The possibility of applying Artificial Intelligence in Waste Management in the developing countries towards building smart cities: Jordan as a case study

1. Background and research problem

The recent surge in urbanization in cities like Amman has further accelerated the stress on urban solid waste management infrastructure. The current waste collection practices in most developing and middle-class cities, including Amman, still use static routing patterns and fixed time schedules with minimal real-time tracking. Although these traditional methods are easy to implement, they are often inefficient in terms of fleet use, fuel consumption, and greenhouse gas emissions.

In Jordanian municipalities, the waste collection process is carried out along fixed routes regardless of the actual fill status of the containers. These processes do not have the ability to adapt to changing conditions and do not use digital data streams in decision-making. With the rise in urbanization and budget constraints, there is an ever-growing need for data-informed, budget-friendly, and environmentally sustainable waste management practices.

Recent breakthroughs in artificial intelligence (AI), Internet of Things (IoT) technology, and optimization modelling provide new avenues for the improvement of collection systems. AI-driven route optimization, especially through Vehicle Routing Problem (VRP) models, can optimize routes in real-time based on demand and capacity. Nevertheless, in many urban settings, technological solutions are implemented without fully taking into account the institutional and governance realities.

This research fills this void by proposing and validating a methodological framework for a mixed-methods approach that combines qualitative system analysis with quantitative AI-driven route optimization. This framework is then validated through its application to the Radwan neighborhood in Amman.

2. Research objectives

The research aims to achieve four main objectives:

(1) To qualitatively analyze the current solid waste collection system and point out the structural and operational limitations.

(2) To develop a quantitative routing system using IoT and AI, which is suited to the local conditions of the municipality.

(3) To compare the performance of the traditional and AI-optimized routes based on certain operational parameters.

(4) To discuss the results in the context of planning, environmental, and policy implications.

3. Methodology

3.1.Research design

The proposed research will employ a mixed-methods research design, which will combine a qualitative system analysis with a quantitative modelling and evaluation process. While the qualitative system analysis will help to identify institutional constraints and limitations, the quantitative modelling process will develop and test an AI-based optimization model.

3.2.Qualitative assessment

The qualitative assessment of the current SWM system in the Radwan neighbourhood was carried out through field observations, and a review of municipal documents. The assessment covered the following aspects:

(1) Collection schemes and schedules

(2) Characteristics of the vehicle fleet

(3) Institutional and governance-related constraints

(4) Operational inefficiencies

The assessment has identified a number of structural issues, including rigid routing schemes, underutilized vehicle capacity, and a lack of data use in the planning process.

3.3.Quantitative model development

The quantitative part involves four steps:

(1) IoT-based data acquisition

The smart containers are equipped with ultrasonic sensors to measure the fill level, Global Positioning System (GPS) modules for the spatial coordinates, and unique Radio Frequency Identification (RFID) tags for the identification of the containers. The data is sent to a central cloud database.

(2) Data processing and demand identification

Containers above a predetermined fill level threshold are identified for collection. The total volume of waste is calculated and matched with the capacity of the vehicles.

(3) AI decision-support and route optimization

The routing problem is defined as a Vehicle Routing Problem (VRP). The optimization problem aims to minimize the total distance travelled and the route duration while satisfying vehicle capacity, depot, and coverage constraints.

(4) Performance evaluation

Two approaches are compared: Conventional fixed route, and AI-optimized route. The performance metrics include: Total distance driven, route duration, driving time on route, and fuel consumption. The performance metrics are presented in a comparative performance table (Table 1).

	Regular route	Optimized route	Reduction/ improvement
Time on route, h:m	2:11	0:44	1:27 (~66%)
Driving time on route, h:m	1:53	0:41	1:12 (~63%)
Total distance driven, km	47.25	16.45	30.80 (~65%)
Fuel consumption, (70 l/km)	33.08	11.52	21.56 (~65%)
Redundant stops	High	Minimal	Significant reduction

Table 1. Comparison between the regular and the optimized routes. Source: (Data has been derived from the authors developed AI simulation model, 2024).

4. Results

The scenario of AI-optimized routing shows a dramatic improvement in all the performance measures considered. Compared to the conventional fixed route, the optimized route has a reduced total travel distance and collection time, as well as enhanced vehicle capacity use.

As shown in Table 1, the optimized scenario performs better than the regular route. The greatest improvement is achieved in route optimization and fuel savings, which suggests that dynamic demand-based routing can be used to overcome the problems associated with static collection routes.

The findings indicate that small changes in the operational environment, using data-driven algorithms, can lead to efficiency gains without the need for heavy infrastructure investments.

5. Discussion

The results underscore the revolutionary power of AI-assisted decision-making in the context of municipal waste management. Unlike other automated solutions that completely displace human control, the proposed approach combines the human-in-the-loop technique, enabling planners to verify and correct optimization results based on real-world conditions.

From a planning point of view, the research shows that technological advancements need to be grounded in institutional settings. The qualitative analysis guarantees that the optimization model is informed by real-world constraints rather than applying algorithmic thinking that is irrelevant to municipal planning.

In terms of environmental sustainability, fuel savings directly impact the reduction of greenhouse gas emissions. In the context of resource-poor cities, such efficiency dividends have both financial and environmental advantages.

6. Policy and planning implacations

There are several implications for practice that can be derived from this study:

(1) A stepwise approach to digitalization can be implemented in municipalities instead of a complete overhaul of the system.
(2) AI optimization can improve efficiency without necessarily increasing the size of the fleet.
(3) Data-driven routing can help with climate change mitigation efforts by reducing emissions.
(4) A mixed-methods approach can make implementation more feasible by aligning technology with reality on the ground.

The model can be applied to other neighborhoods in Amman or other developing cities.

7. Robustness, and future directions

To maintain methodological integrity, sensitivity analysis was factored into the optimization process. The vehicle routing problem was validated for different thresholds of fill-level to determine the impact of different collection points on route optimization. Initial results show that lower thresholds result in more frequent visits but negatively impact the efficiency of load consolidation, while higher thresholds enhance capacity factors with a slight increase in risk of overflow. This suggests the need to align system parameters with service requirements and waste generation rates.

Future studies can extend the approach framework to the city-wide level, accounting for multi-depot routing, diverse vehicle fleets (including electric collection vehicles), and stochastic demand models. Coupling with smart city infrastructure and municipal Geographic Information Systems (GIS) would further improve operational adaptability. Furthermore, incorporating cost-benefit analysis and lifecycle environmental assessments would offer a more complete sustainability assessment.

In general, the results confirm the importance of integrating qualitative institutional diagnosis with quantitative AI-based optimization. This ensures that technological innovation is kept grounded in operational realities while promoting efficiency, environmental sustainability, and evidence-based urban planning.

8. Conclusion

This paper establishes and validates a mixed-methods approach to AI-assisted solid waste collection optimization in Al-Radwan, Amman. Through the combination of qualitative system analysis and quantitative IoT-integrated modeling and VRP optimization, the paper illustrates the efficacy of the approach in terms of increased efficiency and environmental sustainability.

The results of the comparison validate the hypothesis that AI-optimized routing is highly effective in minimizing distance, time, fuel, and emissions compared to traditional fixed routes. Notably, the paper establishes that innovation in municipal service delivery should be situated within institutional analysis to ensure relevance and applicability.

Future studies can be expanded to include real-time traffic information, multi-vehicle routing, and economic cost-benefit analysis at the city level.