Discrete Choice-Based Optimization Approach for Dynamic Large-Scale Multi-Compartment Vehicle Routing in Reverse Logistics.

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1 INTRODUCTION

The growing challenges of urban waste management underscore the necessity of optimizing waste collection processes. The collection phase has traditionally been a major cost driver in waste management, contributing to nearly 70% of the overall expenses (Mohammadi et al., 2023; Rahmanifar et al., 2023). Such high costs arise primarily from the inflexibility and inefficiency of the fixed routing and scheduling for collection vehicles. In response, this paper proposed a dynamic vehicle routing problem (DVRP) framework, which enables real-time adjustment of routes, and introduces the use of multi-compartment vehicles to consider both efficiency and sustainability. Technological progress, especially with the integration of sensors and Internet of Things (IoT) devices, empowers the real-time monitoring of waste bin and vehicle routing. This integration not only streamlines waste management operations by preventing unnecessary visits but also mitigates the risk of delayed service to the bins. The real-time data provided by these technological tools facilitates a more dynamic and responsive approach to route optimization and scheduling (Al-Jabi and Diab, 2018; Anghinolfi et al., 2013; Faccio et al., 2011).

In 2022, Yang et al discussed the integrating multi-compartment electric vehicles (EVs) for municipal solid waste management, emphasizing smart waste bins and chance-constrained programming to enhance collection efficiency. Their study introduces the Chance-Constrained Multi-Compartment Electric Vehicle Routing Problem (CCMCEVRP), aiming to optimize routing under waste generation uncertainties and evaluate the cost-effectiveness of using multi-compartment EVs versus traditional methods. While confirming the cost and environmental benefits of multi-compartment EVs, the study overlooks the optimization time crucial for real-world applications. Our proposed work addresses both the solution quality and computational time(Yang et al., 2022). It innovatively applies the discrete choice model (DCM) for dynamic vehicle routing, adjusting to variability in waste production and network changes. The DCM determines the most likely next subzone for bin collection at each decision-making epoch, enhancing routing efficiency and aligning the system's responsiveness with real-time urban waste collection dynamics.

2 METHODOLOGY

DVRP framework necessitates a responsive online policy which plays a critical role in making quick decisions regarding the new arrived information for preoptimization of routes and the necessary adjustments in real-time. Sequential stochastic optimization, also known as a Markov decision process, is a mathematical framework often used for DVRPs under uncertainty. This method helps in making decisions sequentially over time by considering the source of uncertainty and dynamisms. However, directly solving processes with traditional dynamic programming techniques is extremely challenging due to the "curse of dimensionality" which refers to the exponential increase in computational time. To address this challenge, Approximate Dynamic Programming (ADP) methods have been developed which involves making decisions based on an estimated "reward-to-go" usually derived through simulations(Zhang et al., 2023). However, balancing computational efficiency with solution quality remains a significant challenge, especially in the context of large-scale DVRPs that require real-time decision-making. Defining decision epochs in a dynamic routing problem, where offline decisions must be continuously updated, presents a significant challenge. Short time intervals between decision epochs can demand excessive computational time, whereas long intervals may delay responses to current changes. Traditionally, decision epochs are determined by either the arrival at the next node along the route or at the arrival of new information. However, these methods are less effective in problem under investigated in this paper where bins are densely located within a single geographical zone, as making frequent route adjustments is impractical due to the proximity of the bins and the minimal expectation of data variation between them. This paper introduces a novel methodology aimed at enhancing the efficiency of urban waste collection by implementing a DCM at critical decision epochs. These epochs are defined as moments when a vehicle completes its visit to the last bin within a current zone. DCM is used to calculate the probability of selecting the next zone for the visit, considering the updated travel time from the last bin of the current zone to each potential next zone and the total aggregated waste generated per zone.

3 APPLICATION

For the DVRP, a connected directed graph G= (V, A) is proposed, where V= {0,…, V} denotes the set of nodes and *A* is a set of arcs. In our example, the graph representing the road network of Rome consists of 55,913 nodes and 56,138 links (see Fig. 1). The mathematical model is designed to minimize the sum of transportation costs and penalties for CO_2 emissions, as well as the fixed costs associated with deploying each truck. The model also adapts to dynamic elements, such as the volume of waste and the presence of hazardous materials. By considering various operational, environmental, and temporal factors, the model stands as a comprehensive system designed for the nuanced needs of urban waste management logistics.

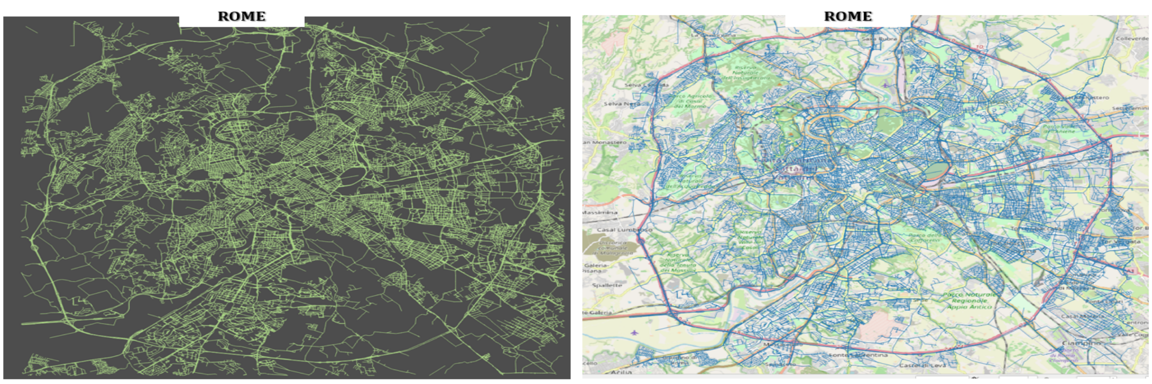

Figure. 1. *Graph Representing the Street Network of Rome, Italy.*

4 COMMENT OF RESULTS

DVRP presents an NP-Hard complexity, indicating that there's no polynomial-time algorithm to solve it optimally. This complexity renders exact methods impractical for real-world sized problems. Instead, metaheuristic algorithms provide a viable alternative, offering high-quality solutions within reasonable computational times. This research examines four notable metaheuristic algorithms including: Tabu Search, Particle Swarm Optimization, Tree Growth Algorithm (TGA), and hybrid of GA and PSO (GAPSO). The Friedman test results indicate significant differences among the four metaheuristic algorithms, with TS performing best in terms of Computation Time (CT) and GAPSO excelling in the RDI-Objective Function metric (See Table 1). The p-values suggest that these differences in performance are statistically significant. Fig. 2 presents two maps depicting the routing paths of a truck based on different planning approaches. On the left, the dynamic approach adjusts the route in real-time, possibly reacting to traffic, bin fullness, or other factors, as indicated by the varied and intricate path pattern. On the right, the static approach shows a truck's route that is pre-planned and unchanging, marked by a more uniform and structured pattern. The dynamic route seems to cover more areas with frequent changes in direction, while the static route is more direct and possibly less responsive to immediate changes in the environment. Table 2. shows the p-values obtained from a Wilcoxon signed-rank test, which is a non-parametric statistical test used to compare two paired groups. In this context, it compares the performance of different optimization algorithms based on their Objective Function (OF) values across three different problem sizes .

Table1. *The result of the Friedman test for large-size problems.*

Metaheuristic	RDI-Objective Function	Rank (RDI-OF)	CT	Rank CT
TGA	3.2	3	3.03	3
TS	1.7	2	1.46	1
PSO	3.6	4	2.00	2
GAPSO	1.6	1	3.90	4
P-value	0.019		0.002	

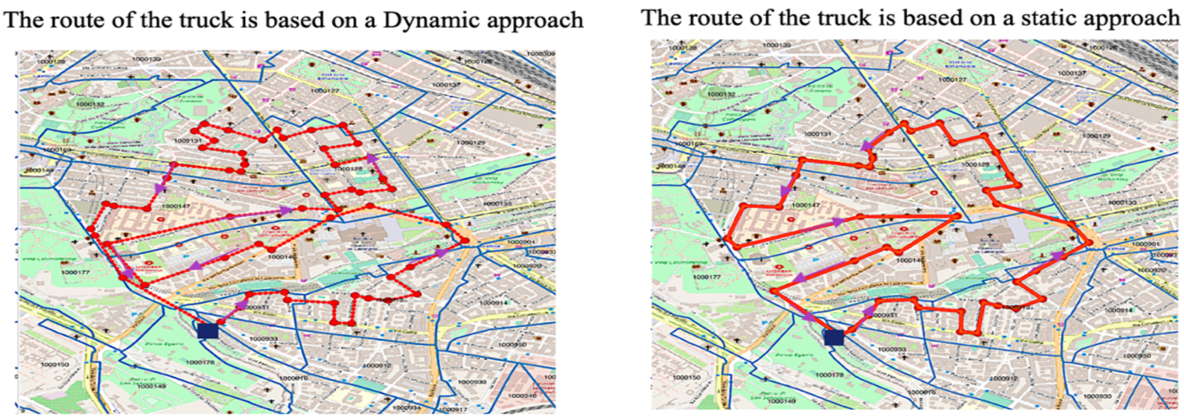

Fig. 2. *A comparison of static and dynamic route scheduling.*

Table 2. *Wilcoxon signed the ranked test according to OF values for all test problems.*

Comparison	P-value (Wilcoxon test)		
	SMALL	MEDIUM	LARGE
TGA versus TS	0.025	0.019	0.028
TGA versus PSO	0.022	0.021	0.048
TGA versus GAPSO	0.033	0.028	0.038
TS versus PSO	0.038	0.048	0.026
TS versus GAPSO	0.046	0.045	0.047
PSO versus GAPSO	0.023	0.047	0.034

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5 REFERENCES

Al-Jabi, M., Diab, M., 2018. IoT-enabled citizen attractive waste management system. Proceedings of 2nd International Conference on the Applications of Information Technology in Developing Renewable Energy Processes and Systems, IT-DREPS 2017 2018-January, 1–5. https://doi.org/10.1109/IT-DREPS.2017.8277804

Anghinolfi, D., Paolucci, M., Robba, M., Taramasso, A.C., 2013. A dynamic optimization model for solid waste recycling. Waste Manag 33, 287–296. https://doi.org/10.1016/J.WASMAN.2012.10.006

Faccio, M., Persona, A., Zanin, G., 2011. Waste collection multi objective model with real time traceability data. Waste Management 31, 2391–2405. https://doi.org/10.1016/j.wasman.2011.07.005

Mohammadi, M., Rahmanifar, G., Hajiaghaei-Keshteli, M., Fusco, G., Colombaroni, C., 2023. Industry 4.0 in waste management: An integrated IoT-based approach for facility location and green vehicle routing. J Ind Inf Integr 36, 100535. https://doi.org/10.1016/J.JII.2023.100535

Rahmanifar, G., Mohammadi, M., Sherafat, A., Hajiaghaei-Keshteli, M., Fusco, G., Colombaroni, C., 2023. Heuristic approaches to address vehicle routing problem in the Iot-based waste management system. Expert Syst Appl 220, 119708. https://doi.org/10.1016/J.ESWA.2023.119708

Yang, J., Tao, F., Zhong, Y., 2022. Dynamic routing for waste collection and transportation with multi-compartment electric vehicle using smart waste bins. Waste Management and Research 40, 1199–1211. https://doi.org/10.1177/0734242X211069738

Zhang, J., Luo, K., Florio, A.M., Van Woensel, T., 2023. Solving large-scale dynamic vehicle routing problems with stochastic requests. Eur J Oper Res 306, 596–614. https://doi.org/10.1016/J.EJOR.2022.07.015