DECISION SUPPORT FRAMEWORK FOR INTEGRATING CONSTRUCTION CONSOLIDATION CENTRE INTO SUSTAINABLE WASTE MANAGEMENT

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Abstract

Inner-city construction projects face severe spatial constraints during the finishing stage, often leading to mixed construction and demolition waste (C&DW) handling and reduced circular performance. This paper proposes a project-level decision-support framework to evaluate outbound C&DW logistics strategies, addressing the lack of project-level comparative tools. The framework integrates economic, environmental, and social indicators in a scenario-based comparison of conventional handling and CCC-enabled reverse logistics. Applied to three Dutch projects, results show cost and emission reductions, with slightly higher logistics intensity. The framework supports ex ante decision-making under spatial constraints.

Introduction

Problem Context

Inner-city construction projects operate under conditions that fundamentally constrain material handling and logistics. Dense urban environments are characterised by limited on-site space, restricted access time windows, and regulatory constraints on vehicle movements. These conditions significantly reduce the feasibility of conventional construction logistics and waste management practices, particularly when compared to projects located in less spatially constrained areas (Guerlain et al., 2019).

These spatial constraints become especially critical during the finishing stage of construction—i.e., the late phase after the building shell is weather-tight, when interior fit-out, final installations, and snagging activities dominate until practical completion. Although the overall volume of construction and demolition waste (C&DW) often decreases towards project completion, the diversity and complexity of waste streams typically increase. This stage produces a heterogeneous mix of materials (e.g., wood off-cuts, drywall, insulation, plastics, metals, and packaging), which requires frequent handling and effective on-site separation—tasks that are difficult to perform on inner-city sites with limited storage capacity (Gálvez-Martos et al., 2018). Although the finishing stage does not necessarily generate the highest waste volume, it is particularly relevant for this study because it combines high waste-stream heterogeneity, frequent handling, packaging waste, and intensive subcontractor coordination. Under inner-city space constraints, these conditions make on-site source separation especially difficult and increase the likelihood that recyclable materials are disposed of as mixed waste.

Under such conditions, mixed C&DW handling often becomes the default practice. Instead of separating waste streams on-site, different materials are commonly disposed together in a single container and transported to recycling facilities in an unsegregated state. This practice is not the result of a deliberate preference for low-quality recycling, but rather a pragmatic response to severe spatial and logistical constraints at the project site (Wang et al., 2010).

The downstream consequences of mixed waste handling are significant. At recycling facilities, unsegregated waste requires additional mechanical sorting, which increases operational costs and energy consumption. In many cases, the economic feasibility of high-quality separation is limited, resulting in valuable materials being downcycled into low-grade applications rather than reused or recycled at their original value level (Bayram and Greiff, 2023). In addition to material degradation, mixed waste handling contributes to higher transport-related emissions and increased urban disturbance through inefficient logistics operations and additional freight movements (Guerlain et al., 2019).

Decision-Making Challenge

Project teams operating in inner-city construction contexts must continuously balance economic cost, environmental performance, and urban impacts under tight spatial and temporal constraints. Decisions regarding C&DW handling during the finishing stage are often made under pressure, with limited flexibility to revise logistical arrangements once construction activities are underway.

In practice, waste-handling decisions at the project level tend to be reactive and fragmented. Waste is frequently treated as an operational by-product rather than as a strategic component of construction logistics planning. As a result, decisions are commonly driven by short-term cost considerations and immediate site feasibility, without a structured ex ante comparison of alternative outbound waste logistics strategies (Brusselaers et al., 2024).

This fragmented decision-making environment is further reinforced by the absence of transparent, project-specific decision-support tools. While general sustainability frameworks and guidelines exist, they rarely provide actionable support for evaluating how different waste handling strategies perform under the specific spatial constraints of inner-city construction sites. Consequently, project managers lack the analytical means to systematically assess trade-offs between cost, emissions, and urban impacts during the finishing stage, when waste complexity is at its highest (Yuan, 2013).

Research Question

In response to the challenges outlined above, this study addresses the following research question:

How can a Construction Consolidation Centre (CCC) be integrated into outbound C&DW management during the finishing stage of inner-city construction projects, and how can the resulting economic, environmental, and social impacts be quantified and compared to support project-level decision-making?

Contribution

This study contributes to construction logistics and waste management in three related respects. It develops a project-specific framework for comparing outbound C&DW strategies during the finishing stage of inner-city projects. It also extends the discussion of CCCs beyond inbound supply logistics by examining their role in reverse logistics and source-separated waste collection. Finally, it brings cost, emissions, and urban disturbance into one comparative structure, allowing alternative waste-handling strategies to be assessed under the same project conditions.

Literature Review and Research Gap

C&DW Management Assessment

Assessment of construction and demolition waste (C&DW) management has been widely addressed in the literature, with a strong emphasis on life-cycle-based evaluation methods. Life Cycle Assessment (LCA) is frequently applied to quantify environmental impacts associated with waste treatment, transport, and recycling processes, while Life Cycle Costing (LCC) is commonly used to assess economic performance across collection, sorting, transport, and disposal activities (Finnveden et al., 2009). Together, these approaches provide valuable insights into the environmental and economic implications of alternative waste management strategies.

However, the majority of existing assessments operate at an aggregate, sectoral, or policy-oriented level. Many studies focus on national waste streams, generic building types, or average treatment scenarios, rather than on individual construction projects with specific spatial and logistical constraints (Yuan, 2013). As a result, the outcomes of such assessments are often descriptive in nature and insufficiently sensitive to project-level conditions such as site size, access restrictions, or construction phase.

In addition, social impacts are only marginally addressed in most C&DW assessment studies. Where social considerations are included, they are often treated qualitatively or discussed conceptually, rather than being operationalised through quantifiable indicators (Zhao et al., 2023). Urban disturbance effects related to freight movements, congestion, and nuisance are therefore rarely integrated alongside environmental and economic performance in a systematic manner (Muñuzuri et al., 2005).

Consequently, while existing C&DW assessment literature provides important methodological foundations, it offers limited support for project-level, scenario-based decision-making in complex inner-city construction contexts, particularly during the finishing stage when waste diversity and logistical pressure are the highest.

Construction Consolidation Centre (CCC)

A Construction Consolidation Centre (CCC) is an off-site logistics facility, typically located outside the dense urban core, where construction materials are received, consolidated, and re-dispatched to site in coordinated deliveries. Existing research shows that CCCs can improve delivery reliability, reduce inbound vehicle trips, and lower transport-related impacts in urban construction projects (Muñuzuri et al., 2005; Russo et al., 2021). They have been widely studied as a logistics solution for improving material delivery efficiency, with consistent evidence of reduced vehicle trips and emissions through coordinated last-mile logistics (Russo et al., 2021).

Most CCC studies focus explicitly on inbound material flows, evaluating performance in terms of delivery efficiency, cost savings, and emission reductions associated with supplier-to-site logistics. These analyses typically assess CCC performance using indicators such as vehicle kilometres travelled, delivery frequency, and load factors, often in comparison with conventional direct-to-site delivery models (Muñuzuri et al., 2005).

By contrast, the application of CCC to outbound logistics, and particularly to C&DW flows, remains largely unexplored (Rubio et al., 2019). Existing CCC literature rarely considers reverse logistics or the potential role of CCC in enabling source-separated waste collection under spatially constrained site conditions. Where waste is mentioned, it is typically treated as a secondary or operational issue rather than as a core component of logistics system design (Guerlain et al., 2019).

As a result, there is a lack of analytical tools and empirical studies that evaluate CCC-enabled reverse logistics for C&DW at the project level. In particular, the literature does not provide structured methods for comparing conventional mixed-waste handling with integrated CCC-based waste strategies under real inner-city constraints.

Research Gap

Despite useful insights from both strands of literature, a practical project-level gap remains. On the one hand, C&DW assessment studies predominantly rely on LCA and LCC approaches that are insufficiently tailored to project-specific, scenario-based decision-making in spatially constrained environments (Finnveden et al., 2009). On the other hand, CCC research has largely focused on inbound logistics, with limited attention to outbound waste flows and reverse logistics applications (Russo et al., 2021).

What is still missing is a project-level method for comparing conventional mixed-waste handling with CCC-supported reverse logistics under the same site conditions. Empirical studies that make this comparison in spatially constrained inner-city settings are still limited. Accordingly, this study develops an ex ante, project-level decision-support framework that explicitly links outbound waste-handling strategies to inner-city logistical constraints and evaluates their economic, environmental, and social implications during the finishing stage of inner-city construction projects. This gap directly informs the framework and method presented in the following section.

Decision-Support Framework and Method

Framework Overview

The framework is used to compare alternative outbound C&DW logistics strategies during the finishing stage of inner-city construction projects. This stage is characterised by high material diversity, frequent logistics operations, and severe spatial constraints, which together complicate conventional waste-handling practices.

The framework adopts a scenario-based comparative logic, enabling project stakeholders to evaluate alternative waste-management strategies under identical project conditions. Two distinct strategies are defined:

- Baseline scenario, representing conventional mixed-waste handling practices commonly observed in spatially constrained inner-city projects (Haag and Jünger, 2023).
- Integrated scenario, representing a coordinated waste-handling strategy enabled through a Construction Consolidation Centre (CCC) with reverse logistics integration (Paddeu, 2018).

The decision context is explicitly project-level and ex ante. The framework is intended to be applied during the procurement and planning phase, when waste-handling strategies can still be adjusted without disrupting ongoing construction activities. The primary stakeholders supported by the framework include contractors, project managers, CCC operators, and, indirectly, municipal authorities responsible for regulating urban freight and construction logistics (Melkonyan et al., 2022; Sobotka and Sagan, 2021).

This setup allows the baseline and integrated scenarios to be compared on the same economic, environmental, and social indicators under the actual spatial conditions of each case (Maxner et al., 2025).

Key Performance Indicator (KPI) Framework

To support multi-criteria decision-making, the framework evaluates outbound C&DW management strategies using a structured set of Key Performance Indicators (KPIs) (Figure 1). The KPIs are limited to indicators that are decision-relevant and operationally estimable during procurement-stage planning and are grouped into three dimensions—economic, environmental, and social—as summarised in Table 1, together with their definitions and units. The framework is intended as a project-level, ex ante comparative assessment of finishing-stage outbound waste logistics rather than a full cradle-to-grave LCA/LCC.

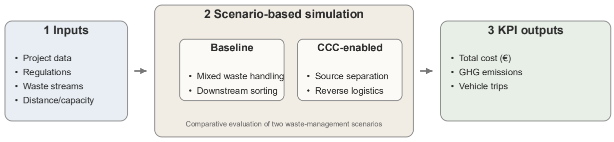

Figure 1: Decision-support framework for outbound C&DW logistics

Table 1: KPI Framework Overview

Dimension	Indicator	Unit	Description
Economic	Transport cost	€	Waste transport costs
Economic	Container handling	€	Container rental and handling
Economic	Sorting & labour	€	On-site sorting labour
Economic	Recovery revenue	€	Income from recyclables
Economic	CO_2 cost	€	Monetised carbon emissions
Environmental	Transport emissions	kg CO_2-eq	Freight-related emissions
Environmental	Sorting emissions	kg CO_2-eq	Waste treatment emissions
Social	Vehicle trips	number	Proxy for urban disturbance

Economic dimension

Economic performance is evaluated as a project-level cost–benefit balance for outbound C&DW logistics, enabling ex ante comparison across scenarios (Brusselaers et al., 2024; Yuan, 2013). Where relevant, carbon pricing is applied to express greenhouse gas emissions as a monetised externality within the economic comparison (Greenstone et al., 2013). Physical emissions are reported separately in the environmental dimension; the CO_2 cost term is included only to support integrated scenario comparison and does not replace the environmental assessment.

Environmental dimension

Environmental performance is assessed using greenhouse gas emissions associated with transport and mixed-waste sorting processes, allowing consistent comparison across logistics configurations (Butera et al., 2015; Hossain et al., 2017; Bayram and Greiff, 2023). Greenhouse gas emissions were selected as the primary environmental indicator because they can be estimated consistently using available project-level inputs, whereas broader impact categories would require a level of process detail beyond the scope of this ex ante project-level assessment.

Social dimension

Social performance is captured through vehicle trips as an operational proxy for urban disturbance associated with waste logistics movements, providing a transparent basis for project-level comparison under typical data constraints (Çolak et al., 2016). Congestion, noise, and traffic-related disturbance are difficult to quantify directly at project level, whereas trip frequency offers a simple and comparable indicator of logistics intensity in dense urban contexts.

Scenario-Based Simulation Logic

The decision-support framework evaluates performance using two explicitly defined simulation scenarios. Both scenarios are modelled using identical project inputs to ensure comparability.

Baseline scenario

The baseline scenario represents conventional C&DW handling practices commonly applied in inner-city construction projects:

- Waste is collected in a single mixed container.
- No on-site waste separation is performed.
- Waste collection is reactive, triggered when the container is full.
- Waste is transported directly to recycling facilities, where mechanical sorting is required.

This scenario reflects a common fallback practice where limited site space and constrained layout conditions reduce the feasibility of stable on-site source separation (Tsegay et al., 2023).

Integrated scenario

The integrated scenario models a coordinated outbound waste-handling strategy enabled through a CCC with reverse logistics integration:

- Waste is separated on-site using multiple small, material-specific containers.
- Empty containers are supplied (and swapped when needed) via the same coordinated inbound delivery trips from the CCC, i.e., no dedicated trips are assumed solely for container provision.
- Inbound material deliveries and outbound waste collection are coordinated.
- Vehicles delivering materials to the site collect full waste containers on return trips.
- Weekly logistics planning is used to improve the coordination and utilisation of construction transport operations (Brusselaers et al., 2024).

By integrating inbound and outbound logistics, the integrated scenario aims to enable source separation without substantially increasing transport demand.

Decision-Support Tool Implementation

The framework is implemented as a project-level decision-support tool (DST) for the ex ante evaluation of alternative outbound waste-handling strategies. The tool uses project-specific inputs, including project type and size, site constraints, finishing-stage waste-generation parameters, distances to CCCs and recycling facilities, and cost, emission, and carbon-pricing parameters (Greenstone et al., 2013; Çolak et al., 2016; Katsela et al., 2022).

The tool simulates baseline and CCC-enabled scenarios under identical case conditions and converts the outputs into comparable economic, environmental, and social KPIs. Assumptions and parameters remain explicit and adjustable, enabling transparent scenario testing prior to implementation (Melkonyan et al., 2022).

Case Studies and Results

Case Study Description

The decision-support framework was applied to three inner-city construction projects in the Netherlands, selected to represent varying degrees of spatial constraint while involving comparable finishing-stage logistics challenges. The cases include two projects in Utrecht and one in Amsterdam, all involving intensive finishing-stage activities under constrained site conditions (Tsegay et al., 2023).

The Renaissance project in Amsterdam represents a highly constrained inner-city context, characterised by extremely limited on-site storage space, strict access windows, and intensive interaction with surrounding urban functions. These conditions severely restrict conventional waste-handling practices during the finishing stage.

The Tivoli project in Utrecht is a heritage renovation located in a dense historic urban area. While spatial constraints are slightly less severe than in the Renaissance case, the project faces access regulations, heritage protection requirements, and restricted on-site container placement, imposing both spatial and regulatory limitations on waste-handling decisions.

The Beneluxlaan project in Utrecht serves as a comparatively less constrained urban case. Although still embedded within the urban fabric, the project benefits from improved access conditions and marginally greater on-site space, providing a contrast for assessing how strategy performance varies with the degree of spatial constraint.

Across all three cases, the finishing stage constitutes the primary focus of analysis due to its high waste-stream heterogeneity and operational complexity. For each project, two waste-handling strategies were evaluated: a baseline scenario representing conventional mixed-waste handling and an integrated scenario based on CCC-enabled reverse logistics.

Table 2: Characteristics of analysed case studies

Case	City	Project type	Site constraint	Finishing complexity
Renaissance	Amsterdam	Redevelopment	Very high	High
Tivoli	Utrecht	Heritage renovation	High	Medium–high
Beneluxlaan	Utrecht	New construction	Moderate	Medium

Economic Performance Results

Economic performance is evaluated based on project-total finishing-stage waste-handling costs for each case study. Cost components include container rental and handling, transport operations, sorting and labour activities, disposal fees, and revenues from recovered materials, consistent with the framework defined in the previous section. Absolute cost levels differ substantially across the three cases because the reported results reflect project totals rather than normalised values; they therefore support within-case scenario comparison more directly than cross-case benchmarking. Figure 2 illustrates the project-total cost difference between the baseline and integrated scenarios for each case.

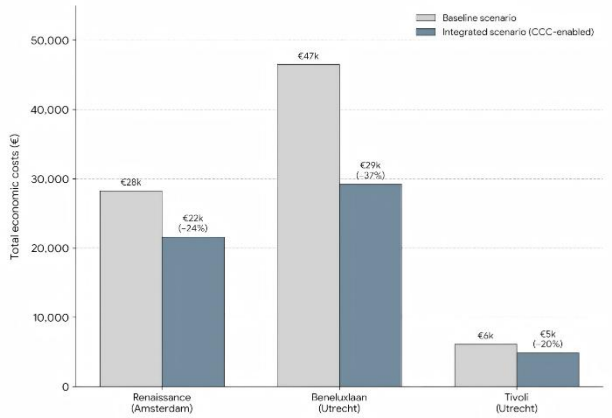

Figure 2: Project-total finishing-stage waste-management costs by case and scenario

In all three cases, the CCC-enabled scenario was less costly than the baseline mixed-waste handling strategy. Total cost reductions range from approximately 20% to 37%, depending on project characteristics and spatial constraints. Differences in absolute cost levels should be interpreted in relation to project-specific scale, finishing-stage scope, and site conditions rather than as like-for-like benchmarks between the three cases. The largest relative savings are observed in the most spatially constrained cases, where baseline logistics are characterised by high transport frequency and handling inefficiencies.

Cost breakdown analysis indicates that savings are primarily driven by reduced transport inefficiencies and increased revenues from material recovery. Although the integrated scenario introduces additional sorting and coordination activities, these costs are outweighed by efficiencies achieved through consolidated logistics operations. In contrast, the baseline scenario exhibits higher downstream disposal and sorting costs due to the treatment of mixed waste streams.

Overall, the economic benefits of CCC-enabled reverse logistics were strongest in cases where limited space and inefficient mixed-waste treatment made the baseline arrangement particularly costly.

Environmental Performance Results

Environmental performance is evaluated based on project-total transport- and mixed-waste-sorting-related CO_2 emissions associated with finishing-stage waste handling (Butera et al., 2015; Bayram and Greiff, 2023). These emissions are calculated consistently across the baseline and integrated scenarios using the parameters defined in the decision-support framework and are intended primarily for within-case comparison rather than cross-case benchmarking. Figure 3 illustrates the difference in project-total transport- and sorting-related CO_2 emissions between the two scenarios in each case.

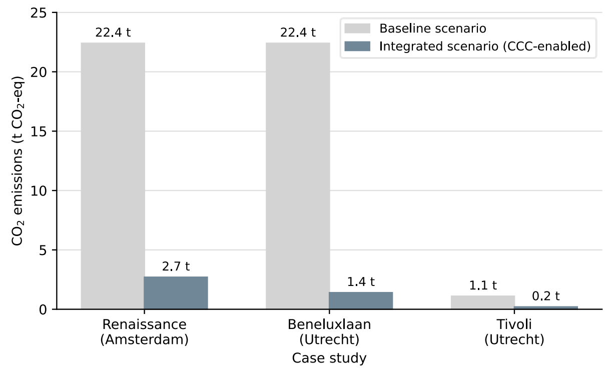

Figure 3: Project-total transport- and sorting-related CO_2 emissions by case and scenario

In all three cases, the integrated scenario produced substantially lower transport- and sorting-related CO_2 emissions than the baseline, with total reductions of roughly 85% to 94%. The dominant contributor to this reduction is the avoidance of energy-intensive downstream sorting processes associated with mixed-waste handling.

Transport-related emissions are also lower in the integrated scenario due to coordinated inbound and outbound logistics enabled by the CCC. Although logistics operations may occur more frequently, improved vehicle utilisation and reduced reliance on dedicated waste transport trips lead to lower overall emissions within the defined project-level assessment boundary (Wu et al., 2023).

Environmental performance gains are particularly pronounced in projects where baseline practices rely heavily on mixed containers and downstream mechanical sorting. In such contexts, source separation enabled through CCC-based reverse logistics offers significant emission avoidance potential.

Social Impact Results

Social impacts are evaluated using the number of vehicle trips as a proxy indicator for urban disturbance, including traffic congestion, noise, and safety risks in dense urban environments (Li et al., 2024).

In contrast to the economic and environmental results, the integrated scenario is associated with a moderate increase in modelled vehicle trips, ranging from approximately 8% to 15% across the three cases. This increase is primarily linked to the more frequent collection of smaller, source-separated waste containers during the finishing stage. Figure 4 shows the modelled number of vehicle trips under the baseline and integrated scenarios for each case.

However, this increase should be interpreted with care. Under the integrated scenario, waste collection is coordinated with inbound material deliveries, meaning that some outbound waste movements may be combined with return legs that would otherwise occur without payload. The vehicle-trip indicator should therefore be understood as an operational proxy reflecting handling rhythm and logistics intensity, rather than as a direct count of net-new urban freight movements. In the baseline scenario, fewer trips may be observed, but these are typically less coordinated and may involve less efficient vehicle utilisation and longer on-site dwell times.

This points to a clear trade-off: the integrated scenario improves cost and emissions performance, but it can also increase the frequency of on-site waste-handling operations. This trade-off highlights the importance of coordination between project-level waste-handling decisions and broader urban logistics planning in highly constrained inner-city environments.

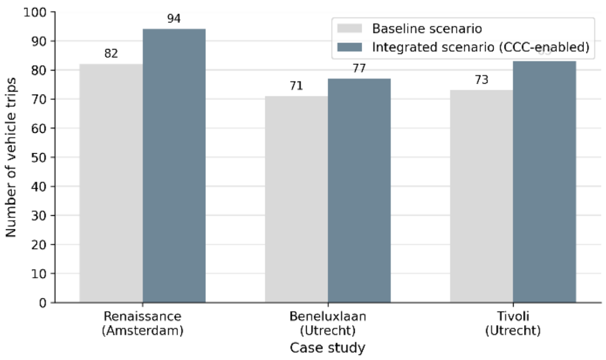

Figure 4: Number of vehicle trips associated with outbound C&DW logistics under baseline and CCC-enabled scenarios

Sensitivity Analysis

To test the robustness of the case-study findings, a threshold-based sensitivity analysis was conducted, focusing on dominant economic and project-constraint parameters. Specifically, we identified (i) the break-even mixed-waste recycling cost at which the baseline strategy becomes economically comparable to the CCC-enabled scenario, and (ii) estimated tipping points for key project constraints, including project size and available on-site storage area, at which the relative performance of the integrated strategy changes.

Across the analysed cases, the CCC-enabled scenario remains environmentally favourable across the tested ranges, while economic performance is more sensitive to market and constraint factors. As summarised in Table 3, the baseline strategy would require a substantial reduction in mixed-waste recycling costs (23.6–30.7%) to become economically comparable to the integrated scenario. In addition, the viability of the integrated strategy is shaped by project scale and available on-site staging capacity, indicating that CCC-enabled reverse logistics should be interpreted as a context-sensitive rather than universally optimal solution.

The thresholds reported in Table 3 are case-specific and should therefore be interpreted as indicative break-even conditions rather than transferable benchmark values.

Table 3: Case-specific sensitivity thresholds: indicative break-even recycling cost and project-constraint tipping points

Case	Break-even recycling cost (€/m³)	Required reduction (%)	Economic scale threshold (m²)	Environmental scale threshold (m²)	On-site storage threshold (m²)
Renaissance	147	25.1	1880	900	100
Tivoli	150	23.6	1900	1850	20
Beneluxlaan	136	30.7	1800	900	25

Discussion

Scalability and Transferability

The framework should not be read as a source of universally applicable threshold values. Its value lies instead in offering a comparison logic that can be adapted to projects with different spatial constraints. In this study, these constraints are operationalised mainly through on-site staging capacity and accessibility conditions, which shape feasible container configurations, handling frequency, and collection feasibility in the baseline and integrated strategies.

Across the three cases, performance differences are driven by how these constraints interact with project-specific scale and duration. Tighter sites restrict material-specific containers and increase swap frequency, whereas less constrained sites allow more stable source separation. The resulting cost and emission outcomes should therefore be interpreted as contingent on local spatial and logistical conditions rather than fixed benchmarks.

Even so, the analytical structure can still be applied to other projects, provided that case-specific inputs are retained. By combining scenario-based comparison with a consistent KPI set, the framework supports ex ante assessment across projects while allowing case-specific inputs to vary.

Sensitivity and Key Enablers

The sensitivity analysis shows that the economic performance of CCC-enabled reverse logistics depends mainly on a small number of market and project-constraint variables. As summarised in Table 3, its economic advantage is particularly sensitive to downstream mixed-waste treatment conditions: the baseline strategy would require a substantial reduction in mixed-waste recycling costs (approximately 23.6–30.7%) to become economically comparable to the CCC-enabled scenario. This indicates that, under typical market conditions, the economic case for integrated reverse logistics is relatively robust, although it may weaken under unfavourable pricing environments (Wu et al., 2023).

Project scale constitutes a second decisive factor. The tipping-point analysis (Table 3) indicates scale thresholds around 1800–1900 m², below which the fixed coordination requirements of CCC-enabled logistics are less likely to be amortised. Smaller or short-duration projects may therefore struggle to realise economic benefits despite potential emission reductions. The analysis further shows that on-site staging capacity acts as a practical feasibility constraint: where available storage space falls below the identified thresholds, the achievable degree of source separation and the operational rhythm of container swaps may be restricted.

Beyond these quantitative sensitivities, institutional and organisational conditions remain key enablers. Effective implementation depends on coordination among contractors, CCC operators, and municipal authorities, particularly with respect to delivery windows, vehicle access regulations, and on-site handling arrangements. In addition, mechanisms such as carbon pricing may strengthen the relative performance of integrated logistics by internalising transport-related emissions that are otherwise excluded from project-level decision-making (Katsela et al., 2022).

CCC-enabled reverse logistics is therefore better understood as a conditional solution: it performs well in some inner-city settings, but not under all project conditions. The proposed framework provides a structured means to identify when integrated outbound waste logistics constitutes a robust and defensible choice under real inner-city constraints.

Limitations

This study has several limitations. It is based on three Dutch case studies, limiting geographical and regulatory generalisability. It provides a project-level, ex ante comparison of finishing-stage outbound waste logistics rather than a full cradle-to-grave LCA/LCC. Social impacts are approximated through vehicle trips, and mixed-waste sorting emissions and other operational parameters rely partly on secondary assumptions. Results are therefore most robust for within-case comparison rather than direct cross-case benchmarking.

Conclusions

This study developed a framework for comparing outbound C&DW strategies during the finishing stage of inner-city construction projects. Using a baseline mixed-waste scenario and a CCC-enabled reverse-logistics scenario, it examines how cost, emissions, and urban disturbance change under different site conditions.

The case-based comparisons suggest that CCC-enabled reverse logistics may improve cost and emission performance under the analysed conditions, while also increasing logistics intensity in some cases. The main contribution is not a universal prescription, but a practical way to judge when integrated outbound waste logistics is feasible and worthwhile under specific spatial and organisational conditions.

Future research

Future research could extend the framework in several directions. BIM-based waste estimation could improve the automation and accuracy of project-level waste forecasting (Guerra et al., 2019).

Real-time logistics data could support more dynamic decision-making during project execution (Brusselaers et al., 2024).

In addition, coupling the tool with urban transport simulation models may help capture network-level effects, while expanding the social assessment could account for worker-related impacts such as handling burden, safety, and usability. Together, these extensions would improve the framework’s relevance for circular decision-making in dense urban construction contexts.

References

Bayram, B., Greiff, K., 2023. Life cycle assessment on construction and demolition waste recycling: a systematic review analyzing three important quality aspects. Int. J. Life Cycle Assess. 28, 967–989. https://doi.org/10.1007/s11367-023-02145-1

Brusselaers, N., Fredriksson, A., Gundlegård, D., Zernis, R., 2024. Decision support for improved construction traffic management and planning. Sustain. Cities Soc. 104, 105305. https://doi.org/10.1016/j.scs.2024.105305

Butera, S., Christensen, T.H., Astrup, T.F., 2015. Life cycle assessment of construction and demolition waste management. Waste Manag. 44, 196–205. https://doi.org/10.1016/j.wasman.2015.07.011

Çolak, S., Lima, A., González, M.C., 2016. Understanding congested travel in urban areas. Nat. Commun. 7, 10793. https://doi.org/10.1038/ncomms10793

Finnveden, G., Hauschild, M.Z., Ekvall, T., Guinée, J., Heijungs, R., Hellweg, S., Koehler, A., Pennington, D., Suh, S., 2009. Recent developments in Life Cycle Assessment. J. Environ. Manage. 91, 1–21. https://doi.org/10.1016/j.jenvman.2009.06.018

Gálvez-Martos, J.-L., Styles, D., Schoenberger, H., Zeschmar-Lahl, B., 2018. Construction and demolition waste best management practice in Europe. Resour. Conserv. Recycl. 136, 166–178. https://doi.org/10.1016/j.resconrec.2018.04.016

Greenstone, M., Kopits, E., Wolverton, A., 2013. Developing a Social Cost of Carbon for US Regulatory Analysis: A Methodology and Interpretation. Rev. Environ. Econ. Policy 7, 23–46. https://doi.org/10.1093/reep/res015

Guerlain, C., Renault, S., Ferrero, F., 2019. Understanding Construction Logistics in Urban Areas and Lowering Its Environmental Impact: A Focus on Construction Consolidation Centres. Sustainability 11, 6118. https://doi.org/10.3390/su11216118

Guerra, B.C., Bakchan, A., Leite, F., Faust, K.M., 2019. BIM-based automated construction waste estimation algorithms: The case of concrete and drywall waste streams. Waste Manag. 87, 825–832. https://doi.org/10.1016/j.wasman.2019.03.010

Haag, P., Jünger, H.C., 2023. Turning a spotlight on construction logistics for a sustainable urban environment—a review of current policy concepts and literature. Front. Built Environ. 9. https://doi.org/10.3389/fbuil.2023.1202091

Hossain, Md.U., Wu, Z., Poon, C.S., 2017. Comparative environmental evaluation of construction waste management through different waste sorting systems in Hong Kong. Waste Manag. 69, 325–335. https://doi.org/10.1016/j.wasman.2017.07.043

Katsela, K., Pålsson, H., Ivernå, J., 2022. Environmental impact and costs of externalities of using urban consolidation centres: a 24-hour observation study with modelling in four scenarios. Int. J. Logist. Res. Appl. 25, 1542–1563. https://doi.org/10.1080/13675567.2021.1915261

Li, C., Wang, D., Chen, H., Liu, E., 2024. Analysis of Urban Congestion Traceability: The Role of the Built Environment. Land 13, 255. https://doi.org/10.3390/land13020255

Maxner, T., Dalla Chiara, G., Goodchild, A., 2025. The State of Sustainable Urban Last-Mile Freight Planning in the United States. J. Am. Plann. Assoc. 91, 88–101. https://doi.org/10.1080/01944363.2024.2324096

Melkonyan, A., Gruchmann, T., Lohmar, F., Bleischwitz, R., 2022. Decision support for sustainable urban mobility: A case study of the Rhine-Ruhr area. Sustain. Cities Soc. 80, 103806. https://doi.org/10.1016/j.scs.2022.103806

Muñuzuri, J., Larrañeta, J., Onieva, L., Cortés, P., 2005. Solutions applicable by local administrations for urban logistics improvement. Cities 22, 15–28. https://doi.org/10.1016/j.cities.2004.10.003

Paddeu, D., 2018. Sustainable Solutions for Urban Freight Transport and Logistics: An Analysis of Urban Consolidation Centers, in: Zeimpekis, V., Aktas, E., Bourlakis, M., Minis, I. (Eds.), Sustainable Freight Transport: Theory, Models, and Case Studies. Springer International Publishing, Cham, pp. 121–137. https://doi.org/10.1007/978-3-319-62917-9_8

Rubio, S., Jiménez-Parra, B., Chamorro-Mera, A., Miranda, F.J., 2019. Reverse Logistics and Urban Logistics: Making a Link. Sustainability 11. https://doi.org/10.3390/su11205684

Russo, S.M., Voegl, J., Hirsch, P., 2021. A multi-method approach to design urban logistics hubs for cooperative use. Sustain. Cities Soc. 69, 102847. https://doi.org/10.1016/j.scs.2021.102847

Sobotka, A., Sagan, J., 2021. Decision support system in management of concrete demolition waste. Autom. Constr. 128, 103734. https://doi.org/10.1016/j.autcon.2021.103734

Tsegay, F.G., Mwanaumo, E., Mwiya, B., 2023. Construction site layout planning practices in inner-city building projects: space requirement variables, classification and relationship. Urban Plan. Transp. Res. 11, 2190793. https://doi.org/10.1080/21650020.2023.2190793

Wang, J., Yuan, H., Kang, X., Lu, W., 2010. Critical success factors for on-site sorting of construction waste: A china study. Resour. Conserv. Recycl. 54, 931–936. https://doi.org/10.1016/j.resconrec.2010.01.012

Wu, F., Mei, S., Xu, H., Hsu, W.-L., 2023. Urban Construction Waste Recycling Path: Robust Optimization. Buildings 13, 2802. https://doi.org/10.3390/buildings13112802

Yuan, H., 2013. Key indicators for assessing the effectiveness of waste management in construction projects. Ecol. Indic. 24, 476–484. https://doi.org/10.1016/j.ecolind.2012.07.022

Zhao, P., Md Ali, Z., Ahmad, Y., 2023. Developing indicators for sustainable urban regeneration in historic urban areas: Delphi method and Analytic Hierarchy Process (AHP). Sustain. Cities Soc. 99, 104990. https://doi.org/10.1016/j.scs.2023.104990