LUMEN ET VIRTUS
ISSN: 2177-2789

MODELING AND SIMULATION APPROACHES FOR OPTIMIZING DIFFUSE LOGISTICS OF URBAN CONSTRUCTION AND DEMOLITION DEBRIS

https://doi.org/10.56238/levv15n43-157

Submitted on: 10/17/2024 **Publication date:** 11/17/2024

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ABSTRACT
The diffuse logistics of urban construction and demolition (C&D) debris are characterized by decentralized generation, fragmented transport routes, and heterogeneous disposal pathways, posing significant operational and environmental challenges for cities. Modeling and simulation techniques provide powerful tools to analyze these complex systems, identify inefficiencies, and support decision-making aimed at improving logistics performance and environmental outcomes. This article presents and discusses key modeling and simulation approaches applicable to diffuse C&D waste logistics, including material flow analysis, optimization models, geographic information systems, agent-based modeling, and discrete-event simulation. Drawing on recent academic literature, the study highlights how these tools can be used to optimize routing, facility location, waste allocation, and policy scenarios. The analysis demonstrates that integrated modeling frameworks are essential for transforming diffuse debris flows into more efficient, transparent, and sustainable urban material management systems.

Keywords: Construction and Demolition Waste. Logistics Modeling. Simulation. Urban Systems. Waste Optimization.

1 INTRODUCTION

Urban construction and demolition activities generate large and spatially dispersed quantities of debris that are managed through complex logistics networks involving multiple actors, transport modes, and disposal or recovery options. In many cities, these networks operate in a diffuse manner, with limited coordination between waste generators, transporters, and treatment facilities. This fragmentation leads to inefficient routing, increased transport distances, higher costs, and elevated environmental impacts. Modeling and simulation techniques have increasingly been applied to capture the dynamics of such systems, enabling planners and policymakers to better understand material flows, evaluate alternative management strategies, and optimize logistics performance under real-world constraints (Ramos et al., 2023; Akhtar & Sarmah, 2018).

Material Flow Analysis (MFA) constitutes one of the foundational approaches for modeling diffuse C&D waste logistics. MFA focuses on quantifying the generation, movement, and destination of materials within a defined spatial and temporal boundary. In urban contexts, MFA allows researchers to map dispersed debris generation points and trace flows toward landfills, recycling facilities, or informal disposal sites. Empirical studies demonstrate that MFA can reveal structural inefficiencies, such as excessive reliance on landfilling or underutilization of recycling capacity, and can support scenario analysis assessing the impacts of policy interventions or infrastructure investments (Brunner & Rechberger, 2016; Ghisellini et al., 2018).

Optimization models are widely used to improve decision-making in diffuse logistics systems, particularly for routing, allocation, and facility location problems. Mathematical programming techniques, including linear programming and mixed-integer optimization, have been applied to minimize transportation costs, greenhouse gas emissions, or total system costs while satisfying capacity, regulatory, and service constraints. In the context of C&D waste, such models can determine optimal routing strategies for multiple small-scale generators, identify the most suitable locations for transfer stations or recycling plants, and allocate debris streams to available treatment options. Research shows that optimization-based planning can substantially reduce vehicle kilometers traveled and improve system-wide efficiency even in highly decentralized urban environments (Bautista & Pereira, 2006; Farahani et al., 2014).

Geographic Information Systems (GIS) play a critical role in modeling diffuse logistics by integrating spatial data related to waste generation, transport networks, land use, and facility locations. GIS-based models enable the visualization and analysis of spatial patterns, supporting more accurate estimation of transport distances, identification of illegal dumping hotspots, and evaluation of accessibility to disposal or recovery facilities. When combined with optimization or simulation techniques, GIS enhances the realism and applicability of logistics models. Numerous studies highlight the effectiveness of GIS-supported planning in urban waste management, particularly for designing decentralized collection systems and minimizing environmental externalities associated with transport (Ghose et al., 2006; Tavares et al., 2009).

Agent-based modeling (ABM) has gained prominence as a method for capturing the behavioral complexity inherent in diffuse C&D waste logistics. ABM represents individual actors such as contractors, informal haulers, regulators, and facility operators as autonomous agents with distinct decision rules and interactions. This approach is particularly suitable for simulating informal or semi-regulated systems, where behavior, compliance, and economic incentives strongly influence outcomes. Applications of ABM in waste management demonstrate its usefulness in exploring how policy instruments, enforcement levels, or economic incentives affect disposal choices, recycling rates, and the emergence of illegal dumping practices over time (Zhang et al., 2019; Salgado et al., 2021).

Discrete-event simulation (DES) is another valuable tool for analyzing operational aspects of diffuse logistics systems. DES models represent logistics processes as sequences of events such as waste generation, loading, transport, unloading, and processing occurring over time. This technique allows for the evaluation of system performance under variable demand, congestion, and capacity constraints. In C&D waste logistics, DES has been used to assess the impacts of introducing transfer stations, mobile recycling units, or scheduling changes on queue times, operational costs, and emissions. Simulation results from multiple studies indicate that relatively small operational adjustments can yield significant performance improvements when informed by detailed process-level modeling (Banks et al., 2010; Vieira & Teixeira, 2018).

Increasingly, researchers advocate for integrated modeling frameworks that combine MFA, optimization, GIS, and simulation techniques. Such hybrid approaches are particularly effective in addressing the multi-scale and multi-actor nature of diffuse logistics systems. By linking strategic-level material flow analysis with operational simulations and spatial analysis, cities can evaluate long-term infrastructure decisions while accounting for short-term operational variability. Integrated models also facilitate the comparison of alternative policy scenarios, such as stricter enforcement, expanded recycling mandates, or incentive-based programs, under realistic assumptions (Ghisellini et al., 2018; Ramos et al., 2023).

Despite their advantages, modeling and simulation approaches face several challenges in practice. Data availability and quality remain significant constraints, especially in cities where informal activities dominate debris handling. Uncertainty in waste generation rates, behavioral responses, and market demand for recycled materials can affect model reliability. Nevertheless, sensitivity analysis and scenario-based simulations can help address these uncertainties and support robust decision-making. Recent literature emphasizes that even imperfect models provide valuable insights by revealing system interactions and trade-offs that are otherwise difficult to observe empirically (Brunner & Rechberger, 2016).

In conclusion, modeling and simulation tools are essential for understanding and optimizing the diffuse logistics of urban construction and demolition debris. Techniques such as material flow analysis, optimization models, GIS-based analysis, agent-based modeling, and discrete-event simulation offer complementary perspectives on system structure, behavior, and performance. When applied in an integrated manner, these approaches enable cities to reduce transport inefficiencies, lower environmental impacts, and improve resource recovery in decentralized waste systems. The continued development and application of these tools will be critical for supporting evidence-based urban waste management policies and advancing more sustainable and resilient material flows.

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