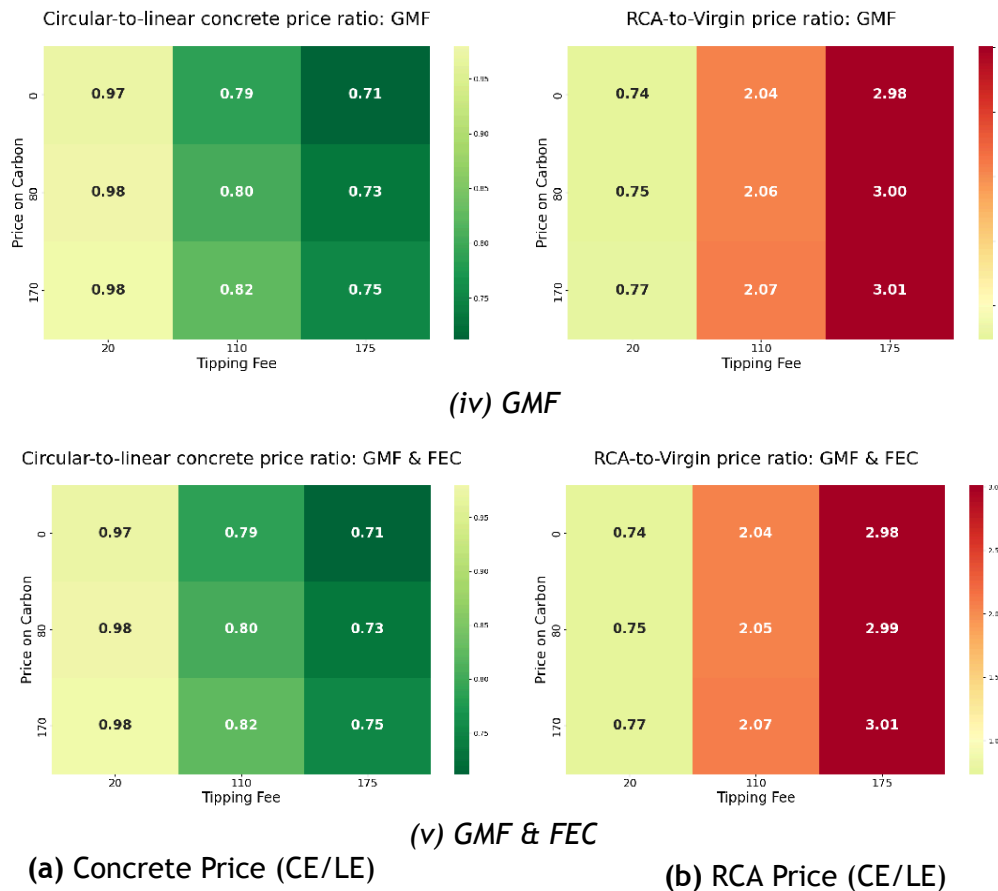


Figure 4: Baseline B-Scenario Analysis Result, Price Ratios (Circular Economy to Linear Economy)

As seen in Figure 4, the circular-to-linear concrete price ratio remains at or below 1 across all policy combinations (Figure 4-a), indicating that the circular concrete option is consistently at least as price-competitive as the linear baseline; in the most unfavorable case (lowest tipping fee and no effective loan), the ratio approaches 1, meaning the two options become comparable. For the aggregate price, however, the RCA-to-virgin price ratio (Figure 4-b) shows a different pattern, with competitiveness strongly influenced by tipping fees.

An increase in the tipping fees, by the government, can improve the competitiveness of the recycled concrete, by penalizing landfilling in the linear pathway. The reason is the difference in landfill exposure implied by the material-flow structure. In the linear configuration, essentially all end-of-life concrete is disposed, so any increase in tipping fees scales with the full demolished mass. In the circular configuration, the tipping-fee shock applies to a much smaller quantity.

Higher government tipping fees paradoxically worsen the price competitiveness of RCA itself relative to virgin aggregate. The reason is driven by the presence of unavoidable residuals in the recycling process. Even under high recovery assumptions, an RCA plant still generates a fraction of non-recoverable waste. As tipping fees increase, the cost of disposing of these residual streams rises and is transferred into the RCA unit cost. Therefore, higher tipping fees can simultaneously improve circular concrete

competitiveness while increasing the minimum price required for RCA, thus reducing its price competitiveness relative to virgin aggregate.

The results show that the strongest government lever to promote RCA consumption is the tipping fees. It is clear that, across all combinations of loan and carbon-price assumptions, increasing tipping fees shifts the RCA-to-virgin aggregate price ratio from < 1 (RCA more economical) to > 1 (virgin aggregate more economical).

Also, from the contractor's perspective it is worthwhile to emphasize that no deviations in the loan structure (among the relevant green loans currently available in the Canadian market) can turn a non-competitive business model (in terms of unit prices alone) into a competitive one or vice versa.

Discussion

Baseline 'A' (Moderate recovery)

In general, transitioning toward circularity, under the right conditions can allow concrete manufacturers to maintain profit margins comparable to linear systems, while offering a lower concrete price and improving their green image. This suggests that circular production is inherently economically attractive under the right conditions.

However, this advantage does not hold true in all policy scenarios. Under minimum tipping fee conditions, the linear process becomes more competitive because the operational cost of landfilling is minimal, and the linear system can reach a 7% profit margin at a lower concrete price than the circular alternative. The circular option still has extra costs for deconstruction, and recovery operations, which must be offset through a higher concrete price.

Conversely, when the tipping fee is high, the linear option becomes less attractive due to increased disposal costs. At the same time, the RCA plant is also affected, since unrecoverable aggregates under the assumed recovery performance must still be sent to landfill. Under Baseline 'A', where recovery and process efficiency are not sufficient to minimize residual disposal, RCA prices can rise sharply (up to about nine times the virgin aggregate price in some scenarios), which can weaken circular price competitiveness despite the government's intent to deter landfilling. Therefore, in the absence of enough process efficiency, increase in the landfill tipping fees by the government can even disadvantage the circularity.

This reveals an important and non-intuitive outcome. Tipping fees alone may not necessarily improve circular feasibility when the infrastructure is not ready. In the absence of higher recovery rates or stronger financial support, circular systems can face additional costs, especially higher RCA prices, which reduces their competitiveness. These results show that recovery performance is the key factor driving the economic feasibility of circular concrete production.

From a Lean perspective, Baseline 'A' reflects industrial process inefficiencies. The circular pathway still contains significant NVA activities, such as the handling and sorting of residuals. Improving recovery performance functions as "Lean waste elimination," reducing the residual stream and the cost burden carried by the business model.

Baseline 'B' (Extreme recovery)

Impact of the Recovery & Recycling Rates - Under Baseline 'B', high recovery performance effectively reduces defects (contamination, losses) and minimizes the

residual stream sent to landfill. Consistent with Lean principles, higher-quality recovery improves process yield, reduces NVA disposal, and enables the circular pathway to deliver the same profit margin at a lower unit price. When recovery and recycling rates reach 95%, system behavior shifts dramatically compared to lower-efficiency cases. High recovery sharply cuts the residual fraction that must be landfilled, stabilizing circular operating costs and driving a decline in the implied RCA unit price. In this high-efficiency regime, circular concrete achieves a lower unit price than the linear baseline—for equivalent profit margins, across all modeled policy conditions.

Specifically, the implied RCA selling price drops to \$22-\$27/ton (compared with a virgin aggregates price of \$30/ton) becoming cost-competitive with virgin aggregate in low-tipping-fee scenarios. These results confirm recovery efficiency as the dominant driver of RCA competitiveness, as it directly controls the landfilled residual fraction and its cost burden.

Moreover, across all tested policy scenarios, the circular configuration consistently achieves a lower concrete unit price than the linear baseline at the target profit margin. This result holds under different carbon prices and financing conditions, implying that once recovery reaches 95%, circular concrete production systematically outperforms the linear process economically in this case.

Effect of Tipping Fees - Tipping fees are most effective when recovery systems already perform well. These fees aim to discourage landfilling by raising disposal costs. However, even in a high-performing circular pathway, a small fraction of material remains unrecoverable and must still be landfilled. Recycling is rarely a 100% efficient process. In even the best-performing systems, a fraction of incoming waste ends up unrecoverable due to contamination or processing limits. When the government increases tipping fees, it creates a dual impact; (i) It raises the total cost of the linear supply chain, as 100% of demolished material is taxed at the landfill gate; (2) It simultaneously increases the OpEx for the RCA plant, which must pay higher fees for its own residual waste.

To maintain the required 7% profit margin, the RCA plant is forced to pass these escalating disposal costs directly into the RCA unit price. This leads to a policy paradox where higher tipping fees can improve the competitiveness of the overall circular concrete contract (by making the linear alternative much more expensive) while simultaneously reducing the price-competitiveness of RCA relative to virgin aggregate.

In Baseline 'B', even with 95% recovery, excessively high fees tend to absorb the financial benefits of recycling into the residual disposal cost structure, effectively counteracting the policy's intent to promote the consumption of recycled material.

This highlights the need for adaptive tipping-fee structures. Tipping fees must be high enough to discourage unnecessary landfilling, yet flexible enough to account for systems that have already reached high recovery (e.g., $\geq 95\%$). This approach penalizes preventable disposal without inflating costs for the small fraction of waste that is physically impossible to recover. By differentiating between these two waste types, policy avoids the paradox where high landfill fees, intended to help the environment, actually undermine the economic competitiveness of circular concrete by driving up its production costs.

Effect of Government Direct Financial Support - Financing mechanisms influence absolute unit prices but do not change the fundamental patterns observed across the results. Among the options tested, GMF produces the largest reduction in both concrete and RCA prices, whereas the Typical Commercial Loan (CSBFP) yields the smallest improvement. The Fonds économie circulaire (FEC), when combined with either financing

scheme, provides an additional but modest decrease by partially offsetting capital expenditures.

Importantly, financing support alone is not sufficient to convert an economically unviable configuration into a viable one. These findings indicate that financial incentives can ease cost pressure, but they cannot substitute for the fundamental requirement of high recovery and recycling performance.

Impact of Carbon Pricing - Since the dominant share of concrete emissions is associated with cement production rather than the aggregates, carbon pricing primarily inflates the cement-related component of the cost structure for both models. Consequently, higher carbon prices increase the overall concrete unit price, but they do not materially lower the implied cost of RCA, since aggregates account for only a small fraction of total embodied emissions. In practice, carbon pricing therefore improves the relative position of circular concrete only marginally: it mainly penalizes the linear baseline through higher cement-related costs, rather than directly strengthening the economics of recycled aggregates.

Conclusion

This study developed and applied an integrated simulation-economics framework to assess the viability of an RCA-based circular concrete business model under alternative policy settings. By linking system dynamics material flows to discounted cashflow analysis and a structured scenario design, the study quantifies how recovery performance and government levers jointly shape profitability and price competitiveness. This study contributes to the circular construction literature by integrating material-flow dynamics, economic viability analysis, and policy evaluation into a single decision-oriented modeling framework. The key contributions are trifold.

Firstly, recovery efficiency is the dominant operational determinant of circular competitiveness. When recovery and recycling performance are moderate, circular configurations may appear attractive under certain conditions but do not remain competitive across the full policy space, as residual landfilling continues to impose costs.

Secondly, policy effectiveness is conditional rather than universal. Landfill tipping fees can improve relative competitiveness; however, if set excessively high, they can increase RCA costs through unavoidable residual disposal. Therefore, adaptive landfill pricing is essential. Financing support reduces price levels but does not alter competitiveness direction; concessional financing provides relief but cannot substitute for high recovery performance. In addition, the impact of carbon pricing on circular competitiveness is limited in this setting because cement dominates concrete emissions; carbon costs primarily inflate shared binder costs in both pathways rather than directly improving the economics of recycled aggregates.

Thirdly, the results have a clear Lean interpretation: improving recovery and recycling performance functions as the elimination of NVA activities which stabilizes operating costs and makes circular pathways robust across policy conditions. Together, these insights provide policymakers and industry stakeholders with a performance-aligned pathway for enabling viable circular concrete supply chains.

From a practical standpoint, scaling circular concrete production therefore requires policy packages aligned with operational performance rather than single-lever interventions. The most effective pathway combines high-yield recovery systems, calibrated landfill pricing, and capital-support instruments that reduce infrastructure barriers.

Future research can build on this work by including additional incentive mechanisms that may further support circular practices. Moreover, while this study identifies high recovery rates as a prerequisite for economic viability, the operational pathway to achieving such performance deserves further investigation through the lens of Lean Construction. In addition, applying the proposed methodology to a representative number of real-world case studies would be necessary for the validation of model's assumptions and results. Moreover, given the generalizability of the modeling framework, future studies can also adapt it to other jurisdictions to account for regional market dynamics and policy contexts.

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