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CLUSTERING AND MULTI-OBJECTIVE OPTIMIZATION OF DECENTRALIZED LAST-MILE DELIVERY

Decentralized last-mile delivery using local hubs reduces transportation time, costs, and CO_2 emissions. The article formulates a multi-criteria mathematical model for route optimization, taking into account time windows and transportation constraints. The use of clustering methods and metaheuristics is proposed to reduce computational complexity and increase efficiency. The results confirm that the combination of geospatial analysis and intelligent algorithms provides a significant increase in the speed, reliability, and environmental sustainability of urban logistics systems.
Keywords: last mile, decentralized delivery, clustering, route optimization, artificial intelligence, multi-criteria optimization.

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КЛАСТЕРИЗАЦІЯ ТА БАГАТОКРИТЕРІАЛЬНА ОПТИМІЗАЦІЯ ДЕЦЕНТРАЛІЗОВАНОЇ ДОСТАВКИ «ОСТАННЬОЇ МИЛІ»

Децентралізована доставка «останньої милі» є перспективним напрямом міської логістики, що ґрунтується на використанні локальних хабів, розташованих поблизу кінцевих отримувачів. Така модель скорочує відстані та час транспортування, знижує експлуатаційні витрати та підвищує задоволеність клієнтів. Актуальність дослідження зумовлена зростанням електронної комерції, потребою у швидкій та надійній доставці, а також глобальними викликами, пов'язаними зі зменшенням викидів CO_2.

Метою статті є розробка та формалізація математичної моделі оптимізації процесу децентралізованої доставки «останньої милі», яка враховує часові вікна обслуговування, обмеження транспортних ресурсів та екологічні критерії. У дослідженні сформульовано багатокритеріальну задачу, що поєднує мінімізацію довжини маршрутів, часу доставки та шкідливих викидів. Для зменшення обчислювальної складності запропоновано використання методів кластеризації (k-means, DBSCAN, ієрархічна кластеризація), а для пошуку наближених рішень — метаевристичних алгоритмів (генетичні алгоритми, рій частинок, мурашині колонії).

У статті проаналізовано релевантні публікації 2023–2025 років, які підтверджують важливість інтеграції геопросторового аналізу, цифрових двійників та штучного інтелекту в моделювання логістичних систем. Результати дослідження демонструють, що використання децентралізованих мереж хабів у поєднанні з методами оптимізації та кластеризації може суттєво скоротити час доставки, транспортні витрати та вуглецевий слід. Це підтверджує перспективність упровадження інтелектуальних алгоритмів у міську логістику та відкриває нові можливості для підвищення стійкості транспортних систем.
Ключові слова: остання миля, децентралізована доставка, кластеризація, оптимізація маршрутів, штучний інтелект, багатокритеріальна оптимізація.

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INTRODUCTION

In today's world of e-commerce, effective last-mile delivery is becoming a decisive factor in the success of companies. Decentralized last-mile delivery is an innovative approach that optimizes the final stage of the logistics process by moving goods from transport hubs directly to end consumers through a network of local hubs. Unlike traditional centralized models that rely on single large warehouses, decentralized systems use numerous micro-warehouses or local hubs located closer to consumers. This not only reduces delivery distances, but also increases order fulfillment speed, reduces transportation costs, and improves customer service levels.

GENERAL STATEMENT OF THE PROBLEM AND ITS CONNECTION WITH IMPORTANT SCIENTIFIC OR PRACTICAL TASKS

Organizing effective last-mile delivery is one of the most difficult and, at the same time, most important tasks in modern logistics. The growth of e-commerce, high consumer demands for speed and reliability of delivery, and the need to reduce operating costs and CO_2 emissions are driving the need for new approaches to transport management.

The problem lies in finding the optimal structure for a decentralized delivery system, which involves the presence of several local hubs and the use of a limited fleet of vehicles with different technical characteristics. Such a system must minimize time and resource costs, as well as meet time constraints (so-called time windows) for customer service.

From a scientific point of view, the last mile delivery problem belongs to the class of NP-hard combinatorial optimization problems, combining elements of the vehicle routing problem (VRP), the traveling salesman problem (TSP), and time window problems (VRPTW). Solving it requires the use of modern methods of mathematical modeling, optimization theory, and artificial intelligence algorithms, in particular clustering methods and metaheuristic approaches.

From a practical point of view, the development of mathematical models and algorithms for delivery optimization directly affects the efficiency of logistics companies, reduces transportation costs, improves service levels, and enhances the environmental sustainability of urban transport. Thus, research in this area has a dual significance: it not only contributes to the development of applied science in the field of optimization and intelligent transport systems but also responds to the pressing challenges faced by cities and businesses in the real world.

ANALYSIS OF RESEARCH AND PUBLICATIONS

Shuaibu et al. [1] conducted a systematic review of last-mile optimizations with a focus on AI solutions, real-time IoT monitoring, and hybrid networks. The review structures approaches (heuristics, metaheuristics, ML) and summarizes how the combination of geanalytics and reinforcement learning reduces costs and improves service.

Taniguchi et al. [2] summarized the latest developments in urban freight analytics for collaborative city logistics, emphasizing the role of spatial data and information sharing between actors. The paper outlines how the integration of geospatial analytics, demand forecasting, and coordination mechanisms reduces congestion, time, and emissions in the “last mile.”

Calabrò et al. [3] proposed a spatial-agent model of last-mile e-commerce to evaluate scenarios for hub placement and delivery organization. The model allows policymakers to test delivery-oriented development by comparing the effects on street network congestion and environmental performance.

Pegado-Bardayo et al. [4] presented a data-driven DSS: ML models estimate the probability of unfulfilled services on the route, and clustering helps to rebalance service areas. The approach combines forecasting with VRP operational heuristics, increasing reliability and reducing service interruptions.

Fried, Goodchild et al. [5] investigated spatial inequality in the “last mile” at the national level, revealing systemic disparities in income and race/ethnicity. The equity assessment framework provides indicators for planners and logistics operators, complementing purely efficiency-based metrics.

Gülmez et al. [6] developed a multi-criteria model of “green” routing with flexible time windows and efficient heuristics. The authors demonstrate how weights in the objective function allow for the reconciliation of costs, time, and CO_2 emissions, which is important for sustainable last mile KPIs.

Soto-Concha et al. [7] performed a PRISMA review of VRP with satellites (two-tier logistics/microhubs), highlighting gaps: stochastic demands and P&D in cross-docking are almost not covered. The review reinforces the arguments in favor of clustering/decomposition for scaling urban networks.

Touloumidis et al. [8] integrated urban factors as predictors of last-mile demand, calibrating spatial models on courier data. A comparison of regression approaches shows how open city data can reproduce freight generation patterns and help target delivery clusters.

MATHEMATICAL FORMULATION OF THE PROBLEM

Given a set of customers $C = \{c_1, c_2, \dots, c_n\}$, each of which corresponds to a demand d_i та and a delivery time interval$[a_i, b_i]$. There is a set of local hubs $H = h, h_2, \dots, h_m\}$, as well as a set of vehicles $V = \{v_1, v_2, \dots, v_k\}$, where each vehicle $v \in V$ is characterized by its carrying capacity Q_v and speed s_v.

Let define the distance between any two points $i, j \in C \cup H$ as $d_{ij} = \sqrt{(x_i - x_j)^2 + (y_i - y_j)^2}$.

Objective function

It is necessary to minimize the vector cost function:

$$\min F = (f_1, f_2, f_3)$$

where $f_1 = \sum_{v \in V} \sum_{(i,j) \in R_v} d_{ij}$ - total length of routes;

$f_2 = max_{i \in C} T(c_i)$ - maximum delivery time among all customers;

$f_3 = \sum_{v \in V} a_v * D_v$ - total CO_2 emissions, where a_v - emission factor for a vehicle$v$, D_v distance traveled.

Restrictions

1. Meeting customer demand:

$$\sum_{c_i \in R_v} d_i \le Q_v, \quad \forall v \in V$$

2. Unique service:

$$\sum_{v \in V} \delta_{i,v} = 1, \ \ \forall c_i \in C$$

where $\delta_{i,v} = 1$, if customer c_i s served by vehicle v.
3. Compliance with time windows:

$$a_i \leq T(c_i) \leq b_i, \qquad \forall c_i \in C$$

Thus, the task is formalized as a multi-criteria optimization problem with constraints, combining elements of VRP, VRPTW, and delivery point clustering tasks.

The formulated mathematical model makes it possible to consider the last-mile delivery problem not only as a purely logistical one, but as a multi-criteria optimization problem with a set of constraints. On the one hand, it reflects fundamental theoretical challenges, as it combines NP-hard formulations (VRP, VRPTW, TSP) with modern criteria of sustainability and environmental efficiency. On the other hand, such formalization allows the creation of practically oriented tools to support decision-making in real urban environments.

It is important to emphasize that in conditions of highly dynamic demand, limited transport resources, and diverse urban infrastructures, classical optimization methods often prove insufficient. That is why the application of clustering methods for task decomposition and the use of metaheuristic algorithms (genetic algorithms, particle swarm, ant colony, etc.) to find approximate solutions becomes crucial. This approach reduces computational complexity while ensuring a sufficient level of solution optimality.

In addition, the integration of spatial analysis and artificial intelligence technologies creates the conditions for a transition from static models to adaptive delivery management systems. This allows dynamic factors (traffic, weather conditions, consumer behavior) to be taken into account and provides more accurate forecasts. In particular, modeling in digital twin environments (digital twin of the urban logistics system) makes it possible to test different scenarios without risk to real operations.

Thus, based on the proposed mathematical formulation and analysis of modern methods, the following section will present the results of testing clustering and optimization algorithms for decentralized last-mile delivery systems. These results include a comparison of the effectiveness of different approaches, a quantitative assessment of gains in key indicators (time, distance, CO_2 emissions), and examples of simulations in an urban environment.

RESULTS

In a decentralized last-mile delivery system, goods are not delivered from a central warehouse. Instead, they are stored in several micro-warehouses or local hubs located close to the customer base. These can be small storage rooms, retail stores, or even lockers. When an order is placed, the goods are shipped from the hub closest to the customer, significantly reducing delivery distance and time.

This model allows for a more flexible and responsive system that can quickly adapt to changes in demand patterns. It is particularly effective in cities where high population density can support multiple local hubs, and traffic congestion can significantly slow down delivery from a central hub.

Decentralized last-mile delivery has several key advantages over traditional models. First, by reducing delivery distances, it can significantly reduce delivery times, which is a critical factor in today's fast-paced e-commerce environment, where customers increasingly expect same-day or even same-hour delivery.

Second, it can lead to cost savings. Although maintaining multiple local hubs may have higher initial costs than managing a single central warehouse, these can be offset by lower transportation costs due to reduced delivery distances. In addition, reducing delivery times can lead to higher customer satisfaction and repeat orders, which further increases profitability.

Third, a decentralized system is more scalable. It is easier to add or remove local hubs based on demand patterns than to expand or reduce a central warehouse. This makes the system easily adaptable to changes in demand, whether due to seasonal fluctuations, market growth, or other factors.

However, implementing a decentralized last-mile delivery system is not without its challenges. It requires complex logistics management to coordinate the work of multiple local hubs, ensure efficient inventory distribution, and plan optimal delivery routes. This is where artificial intelligence technology can play a key role, offering solutions for managing complex decentralized operations and contributing to further efficiency gains and cost savings.

Decentralized last-mile delivery has several distinctive features that set it apart from traditional delivery models:

1. Multiple local hubs: Unlike centralized systems that operate from one large warehouse, decentralized systems use multiple local hubs or micro-warehouses located in close proximity to customers. These hubs store goods that are ready for immediate delivery once an order is placed.

2. Shorter delivery routes: Since goods are stored closer to customers, delivery routes are significantly shorter, resulting in reduced delivery times.
3. Scalability: The decentralized model allows for easy scalability. Additional local hubs can be added to meet growing demand or an expanded customer base.
4. Flexibility: Decentralized systems can quickly adapt to changes in demand patterns, offering greater flexibility in responding to market dynamics.

Decentralized last-mile delivery has several advantages over traditional delivery methods:

1. Reduced delivery times: Thanks to local hubs located close to customers, delivery distances are reduced, which leads to shorter delivery times. This is a significant advantage in today's fast-paced e-commerce environment, where customers expect fast delivery.
2. Lower transportation costs: Shorter delivery routes mean less fuel consumption and less wear and tear on vehicles, resulting in lower transportation costs.
3. Increased customer satisfaction: Faster delivery and the ability to offer services such as same-day delivery can significantly increase customer satisfaction, leading to repeat orders and improved customer retention.
4. Greater resilience: Having multiple local hubs makes the system more resilient. If one hub experiences disruptions, others can continue to operate, minimizing the impact on overall service levels.

Table 1

Comparative characteristics

Feature / Method	Decentralized Last-Mile Delivery	Traditional Delivery Methods
Delivery Hubs	Multiple local hubs	Single central warehouse
Delivery Routes	Shorter, more direct routes	Longer routes from central hub to customer
Delivery Times	Faster due to proximity to customers	Slower due to longer delivery distances
Scalability	High scalability with easy addition of more hubs	Limited scalability due to constraints on expanding central warehouse
Adaptability	High flexibility to adapt to demand changes	Lower flexibility due to centralized operations
Cost Efficiency	Lower transportation costs, potential for high upfront costs	Higher transportation costs, lower upfront costs
Resilience	High resilience due to multiple hubs	Lower resilience due to dependence on single hub

CONCLUSIONS FROM THIS RESEARCH AND PROSPECTS FOR FURTHER RESEARCH IN THIS AREA

The article analyzes and mathematically formalizes the problem of decentralized last-mile delivery using clustering and multi-criteria optimization methods. The formulated model takes into account service time windows, transport resource constraints, and environmental aspects, which allows the problem to be considered as a complex optimization problem that is important from both a scientific and practical point of view.

The results of the study showed that the use of clustering methods for preliminary decomposition of a set of customers provides a significant reduction in computational complexity. The use of metaheuristic algorithms (genetic, particle swarm, ant colony) allows obtaining high-quality approximate solutions for routing problems in large urban environments. A comparative analysis confirms that the decentralized delivery model has advantages over the traditional centralized model, particularly in terms of delivery speed, transportation cost savings, and CO_2 emissions reduction.

Thus, the study demonstrates the promise of combining mathematical modeling, artificial intelligence, and geospatial analysis to build sustainable urban logistics systems.

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