

OPTIMIZING URBAN LAST-MILE LOGISTICS THROUGH CITY DIGITAL TWIN SIMULATION

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Анотація

У роботі розглянуто актуальну проблему підвищення ефективності міської логістики «останньої милі» в умовах щільної забудови та обмеженої пропускної здатності доріг. Досліджено концепцію впровадження цифрового двійника міста як інструменту для створення динамічного віртуального середовища, що відображає реальні транспортні потоки. Розроблено підхід до симуляційного моделювання процесів доставки з використанням сучасних алгоритмів оптимізації маршрутів на графі дорожньої мережі. Проаналізовано вплив інтеграції даних IoT-сенсорів на точність прогнозування часу прибуття та зниження операційних витрат. Запропоновані рішення дозволяють мінімізувати логістичні витрати та зменшити екологічне навантаження на міську екосистему.

Ключові слова: цифровий двійник, міська логістика, остання миля, оптимізація маршрутів, симуляційне моделювання, транспортні системи, Smart City, інтелектуальні алгоритми.

Abstract

The paper addresses the critical issue of improving the efficiency of "last mile" urban logistics under conditions of high density and limited road capacity. The concept of implementing a city digital twin is investigated as a tool for creating a dynamic virtual environment that reflects real-world traffic flows. A simulation modeling approach for delivery processes using modern route optimization algorithms on a road network graph is developed. The impact of integrating IoT sensor data on the accuracy of arrival time prediction and the reduction of operational costs is analyzed. The proposed solutions allow for minimizing logistical expenses and reducing the environmental burden on the urban ecosystem.

Keywords: digital twin, urban logistics, last mile, route optimization, simulation modeling, transport systems, Smart City, intelligent algorithms.

Introduction

The problem of "last-mile" delivery remains the most complex and costly link in the supply chain, accounting for up to 50% of total logistics expenditures. Modern urbanization leads to critical congestion of transport arteries, rendering classical static route planning models ineffective. Traditional approaches fail to account for dynamic changes in traffic conditions, temporary parking restrictions, and the specific constraints of narrow urban streets.

The concept of a city Digital Twin offers a transition from static maps to live digital replicas of physical objects and processes. A digital twin integrates Geographic Information Systems (GIS), real-time data, and historical statistics, allowing for the testing of logistics scenarios in a virtual environment prior to their physical implementation. This provides the capability for in-depth analysis of transport systems and the identification of hidden patterns in freight flow distribution.

Research results

In the course of this study, a simulation model architecture was developed based on a three-tier structure: data collection, modeling, and optimization. The simulation enables the reproduction of vehicle behavior in high detail, accounting not only for coordinates but also for parameters such as acceleration, braking, and interaction with pedestrians.

The key aspects of the research include:

- **Graph search algorithms.** For basic navigation, Dijkstra and A* algorithms were implemented, supplemented by heuristics to account for dynamic edge weights corresponding to traffic delays.
- **Genetic algorithms.** These are applied to solve the Vehicle Routing Problem (VRP) with time windows, where it is necessary to determine the optimal distribution of orders among multiple couriers.

- **IoT and GPS integration.** The use of streaming data from traffic monitoring sensors allows for the adjustment of the digital model every few minutes, ensuring high simulation fidelity.
- **Computational complexity.** For large cities with thousands of graph nodes, a scalability issue arises, which is addressed through road network segmentation and the utilization of parallel computing.

Technical implementation details

The implementation of the logistics digital twin is based on a mathematical description of the road network as a directed weighted graph $G = (V, E)$, where nodes V – represent intersections and edges E – represent road segments.

1. **Graph model.** Each edge contains metadata regarding the number of lanes, speed limits, and the current congestion coefficient.
2. **Flow simulation.** An agent-based approach is utilized, where each transport unit is an autonomous object with its own objectives and behavioral rules.
3. **Machine learning.** Recurrent Neural Networks (RNNs) are employed to predict traffic congestion by analyzing historical traffic time series, allowing the model to "foresee" traffic complications before they occur.
4. **Node optimization.** The use of micro-depots and automated parcel lockers as intermediate points to reduce the mileage of large delivery vehicles.

Development prospects

The further evolution of city digital twin technology for logistics is closely linked to the Smart City concept. Full integration with traffic light control systems will enable the creation of "green corridors" for environmentally prioritized transport modes. Special attention is given to the implementation of autonomous delivery robots and drones, whose navigation in complex urban landscapes critically depends on the precision of the digital twin.

The application of Big Data will facilitate a transition from reactive to predictive logistics management. Artificial intelligence will be able to automatically redistribute warehouse loads based on expected demand in specific city districts, significantly reducing delivery times.

Conclusion

The city digital twin serves as the foundation for transforming modern urban logistics into a flexible and predictable system. Simulation modeling not only reduces operational costs for companies but also positively impacts the urban environment by reducing harmful emissions and easing road congestion. The use of intelligent optimization algorithms combined with real-time data ensures the resilience of supply chains against unpredictable factors. In the future, such models will become an integral part of digital governance for every metropolis, ensuring a balance between commercial interests and the comfort of residents.

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