GREEN CITIES
GREEN LOGISTICS FOR GREENER CITIES

7th International Conference Green Cities 2026 – Green Logistics for Greener Cities, 15-17 April 2026, Szczecin, Poland

Method of Dynamic Routing for Last-Mile Out-of-Home Delivery in Urban Areas

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Abstract

With the rapid growth of e-commerce and the widespread deployment of parcel lockers, micro-depots, and pick-up and drop-off stations, last-mile out-of-home (OOH) delivery requires routing strategies that can adapt to the rapidly changing conditions of urban areas. Static route planning approaches are unable to account for real-time changes in traffic flow speed, temporary congestion, or short-term disruptions, often resulting in inefficient delivery and increased operational costs. This highlights the need for a method capable of dynamically routing freight deliveries based on the actual state of the urban road network (URN).

A dynamic routing method for last-mile OOH freight delivery is proposed, which integrates continuous monitoring of the URN state with intelligent optimization algorithms. The method enables online adjustment of delivery routes based on up-to-date aggregated information on the URN, obtained from multiple sources such as GIS, IoT traffic sensors, and VANET or MANET systems.

Within the proposed method, the task of delivery route optimization is formulated as an asymmetric dynamic traveling salesman problem (DTSP), where the URN is represented as a bidirectional weighted graph. The vertices of the graph correspond to delivery points, while the edges represent optimal routes between vertex pairs according to specific criteria (e.g., time, distance, fuel consumption). Each edge is defined as a sequence of URN sections forming the route between the corresponding vertices, allowing the method to account for the current state of the road network and dynamically update edge weights in response to changes in URN section characteristics.

For route optimization within the DTSP framework on the graph, a modified ant colony optimization algorithm (ACO_{mod}) is utilized. ACO_{mod} is based on the classical ACO but is enhanced with specialized mechanisms that allow effective consideration of dynamic changes in the graph. The algorithm implements the capability to fix the optimal configuration of a partially traversed route, which serves as a topological representation of the actual configuration of the corresponding URN segment, prior to updating the graph. This ensures that the current state of the URN is correctly accounted during dynamic routing.

This approach is particularly suitable for OOH delivery operations due to their fixed yet widely distributed network of delivery points. Such points are typically located in areas with heterogeneous traffic dynamics, making them highly sensitive to routing inefficiencies. The proposed method accounts for the geographical layout of the delivery points and the structure of the surrounding URN, enabling more accurate decision-making and reducing detours or redundant traversal.

To validate the proposed method, simulation studies were conducted for OOH delivery to the Polish delivery company InPost's parcel lockers within the Warsaw URN. Results show that even moderate shifts in traffic conditions can alter optimal delivery route order, and that continuous re-optimization reduces total travel time and unnecessary vehicle movement. These findings demonstrate the potential of the proposed method for addressing practical OOH delivery problems under complex urban area settings.

Keywords: Dynamic routing; Last-mile out-of-home delivery; Urban road network; Optimization methods; Intelligent transport systems.

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1 Introduction

The rapid growth of e-commerce has fundamentally transformed last-mile delivery logistics, with out-of-home (OOH) delivery networks – comprising parcel lockers, micro-depots, and pick-up and drop-off (PUDO) stations – playing an increasingly central role in urban freight distribution (Iwan, Kijewska, & Lemke, 2016). Unlike traditional home delivery, OOH delivery relies on a fixed yet widely distributed set of delivery points, often located in areas characterized by heterogeneous traffic dynamics. This makes OOH delivery operations highly sensitive

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to routing inefficiencies, as even moderate changes in traffic conditions can significantly affect delivery schedules and operational costs.

Static route planning approaches, which are commonly used in conventional vehicle routing problems (VRP), are unable to account for real-time changes in traffic flow speed, temporary congestion, or short-term disruptions on urban road network (URN) sections (Pillac, Gendreau, Guéret, & Medaglia, 2013). As a result, they often lead to suboptimal delivery routes, increased travel time, higher fuel consumption, and greater emissions – outcomes that are particularly problematic in the context of green urban logistics and sustainable freight distribution (Silva, Amaral, & Fontes, 2023; Lauenstein & Schank, 2022). This highlights the need for dynamic routing methods capable of adapting delivery routes based on the actual, evolving state of the URN.

Recent advances in intelligent transportation systems (ITS) have provided a technological foundation for addressing these challenges. Modern geographic information systems (GIS), Internet of Things (IoT) traffic sensors, vehicular ad hoc networks (VANET) and mobile ad hoc networks (MANET) enable the real-time acquisition and processing of traffic data on URN sections (Zantalis, Koulouras, Karabetsos, & Kandris, 2019; Badole & Thakare, 2023; Camp, Boleng, & Davies, 2002). However, the development of adequate adaptive methods for discrete route optimization that simultaneously consider the real URN configuration and dynamic traffic flow conditions during delivery operations remains an open research problem (Danchuk & Hutarevych, 2024a; Danchuk, Hutarevych, & Taraban, 2025).

Although dynamic routing is widely implemented in practice by logistics companies, these solutions are typically proprietary, heuristic-driven, and not formally described in the scientific literature. As a result, their internal mechanisms, assumptions, and adaptability to varying urban traffic conditions remain largely opaque and difficult to reproduce or systematically analyze.

In contrast, this study aims to bridge the gap between industrial practice and scientific formalization by proposing a transparent and reproducible dynamic routing framework. The contribution of this work lies not in introducing the concept of dynamic routing itself, but in providing a rigorous methodological formulation that explicitly integrates real-time urban road network (URN) state monitoring with a dynamic traveling salesman problem (DTSP) representation and an adaptive optimization algorithm.

In this context the paper proposes a dynamic routing method specifically designed for last-mile OOH freight delivery in urban areas. The method integrates continuous monitoring of the URN state with a modified ant colony optimization algorithm (ACO_{mod}) to enable online adjustment of delivery routes. The delivery route optimization task is formulated as an asymmetric dynamic traveling salesman problem (DTSP), where the URN is represented as a bidirectional weighted graph. The proposed approach is validated through simulation studies using the Warsaw URN, with OOH delivery to InPost parcel lockers as the application scenario.

2 Literature review

Last-mile delivery accounts for a significant share of total supply chain costs and is widely recognized as the most inefficient and environmentally burdensome segment of urban freight distribution (Silva, Amaral, & Fontes, 2023). The rapid expansion of e-commerce has intensified this challenge, driving a sharp increase in demand for delivery to OOH points such as parcel lockers and PUDO stations (Iwan, Kijewska, & Lemke, 2016). The design principles for sustainable last-mile logistics emphasize the need for innovative operational solutions, including urban micro-consolidation centers, alternative transport modes, and, critically, intelligent route optimization (Lauenstein & Schank, 2022). However, most existing optimization and machine learning solutions applied to last-mile logistics focus on static or semi-dynamic scenarios without fully accounting for real-time traffic dynamics (Giuffrida, Fajardo-Calderin, Masegosa, Werner, Steudter, & Pilla, 2022).

From a methodological standpoint, the delivery route optimization problem is commonly formulated within the vehicle routing problem (VRP) framework, which is a well-known NP-hard combinatorial optimization problem concerned with finding optimal routes for a fleet of vehicles serving spatially distributed points (Pop, Cosma, Sabo, & Pop Sitar, 2024). VRP can be classified into static VRP (SVRP), where all parameters are known in advance, and dynamic VRP (DVRP), where some parameters change over time (Pillac, Gendreau, Guéret, & Medaglia, 2013). Within DVRP, the dynamic traveling salesman problem (DTSP) is of particular relevance for freight delivery optimization, as it involves finding the optimal order of visiting a set of nodes under changing edge costs (Danchuk, Comi, Weiß, & Svatko, 2023).

The integration of real-time traffic data into route optimization relies on several complementary technologies. GIS-based approaches are the most widely adopted, as modern platforms such as Bing Maps combine data about the actual URN configuration with real-time traffic information, providing up-to-date travel time and distance estimates that account for congestion, accidents, and temporary closures (Danchuk & Hutarevych, 2024a). Their broad spatial coverage and standardized APIs make them particularly suitable for city-wide route optimization. IoT traffic sensors – including inductive loop detectors, radar sensors, and video cameras – offer higher measurement accuracy for traffic flow parameters such as intensity, speed, and density, but their coverage is typically limited to major arterials, requiring extrapolation methods for uncovered sections (Ye, Yan, Wei, Zhou, Li, Shen, & Wang, 2021; Danchuk, Hutarevych, & Taraban, 2025). Ad hoc network systems provide a decentralized alternative: VANET enable V2V and V2I communication where vehicles act as mobile sensors, while MANET extend this concept to a broader class of self-organizing wireless nodes including pedestrian devices and delivery robots. Both VANET and MANET can provide dense, low-latency traffic data without fixed infrastructure, though challenges of connectivity stability, data reliability, and critical mass of equipped nodes currently limit their standalone applicability (Badole & Thakare, 2023; Camp, Boleng, & Davies, 2002).

A unified DTSP formulation that accounts for traffic dynamics on URN sections using ITS sensor data was first presented for sustainable urban delivery (Russo & Comi, 2021). The feasibility of optimal freight routing with dynamic updates using a modified ant colony algorithm was demonstrated for smart logistics applications (Danchuk, Comi, Weiß, & Svatko, 2023). An adaptable dynamic routing system using GIS data was proposed and validated on the Warsaw URN, where re-optimization resulted in complete route sequence rebuilding due to traffic redistribution (Danchuk & Hutarevych, 2024a). This approach was extended to handle limited traffic information by combining real-time IoT sensor data with historical traffic parameters from representative URN sections in Kyiv, achieving time savings of up to 19.4% (Danchuk, Hutarevych, & Taraban, 2025). The methodology was further extended to handle delivery time windows, demonstrating route adaptability when traffic congestion threatened to violate scheduled deliveries (Danchuk, Hutarevych, Popov, & Busquets-Mataix, 2025).

At the same time, the specific context of last-mile OOH delivery has received comparatively little attention. OOH delivery networks possess distinct characteristics: their points are permanently fixed yet widely distributed across urban zones with heterogeneous traffic dynamics, and a single delivery tour traverses URN sections with fundamentally different congestion patterns, making route quality highly sensitive to localized traffic changes. These features make OOH delivery a particularly suitable and practically relevant domain for applying dynamic routing with continuous re-optimization. Accordingly, this study adapts the dynamic routing methodology to last-mile OOH delivery within the DTSP framework.

It is important to note that while dynamic routing is actively used in industrial logistics systems, most existing academic studies either consider simplified dynamic scenarios or rely on periodically updated models that do not fully capture continuous changes in URN conditions (Giuffrida, Fajardo-Calderin, D. Masegosa, Werner, Steudter, & Pilla, 2022). Moreover, there is a lack of formally described methods that explicitly combine multi-source real-time URN monitoring, route-level aggregation of road section characteristics, and dynamic optimization with preservation of partially executed routes. This gap motivates the development of the proposed method.

3 Methodology

In context of proposed dynamic routing method for last-mile OOH delivery, route optimization problem is formulated as an asymmetric DTSP on a bidirectional weighted graph $G = (V, E)$, where $V = \{0, 1, \ldots, n-1\}$ is the set of vertices representing OOH delivery points (with vertex 0 being the depot) and E is the set of directed edges connecting each pair of vertices. Each edge (i, j) is defined by a set of alternative routes between vertices i and j. Each such route consists of URN sections that the vehicle sequentially traverses between delivery points i and j. The weight of each edge is determined by the most optimal route among alternatives according to a function of the attributes of route's URN sections, such as travel time, distance, traffic flow parameters, environmental indicators, noise pollution, and others.

The proposed method should be interpreted as a formalization of dynamic routing principles that are often applied in practice but rarely described in a structured and reproducible form.

Unlike industrial black-box solutions, the presented approach provides a transparent representation of the routing problem, where the interaction between real-time URN state monitoring and optimization is explicitly defined within the DTSP framework.

Here the graph is asymmetric because the weight of edge (i, j) generally differs from the weight of edge (j, i), reflecting the directional nature of the urban road network (URN) and possible differences in route characteristics depending on travel direction. The dynamic nature of the problem arises from the fact that edge weights vary over time due to changes in traffic flow conditions, such as fluctuations in average speed, congestion levels, incidents, or temporary road restrictions affecting URN sections. Consequently, the cost matrix of the graph is time-dependent, where each element represents the weight of the most optimal route between delivery points i and j according to specified criterion. The construction of such a graph can be achieved by leveraging GIS services with real-time traffic data, such as Azure Maps.

To support dynamic routing of last-mile OOH deliveries under continuously changing URN conditions, a dynamic routing information system based on real-time URN data is proposed.The conceptual model of the system is schematically presented in Figure 1. The proposed information system performs two primary functions: monitoring the state of the URN based on road section characteristics obtained from multiple data sources, and supporting dynamic online route optimization using real-time data describing the URN conditions.

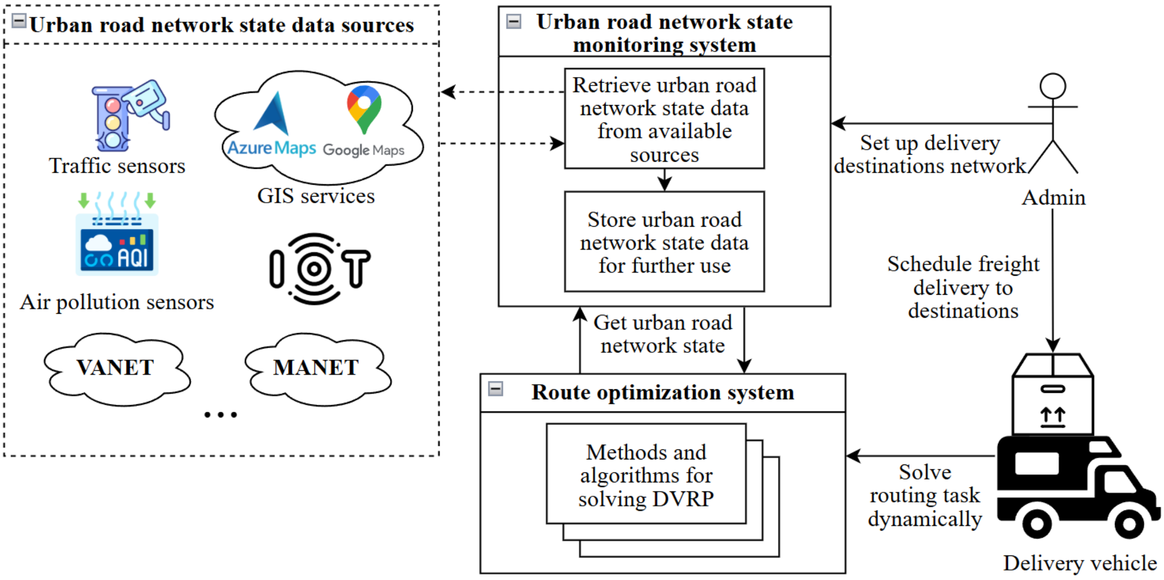

Fig. 1. Model of the dynamic routing system for OOH delivery based on real-time urban road network conditions

To monitor the state of the URN, it is necessary to collect and process data from all available information sources describing both the dynamic and static characteristics of its sections. In this context, particular importance is assigned to monitoring the dynamic characteristics of URN sections, including traffic flow parameters (average speed, density, and intensity), environmental indicators (emissions of carbon dioxide (CO_2), particulate matter (PM), nitrogen oxides (NO_x), sulphur oxides (SO_x), volatile organic compounds (VOCs), etc.), noise pollution, and others. Special attention should be paid to environmental indicators, as they play a significant role in the implementation of modern urban transport logistics approaches aimed at achieving the principles of sustainable development. To support the collection and storage of such data and to generate consolidated information on URN conditions, the proposed information system includes a dedicated component referred to as the Urban Road Network State Monitoring Subsystem (see Figure 1). This subsystem incorporates modules for processing and storing information on road sections conditions obtained from various sources, including GIS-based mapping services (e.g., Azure Maps, Google Maps), IoT traffic sensors, VANET, MANET, air pollution monitoring devices, and other data providers.

In the proposed dynamic routing information system, the task of dynamic route optimization is performed by the Route Optimization Subsystem (see Figure 1). This subsystem integrates various optimization methods and algorithms designed to address different types of DVRPs. It is important to note that the optimization approaches implemented within the system must be sufficiently versatile to handle problems characterized by complex, multi-criteria objective functions, while also remaining flexible and responsive to dynamic changes in the state of the urban road network.

The proposed dynamic routing information system is intended to be deployed by logistics operators and courier companies performing last-mile OOH delivery in urban areas. The system administrator configures the system by connecting available URN state data sources and registers the network of delivery destinations, including parcel lockers, micro-depots, and pick-up and drop-off (PUDO) stations. According to operational needs, the logistics operator assigns delivery task to vehicle, specifying the set of destinations to be served and the return to the depot as the final stop. At the start of the journey from the depot, the driver or onboard system submits a route optimization request, including all necessary input data for the given DVRP type. The Route Optimization Subsystem retrieves the current URN state data in the representation required by the problem type, determines the optimal delivery sequence and path using the most appropriate method, and returns the optimized route to the vehicle. Throughout route execution, dynamic re-optimization is triggered in response to significant changes in traffic characteristics on URN sections, the appearance of new orders, or other factors affecting route feasibility or efficiency, ensuring continuous adaptation to real-world urban conditions.

The route optimization within the DTSP framework is performed using a modified ant colony optimization algorithm (ACO_{mod}), which is based on the classical ACO (Dorigo & Stützle, 2004) but incorporates specialized mechanisms for handling dynamic changes in the graph (Danchuk & Hutarevych, 2024b). The key modification involves the introduction of a fixation mechanism for partially traversed routes. Specifically, ACO_{mod} introduces Pre_k – a list of graph edges that ant k must follow within the optimal configuration of the partially completed route, ignoring the probabilistic transition rule of the classical algorithm. When ant k is at vertex j, it moves to vertex i if $(j, i) \in Pre_k$; otherwise, the next vertex is determined by the classical probabilistic rule. This modification ensures that the current state of the URN is correctly accounted during dynamic routing by preserving the configuration of the already-traversed route segments before graph updates.

Verification of the ACO_{mod} algorithm was carried out through testing on a set of well-known static TSP benchmark problems (Oliver30, Eil51, Berlin52, St70, Eil76, KroA100, Eil101, Pr107) in comparison with the classical ACO, genetic algorithm (GA), and evolutionary simulated annealing (ESA). The results demonstrated an acceptable accuracy level with deviations of up to 4% in worst-case scenarios, which is considered satisfactory for practical applications in urban transport logistics (Danchuk & Hutarevych, 2024b).

4 Results and Discussion

The proposed dynamic routing method for last-mile OOH delivery was validated through simulation studies using a fragment of the Warsaw URN. InPost, one of Europe's largest OOH delivery operators with an extensive network of parcel lockers ("Paczkomat") in urban areas, was selected as the application scenario. Parcel locker locations of InPost within the Warsaw URN (Points #1–11) were selected as delivery destinations, while the depot was located at an InPost logistics hub (Point #0), as shown in Figure 2.

In scope of simulation studies, the following assumptions are made:

- The delivery route is circular, originating and terminating at the depot, with parcels delivered sequentially to each OOH delivery destination
- The optimization criterion is the minimization of the total time spent on delivering parcels to the specified parcel locker locations followed by a return to the distribution point (depot)
- Unloading time at parcel lockers, nomenclature, mass, and volume of the parcels are not considered
- In each set of URN sections corresponding to a particular graph edge, there will always be alternative routes
- Graph updates and route re-optimization are triggered upon the vehicle's arrival at each delivery point
- Graph edge weight variations reflect changes in traffic flow dynamics on URN sections, including speed reductions due to traffic signals, congestion, and other disruptions

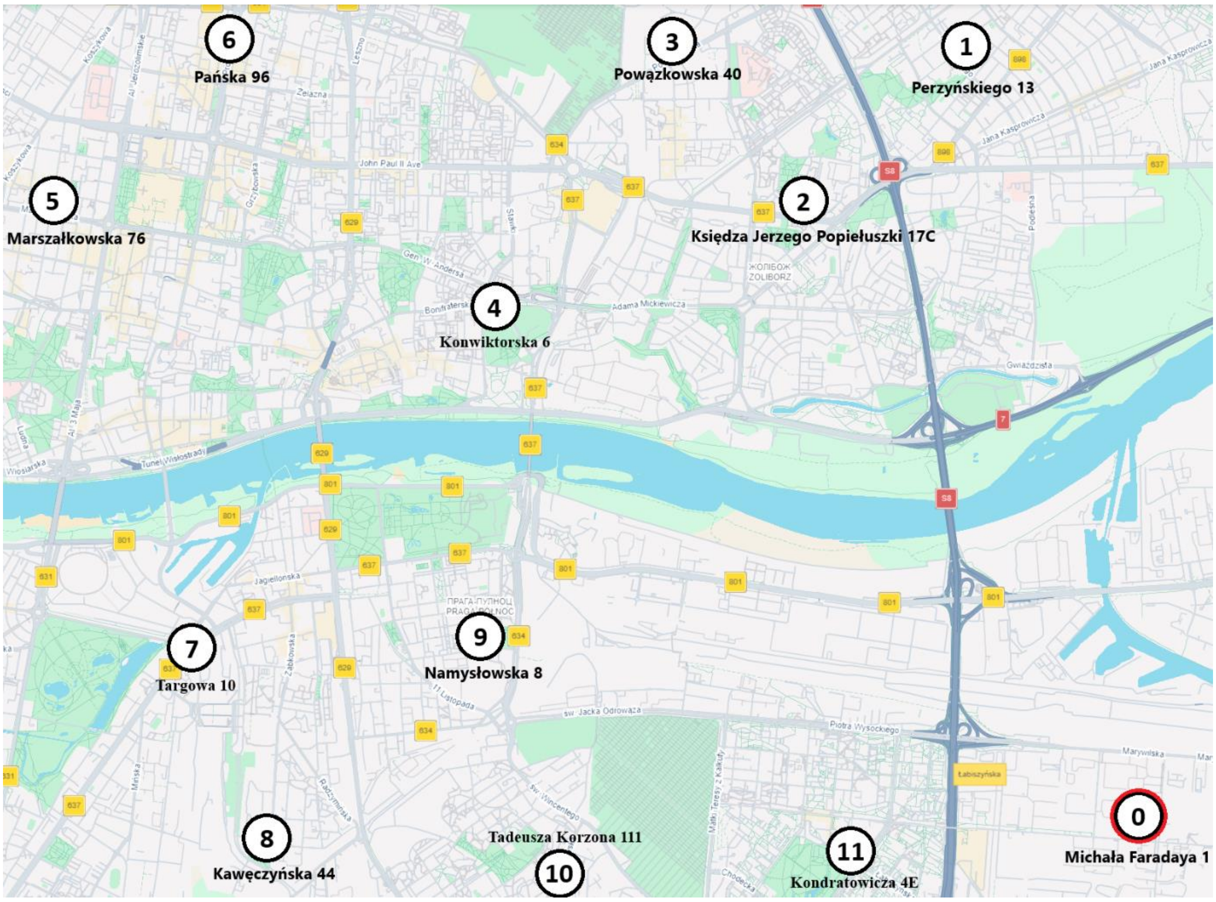

Fig. 2. Locations of the InPost depot (Point #0) and parcel lockers (Points #1-11) on the map of Warsaw

Within the simulation studies, the weighted bidirectional graph for solving the dynamic routing task in the DTSP framework was constructed using the Azure Maps API, which provided travel time estimates between all pairs of delivery points based on the state of the Warsaw URN. To reflect the dynamic nature of urban traffic, graph edge weights were subject to changes during the delivery process simulation, representing variations in traffic flow conditions on URN sections. These changes resulted in variations of expected travel time between delivery destinations of up to 15% relative to the initial estimates.

The results of the simulation study on dynamic routing for OOH delivery to InPost parcel lockers are presented in Table 1. The symbol * denotes the delivery point at which route re-optimization is performed. The column "Current Time" indicates the time of day when the re-optimization takes place. The column "Optimal Route" shows the optimal sequence of delivery points obtained as a result of re-optimization at the corresponding delivery point. The column "Current" presents the expected travel time (in seconds) for the optimal route obtained during the re-optimization at that point. The column "Previous" indicates the expected travel time of the route obtained during the previous re-optimization, recalculated for the current state of the URN. The column "Initial" provides the expected travel time of the route obtained during the initial optimization at the time of departure from the depot, also evaluated according to the current URN conditions. The section of the route that changes as a result of re-optimization is indicated in parentheses.

Table 1. Results of dynamic routing for OOH delivery to InPost parcel lockers in Warsaw URN.

Time	Optimal Route	Optimal route expected time, s		
		Current	Previous	Initial
07:00:00	0*=>1=>2=>3=>4=>9=>6=>5=>7=>8=>10=>11=>0	9087	-	-
07:22:02	0=>1*=>2=>3=>4=>9=>6=>5=>7=>8=>10=>11=>0	9062	9062	9062
07:28:53	0=>1=>2*=>(3=>9=>4=>6)=>5=>7=>8=>10=>11=>0	9401	9896	9896
07:37:45	0=>1=>2=>3*=>(4=>6=>5=>7=>8=>10=>9=>11)=>0	9780	9787	9799
07:51:35	0=>1=>2=>3=>4*=>6=>5=>7=>(8=>9=>10=>11)=>0	9655	9717	9815
08:08:37	0=>1=>2=>3=>4=>6*=>5=>7=>8=>9=>10=>11=>0	9453	9453	9864
08:26:37	0=>1=>2=>3=>4=>6=>5*=>7=>(8=>10=>9=>11)=>0	9753	10015	10352
08:45:18	0=>1=>2=>3=>4=>6=>5=>7*=>8=>10=>9=>11=>0	9628	9628	10259
08:51:09	0=>1=>2=>3=>4=>6=>5=>7=>(8*=>9=>10=>11)=>0	9487	9643	10315
09:04:01	0=>1=>2=>3=>4=>6=>5=>7=>8=>9*=>10=>11=>0	9568	9568	10376
09:15:16	0=>1=>2=>3=>4=>6=>5=>7=>8=>9=>10*=>11=>0	9683	9683	10481
09:29:06	0=>1=>2=>3=>4=>6=>5=>7=>8=>9=>10=>11*=>0	9660	9660	10466
09:41:00	0=>1=>2=>3=>4=>6=>5=>7=>8=>9=>10=>11=>0*	-	9660	10466

As evident from Table 1, meaningful route restructuring occurred at five of the eleven delivery stops – Points #2, #3, #4, #5, and #8 – driven by changes in traffic flow conditions across the Warsaw URN sections. At Point #2 at 07:28:53, the delivery subsequence was reorganized from (3=>4=>9=>6) to (3=>9=>4=>6), reducing the expected total route time by 495 s (≈5.0%) relative to the previously optimized configuration. Subsequent re-optimizations at Points #3 and #4 produced further incremental improvements, with the cumulative saving versus the static initial route reaching 160 s (≈2.7%) by 07:51:35.

The most pronounced restructurings occurred at Points #5 and #8. At Point #5 at 08:26:37, the tail section was reorganized to (8=>10=>9=>11), reducing the expected route time by 262 s versus the previous route and by 599 s (5.8%) versus the initial estimate. At Point #8 at 08:51:09, a further reordering to (8*=>9=>10=>11) yielded an additional saving of 156 s, bringing the total benefit relative to the initial optimization to 828 s (≈14 min, or 8.0%). At Points #1, #6, #7, #9, and #10, the current and previous route times were identical, indicating no material change in URN conditions and correctly resulting in no route restructuring.

Overall, the dynamically optimized route completed the full delivery tour in 9,660 s (≈161 min), compared to 10,466 s (≈174 min) for the static initial route – a total saving of 806 s (≈13 min, or 7.7%). These results confirm the efficiency and adaptability of the proposed dynamic routing method for last-mile OOH delivery under changing URN conditions.

The obtained results demonstrate not only the quantitative improvement in total travel time but also the structural sensitivity of the optimal route to localized traffic variations. This confirms that even moderate perturbations in traffic conditions can lead to non-trivial reordering of delivery sequences, highlighting the importance of continuous re-optimization in urban logistics systems with heterogeneous traffic dynamics.

5 Conclusions

A dynamic routing method for last-mile OOH freight delivery in urban areas has been proposed, targeting networks of fixed delivery points such as parcel lockers and PUDO stations. The method integrates continuous monitoring of the URN state with intelligent optimization algorithms, enabling real-time adjustment of delivery routes using up-to-date aggregated data from multiple sources, including GIS platforms, IoT traffic sensors, VANET and MANET systems, and other relevant data sources.

Within the proposed framework, the delivery routing task is formulated as an asymmetric DTSP on a bidirectional weighted graph, where OOH delivery points – parcel lockers, micro-depots, and PUDO stations – are represented as vertices, and edges correspond to optimal routes between vertex pairs based on specified criteria. To solve the optimization problem, ACO_{mod} algorithm is applied, extending the classical ACO by allowing the optimal configuration of a partially traversed route to be fixed before dynamic graph updates.

From a practical standpoint, the proposed method provides a transparent and implementable framework that can serve as a foundation for decision-support systems in urban logistics.

In contrast to proprietary industrial solutions, the method enables reproducibility, adaptability, and systematic evaluation of routing strategies under varying traffic conditions, which is essential for both academic research and real-world deployment in sustainable urban logistics systems.

Simulation studies conducted for deliveries to InPost parcel lockers within the Warsaw URN demonstrated the practical applicability of the proposed approach. OOH delivery networks, characterized by fixed yet widely distributed delivery points located in urban zones with heterogeneous traffic dynamics, are particularly sensitive to routing inefficiencies. The results confirm that even moderate variations in traffic conditions may significantly affect the optimal order of visits to parcel lockers and PUDO stations, highlighting the importance of continuous dynamic route re-optimization for improving the efficiency of last-mile delivery operations.

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