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A Hierarchical Coordination Framework for Municipal Solid Waste Collection Management under Uncertainty

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Abstract. Municipal solid waste collection systems require coordinated decisions across strategic, tactical, and operational horizons, yet the optimization literature remains fragmented across planning levels and often treats uncertainty only within isolated model formulations. This paper proposes a hierarchical coordination framework for municipal solid waste collection management under uncertainty. The framework is defined as an interface-based, modular coordination artifact composed of reusable optimization modules, standardized input–output interfaces, and an uncertainty layer that enables alternative evaluation perspectives without requiring a monolithic reformulation of the underlying models. The proposed architecture links long-term fleet transition and modernization decisions with tactical fleet sizing, allocation, and utilization, as well as detailed operational routing and scheduling. Its main contribution is conceptual and design-oriented: it formalizes the roles of decision modules, the logic of top-down decision propagation and bottom-up performance feedback, and the architectural conditions under which validated optimization models can function as parts of a reusable multi-level decision-support structure. By positioning uncertainty as an external evaluation layer, the framework provides a basis for future comparative assessment under deterministic, stochastic, and distributionally robust perspectives. The paper thus contributes a structured coordination logic for integrating previously isolated optimization models in municipal solid waste collection management.

Keywords: municipal solid waste management, integrated decision-support framework, uncertainty modeling, modular optimization, strategic management, tactical management, operational management

Mathematics Subject Classification: 90C11, 90C15, 90C47, 90B06

JEL Classification: C61, C44, Q53

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1. INTRODUCTION

Municipal solid waste (MSW) generation is increasing worldwide, driven by urbanization, population growth, and changing consumption patterns. Recent estimates indicate that global waste generation already exceeds 2 billion tonnes annually and may continue to grow substantially in the coming decades if no systemic interventions are undertaken (Chen et al., 2020; Wilson et al., 2015; World Bank Group, 2018). This trend intensifies environmental, economic, and public health pressures, particularly in urban systems, where collection and transport remain among the most resource-intensive components of municipal solid waste management (MSWM) (Aliahmadi et al., 2020; Beliën et al., 2014; Clark & Helms, 1972). Ineffective collection and disposal practices contribute to greenhouse gas emissions, land degradation, and risks to soil and groundwater quality, thereby reinforcing the need for more coordinated and sustainable waste management systems (Adeleke et al., 2020; Antmann et al., 2013; Chen et al., 2020).

In response, the integrated solid waste management (ISWM) perspective has become an important reference point for both researchers and practitioners, as it promotes coordinated decision-making across the full value chain, from waste generation and collection to recovery and final disposal (Asefi et al., 2019a; 2019b; Jakubiak, 2014; 2015; Jakubiak & Śliwka, 2013). Within this perspective, MSWM systems can be understood as multi-level socio-technical systems in which long-term investment choices, medium-term fleet planning decisions, and short-term operational schedules are interdependent. Operations research (OR), especially mixed-integer linear programming (MILP) and vehicle routing problem (VRP) formulations, has provided a rich methodological basis for improving efficiency, sustainability, and service quality across these decision layers (Adeleke et al., 2020; Beliën et al., 2014; Hannan et al., 2020).

The existing literature offers numerous optimization models for individual decision layers in MSWM. At the strategic level, studies address facility location-routing, long-term capacity expansion, and multi-period fleet transition under environmental and regulatory pressures (Asefi et al., 2019a; Beliën et al., 2014). Tactical studies focus on districting, fleet sizing and allocation, and the assignment of heterogeneous vehicles to waste streams or service areas (Beliën et al., 2014; Gdowska et al., 2019). Operational studies, in turn, concentrate on routing and scheduling under detailed constraints such as time windows, vehicle compatibility, depot synchronization, and service balancing, increasingly supported by digital technologies, including IoT and GPS-based monitoring (Billa et al., 2014; Korcyl et al., 2019; Książek et al., 2021).

The author's previous work contributes to these streams at all three managerial levels. At the operational level, earlier studies proposed routing-oriented MILP formulations for selective waste collection, including heterogeneous fleets, multiple waste streams, workload balancing, and alternative decision-support implementations (Gdowska et al., 2020; Ilasz et al., 2023; Korcyl et al., 2016; 2019; Książek et al., 2021). At the tactical level, fleet-sizing and allocation models were developed by linking fleet availability and service requirements to routing feasibility (Gdowska et al., 2019). At the strategic level, multi-period models were formulated to support fleet transition and modernization decisions under cost, policy, and sustainability constraints (Bieda et al., 2023; Gdowska et al., 2025). Taken separately, these studies demonstrate the availability of strong analytical modules for each planning level.

However, the presence of strong single-level models does not automatically imply a coherent multi-level decision framework. A key limitation of the current literature is not the absence of optimization models, but their fragmentation across managerial horizons and decision contexts. Strategic, tactical, and operational studies are usually developed and evaluated separately, which makes it difficult to coordinate long-term investment decisions with medium-term fleet planning and day-to-day collection execution. As a result, high-level decisions may remain insufficiently connected to downstream operational realities such as route feasibility, vehicle-specific constraints, range limitations, facility dependencies, and service balancing requirements (Bieda et al., 2023; Korcyl et al., 2019; Książek et al., 2021). This problem is especially relevant in the context of fleet transition towards lower-emission technologies, where strategic modernization choices must remain compatible with operational capabilities and infrastructure conditions (Bieda et al., 2023; Gdowska et al., 2025).

A second limitation concerns the treatment of uncertainty. Although growing amounts of operational data are available through monitoring and digital technologies, uncertainty remains an important feature of MSWM systems, particularly at the planning and coordination levels. Waste quantities, waste composition, service times, travel conditions, and the practical consequences of behavioral or participation changes may vary over time and across service areas (Antmann et al., 2013; Chen et al., 2020; Hannan et al., 2020). Yet many strategic and tactical studies still rely on deterministic representations or only limited forms of stochasticity, which complicates the design of decision support that remains informative under changing operating conditions (Aliahmadi et al., 2020; Antmann et al., 2013). This does not mean that uncertainty cannot be reduced through better sensing or better data; rather, it means that a reusable coordination framework should explicitly accommodate uncertainty-aware evaluation when integrating decisions across multiple planning levels.

These observations motivate the need for a hierarchical coordination perspective. Rather than proposing yet another isolated optimization model, this paper addresses how previously validated OR models can be organized into a coherent decision-support architecture for municipal solid waste collection management under uncertainty. The focus is therefore on conceptual integration: how strategic, tactical, and operational modules can be linked through standardized interfaces, how information should propagate downward and upward across the hierarchy, and how uncertainty can be incorporated as an evaluation layer without forcing a single monolithic reformulation.

Accordingly, the objective of this study is to propose a hierarchical coordination framework for municipal solid waste collection management under uncertainty. The framework is defined here as an interface-based coordination artifact composed of: reusable optimization modules representing the strategic, tactical, and operational levels; an explicit input–output logic governing cross-level information exchange; and an uncertainty layer that enables alternative evaluation perspectives, including deterministic, stochastic, and distributionally robust interpretations. In this sense, the contribution of the paper is conceptual and design-oriented: it specifies the architecture, roles, and interactions of the modules, rather than reporting a completed computational validation of their joint performance (Bieda et al., 2023; Gdowska et al., 2019; Korcyl, et al., 2019).

More specifically, the paper makes four contributions. First, it identifies a research gap in the fragmentation of OR models for MSWM across the strategic, tactical, and operational planning horizons (Gdowska, 2021). Second, it proposes a hierarchical coordination architecture that organizes previously validated optimization modules into a reusable multi-level decision-support structure (Bieda et al., 2023; Gdowska et al., 2019; Korcyl et al., 2019). Third, it formalizes the roles of interfaces, cross-level information flows, and performance indicators needed to connect decisions across managerial levels. Fourth, it positions uncertainty handling – including deterministic, stochastic, and distributionally robust perspectives – as an evaluation layer for future comparative assessment rather than as a requirement for constructing a single integrated optimization model (Aliahmadi et al., 2020; Antmann et al., 2013; Hannan et al., 2020).

The framework builds on validated optimization models developed in the authors' earlier studies, but its purpose is broader than simply combining prior formulations. It provides a structured way to represent interdependencies among planning levels, to formalize the interfaces through which decisions and performance indicators are exchanged, and to position uncertainty handling as a comparative evaluation layer. Behavioral mechanisms are not explicitly modeled in this paper; where relevant, their effects are captured indirectly through parameters that influence demand, service conditions, or operational variability (Antmann et al., 2013; Hannan et al., 2020).

To achieve this objective, the study addresses the following research questions:

RQ1: How can strategic, tactical, and operational decision problems in municipal solid waste collection management be organized within a reusable hierarchical coordination framework?

RQ2: What interfaces, decision outputs, and performance indicators are required to enable coherent information exchange across these three managerial levels?

RQ3: How can uncertainty be incorporated into such a framework as an evaluation layer without requiring a fully monolithic reformulation of all underlying models?

RQ4: What computational validation agenda is appropriate for assessing the proposed framework in future research?

The remainder of the paper is organized as follows. Section 2 reviews the relevant literature and identifies the research gap that motivates the framework. Section 3 presents the hierarchical coordination architecture and the roles of its constituent modules. Section 4 formalizes the interface logic, cross-level coordination workflow, and role of uncertainty within the framework. Finally, Section 5 concludes the paper by summarizing the contribution and outlining a future computational validation agenda.

2. RELATED WORK AND RESEARCH GAP

The literature on optimization-based municipal solid waste management (MSWM) is extensive and methodologically diverse. Existing studies span strategic network and infrastructure decisions, tactical capacity and resource planning, and operational collection and routing under different forms of uncertainty. At the same time, survey evidence indicates persistent limitations in cross-level integration, uncertainty modeling, and the explicit incorporation of behavioral aspects into MSWM optimization models (Gdowska, 2021). Thus, the main research challenge is no longer the absence of optimization models per se, but rather the lack of reusable coordination structures that can link validated models across planning horizons.

From a broader sustainability perspective, MSWM is increasingly framed within integrated solid waste management (ISWM) and circular-economy thinking, which call for coordinated treatment of waste generation, collection, transport, treatment, recovery, and disposal (Alshaikh & Abdelfatah, 2024; Asefi et al., 2020; Kurian, 2006; Urbańska et al., 2023). Within this context, mathematical programming, AI-enabled decision support, and data-driven approaches are increasingly used to improve the efficiency and sustainability of waste systems (Alshaikh & Abdelfatah, 2024; Bányai et al., 2019; Li et al., 2025). This is particularly important because collection and transportation remain the dominant cost components of municipal waste systems, often accounting for 80–90% of total expenditure (Beliën et al., 2014; Das & Bhattacharyya, 2015; Sulemana et al., 2018). Consequently, routing and routing-related models remain central to the optimization literature, both because of their operational importance and because they strongly influence the feasibility and cost of higher-level planning decisions (Alshaikh & Abdelfatah, 2024; Sharma et al., 2017; Sulemana et al., 2018).

At the operational level, a substantial body of work formulates waste collection as variants of the vehicle routing problem and related mixed-integer models. Typical modeling features include heterogeneous fleets, separated waste streams, workload balancing, time-dependent considerations, and urban service constraints. Within this stream, the authors' earlier work developed MILP-based routing models for selective waste collection, including a multi-landfill formulation and a more detailed selective collection routing model (Korcyl et al., 2016; 2019), as well as extensions emphasizing route balancing with heterogeneous fleets (Książek et al., 2021). Additional contributions include decision-support implementations based on spreadsheet solvers and problem settings that reflect small-town collection systems (Gdowska et al., 2020; Ilasz et al., 2023). Operational planning is also supported more broadly by GIS-based routing approaches and studies emphasizing the role of routing structure in fleet selection and service cost (Billa et al., 2014; Clark & Helms, 1972).

At the tactical level, the literature typically addresses districting or zoning, fleet sizing and mix, and vehicle allocation to waste streams or service areas. This layer is particularly important because it translates service targets, demand profiles, and routing feasibility into resource decisions that remain implementable in daily operations. The authors' related work contributes to this layer through a fleet optimization model for selective solid waste collection that explicitly links fleet sizing and allocation decisions to routing feasibility (Gdowska et al., 2019). More generally, tactical studies often rely on decomposition or hybrid solution methods to preserve tractability in integrated settings, including Benders-type decomposition and metaheuristic support for large-scale routing-related subproblems (Mahéo et al., 2021; 2023; Xie & Shi, 2024).

At the strategic level, MSWM research addresses multi-echelon design problems such as facility location, technology selection, infrastructure planning, and long-term capacity or transition decisions. Many of these studies are formulated as integrated location–routing or network design problems in order to reduce the inefficiencies of sequential planning (Asefi et al., 2020; Mahéo et al., 2023). Strategic design decisions frequently involve socially sensitive and operationally consequential facilities, such as landfills or transfer stations, whose location and technology choices have long-lasting economic and environmental implications (Ghiani et al., 2014; 2021; Souza Melaré et al., 2017). In this stream, the authors' strategic work focuses on multi-period fleet transition and modernization under sustainability and emission constraints (Bieda et al., 2023; Gdowska et al., 2025), thereby highlighting the need to align long-term transition pathways with medium-term fleet availability and downstream operational feasibility.

A separate but related strand of the literature concerns uncertainty. Municipal waste systems are affected by fluctuating waste generation, changing material composition and quality, operational disruptions, and market volatility. Nevertheless, deterministic formulations continue to dominate many strategic and tactical models, even though this simplifying assumption is often unrealistic in practice (Aliahmadi et al., 2020; Antmann et al., 2013). Several integrated planning studies address uncertainty through stochastic, chance-constrained, interval, or fuzzy formulations. For example, Xu et al. (2009) propose a stochastic robust chance-constrained programming model, Li et al. (2019) develop an inexact two-stage stochastic formulation, and Zaeimi and Rassafi (2021) present an integrated stochastic network design model with chance constraints. Fuzzy and possibilistic approaches have also been used to capture imprecise MSWM parameters (Biswas & De, 2019). However, most of these contributions treat uncertainty as an exogenous modeling feature embedded in a particular formulation rather than as a reusable evaluation layer applicable across a family of linked decision modules.

In this regard, a promising methodological direction is represented by robust and distributionally robust approaches, which allow decision support under ambiguity when probability distributions are only partially known. In the MSWM domain, such approaches remain relatively limited. An important exception is the bilevel distributionally robust model by Xiong et al. (2021), which introduces decision-dependent ambiguity by incorporating sorting-at-source policies that affect uncertainty in feedstock composition and volume. This contribution is methodologically important because it shows how policy-dependent uncertainty can be embedded in a distributionally robust optimization setting. However, the model remains static in time and does not explicitly connect strategic, tactical, and operational collection decisions within a hierarchical municipal collection system. More broadly, robust decision-making perspectives emphasize the value of evaluating decisions across a range of plausible futures when statistical identification is weak (Lempert et al., 2006).

Recent studies also show that digital technologies can significantly improve operational visibility and responsiveness. IoT-based sensing, fill-level monitoring, GPS data, and GIS integration can support dynamic scheduling, reduce unnecessary mileage, and improve service regularity (Alshaikh & Abdelfatah, 2024; Billa et al., 2014; Li et al., 2025; Saukenova et al., 2022). Such developments strengthen the case for multi-period and multi-level planning architectures, because the availability of richer operational information does not eliminate uncertainty at higher planning levels; instead, it increases the need to connect evolving service conditions with tactical and strategic adaptation (Bányai et al., 2019; Copara et al., 2025; Li et al., 2025; Saukenova et al., 2022). At the same time, broader sustainability-oriented studies on resource recovery, urban mining, and circularity reinforce the importance of system-level perspectives that connect collection decisions with downstream recovery and environmental performance (Copara et al., 2025; Ghimire & Ariya, 2020; Iqbal et al., 2022).

The literature suggests a clear research gap. Strong optimization models exist at the strategic, tactical, and operational levels, and a variety of methods have been proposed to address uncertainty within specific formulations. However, there is still limited work on hierarchical and reusable coordination architectures that link validated models across planning horizons, formalize the interfaces through which decisions and performance indicators are exchanged, and allow uncertainty to be treated as a comparative evaluation layer rather than only as an internal feature of a single integrated model (Gdowska, 2021). In particular, the literature provides only limited support for a like-for-like comparison of the deterministic, stochastic, and distributionally robust perspectives on the same modular decision stack.

Accordingly, the present study does not propose another single integrated optimization model. Instead, it develops a hierarchical coordination framework for municipal solid waste collection management under uncertainty. The framework synthesizes partial precedents into a reusable decision-support architecture that links strategic fleet transition planning, tactical fleet sizing and allocation, and operational selective-collection routing. It draws on prior work on selective and multi-fraction MSW systems (Batur et al., 2020; Gnoni et al., 2008), integrated planning under uncertainty (Li et al., 2019; Xu et al., 2009; Zaeimi & Rassafi, 2021), behavioral and policy-sensitive perspectives in MSW system design (Mofid-Nakhaee et al., 2020), and decision-aware DRO concepts (Xiong et al., 2021). In this way, the paper addresses a gap in coordination logic and framework design rather than a gap in isolated model development.

Beyond this central gap, the broader literature identifies several related challenges that further motivate integrated, uncertainty-aware decision-support structures. These include limited optimization attention to the upstream waste-generation stage (Alshaikh & Abdelfatah, 2024; Asefi et al., 2020; Bányai et al., 2019), the growing importance of multi-criteria and sustainability-oriented decision models under uncertainty (Alshaikh & Abdelfatah, 2024; Asefi et al., 2020; Li et al., 2025), and regional research gaps in contexts with severe data and infrastructure limitations (Alshaikh & Abdelfatah, 2024; Copara et al., 2025; ElSaid & Aghezzaf, 2018; Sahib & Hadi 2021; Sulemana et al., 2018). Additional studies emphasize the role of socioeconomic drivers in waste forecasting (Izquierdo-Horna et al., 2022; Teshome et al., 2023), the need for system-level performance evaluation (Hao et al., 2024; Simonetto & Borenstein, 2007; Vargas et al., 2022), and the importance of stakeholder-sensitive approaches for circular-economy performance and recovery planning (Iqbal et al., 2022; Khan et al., 2022; Kundaria et al., 2021). These broader perspectives reinforce the need for modular, integrative, and adaptable frameworks, even when they are not explicitly modeled in the present study.

3. FRAMEWORK OVERVIEW

This study adopts a design science research (DSR) perspective to develop a hierarchical coordination artifact for municipal solid waste collection management under uncertainty. In line with DSR principles, the contribution is positioned as a prescriptive, design-oriented artifact that structures how decision support should be organized across managerial levels, rather than as a new monolithic optimization model (Aken, 2011; Hevner et al., 2004). More specifically, the proposed artifact defines a reusable coordination architecture composed of decision modules, standardized interfaces, and explicit information flows linking strategic, tactical, and operational planning.

The framework is developed through an abductive synthesis of a coherent stream of optimization studies addressing complementary decision problems within municipal solid waste collection systems. Here, abductive refers to an iterative mode of reasoning in which the artifact is shaped by moving back and forth between the coordination problem, the available model-based knowledge, and the emerging architecture of the framework, rather than being derived from a single theory or induced from one empirical case alone (Alvesson & Sköldberg, 2018; Dubois & Gadde, 2002; Sætre & Van de Ven, 2021). In this sense, the earlier studies provide the domain-specific modeling foundation, while the present paper contributes the interface specification, cross-level coordination logic, and architectural abstraction that allow these modules to function as parts of a reusable hierarchical decision-support structure.

The architecture is informed by a coherent stream of optimization studies that address complementary decision problems in municipal solid waste collection systems. These studies were developed around closely related planning contexts and together illustrate how one system can be viewed through different analytical lenses: long-term fleet transition, medium-term fleet sizing and allocation, and day-to-day routing feasibility. The present paper does not merely compile these contributions. Its added value lies in abstracting from them a common coordination logic, formalizing standardized module interfaces, and defining how information should propagate across planning horizons. In this sense, the earlier studies provide the domain-specific modeling foundation, whereas the present article contributes the hierarchical integration structure that connects them.

Accordingly, the framework is defined here as a coordination artifact composed of three elements. First, it contains reusable optimization modules associated with the strategic, tactical, and operational levels. Second, it introduces standardized input–output interfaces that govern the exchange of decisions, constraints, and key performance indicators across these levels. Third, it incorporates an uncertainty layer that allows the same modular architecture to be interpreted under deterministic, stochastic, or distributionally robust perspectives without requiring a single integrated reformulation. This separation between internal model structure and external evaluation logic is central to the framework's conceptual design.

At the strategic level, the framework captures long-term choices such as fleet transition pathways, technology portfolios, and policy- or sustainability-driven capacity envelopes. At the tactical level, these decisions are translated into implementable plans for fleet sizing, fleet mix, allocation, and utilization. At the operational level, detailed routing and scheduling decisions ensure that collection services remain feasible under local constraints such as waste-stream compatibility, route structure, service times, and infrastructure dependencies. The framework, therefore, treats the three levels not as isolated optimization problems, but as interdependent decision layers connected through top-down decision envelopes and bottom-up performance feedback.

A central design principle of the framework is that uncertainty should not be treated solely as an internal property of one particular mathematical formulation. Instead, uncertainty is introduced as a cross-cutting evaluation layer that acts on the inputs and outputs of modular decision components. This allows the same underlying architecture to support different interpretations of uncertainty, including deterministic, stochastic, and distributionally robust perspectives, while preserving modularity. In conceptual terms, this layer captures variability in demand, waste composition, service conditions, and other operationally relevant factors that affect the consistency of decisions across planning levels. Table 1 summarizes how a selected set of related studies can be interpreted within the proposed framework. The purpose of this mapping is not to suggest that the framework is reducible to a collection of prior models. Rather, it illustrates that the architecture emerges from a coherent modeling portfolio focused on a single municipal collection system at different decision resolutions. What is new in the present study is the explicit formalization of roles, interfaces, and coordination rules that enable such modules to function as parts of a reusable hierarchical decision-support structure.

Table 1. *Representative OR problem areas in Municipal Solid Waste Management*

Publication	Decision level	Dominant role in framework
Korcyl et al., 2015	Operational	Provides the baseline logic for daily logistical execution. It focuses on generating optimal routes for a heterogeneous fleet while strictly respecting the time windows set by both clients and the depot. Its role in the framework is to minimize the total number of vehicles required for standard collection tasks before additional complexities, such as multi-stream selective collection or intermediate landfill visits, are integrated.
Korcyl et al., 2016	Operational	Focuses on daily logistical execution, determining the optimal stop sequence for a heterogeneous fleet to ensure all clients are served within time windows, minimizing travel distance, and coordinating mandatory landfill visits.
Korcyl et al., 2019	Operational	Translates tactical plans into daily activities by generating specific collection schedules for multiple segregated waste streams (bio, paper, glass) with a limited fleet while respecting service quality requirements.
Gdowska et al., 2020	Operational	Provides decision support for daily route generation and visualization, enabling managers to evaluate the efficiency of current manual scheduling strategies against optimized benchmarks.
Ilasz et al., 2023	Operational	Provides exact solutions for daily travel sequences in rural or complex road networks (characterized by dead-end streets) to minimize fuel consumption and emissions through efficient routing.

Table 1 (cont.)

Publication	Decision level	Dominant role in framework
Korcyl et al., 2020	Tactical	Serves as a synthesis and comparative framework within the management structure. It identifies and categorizes the evolution of system requirements – moving from basic routing to complex selective collection – helping managers determine the appropriate level of model complexity needed to satisfy specific municipal regulations. It bridges the gap between purely mathematical routing and high-level strategy by documenting how policy changes (like 5-stream segregation) necessitate more complex operational models.
Książek et al., 2021	Tactical	Coordinates route design with labor management by balancing travel distance and assigned working time across different collector teams to prevent workload disparities.
Gdowska et al., 2019	Tactical	Addresses medium-term resource allocation by determining the minimum number and types of vehicles required to meet service demand, effectively linking fleet composition decisions with the constraints of daily routing.
Gdowska & Zaucha, 2025;	Tactical-Strategic	Bridges high-level planning and daily routing by partitioning urban areas into compact, balanced service sectors, ensuring equitable workload distribution and efficient crew allocation.
Gdowska & Pham, 2026	Tactical-Strategic	Links tactical allocation and shipment decisions with the strategic goal of material recovery, endogenously determining the timing of rare-metal sales based on accumulation thresholds under binding emission caps.
Gdowska et al., 2025	Strategic	Focuses on long-term investment planning by coordinating multi-period schedules for purchasing new vehicles and retrofitting existing ones to ensure compliance with tightening emission standards, such as the 'European Green Deal'.
Bieda et al., 2023	Strategic	Serves as a strategic planning tool for long-term organizational transformation. Its primary role is to develop optimal multi-period schedules for the modernization and substitution of vehicles to ensure a sustainable transition towards a zero-emission fleet. Employing a MARKAL-inspired mixed-integer linear programming model enables decision-makers to evaluate the economic and ecological trade-offs of fleet investments over a multi-year horizon while satisfying increasingly stringent emission limits mandated by regulations like the European Green Deal. It focuses on high-level coordination for purchasing new greener vehicles and retrofitting existing units to meet mandatory zero-emission vehicle thresholds.
Korcyl et al., 2026	Strategic	Supports long-term organizational transformation by developing cost-efficient transition pathways to replace legacy vehicles with cleaner technologies (electric and hydrogen) and by evaluating the strategic role of outsourcing under budget and emission constraints.
Gdowska, 2021	Cross-cutting	Establishes a taxonomy for the entire field, classifying various tasks into strategic (facility siting), tactical (districting, fleet sizing), and operational (routing) levels to identify system-wide coordination gaps.

Conceptually, the framework operates across three decision levels: strategic, tactical, and operational. The strategic layer defines long-term directions and admissible decision envelopes. The tactical layer translates these envelopes into implementable resource plans. The operational layer evaluates service feasibility through detailed routing and scheduling logic. Across all three levels, uncertainty is represented by the parameter vector ξ, which captures variability in waste quantities, service conditions, and other operationally relevant inputs that affect downstream feasibility and performance.

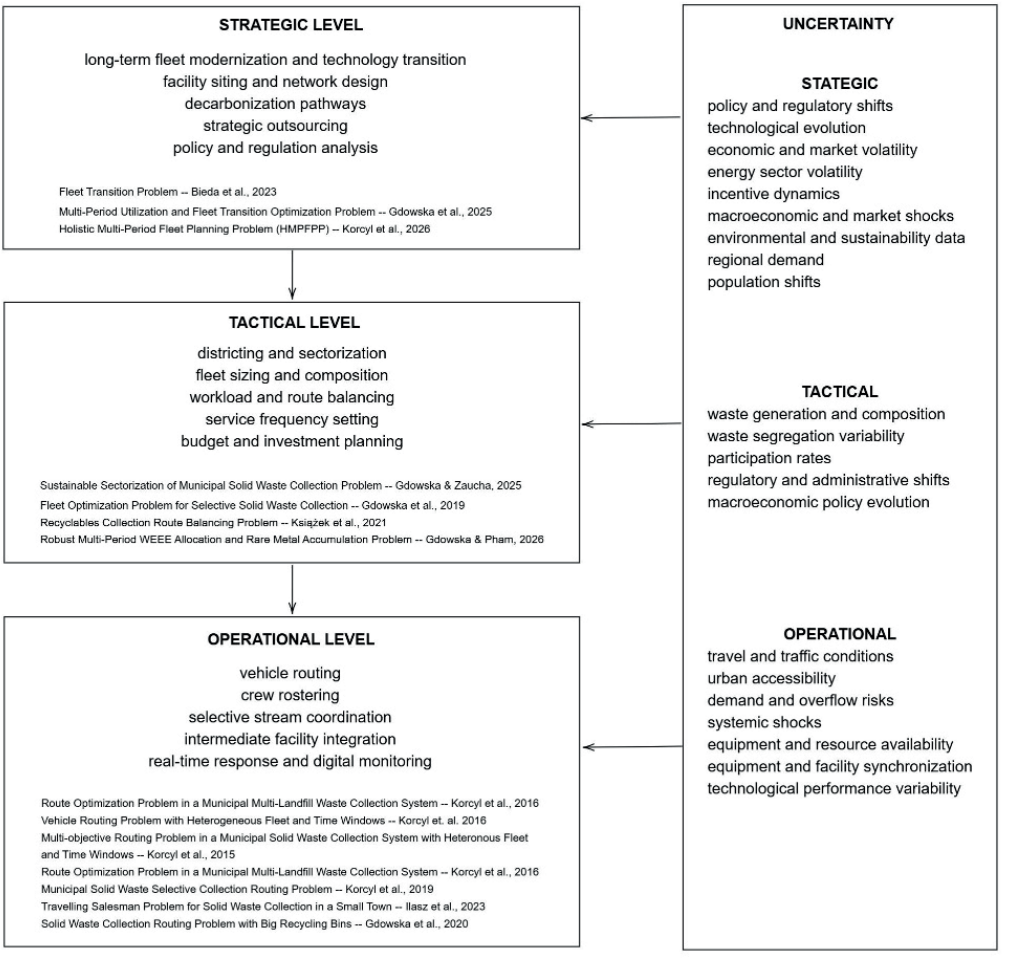

Fig. 1. *Hierarchical coordination framework for municipal solid waste collection management under uncertainty*

Figure 1 illustrates the proposed architecture. It shows the three-level hierarchy, the standardized interfaces between layers, the top-down propagation of decision envelopes, the bottom-up propagation of performance indicators, and the uncertainty layer that surrounds the framework, serving as an external evaluative perspective rather than an internal replacement for the component models. We provide a central operational summary of the artifact, specifying, for each decision layer, the main decision role, required inputs, and outputs or key performance indicators propagated to the remaining modules (see Table 2 in Section 4.1). The following subsections describe the three levels of the framework and the interface logic that links them into one hierarchical coordination structure.

3.1. Operational decision modules

At the operational level, the framework draws on a family of routing and scheduling models formulated as mixed-integer linear programs for selective municipal solid waste collection. These models represent the most detailed decision layer of the architecture, where daily service feasibility is assessed under constraints related to heterogeneous fleets, multiple waste fractions, route balancing, vehicle–facility compatibility, and realistic urban operating conditions. In the proposed framework, the operational layer is responsible not only for generating routing and scheduling decisions but also for producing the performance indicators that inform higher-level planning.

The development of this modeling stream began with earlier application-oriented analyses of heterogeneous fleets and service-time constraints (Korcyl et al., 2015), which provided the practical and methodological foundation for later MILP formulations. A first formal step was the selective collection model with multiple disposal facilities proposed in Korcyl et al. (2016). This formulation was subsequently generalized to the Municipal Solid Waste Selective Collection Routing Problem (MSWSCRP) (Korcyl et al., 2019), which serves as the principal operational decision module in the present framework.

A further extension was introduced through the Recyclables Collection Route Balancing Problem (RCRBP) (Książek et al., 2021), which complements routing feasibility with workload-balancing considerations. Within the framework, this contribution is particularly important because it enriches the operational layer with balance- and equity-related key performance indicators, such as workload dispersion, that can be propagated upward to tactical planning. Additional practitioner-oriented implementations in spreadsheet environments (Gdowska et al., 2020; Ilasz et al.; 2023) demonstrate that the same operational logic can also be explored in simplified, implementation-oriented settings, thereby supporting the practical interpretability of the framework.

The framework, therefore, treats these studies not as isolated routing formulations, but as a coherent family of operational modules developed around a single municipal collection system, viewed at different levels of formal and practical detail. Their role in the architecture is to provide the detailed routing, scheduling, and service-feasibility logic upon which higher-level coordination depends. Importantly, these modules are not reformulated here. Rather, they are reused as operational building blocks within a broader hierarchical structure.

Earlier formulations are retained in the framework as reference operational abstractions rather than discarded as superseded variants. In particular, the model of Korcyl et al. (2016) remains useful as an alternative operational representation in settings where unloading infrastructure and facility assignment play a stronger role. Likewise, the synthetic study in Korcyl et al. (2020) plays a unifying role by systematizing routing variants, objective structures, and constraint families developed in the earlier operational studies. Within the proposed framework, this contribution functions as an operational model harmonization layer, supporting consistency in decision variables, performance indicators, and scenario interpretation across alternative routing modules.

3.2. Tactical decision modules

At the tactical level, the framework embeds decision modules concerned with fleet sizing, fleet mix, allocation, and utilization. This level plays an intermediate coordination role: it translates strategic fleet envelopes and service targets into implementable resource plans while remaining sensitive to the routing feasibility conditions generated at the operational layer. In other words, the tactical layer acts as the main bridge between long-term transition decisions and day-to-day collection execution. The central tactical module is the Fleet Optimization for a Selective Solid Waste Collection System (FOPSSWCS) proposed by Gdowska et al. (2019). That model links fleet availability and allocation decisions with selective collection requirements and routing feasibility, thereby providing the core resource-coordination logic of the framework. In the present architecture, its role is to convert strategic admissibility conditions into period-specific fleet configurations that can be implemented operationally.

The tactical layer is further enriched by contributions that address scalability and temporal coordination. The cluster-based optimization approach proposed by Gdowska and Zaucha (2025) provides an optional decomposition and sectorization mechanism for larger urban systems. Within this framework, this model functions as a tactical scalability layer that aggregates territories and workloads to reduce problem dimensionality while preserving decision relevance. In turn, the multi-period fleet utilization and transition perspective developed by Gdowska et al. (2025) strengthens the temporal coupling between evolving fleet availability, utilization intensity, and lower-level feasibility conditions. These tactical contributions define the framework's intermediate coordination logic. Their role is not limited to choosing the number of vehicles. They also aggregate operational requirements into resource-level decisions, translate strategic directions into implementable fleet plans, and propagate feasibility- and utilization-related information upward and downward across the hierarchy. This makes the tactical layer the principal mediator between strategic intent and operational reality.

3.3. Strategic decision modules

At the strategic level, the framework incorporates multi-period planning models concerned with long-term fleet transition, modernization, and technology choice under policy, budgetary, and environmental constraints. This layer defines the architecture's highest-level decision logic by specifying transition pathways, technology portfolios, and admissible capacity envelopes within which lower-level decisions must operate. These strategic elements are included in the framework to the extent that they shape the feasibility of the collection system, the conditions for fleet transition, and downstream operational performance.

The baseline strategic module is the Fleet Transition Problem (FTP) introduced by Bieda et al. (2023). This model captures long-term technology replacement and emission-compliance decisions and therefore provides the foundation for representing strategic modernization pathways in the framework. Its importance lies in making explicit that collection management decisions are shaped not only by operational efficiency but also by long-term sustainability and regulatory commitments.

This strategic perspective is further extended by the holistic decision-support model proposed by Korcyl et al. (2026), which broadens fleet-transition planning to include energy and sustainability considerations. Within the framework, this contribution defines strategic sustainability envelopes and technology assumptions that constrain tactical fleet utilization and affect downstream operational feasibility. In this way, the strategic layer does not directly solve routing or allocation problems, but determines the admissible decision space in which these lower-level modules can operate.

The multi-period transition and utilization perspective developed by Gdowska et al. (2025) plays an important role in linking the strategic and tactical layers. In the framework, it provides the temporal coupling mechanism through which long-term transition pathways can be interpreted in terms of evolving fleet availability and resource conditions. As a result, the strategic layer is not treated as a detached planning horizon, but rather as the source of decision envelopes that must remain coherent with lower-level feasibility and performance constraints.

4. INTERFACE LOGIC AND COORDINATION WORKFLOW

This section provides the operational specification of the proposed framework, including its interface logic and coordination workflow. The key design principle is that each optimization model retains its internal mathematical structures, while integration is achieved through explicit input–output interfaces and hierarchical information exchange across decision levels. In this sense, the framework can be interpreted as a call-and-return coordination logic: the strategic layer generates strategic bounds for lower-level planning, the tactical layer translates them into tactical resource conditions and operational templates, and the operational layer evaluates detailed service feasibility and returns propagated indicators and aggregated feasibility summaries for higher-level interpretation. For consistency with Table 2 and Figure 2, the framework distinguishes three main cross-level interface categories: strategic bounds propagated from the strategic to the tactical layer, tactical resource conditions propagated from the tactical to the operational layer, and aggregated feasibility summaries and propagated indicators returned upward from lower-level execution and evaluation.

Table 2. *Standardized interfaces enabling cross-level integration*

Level	Primary decisions	Inputs (from data and upper levels)	Outputs and propagated indicators
Strategic	– facility siting and location-allocation: deciding the optimal number, location, and size of landfills, transfer stations, material recovery facilities, and specialized sorting units; – fleet modernization and transition schedules: determining multi-period pathways for purchasing new vehicles, retrofitting existing ones, and substituting legacy units with zero-emission technologies (electric, hydrogen, CNG); – technology selection and process-network design: selecting the optimal mix of treatment technologies (e.g., recycling, composting, thermal rendering) and designing the high-level process flows; – strategic outsourcing: evaluating the trade-off between operating an internal fleet and utilizing external service providers to maintain service continuity under capacity or emission constraints; – decarbonization and policy alignment: establishing high-level strategies to align organizational operations with international regulatory frameworks like the European Green Deal	– regulatory frameworks: policy mandates such as the European Green Deal, 'Fit for 55' and national electromobility acts; – technological parameters: performance data for various powertrains (diesel, electric, hydrogen, CNG), including unit emissions, purchase prices, and energy efficiency; – macroeconomic data: long-term projections for fuel and energy prices, discount rates, and inflation trajectories; – system baseline: initial fleet inventory and current facility capacities; – demand forecasts: long-term projections of service demand driven by urbanization and demographic shifts	– fleet modernization schedules: multi-period pathways for vehicle purchasing, retrofitting, and substitution; – decarbonization pathways: high-level strategies to align organizational energy consumption with climate neutrality goals; – network design: optimal locations and capacities for landfills, sorting units, and transfer stations; – strategic sourcing policy: decisions regarding the balance between internal fleet operation and partial outsourcing; – total discounted cost (TCO): the net present value of all investment and operational expenditures over the planning horizon; – aggregate emissions reductions: cumulative reduction in pollutants (CO_2, NO_x, PM) relative to regulatory caps; – ZEV share: the percentage of zero-emission vehicles within the total fleet; – critical metal recovery feasibility: the volume and timing of secondary raw material extraction in WEEE systems
Tactical	– districting and sectorization: partitioning the urban service area into compact, contiguous, and balanced zones to ensure equitable workload distribution among crews; – fleet sizing and composition: determining the minimum number and specific types of vehicles (e.g., small-sized trucks for narrow streets vs. large trucks) required to meet regional demand;	– strategic allocation: assigned fleet size, technological mix, and allocated budgets for the period;	– service sectors (districting): partitioning of urban areas into compact, contiguous, and balanced zones – service calendars: optimized periodic frequencies for emptying containers (e.g., weekly visit schedules);

Table 2 (cont.)

Level	Primary decisions	Inputs (from data and upper levels)	Outputs and propagated indicators
Tactical	– service frequency and periodicity setting: establishing the weekly or monthly schedule for visiting collection points and emptying containers to minimize overflow risks; – allocation of zones to facilities: assigning specific service subareas to particular depots, transfer stations, or processing centers; – workload balancing: designing tactical templates that equalize driven distances or collected volumes across different collector teams to ensure operational fairness	– environmental constraints: period-specific emission caps passed down from long-term sustainability goals; – regional waste profile: detailed data on waste generation rates, seasonal variability, and material composition by district; – spatial data: road network maps, GIS coordinates of collection points, and urban accessibility profiles	– fleet-stream assignments: designation of specific vehicle types to dedicated waste streams (e.g., bio vs. plastic); – workload equity: statistical variance in driving distance or collection volume assigned to different crews; – service efficiency: estimated total distance and fuel consumption required to serve a specific sector; – reliability indices: risk levels for container overflow or overtime based on historical generation patterns
Operational	– vehicle routing and sequencing: finding the optimal, shortest, or most cost-effective sequence of collection nodes for each vehicle while respecting all operational constraints; – stop and crew assignment: assigning specific stops and daily routes to individual vehicles and collection crews; – scheduling with time windows: determining precise arrival and departure times for every node to ensure service occurs within client- or municipal-defined time intervals; – facility visit coordination: scheduling mandatory unloading trips at landfills or specialized sorting units within a vehicle's daily tour before it returns to the depot; – real-time response and dynamic rerouting: adapting daily routes in near real-time to account for traffic congestion, equipment failure, or sudden container overflows	– tactical plans: assigned collection sectors, daily stop lists, and dedicated waste streams; – constraint data: pickup time windows set by clients or municipal regulations; – operational context: network travel times, distances, and specific road constraints like dead-end streets; – dynamic data: real-time IoT inputs such as container fill levels and traffic congestion	– optimized routing sequences: specific stop-by-stop sequences for each vehicle to serve all nodes; – arrival and departure schedules: detailed timing for every collection stop and terminal point; – facility visit coordination: mandatory unloading trips to landfills or specialized sorting units; – fleet utilization: the number of active vehicles required to perform the day's service; – distance and emissions: realized driven kilometrage and actual fuel/energy consumption for the shift; – service quality: success rate in meeting customer time windows and avoiding service delays; – time loss: aggregate wait or dwell times caused by traffic or early arrival at nodes

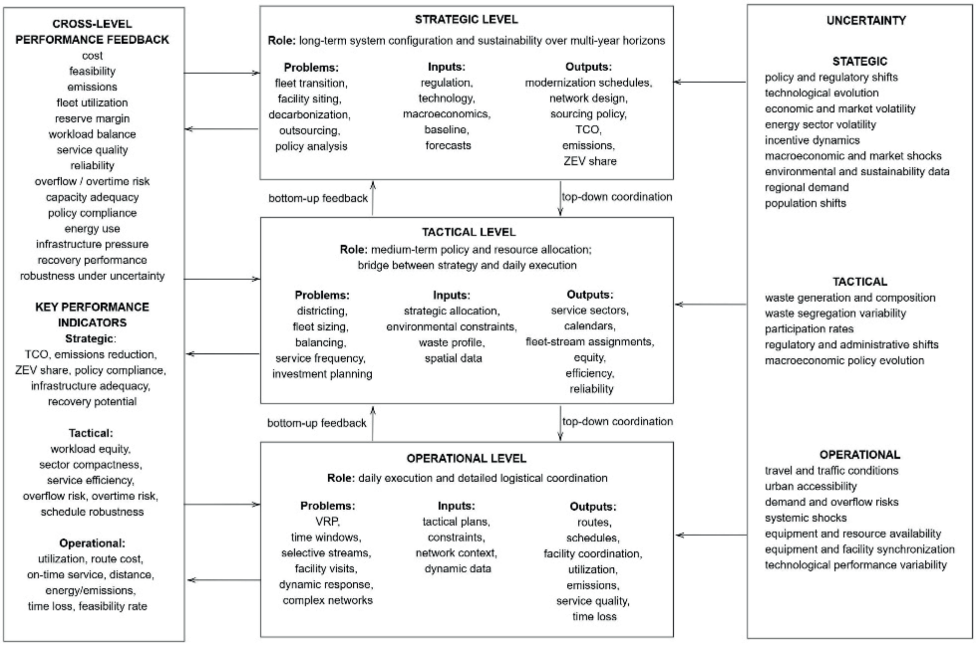

Fig. 2. *Three-level hierarchical planning architecture with interface-based coordination*

The purpose of this section is not to present a completed computational validation, but to formalize how the proposed artifact coordinates decision modules within one reusable architecture. The framework is operationalized through three elements: standardized interfaces between planning levels, top-down and bottom-up information flows, and a generic coordination workflow that can later support alternative deterministic, stochastic, and distributionally robust evaluation perspectives.

4.1. Inputs and outputs of decision layers

The abductive synthesis introduced in the previous section justifies the selection and integration of the modules, whereas the framework is operationally specified through the interface summary in Table 2, the graphical representation in Figure 2. The general principle is that decision envelopes are propagated top-down, whereas performance indicators and feasibility-related summaries are propagated bottom-up across planning horizons.

Strategic layer

The strategic layer defines the long-term configuration, capacity, technological trajectory, and sustainability of the municipal solid waste management system over multi-year horizons (Bieda et al., 2023; Gdowska & Pham, 2026; Gdowska et al., 2025; Korcyl et al., 2026). Its primary decisions concern fleet modernization and transition schedules, facility siting and network design, technology selection and process-network design, strategic outsourcing, and decarbonization and policy alignment. The inputs to this layer include regulatory frameworks, technological parameters, macroeconomic data, the system baseline, demand forecasts, and aggregated lower-level feasibility or performance summaries. Its outputs take the form of strategic plans and bounds for lower-level planning, including the fleet-transition pathway, the admissible technology set, the fleet-capacity envelope, the strategic sourcing policy, and the infrastructure or facility design assumptions. These outputs are accompanied by aggregate indicators, including total discounted cost, cumulative emissions reductions, the share of zero-emission vehicles, and, where relevant, the feasibility of critical metal recovery.

Tactical layer

The tactical layer bridges strategic goals and daily operations by translating long-term directions into medium-term policy and resource allocation decisions over weekly or monthly planning horizons (Gdowska et al., 2019; Gdowska & Zaucha, 2025). Its primary decisions concern districting and sectorization, fleet sizing and composition, service-frequency setting, allocation of zones to facilities, and workload balancing across crews. The inputs to this layer include strategic bounds, assigned fleet size and technological mix, budget allocations, period-specific environmental constraints, regional waste-generation profiles, spatial and network data, and nominal or scenario-based demand information. The outputs are operational templates and resource conditions for lower-level planning, including the fleet-allocation plan, utilization rules, service sectors, service-frequency calendars, fleet-stream assignments, and resource-availability conditions. These outputs are accompanied by propagated indicators, such as workload equity, estimated service efficiency, and reliability indices related to overflow or overtime risk.

Operational layer

The operational layer transforms tactical templates into the daily execution of collection services and constitutes the detailed service-feasibility component of the framework (Korcyl et al., 2016; 2019; Książek et al., 2021). Its primary decisions concern vehicle routing and sequencing, stop and crew assignment, scheduling with time windows, facility-visit coordination, and dynamic adaptation under disruptions. The inputs to this layer include tactical resource conditions, assigned collection sectors, stop lists, dedicated waste streams, network data, facility structure, time-window constraints, operational parameters, and uncertain realizations represented by ξ, including dynamic information such as traffic conditions or container fill levels. The outputs include detailed routing and scheduling plans, realized routing costs, facility-visit coordination, service-feasibility indicators, and workload-related KPIs propagated upward, including fleet utilization, realized distance and emissions, service-quality measures, and time-loss indicators.

Cross-level coordination workflow

At the strategic, tactical, and operational levels of municipal solid waste management and fleet transition, the inputs and outputs, together with their associated indicators, form a hierarchical coordination workflow. The strategic layer generates strategic plans and bounds, including the fleet transition pathway, the admissible technology set, the fleet capacity envelope, the strategic sourcing policy, and the infrastructure or facility design assumptions. The tactical layer translates these strategic bounds into implementable fleet-allocation plans, utilization rules, service sectors, service-frequency calendars, fleet-stream assignments, and other resource-availability conditions for daily execution. The operational layer then transforms these tactical resource conditions into detailed routing and scheduling plans that comply with network, facility, and service constraints. In the reverse direction, the operational layer returns the realized routing cost, service-feasibility indicators, and workload-related KPIs; the tactical layer aggregates these results into feasibility summaries and medium-term indicators such as workload equity, service efficiency, and reliability; and the strategic layer interprets the resulting evidence in terms of long-term cost, emissions, fleet transition, and sustainability performance. In this way, the framework preserves the autonomy of each decision level while making explicit the top-down propagation of strategic and tactical conditions and the bottom-up propagation of feasibility summaries and performance indicators.

4.2. Conceptual coordination algorithm

Algorithm 1 summarizes the framework as a generic coordination scheme. It should be interpreted as the conceptual execution logic of the artifact rather than as a computational protocol. Its role is to clarify how decisions and indicators move across the hierarchy and how the same architecture can, in future studies, be evaluated under alternative uncertainty perspectives.

Within the proposed architecture, uncertainty is represented by the parameter vector ξ, which captures variability in operationally relevant conditions such as waste quantities, waste composition, service times, travel conditions, and other factors affecting feasibility and performance across decision levels. Importantly, uncertainty is not introduced here to redefine the internal mathematical structure of the strategic, tactical, or operational modules. Instead, it acts on the same interface logic through which strategic bounds, tactical resource conditions, and propagated feasibility and performance summaries are exchanged.

This design choice is conceptually important because it separates the coordination logic from the uncertainty interpretation. The former specifies how modules exchange information and how decisions propagate across levels; the latter determines how the same hierarchical architecture may be interpreted under different assumptions about uncertain conditions. In this sense, the framework can support alternative uncertainty-aware readings, including nominal, scenario-based, and distributionally robust perspectives, without requiring a redesign of the underlying modules.

The conceptual purpose of the present paper is not to implement these alternative paradigms, but to specify the framework in a way that enables future computational validation under alternative uncertainty perspectives. Accordingly, deterministic, stochastic, and distributionally robust perspectives are not treated here as separate optimization frameworks, but as alternative perspectives through which the same modular architecture may later be examined. This positioning preserves the conceptual clarity of the framework while establishing the architectural basis for subsequent computational validation.

5. CONCLUSION AND FUTURE RESEARCH

This study proposed a hierarchical coordination framework for municipal solid waste collection management under uncertainty. The framework is positioned as an interface-based, modular coordination artifact that links validated optimization models across strategic, tactical, and operational planning horizons rather than replacing them with a single monolithic formulation. Its core logic is a call-and-return coordination scheme: strategic fleet-transition decisions define admissible technology and capacity envelopes; tactical planning translates these envelopes into implementable fleet-sizing, allocation, and utilization rules; and operational routing modules provide detailed service-feasibility and performance indicators that can be propagated upward to inform higher-level planning.

The paper's main contribution is conceptual and design-oriented. First, it addresses a persistent gap in the MSWM literature by shifting attention from isolated optimization models towards a reusable hierarchical coordination architecture. Second, it formalizes the roles of the strategic, tactical, and operational modules within a single decision-support structure. Third, it specifies the interfaces through which decision envelopes, feasibility conditions, and performance indicators are exchanged across planning levels. Finally, it positions uncertainty not as a requirement for constructing a single integrated optimization model, but as a cross-cutting evaluation layer through which the same architecture can later be interpreted under deterministic, stochastic, or distributionally robust perspectives.

To answer the research questions posed in the Introduction, the study shows that strategic, tactical, and operational decision problems in municipal solid waste collection management can be organized within a reusable hierarchical coordination framework by assigning them distinct yet interdependent roles within a modular decision-support architecture (RQ1). Second, it identifies the interfaces required for coherent cross-level information exchange, namely top-down decision envelopes and resource conditions, and bottom-up feasibility and performance summaries, including KPIs relevant to fleet transition, service efficiency, workload balance, and routing feasibility (RQ2). Third, it shows that uncertainty can be incorporated not through a monolithic reformulation of all component models, but as an external evaluation layer through which the same modular architecture can be interpreted under deterministic, stochastic, and distributionally robust perspectives (RQ3). Fourth, it indicates that the appropriate computational validation agenda is comparative and multi-stage: future studies should examine the framework through controlled integration experiments, compare coordinated and fragmented planning regimes, and assess the same modular architecture under alternative interpretations of uncertainty using common performance indicators and case-based data (RQ4). The framework thus contributes a structured way of thinking about coordination in municipal solid waste collection management. It shows how long-term modernization and transition decisions can be connected to medium-term fleet planning and detailed routing feasibility without sacrificing the tractability and interpretability of level-specific models. In this sense, the framework does not compete with existing optimization formulations; rather, it organizes them into a coherent architectural logic that makes explicit interdependencies across planning horizons.

From a practical perspective, the proposed artifact offers a pathway for aligning policy-oriented and operational decision-making. Strategic sustainability and modernization goals can be interpreted in terms of admissible fleet envelopes, tactical plans can be assessed in relation to operational implementability, and routing-based feasibility indicators can be fed back into higher-level planning discussions. Because the framework is modular, it is also compatible with the reuse of existing optimization tools and model portfolios, which is important for municipalities and analysts who cannot redesign their decision-support systems from scratch.

At the same time, the paper remains intentionally conceptual. It does not claim to provide a completed computational validation of the framework, nor does it argue that one uncertainty paradigm has already been shown to dominate another within the proposed architecture. Instead, the present study establishes the conceptual, architectural, and interface foundations needed for such an assessment. The value of the framework, therefore, lies in its explicit coordination logic, interface specification, and hierarchical organization of decision roles at this stage. In design-science terms, the contribution lies in specifying a reusable coordination artifact rather than in empirically verifying a single instantiation.

Several directions for future research follow directly from this contribution. First, the framework should be computationally validated through controlled integration studies comparing coordinated and fragmented planning regimes. Second, the external uncertainty layer should be used to examine how the same modular architecture performs under deterministic, stochastic, and distributionally robust interpretations. Third, future work should investigate how strategic fleet-transition decisions affect operational routing feasibility, especially in the presence of lower-emission or electric vehicle technologies. Fourth, scalability issues in larger urban systems may motivate decomposition, sectorization, clustering, surrogate modeling, or hybrid metaheuristic support. Finally, richer empirical validation, based on municipal case studies and operational data, would help assess the framework's external validity and implementation potential.

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