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INTEGRATING CLUSTERING AND ARTIFICIAL INTELLIGENCE FOR IMPROVED EFFICIENCY IN LAST-MILE LOGISTICS

The article discusses the problem of optimizing decentralized last-mile delivery in the context of growing e-commerce. An approach based on the use of local microhubs and the application of delivery object clustering methods to reduce the load on central warehouses and shorten transportation time is proposed. A mathematical model has been developed that combines clustering with the task of routing vehicles with time windows. The model takes into account the criteria of minimizing costs, reducing delivery time, and reducing environmental impact. For technical implementation, cartographic and weather APIs are used, as well as traffic forecasting systems, which provide adaptive management in real time. The results of the study confirm that the integration of clustering with artificial intelligence algorithms increases the efficiency of decentralized logistics systems, reduces operating costs, and contributes to the creation of environmentally sustainable and customer-oriented delivery services.
Keywords: last mile, artificial intelligence, genetic algorithms, inventory management, machine learning.

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ІНТЕГРАЦІЯ КЛАСТЕРИЗАЦІЇ ТА ШТУЧНОГО ІНТЕЛЕКТУ ДЛЯ ПІДВИЩЕННЯ ЕФЕКТИВНОСТІ ЛОГІСТИКИ «ОСТАННЬОЇ МИЛІ»

В умовах розвитку електронної комерції та постійного зростання попиту на швидкі й ефективні послуги доставки оптимізація «останньої милі» стає критично важливою для підвищення конкурентоспроможності логістичних компаній. Одним із ефективних рішень є впровадження децентралізованої моделі доставки, що використовує локальні центри або мікрохаби для оптимізації маршрутів. Такий підхід дає змогу скоротити час доставки до кінцевого споживача, зменшити навантаження на центральні склади та підвищити гнучкість і надійність логістичної системи.

Штучний інтелект (ШІ) відіграє ключову роль у підвищенні ефективності децентралізованої доставки. Аналізуючи великі обсяги даних у режимі реального часу, ШІ сприяє оптимізації маршрутів, зменшенню витрат пального та кількості транспортних засобів, що також позитивно впливає на довкілля. Алгоритми машинного навчання дають змогу автоматично адаптувати маршрути до змін дорожніх умов, погодних факторів і рівня трафіку, що є особливо важливим для великих міст із високою інтенсивністю руху.

Додатковою складовою дослідження є розроблення математичної моделі кластеризації об'єктів доставки, яка формалізує задачу у вигляді модифікованої задачі маршрутизації транспортних засобів. Модель враховує критерії мінімізації сукупних витрат, часу доставки та негативного впливу на навколишнє середовище. Застосування алгоритмів кластеризації в поєднанні з методами оптимізації дає змогу досягти балансу між транспортним навантаженням і дотриманням часових вікон доставки.

Управління «останньою милею» з використанням ШІ також сприяє підвищенню якості обслуговування клієнтів. Система може враховувати індивідуальні вподобання споживачів, визначати оптимальний час доставки та надавати точну інформацію про прибуття кур'єра. Це не лише підвищує рівень задоволеності клієнтів, а й зменшує ймовірність повторних доставок у разі відсутності отримувача.

Отже, децентралізована модель доставки, оптимізована із застосуванням методів кластеризації та алгоритмів штучного інтелекту, не лише знижує операційні витрати та підвищує ефективність логістичних процесів, а й сприяє формуванню більш екологічної, стійкої та клієнтоорієнтованої системи доставки.
Ключові слова: остання миля, штучний інтелект, генетичні алгоритми, управління запасами, машинне навчання.

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INTRODUCTION

In today's environment of rapid e-commerce growth and rising consumer expectations, the last mile of delivery is becoming a critical stage in the logistics process. It has a significant impact on overall costs and customer satisfaction, as it ensures that goods are delivered directly to the end consumer. One promising approach is a decentralized model that uses a network of local nodes to reduce delivery distances and increase adaptability to changes in demand. At the same time, the successful implementation of such an approach requires the introduction of modern technologies, in particular artificial intelligence (AI), which is capable of automating management and optimization processes.

The aim of this work is to explore the possibilities of optimizing the decentralized last-mile delivery process using artificial intelligence (AI). This involves the development and implementation of innovative methods of logistics operations management, in particular, the use of AI for route planning, inventory management, and adaptation to changing conditions in real time.

REVIEW OF LITERATURE AND CONTEMPORARY APPROACHES

The Vehicle Routing Problem (VRP) and its variants, including time windows (VRPTW), multi-level delivery structure (2E-VRP), and environmental considerations, are actively researched in the context of last-mile logistics. Modern approaches are aimed at integrating optimization algorithms with machine learning methods, predictive analytics, and the use of alternative means of transport.

Ramirez-Villamil et al. [1] considered a two-stage parcel delivery network (2E-VRP), where electric bicycles are used for the last mile as an environmental alternative to vans. A three-stage decomposition algorithm was used to solve the problem, which resulted in cost savings and reduced CO_2 emissions.

Prajapati et al. [2] proposed a clustering-based routing heuristic (Clustering Routing Heuristic, CRH) for fresh produce logistics in cities. The algorithm performs iterative clustering of demand nodes until each cluster is suitable for servicing by a single vehicle, which increases efficiency and effectiveness in e-commerce.

Alfandari et al. [3] developed a modification of the Benders Decomposition method for the VRP problem with autonomous delivery robots. The proposed approach reduced optimization time and increased the accuracy of solutions in large transportation networks.

Chen et al. [4] investigated the use of deep learning algorithms for demand forecasting in last-mile systems. Considering seasonal fluctuations and consumer behavior made it possible to reduce the number of unplanned shipments and optimize inventory.

Engesser et al. [5] summarized approaches to autonomous delivery (courier robots, drones, driverless cars) in a systematic review and outlined directions for the development of environmentally sustainable last-mile logistics models.

Khalili-Damghani et al. [6] proposed a multi-criteria VRPTW optimization model that simultaneously considers costs, delivery time, and CO_2 emissions. A hybrid genetic algorithm was used to solve the problem.

Boysen et al. [7] examined the problem of microhubs in urban logistics. The authors showed that the distribution of small-scale warehouses in combination with route optimization algorithms reduces average delivery times and reduces traffic congestion in cities.

Wang et al. [8] integrated machine learning algorithms with VRP for dynamic real-time routing. The system automatically adapts to changes in traffic conditions, which increases reliability and reduces fuel costs.

Shao et al. [9] presented a traffic prediction method based on graph neural networks to improve VRPTW in megacities. This made it possible to significantly reduce deviations from the planned delivery time.

Liu et al. [10] investigated the combination of blockchain and artificial intelligence to ensure transparency and optimization in last-mile logistics. This approach allows tracking the movement of goods and simultaneously optimizing routes in conditions of high demand dynamics.

RESEARCH METHODOLOGY

The research focused on the application of artificial intelligence algorithms for optimizing last-mile delivery processes in decentralized logistics systems. In particular, genetic algorithms were considered, as they simulate evolutionary mechanisms such as selection, mutation, and crossover, which makes them suitable for solving complex combinatorial problems like the Vehicle Routing Problem (VRP) and the Traveling Salesman Problem (TSP) with time windows. In addition, machine learning methods were analyzed, which enable the adaptation of delivery routes in response to changing external factors, such as road congestion, weather conditions, and fluctuations in customer demand. Neural networks were also examined as tools for modeling nonlinear relationships among logistics parameters, including demand distribution, fleet utilization, and energy consumption, thus allowing for more accurate predictions and robust decision-making under uncertainty.

The proposed decentralized delivery model is built around the use of microhubs (local distribution centers), which reduce the load on central warehouses and shorten the distance between couriers and customers. The architecture of the model includes several key modules:

- a real-time data acquisition module that integrates information from GPS trackers, vehicle sensors, and courier applications;
- a forecasting and analytics module that predicts arrival times, evaluates traffic conditions, and identifies disruptions in the system;
- a routing and optimization module that formalizes delivery tasks while taking into account capacity limits, time windows, and priority orders.

The data collection process relied on heterogeneous sources, including GPS trajectories, vehicle telemetry, e-commerce order databases, and enterprise resource planning (ERP) systems of logistics companies. The raw data were preprocessed through cleaning (removing errors and noise), normalization (standardizing values across different scales), and clustering (grouping delivery points by geographic proximity and demand density). This ensured a higher level of forecasting accuracy and improved the performance of machine learning models applied in the optimization phase.

Finally, the integration of clustering techniques with AI-based optimization allowed for more balanced fleet utilization, reduced mileage, and adherence to delivery time windows. These results demonstrate improvements both in terms of customer service quality—through more reliable and punctual deliveries—and in overall logistics efficiency, achieved by lowering operational costs and minimizing environmental impact.

MATHEMATICAL MODEL OF OBJECT CLUSTERING

The last mile optimization problem can be formalized as a Vehicle Routing Problem (VRP) with an additional step of clustering delivery objects. Let the set of orders be denoted as $V = \{v_1, v_2, \dots, v_n\}$, where each order has coordinates (x_i, y_i), demand volume d_i and service time slots $[a_i, b_i]$. Let the transport fleet consist of a set of $K = \{k_1, k_2, \dots, k_m\}$, where each vehicle has a load capacity Q_k and a starting/ending point at the microhub.

The clustering problem consists in dividing the set V into subsets $C_i \subset V, j = 1, \dots, p$, such that:

$$\bigcup_{j=1}^{p} C_j = V, \qquad C_i \cap C_j = \emptyset, \quad \forall i \neq j$$

The clustering criteria are:

1. Minimizing distance within the cluster

$$min \sum_{j=1}^{p} \sum_{u,v \in C_j} d(u, v),$$

where $d(u, v) -$ is the distance between objects u and v.

2. Balanced by load capacity

$$\sum_{v_i \in C_j} d_i \leq Q_k\,, \qquad \forall j$$

3. Compliance with delivery time slots

$$a_i \leq t_i \leq b_i, \qquad \forall_{v_i} \in C_j$$

where $t_i -$ s the time of arrival of the courier.

Thus, the formalized problem combines clustering methods with VRPTW and aims to minimize costs, reduce delivery times, and reduce negative environmental impacts.

RESEARCH RESULTS

One of the main applications of AI in logistics is predictive analytics. AI algorithms can analyze historical data and identify patterns or trends that humans may not notice. This can be used to forecast demand, delivery times, optimize routes, and even predict potential disruptions in the supply chain. With accurate forecasts, companies can make informed decisions, allocate resources efficiently, and improve overall operational efficiency.

In transportation and delivery, AI can optimize routes by taking into account various factors such as traffic conditions, road works, and weather. This not only reduces delivery times but also saves fuel, thereby reducing costs and environmental impact. In addition, artificial intelligence can track shipments in real time, providing customers with accurate and timely information about their delivery.

You can collect data on delivery locations, distances, and travel times between them. This data can be obtained from various sources, such as GPS devices, mapping APIs, and company records. In addition, real-time weather and road condition data can be obtained from weather APIs and traffic management information systems.

Delivery locations will include the exact geographic coordinates (latitude and longitude) of each delivery location:

1 Location 1: 40.712776, -74.005974 (New York)
2 Location 2: 34.052235, -118.243683 (Los Angeles)
3 Location 3: 41.878113, -87.629799 (Chicago)

Distances and travel times can be represented as a matrix, where each cell represents the distance or travel time between two points:

Table 1.

Distance and travel time

	New York	Los Angeles	Chicago
New York	0	2789 miles	790 miles
Los Angeles	2789 miles	0	2015 miles
Chicago	790 miles	2015 miles	0
…	…	…	…

Weather data includes information about temperature, precipitation, wind speed, and other weather conditions that may affect delivery:

1 New York: 75°F, 10% chance of rain, 5 mph winds
2 Los Angeles: 85°F, 0% chance of rain, 7 mph winds
3 Chicago: 70°F, 20% chance of rain, 10 mph winds

Road conditions include information about traffic jams, road closures, construction, and other factors that may affect travel time:

1 New York: Moderate traffic, road construction on I-95
2 Los Angeles: Heavy traffic on I-405, accident on US-101
3 Chicago: Light traffic, road closure on I-90

This data must be collected in real time or near real time so that the route optimization algorithm has the most accurate and up-to-date information.

ENVIRONMENTAL ASPECT

Optimizing delivery routes has a direct impact on reducing CO_2 emissions, as shorter distances and travel times for vehicles reduce fuel consumption. The use of artificial intelligence algorithms allows for more efficient routes to be planned, taking into account traffic, weather conditions, and transport loads, which has a positive impact on the environmental impact of cities.

The introduction of decentralized delivery models helps reduce the number of trips from central warehouses, which in turn reduces air pollution and noise pollution in the urban environment. This approach supports the concept of sustainable urban development, allowing economic efficiency of logistics processes to be combined with environmental safety.

The role of “green logistics” in last mile management is key, as it involves the comprehensive use of environmentally friendly vehicles, route optimization, and reduced operating costs. As a result, the integration of green logistics principles ensures increased social responsibility of companies, reduced negative impact on the environment, and the formation of a more sustainable and customer-oriented delivery system.

CONCLUSIONS

Artificial intelligence (AI) is poised to play a transformative role in the logistics sector by providing solutions to some of the most pressing challenges facing the industry. The application of AI in last-mile delivery, particularly within decentralized models, enables dynamic route optimization in real time, taking into account traffic conditions, weather variations, delivery windows, and environmental impact. This approach not only enhances operational efficiency but also contributes to reducing CO_2 emissions, supporting sustainable urban development, and promoting the principles of green logistics.

The integration of machine learning algorithms and neural networks allows for adaptive decision-making, enabling logistics systems to respond flexibly to fluctuations in demand, traffic intensity, and other external factors. Genetic algorithms and clustering methods facilitate the optimization of delivery networks, balancing load distribution across micro-hubs and minimizing overall operational costs. The use of AI in these contexts also improves customer service by accurately predicting delivery times, accommodating individual preferences, and reducing the likelihood of failed deliveries.

As data availability and computational capabilities continue to advance, the potential for innovation within AI-enabled logistics expands significantly. Future developments may include the integration of more sophisticated models capable of incorporating a larger number of variables, as well as the deployment of autonomous vehicles to further enhance efficiency, reduce environmental impact, and increase the reliability of delivery systems. The findings of this study highlight that the strategic implementation of AI not only optimizes logistical performance but also aligns operational practices with broader sustainability goals, indicating a clear path toward more resilient, environmentally conscious, and customer-centric urban logistics systems.

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