UDC 004.78:656.1:004.9 DOI https://doi.org/10.32782/1995-0519.2025.1.17

THEORETICAL JUSTIFICATION FOR THE DEVELOPMENT OF AN IOT SYSTEM FOR FREIGHT TRANSPORTATION MANAGEMENT

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Modern logistics is a key Component of the global economy, ensuring the delivery of goods to any corner of the world. However, the industry faces numerous challenges, such as cargo preservation (especially for perishable goods) and route optimization. The lack of proper monitoring of transportation parameters – such as temperature, humidity, lighting, geolocation, and vehicle conditions – often leads to product spoilage, significant financial losses, and inefficiencies in transportation processes. This research aims to develop an IoT system that comprehensively addresses these challenges.

Methodology. As part of this work, a conceptual model of an IoT-based freight transportation management system was developed, encompassing data collection, transmission, processing, and analysis levels. Mathematical models were employed to optimize routes, detect anomalies, and predict risks. The system integrates cutting-edge IoT technologies, including sensors, network data transmission protocols (LoRaWAN, GSM), and analytical algorithms, enabling real-time monitoring and decision-making.

Findings. The proposed IoT system enables continuous monitoring of transportation parameters, including temperature, humidity, vibration, and geolocation. It optimizes delivery routes, reducing fuel costs and shortening delivery times. Additionally, through machine learning, the system can predict potential risks, such as vehicle breakdowns or deviations from predefined conditions, enhancing overall efficiency and reliability.

Findings. The scientific novelty of this research lies in the development of a comprehensive IoT system that integrates data collection, transmission, processing, and analysis within logistics processes. The uniqueness of the model is its ability to automatically respond to deviations, predict risks, and ensure full control over transportation conditions.

Practical value. The implementation of the system significantly reduces cargo losses by enabling timely responses to changes in transportation conditions. Route optimization helps lower fuel and maintenance costs, enhancing the competitiveness of companies. Additionally, the system improves customer service quality and contributes to the development of transportation infrastructure.

Conclusions. The proposed IoT system is a powerful tool for modern logistics, enabling automated monitoring and management of freight transportation. It helps preserve cargo quality, reduce costs, and enhance the efficiency of logistics processes. The adoption of such technologies is a crucial step toward the digitalization and optimization of the transportation industry, unlocking new opportunities for companies in the global marketplace.

Key words: Internet of Things (IoT), information system, conceptual modeling, mathematical modeling, automotive transport, logistics, freight transportation, transportation condition monitoring.

Introduction. Modern logistics plays a crucial role in the global economy, ensuring the transportation of goods at all stages of the supply chain. However, the industry faces several challenges, with the most pressing being cargo preservation – particularly for perishable goods – and delivery route optimization. The lack of proper monitoring of transportation conditions, such as temperature, humidity, or vehicle geolocation, often leads to cargo spoilage, significant financial losses, and reduced operational efficiency. Additionally, vehicle malfunctions or inefficiently planned routes substantially increase transportation costs and delivery times.

One potential solution to these issues is the use of innovative IoT technologies, which enable continuous monitoring and control of transportation conditions and vehicle status. Installing sensors on cargo and vehicles allows real-time tracking of critical parameters, ensuring cargo preservation and transportation efficiency. Integrating this data into cloud-based processing systems facilitates automated anomaly detection and risk analysis.

Another effective approach is the development of mathematical models for route optimization, risk prediction, and cost reduction. These strategies help create a comprehensive transportation management system that enhances logistics efficiency, minimizes loss risks, and improves customer service quality. This study proposes the development of a conceptual IoT system model that integrates modern technologies and analytical tools to address these challenges effectively.

The aim of the study. The aim of this study is to develop a theoretical foundation for the design of an IoT system that enables comprehensive monitoring of cargo conditions and vehicle status.

Analysis of recent research and publications. Study [1] analyzes the implementation of IoT in intelligent transportation systems, discussing benefits such as improved road safety and optimized use of transportation infrastructure, as well as challenges related to IoT integration within transportation systems.

Study [2] presents the development of a global system that integrates and connects vehicles using VANET, IoT, and artificial intelligence technologies. The goal is to reduce the number of accidents by implementing specialized traffic rules and utilizing a cloud-based database to collect real-time vehicle speed data.

The authors of study [3] introduce an IoT solution for urban traffic monitoring, which collects and analyzes data on driver behavior, including GPS coordinates, speed, and fatigue levels, to enhance road safety and improve urban infrastructure.

The Internet of Things (IoT) holds immense potential in the transportation sector by enabling process automation, enhancing safety, and improving the efficiency of transportation operations, as noted by the authors of study [4]. Specific IoT applications, such as smart traffic lights, autonomous vehicles, and cargo monitoring systems, highlight the significant prospects of this technology. At the same time, it is crucial to address security challenges, integrate IoT into existing transportation infrastructure, and leverage mathematical models.

The justification for the development of information systems that enable fuel consumption calculations based on vehicle characteristics, traveled distance, and average speed – primarily for enhanced control over CO_2 emissions' environmental impact and tracking user expenses – is presented in study [5].

Study [6] provides an overview of modern sensor selection methods for monitoring traffic flows, emphasizing the importance of network observability and modeling for efficient sensor placement in intelligent transportation systems.

The assessment of IoT technologies, particularly BLE beacons, for supporting autonomous vehicles in urban environments is explored in study [7]. The results indicate that such technologies can enhance road safety and traffic efficiency.

The findings of study [8] propose a prototype IoT-based telemetry system for real-time monitoring of cargo weight and truck location, contributing to improved control efficiency and reduced economic losses in the land freight sector.

Corporate information systems of companies providing large-scale telecommunication and information services require the automation of key business processes, such as billing and payment accounting, as stated in study [9]. The Internet of Things (IoT) plays a crucial role in such systems by enabling real-time service consumption monitoring, management, and analysis.

The authors of study [10] introduce a novel Federated-IoT-enabled Intelligent Transport System (ITS) that integrates convolutional neural networks with edge computing to enhance data processing efficiency in transportation systems.

Presentation of the main research material. The development of an efficient IoT-based freight transportation management system requires a well-structured organization of its components and interaction levels. A conceptual model of such a system allows for the visualization of key processes, from data collection via sensors to decision-making based on data analysis. The model accounts for both external factors influencing logistics operations and feedback loops that enable real-time system adjustments. Color coding of model elements helps clearly distinguish different levels and components.

Fig. 1 presents a multi-level conceptual model of an IoT-based freight transportation management system. Input data collected via sensors (e.g., temperature, humidity, geolocation) are fed into the system (marked in green). External factors, such as weather conditions or road status, impact system functionality (marked in red). The system comprises multiple levels: data collection, transmission, processing, analysis, and decision-making (marked in blue). Feedback loops (red dashed lines) facilitate real-time adaptation and system improvement. Finally, the system's output (optimized routes, notifications) is delivered to users (operators, drivers, clients), enhancing the efficiency of logistics processes.

Let's describe the levels of the developed model in more detail.

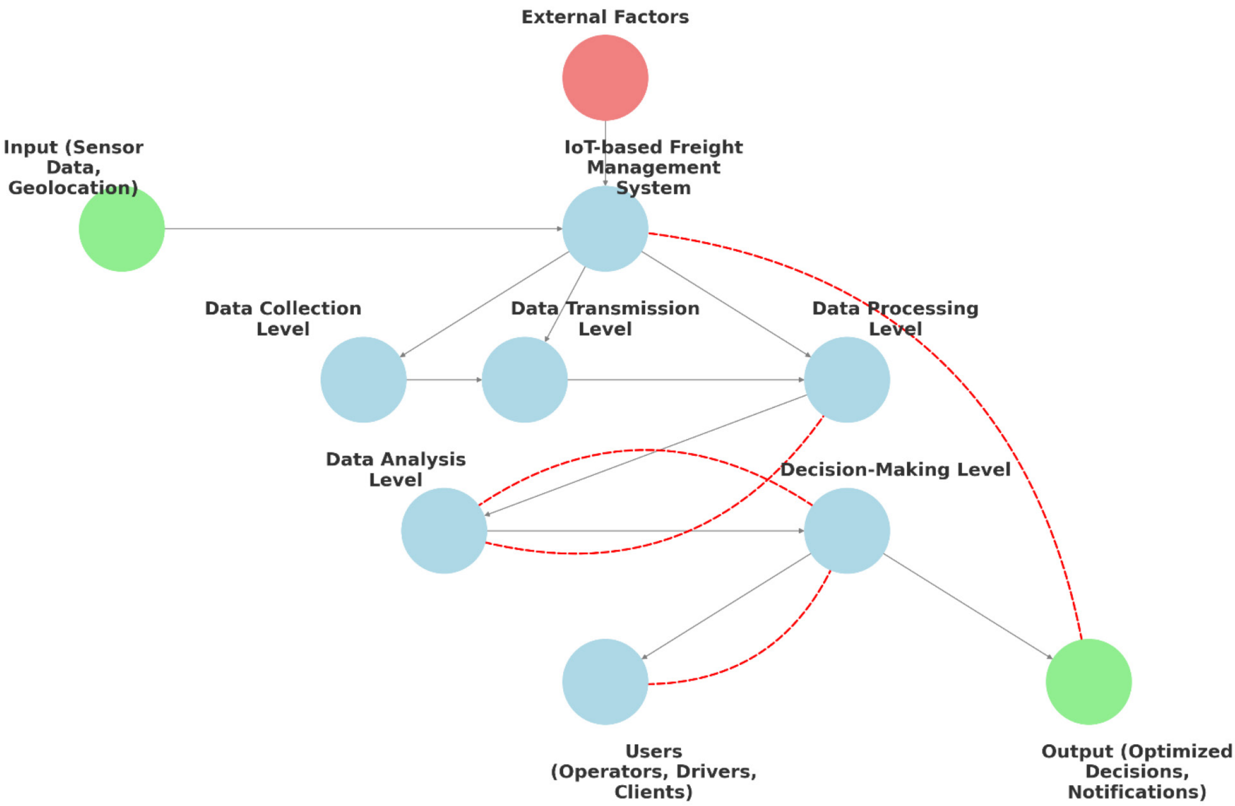

Fig. 1. Conceptual Model of an IoT System for Freight Transportation Management

Data collection level (efficient monitoring of cargo and vehicle conditions).

Data collection is a fundamental stage where the IoT system gathers all necessary information about cargo, vehicles, and transportation conditions. This process relies on various sensors that continuously capture parameters affecting transportation efficiency. For instance, to ensure proper cargo preservation, temperature and humidity sensors are installed, allowing real-time tracking of any changes that could impact transportation quality, particularly for perishable goods.

Additionally, for specific types of cargo – such as pharmaceutical products or goods sensitive to light – light level sensors are used. These ensure safe storage by preventing exposure that could lead to product damage.

Another critical aspect is vehicle monitoring through onboard sensors that assess technical conditions. These sensors measure vibration levels to evaluate suspension performance, fuel consumption, and key technical parameters, such as engine status, braking system performance, and other vital components.

GPS/GLONASS geolocation modules play a crucial role in tracking vehicle positions with high accuracy. This capability is particularly important for route monitoring and ensuring timely responses to potential disruptions or deviations.

The collected data, represented as numerical values and parameters, is then transmitted to the next system level for further processing and analysis.

Data transmission level (ensuring reliable and high-speed communication)

Once data is collected, it must be transmitted quickly and reliably to servers or cloud platforms for further analysis and processing. Various data transmission technologies are utilized to achieve this. In areas with high network coverage density, standard communication technologies such as Wi-Fi or GSM/3G/4G/5G are used, ensuring high-speed and reliable connectivity.

For remote or hard-to-reach regions where energy efficiency and long-range communication are crucial, more power-efficient technologies like LoRaWAN or NB-IoT are employed. These technologies are ideal for low-power IoT devices, such as temperature or humidity sensors, providing stable data transmission over long distances.

Data can be stored either on local servers (on-premises) to enhance security and control or on cloud platforms (such as AWS, Azure, or Google Cloud), which help reduce infrastructure costs while offering flexibility and scalability for the system.

Data processing level (high-quality preparation for analysis)

At this stage, the system performs preliminary processing of collected data to prepare it for further analysis. First, data filtering is conducted to eliminate noise, errors, and missing values. This step ensures more accurate and reliable data for subsequent analysis.

After filtering, the data is aggregated into a unified model, allowing different parameters to be integrated into a structured format for analysis. For example, a comprehensive model can be built that simultaneously considers cargo temperature, vehicle condition, fuel consumption, and geolocation.

Additionally, threshold values are configured for each parameter at this level. For instance, an acceptable temperature range is set to ensure cargo preservation, and any deviation beyond this range is recorded as a critical error.

To handle large-scale data processing, modern platforms such as Apache Kafka and Apache Spark are utilized, along with efficient databases like PostgreSQL, MongoDB, and TimescaleDB, ensuring high-speed data processing and storage.

Analysis level (anomaly detection and route optimization)

Data analysis is a crucial stage where the system detects anomalies in transportation conditions and helps optimize delivery routes. Analytical algorithms identify deviations from predefined parameters, such as temperature exceeding the allowed threshold or route violations, which may indicate malfunctions or unauthorized actions.

Another key aspect of analysis is route optimization. By considering vehicle geolocation, road traffic conditions, and fuel consumption, the system can determine the most efficient transportation route, significantly reducing fuel costs and delivery time.

Additionally, data analysis enables risk prediction and early detection of potential vehicle failures, allowing proactive measures to be taken. Machine learning and predictive modeling techniques, such as TensorFlow and Scikit-learn, are utilized to generate forecasts based on historical data, improving decision-making and operational efficiency.

Decision-making level (automation and management)

At the final stage, the analysis results are integrated into the decision-making system, enabling the automation of management processes. If the system detects deviations from normal conditions, it can automatically adjust the vehicle's route, notify the driver or dispatcher about the issue, or even initiate corrective actions, such as redirecting the vehicle for maintenance.

The system also provides recommendations for dispatchers regarding further actions, improving the speed and accuracy of decision-making. Mobile applications for drivers and web-based dashboards for dispatchers offer real-time access to all essential information, ensuring seamless monitoring and response.

Integration with ERP and CRM systems allows for the consolidation of all supply chain management aspects into a unified information platform, enhancing operational efficiency and transparency.

The mathematical representation of the conceptual IoT-based freight transportation management model can be structured into different levels, each representing the system's core functions. This approach formalizes the data flow, processing, analysis, and decision-making, providing a structured framework for system optimization.

1. Data collection level.

At this level, the system gathers information from sensors. The data is represented as a set:

$$D = \{T_i(t), H_i(t), L_i(t), V_i(t), G_i(t) \mid t = 1, \ldots, n\}, \quad (1)$$

where $T_i(t)$ – temperature collected by the *ith* sensor at time *t*; $H_i(t)$ – humidity; $L_i(t)$ – light level; $V_i(t)$ – vibration; $G_i(t)$ – vehicle geolocation.

This data is structured as an input stream:

$$I(t) = \sum_{i=1}^{n} D_i(t), \quad (2)$$

where n – number of sensors.

2. Data transmission level.

Data transmission depends on network bandwidth and latency. The data transfer rate is modeled as:

$$R = B/T, \quad (3)$$

where B – data volume (in bytes); T – transmission time.

The probability of successful data transmission can be expressed as a function of channel redundancy:

$$P_{suc} = 1 - P_{losses}(1 - R_{reserve}), \quad (4)$$

where P_{losses} – probability of data loss; $R_{reserve}$ – redundant bandwidth.

3. Data processing levels.

Data processing involves filtering, aggregation, and normalization. Data filtering is performed using a smoothing filter:

$$\widehat{D}(t) = \frac{1}{k}\sum_{j=1}^{k} D(t-j), \tag{5}$$

where k – number of previous measurements.

Data aggregation can be represented as:

$$D_{агр}(t) = \bigcup_{i=1}^{n} \widehat{D}(t). \tag{6}$$

4. Data analysis level.

Data analysis includes anomaly detection and route optimizatio.

Anomaly detection. An anomaly is detected if the value exceeds the threshold:

$$E_i(t) = \begin{cases} 1, & \left|D_i(t) - D_{opt}\right| > \Delta_i \\ 0, & \text{otherwise.} \end{cases} \tag{7}$$

Route optimization. Route optimization is based on finding the shortest path. For example, using Dijkstra's algorithm:

$$C(i,j) = \min \sum_{k=1}^{m} w_{i,k}, \tag{8}$$

where $w_{i,k}$ – the weight between nodes i and k, a m – the number of nodes.

5. Decision-making level.

Decisions are made based on data analysis. For example, the decision-making function could be as follows:

$$R(t) = f(A(t), B(t)), \tag{9}$$

where $A(t)$ – result of anoly detection; $B(t)$ – optimal route.

If $A(t) = 1A$, meaning an anomaly is detected, then:

$R(t)$ = "Redirect the vehicle for maintenance".

6. Interrelationships between levels.

The overall structure of the system can be described as a set of functions:

$$S(t) = g(I(t), R(t), F(t)), \tag{10}$$

where $S(t)$. – system state; $I(t)$ – input data; $R(t)$ – results of processing and analysis; $F(t)$ – feedback for correction.

Thus, the proposed model allows for the mathematical description of the operation of an IoT-based freight transportation management system. The use of these levels and functions helps optimize transportation, minimize costs, and ensure cargo preservation.

Research findings. In the course of the study, a conceptual model of an IoT-based freight transportation management system was developed, encompassing all stages of data collection, transmission, processing, analysis, and decision-making. The main findings of the research include:

1. Development of a multi-level model (key levels of system operation were identified: data collection, transmission, processing, analysis, and decision-making; functional relationships between the levels were described, including feedback mechanisms for adaptation and improvement of system performance).
2. Route optimization (the implementation of the shortest path algorithm will reduce transportation costs).
3. Transportation condition monitoring (the use of sensors to monitor temperature, humidity, and vibration will ensure cargo preservation, especially for perishable goods. Specifically, detecting deviations from optimal transportation conditions will help avoid product damage).
4. Data transmission efficiency (modeling showed that the use of energy-efficient protocols, such as LoRaWAN and NB-IoT, ensures stable data transmission in remote areas with minimal energy consumption).
5. Data transmission efficiency (modeling showed that the use of energy-efficient protocols, such as LoRaWAN and NB-IoT, ensures stable data transmission in remote areas with minimal energy consumption).

The results obtained demonstrate the high efficiency of the proposed IoT system in enhancing logistics operations, reducing costs, and minimizing the risk of cargo loss.

In addition to the aforementioned results and the benefits they offer, it is also important to highlight that:

– the proposed system will enable risk prediction (data analysis will allow the identification of potential issues, such as vehicle breakdowns or route deviations, allowing timely responses to critical situations);

– the system will integrate feedback loops that will facilitate automatic process adjustments, improving reliability and operational stability;

– through effective route management, the system will contribute to fuel cost reduction and minimize cargo loss risks, ensuring the economic efficiency of the system;

– timely delivery, notifications, and transparency in logistics processes will increase customer trust and satisfaction;

– the IoT system will seamlessly integrate with ERP and CRM platforms, creating a unified information ecosystem for logistics management.

Conclusions. During the study, a comprehensive conceptual model of an IoT-based freight transportation management system was developed, which takes into account all aspects of logistics processes.

The developed IoT system will provide comprehensive real-time monitoring of transportation conditions and vehicle status, significantly reducing the risk of cargo spoilage.

Route optimization, using shortest path algorithms and geolocation data analysis, will help reduce fuel costs, shorten delivery times, and improve the efficiency of logistics processes.

The use of energy-efficient data transmission technologies, such as LoRaWAN and NB-IoT, will ensure stable data transmission even in remote areas with minimal energy consumption.

The implementation of feedback loops between the system levels will facilitate adaptation to changing transportation conditions, allowing for quick responses to unforeseen situations.

The proposed model will have high practical value and can be integrated into logistics processes to enhance their transparency, efficiency, and reliability.

Thus, the developed IoT system is an important solution for modern logistics, aimed at preserving cargo quality, optimizing processes, and reducing costs.

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ТЕОРЕТИЧНЕ ОБҐРУНТУВАННЯ СТВОРЕННЯ IОТ-СИСТЕМИ ДЛЯ УПРАВЛІННЯ ВАНТАЖНИМИ ПЕРЕВЕЗЕННЯМИ

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Сучасна логістика є ключовим складником глобальної економіки, що забезпечує доставку товарів у будь-який куточок світу. Проте галузь стикається із численними викликами, як-от збереження вантажів (особливо швидкопсувних) та оптимізація маршрутів доставки. Відсутність належного моніторингу параметрів перевезення (температура, вологість, освітленість, геолокація, стан транспортних засобів) часто призводить до псування товарів, значних фінансових втрат і неефективності транспортних процесів. Дослідження спрямоване на створення IoT-системи, яка дасть змогу комплексно виконувати ці завдання.

Методологія. У межах роботи розроблено концептуальну модель IoT-системи управління вантажними перевезеннями, яка охоплює рівні збору, передавання, обробки та аналізу даних. Використано математичні моделі для оптимізації маршрутів, виявлення аномалій і прогнозування ризиків. Система інтегрує сучасні IoT-технології, як-от сенсори, мережеві протоколи передавання даних (LoRaWAN, GSM) та аналітичні алгоритми, що забезпечують оперативний моніторинг й ухвалення рішень у реальному часі.

Результати. Запропонована IoT-система дає змогу здійснювати безперервний моніторинг параметрів перевезення (температура, вологість, вібрація, геолокація); оптимізувати маршрути доставки, що зменшує витрати на пальне та скорочує час доставки; прогнозувати можливі ризики, як-от поломки транспорту чи відхилення від заданих умов, завдяки машинному навчанню.

Оригінальність. Наукова новизна дослідження полягає в розробці комплексної IoT-системи, яка інтегрує збір, передачу, обробку та аналіз даних у логістичних процесах. Унікальність моделі полягає в можливості автоматично реагувати на відхилення, прогнозувати ризиків і забезпечувати повний контроль за умовами перевезення.

Практична цінність. Упровадження системи забезпечує значне зменшення втрат вантажів завдяки своєчасному реагуванню на зміни умов перевезення. Оптимізація маршрутів сприяє скороченню витрат на пальне й технічне обслуговування транспорту, що підвищує конкурентоспроможність компаній. Крім того, система дає змогу покращити якість обслуговування клієнтів і сприяє розвитку транспортної інфраструктури.

Висновки. Запропонована IoT-система є потужним інструментом для сучасної логістики, який допомагає автоматизувати моніторинг й управління перевезеннями. Вона сприяє збереженню якості вантажів, зниженню витрат і підвищенню ефективності логістичних процесів. Використання таких технологій є важливим кроком до цифровізації та оптимізації транспортної галузі, що створює нові можливості для компаній у глобальному середовищі.

Ключові слова: Інтернет речей (IoT), інформаційна система, концептуальне моделювання, математичне модулювання, автомобільний транспорт, логістика, вантажні перевезення, моніторинг умов перевезення.

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Стаття надійшла 27.01.2025