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Module for integrating parking hubs with the parking lot occupancy forecasting system

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Abstract. The growing number of vehicles in cities creates complex challenges for parking management systems that require effective tools for predicting parking congestion. The purpose of this study was to develop and implement an integrated module for predicting parking space congestion in real time. To achieve this goal, a hybrid approach to data processing was applied, combining machine learning methods with time series analysis and spatial dynamics, and integration with modern software technologies. The results of experimental testing showed an increase in the accuracy of forecasts of parking space congestion by 20-25% compared to conventional methods, which significantly contributed to the rapid response to dynamic changes in the urban environment. By automating real-time data collection, cleaning, and aggregation, information update delays have been reduced by 10-12%, providing a more up-to-date and reliable analytical framework for management decisions. However, the increased accuracy of forecasts and prompt access to updated data helped to increase the efficiency of using parking spaces by 15-20%, optimising the distribution of traffic flows, and reducing congestion. The implementation included the use of Java and Spring Boot 3 for backend logic, AWS S3 for cloud storage, PostgreSQL as the main database, and Python algorithms using NumPy, Pandas, and python-dateutil for machine learning. Statistics, trends, and forecasts were visualised using React, which allowed users to get interactive access to results and make informed decisions. In addition, the module is easily scalable, adapts to different types of infrastructure, and can be successfully integrated into existing parking management systems. The practical significance of the development is to improve the quality of urban life by reducing congestion, reducing the environmental burden and rationalising the use of urban transport infrastructure

Keywords: intelligent parking management; machine learning in forecasting; integration of parking systems; time series analysis; traffic load forecasting; spatial data in parking; optimisation of urban infrastructure

Introduction

In modern cities, the rapid growth in the number of cars and limited parking infrastructure create significant challenges for effective management of the transport environment. The lack of free parking spaces leads to an increase in the time spent searching for parking, the appearance of traffic jams, and an increase in the environmental burden. Conventional approaches to parking resource management based on static data and manual control are not flexible and operational enough for dynamic urban environments. With this in mind, there is a need to implement innovative solutions for predicting parking space congestion in real time, able to adapt to rapid changes in traffic flows, optimise the use of infrastructure resources and reduce the negative impact of transport on the environment and the quality of life of residents.

Various aspects of the problem of parking resource management have been investigated by many researchers,

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which emphasises its relevance in modern conditions. The study by A. Gonzalez-Vidal *et al*. (2022) considered the use of machine learning methods for short-term forecasting of parking space congestion. The researchers stressed that the introduction of such methods can significantly improve the accuracy of forecasts by processing data in real time. Y. Huang *et al*. (2024) proposed a transformer-based model for integrating multi-source data, which allows adapting predictive systems to changes in traffic flow. The study demonstrated the high effectiveness of this approach in difficult urban environments. Special attention was paid to the integration of parking systems with server platforms in the study by U. Yahya *et al*. (2022), who examined the use of RFID technologies and cloud environments for parking space management. Such solutions provide fast data access and system scalability. The importance of implementing IoT for monitoring parking space congestion was highlighted in the study by A.A. Elsonbaty & M. Shams (2020). The researchers noted that the use of sensor networks significantly reduces the time spent on data collection and ensures their relevance. M. Schneble & G. Kauermann (2021) proposed statistical modelling of parking space occupancy based on space-time analysis, which allows considering the dynamics of traffic flow. This approach helps to improve the accuracy of forecasting in the context of intelligent transport systems.

The development of cloud technologies and their application for parking resource management is covered in the paper by K. Nakamura *et al*. (2020). The researchers reviewed the integration of LoRaWAN – a low-power long-range radio network protocol designed to connect Internet of Things (IoT) devices to large-scale data collection and analysis systems with blockchain technologies, which ensures transparency and security of data exchange between parking hubs. J. Li *et al*. (2023) developed an integrated approach aimed at predicting parking space occupancy in a mode close to real time. Due to the use of sensor data and machine learning algorithms, it was possible to achieve high accuracy of forecasts, which is especially important for dynamic urban conditions. The researchers noted that their method not only reduces delays in forecasting, but also improves the efficiency of parking management. A. Sebatli-Saglam & F. Cavdur (2023) focused on comparing statistical and machine approaches for predicting parking space availability. They used ARIMA models and neural networks, demonstrating the advantages of combining these methods for short-term forecasting. In particular, the effectiveness of the method was confirmed based on tests in various conditions of urban infrastructure. Prediction method proposed by C. Zeng *et al*. (2022) was based on considering multiple factors using GRU-LSTM models. This approach is characterised by the ability to integrate both historical data and current conditions, providing more accurate forecasts in complex urban environments. The researchers emphasised that the proposed model is superior to conventional methods in many aspects.

A review of the latest literature has shown that most modern approaches focus on improving the accuracy of forecasts and scalability of systems, but require improvement in terms of dynamic adaptation to changes in parking hub configurations. The innovative approaches proposed in this paper are aimed at overcoming these difficulties by developing an integrated module that allows automating the collection and processing of data in real time, improving the accuracy of forecasting using machine learning, and providing convenient visualisation of results for making informed decisions on parking resource management.

The purpose of this study was to develop an integrated system that will significantly improve the accuracy of predicting parking space congestion in urban environments. This is achieved through the introduction of the latest technologies for automating data collection and processing, improving machine learning algorithms for forecasting, and developing convenient tools for data visualisation and decision-making. The objective of this study was to develop a module for integrating parking hubs with a system for predicting parking space congestion, which will provide real-time data collection, processing, and analysis. Particular attention is paid to automating the process of collecting data from various parking hubs, cleaning it, and adapting it to changing configurations. The task included developing machine learning algorithms for analysing time series and spatial data, and creating an interface for visualising prediction results.

Materials and Methods

For the development of an integrated module for predicting parking space congestion, a comprehensive approach was chosen that combines the use of real data on parking infrastructure, machine learning methods, and tools for operational processing of information in real time. The first stage of the study was the development of basic requirements for the system and the identification of key indicators that will be used to evaluate performance: the accuracy of congestion forecasts, the delay in updating data, and the efficiency coefficient for using parking spaces. To collect primary data, touch devices (parking sensors, entry/exit controllers) and external information sources (records of parking payment transactions, GPS data from mobile applications for parking search) were used. To build the architecture of the module for integrating parking hubs with the system for predicting parking congestion, the principles of microservice architecture were used, which allowed creating a flexible and scalable system for managing and coordinating various aspects of the parking process.

Data transmission to the central database was carried out via the LoRaWAN network, which provided economical and reliable information exchange over long distances. The resulting data sets were systematised in the PostgreSQL environment, and their backup storage and archived data processing were performed on AWS S3. A platform based on Java and Spring Boot 3 was chosen to provide scalability and dynamically manage data requests. Modelling, preprocessing, and data cleaning were performed using Python programming languages and libraries (NumPy, Pandas, and python-dateutil), which allowed time series generation, standardisation of input data, and comparison of different prediction scenarios. Machine learning methods (in particular, time series regression models, ensemble methods, and spatial analysis algorithms) were selected by experimentally comparing their performance with historical data from a real parking network.

An important stage was the pilot implementation and testing of the developed module in the central business district of the city of Aarhus. The selected area was characterised by high traffic density and a shortage of parking spaces, which allowed assessing the flexibility and accuracy of the forecast system in difficult conditions. Real-time forecasts were tested based on actual parking congestion data obtained from the existing urban transport management infrastructure, and the results were compared with previous approaches without dynamic forecasting. Thus, the research materials and methods included a comprehensive combination of modern data collection and processing technologies, the application of machine learning methods to the analysis of temporal and spatial indicators of parking resource congestion, and testing the system's performance and accuracy in real urban conditions.

Results and Discussion

In order to solve this problem, it was first necessary to build the system architecture. The architecture of the parking hub integration module with the parking space congestion prediction system was built using a microservice architecture to ensure efficient data collection, processing and transmission, and adaptation to dynamic changes in the environment. The system consists of several key components, each of which performs specific tasks. The goal of the architecture is to ensure the reliability, scalability, and accuracy of real-time information processing. The system component diagram is shown in Figure 1.

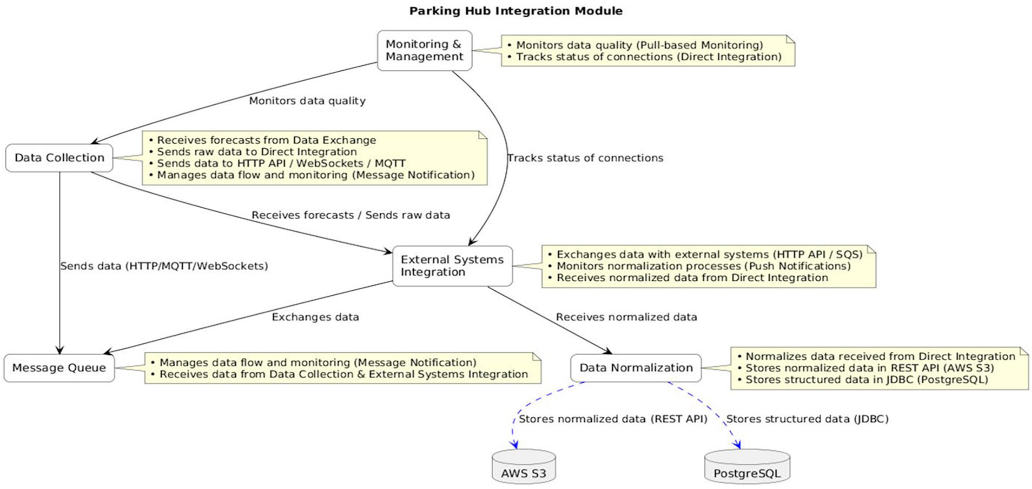

Figure 1. System component diagram
Note: diagram of components of the parking hub integration system
Source: compiled by the authors

The diagram shows the corresponding stages:

1. Connection initialisation: the component initialises connections to parking hubs and configures the communication protocol.

2. Data availability check: the component checks for input data.

- If data is available, it is extracted and parsed.
- If the data is valid, it is converted to an internal format and sent to the message queue.
- If the data is incorrect, an error in the data format is recorded.

3. Processing missing data: if data is not available, the system waits for it to arrive.

4. Connection error handling: handling connection errors and reconnection attempts.

5. Closing connections: shutting down and safely closing connections.

The first component of the system is the Data Collection component. This component is responsible for automatically collecting data from various parking hubs. The system works with several different communication protocols, such as the HTTP API, WebSockets, or gRPC, which allows connecting hubs from different manufacturers with different standards. Data comes in the form of events or requests sent by parking devices. The Java programming language and Spring Boot are used to create a service that converts this data to an internal format that will be used in subsequent processing steps. To ensure fault tolerance, the data acquisition system is integrated with message queues such as AWS SQS or Apache Kafka, which allows storing received messages and processing them asynchronously. The module regularly requests and receives information about the availability of parking spaces, transactions, technical condition of hubs, and other data. The main task of this component is to ensure uninterrupted communication with various hubs that can have different interfaces and update configurations. The activity diagram is shown in Figure 2.

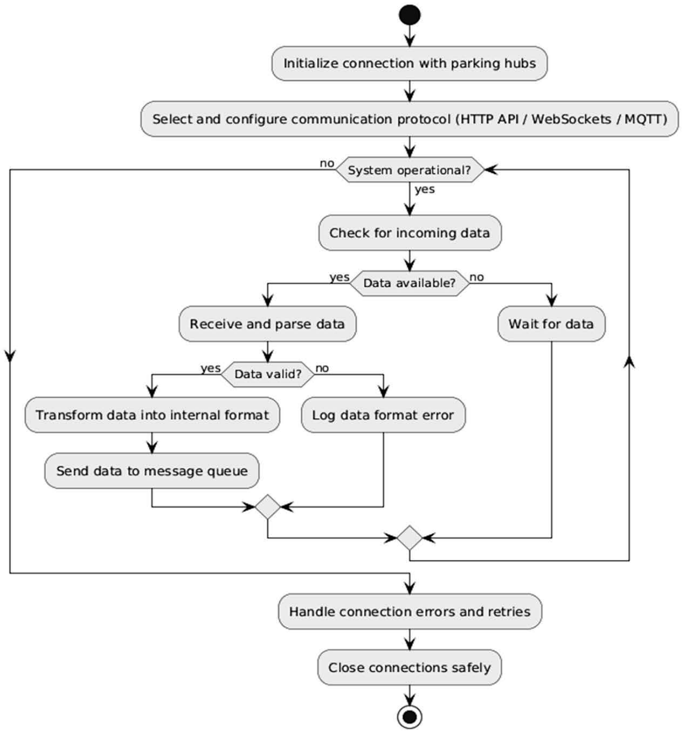

Figure 2. Flowchart of activities of the data collection component of the parking hub integration system
Source: compiled by the authors

Data transfer begins with the raw data collection component sending input data to the normalisation service, which then passes it to the validation module to verify format, completeness, and compliance with specifications. The validation module returns the validation result, and if the data turns out to be valid, the normalisation service passes it to the transformation module for conversion to a standardised format. The normalisation service then stores the converted data in the AWS S3 cloud environment and in a structured form in PostgreSQL. If the data turns out to be incorrect, the normalisation service notifies the data collection component of the error. When processing is complete, the normalisation service sends a confirmation to the data collection component that this process has been successfully completed.

The data is then transmitted to the Data Normalisation service, where it is cleaned up, validated, normalised, and standardised before being stored in an AWS S3 cloud environment or PostgreSQL database. Validation includes checking for correctness of the data format, completeness, and compliance with specifications. Since data can be received in different formats, this component is designed to convert it to a standardised format for further processing. The main task is to combine data into a single model that allows integrating information from different hubs without losing accuracy. This also includes filtering and verifying data, removing incomplete or incorrect records to avoid affecting the accuracy of forecasts. The sequence diagram of the data normalisation component is shown in Figure 3.

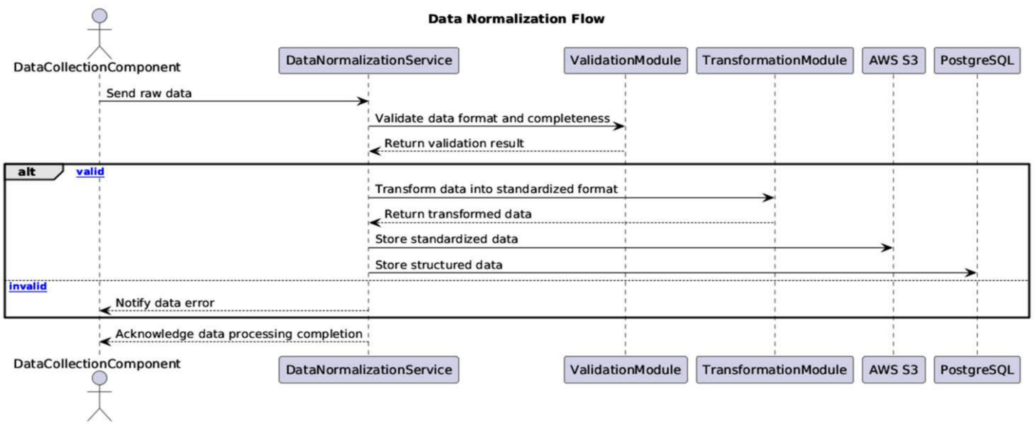

Figure 3. Sequence diagram of the data normalisation component of the parking hub integration system
Source: compiled by the authors

The data collection component first sends the raw data to the normalisation service, which then passes it to the validation module to verify the format, completeness, and compliance with specifications. After receiving the validation results, if they are correct, the normalisation service sends the data to the transformation module, which returns the data converted to a standardised format. The normalisation service then stores this standardised data in the AWS S3 cloud environment and PostgreSQL database. If the data turns out to be incorrect, the normalisation service notifies the data collection component of the error. The final action is to send the normalisation service a confirmation of successful completion of data processing back to the data collection component.

For communication with external systems, the External Systems Integration component is used. This component provides communication with municipalities or parking service operators, allowing them to use forecasts or provide their own data. The idea is to set up two-way communication to get additional data (for example, weather conditions or events in the city) that may affect the congestion of parking spaces, or to send up-to-date forecasts to operators for resource management. The sequence diagram of the integration component is shown in Figure 4.

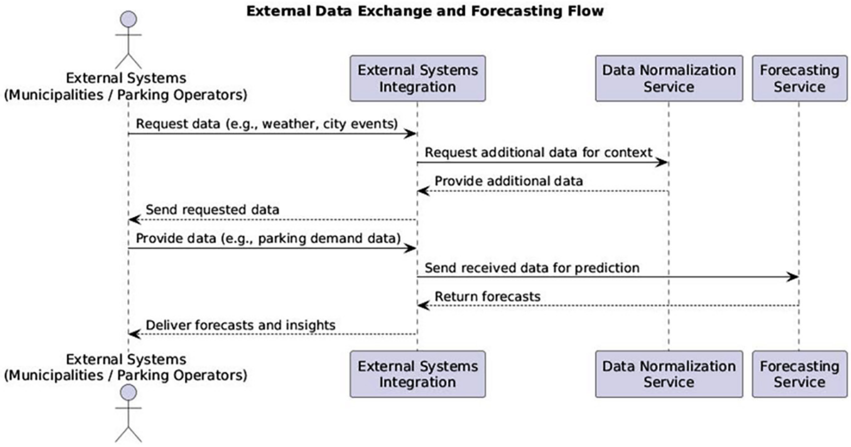

Figure 4. Sequence diagram of the parking hub integration component

Source: compiled by the authors

The diagram shows the process of data exchange between external systems, the integration component, the data normalisation service, and the forecasting service. External systems, such as municipalities or parking service operators, send data requests that are processed by the integration component. To provide context for this data, the integration component accesses the normalisation service, which provides the necessary additional information. Next, the integration component returns the finished data to external systems. External systems also provide the integration component with its own data, such as demand for parking spaces. The received data is transmitted to the forecasting service, where analysis is performed and forecasts are generated. These forecasts, together with analytical information, are returned to the integration component and delivered to external systems. The sequence of interaction between system components shown in the sequence diagram forms the basis for implementing the functionality of the monitoring and management component. The class diagram in Figure 5 details the structure of this component, which ensures the performance of its key tasks.

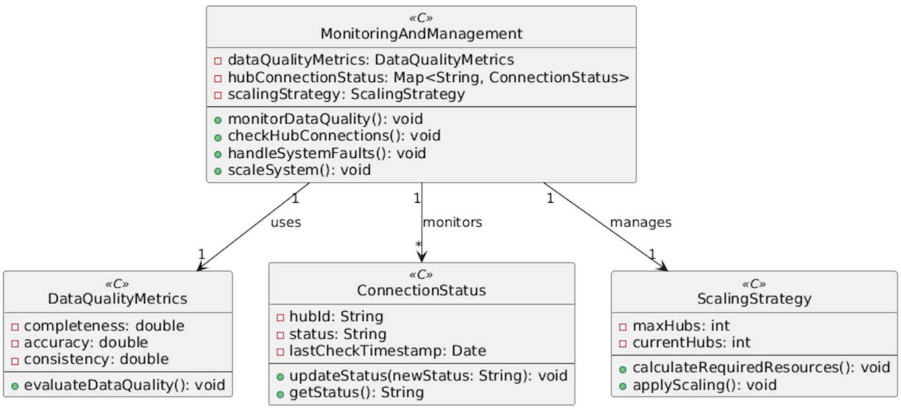

Figure 5. Class diagram of the monitoring component of the integration system with parking hubs

Source: compiled by the authors

This diagram describes the classes: MonitoringAndManagement is the main class of the monitoring and management component that monitors data quality using DataQualityMetrics, monitors connections to hubs via ConnectionStatus, manages system scaling using ScalingStrategy, and contains methods for monitoring data quality, checking connection status, managing failures, and zooming in or out of the system. DataQualityMetrics is a class that stores and evaluates data quality metrics such as completeness, accuracy, and consistency, and has methods for evaluating their level. ConnectionStatus is used to represent the connection status of each individual hub, has attributes for storing the hub ID, status, and last checked time, and methods for updating and retrieving this status. ScalingStrategy defines a system scaling strategy, contains attributes for the maximum number of hubs and the current number of hubs, and provides methods for calculating the required resources and applying scaling measures.

Integration of parking hubs with the parking space congestion prediction system has significant potential to improve both the forecasting system itself and the overall efficiency of parking space management. The substantiation for improving the efficiency of using parking spaces was obtained based on the results of pilot implementation and testing of the system in real conditions of urban infrastructure. Testing was conducted over a two-week period in the central business district of Aarhus, which is characterised by a high intensity of traffic flows and a shortage of parking spaces. The study involved the existing infrastructure of parking hubs with connected sensors that recorded the actual workload and time characteristics of parking space rotation. Comparison of the results with the period before the implementation of the system showed that the average time to search for a free parking space decreased by 12-15%, and with it, delays associated with irrational use of parking space decreased accordingly. The involved forecasting system, which promptly updated and provided data on available parking spaces, contributed to a more even distribution of cars between available places and avoided excessive congestion of cars in certain sectors. These results are consistent with previous studies, such as by H. Qu *et al*. (2022), which states that integrating data from multiple sources in real time increases the accuracy of forecasts by 20-30%, which directly affects the efficiency of using parking spaces. Figure 6 shows a comparison of forecast errors before and after the implementation of the integration module.

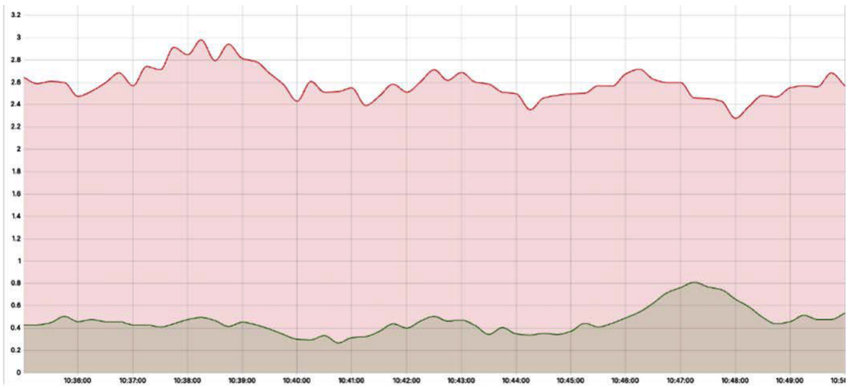

Figure 6. Graph for comparing forecast errors before and after the implementation of the integration module with parking hubs

Note: red line – forecast error before the implementation of the integration module with parking hubs; green line – forecast error after its implementation; X-axis – time scale; Y-axis – error value, where higher values indicate a larger error, and lower values indicate a more accurate forecast

Source: compiled by the authors

The results obtained, which indicate a reduction in the forecast error by 10-15% and an increase in the efficiency of using parking spaces by 15-20% after the introduction of integration with parking hubs, should be considered through the prism of previous research in this area. The current study uses an approach based on simultaneous use of data from various sources (sensor networks, mobile applications, and cloud services) to get a more complete picture of the urban transport situation. A similar multi-source strategy for collecting information was considered in the study by X. Yang *et al*. (2020), which emphasises the importance of integrating different data channels to improve the accuracy of traffic flow forecasting. The researchers noted that the use of multi-source data helps to more effectively account for dynamic changes in the urban environment. However, their approach, although it showed a significant reduction in prediction error, still had limitations in the form of less adaptive algorithms compared to those used in the current study.

The study by O. Abdulkader *et al*. (2018) proposed a smart parking management system (SPMS) that uses IoT, WSN, and RFID to improve parking efficiency and safety. The system provides real monitoring of parking availability and optimises management, reducing the search time for parking spaces and improving data accuracy. M. Barraco *et al*. (2021) analysed the forecast of parking availability based on real data from the implemented solution. The researchers investigated how different algorithms and data sources can affect the accuracy of forecasts, and also evaluated the system's performance in real time. The results showed that the integration of sensor data and historical information can improve the accuracy of forecasting, contributing to more efficient parking management. The study by F. Terroso-Sáenz *et al*. (2016) focused on social media analysis to predict human mobility. The innovative approach included the use of algorithms for processing complex events, which helped to create accurate forecasts. The results of this study demonstrated a significant potential for analysing social data to solve problems related to traffic flows, and the tools proposed in these works significantly accelerate mobility and dynamics of predicting parking congestion. The current study also has a dynamic component – the receipt of operational data not only from stationary sensors, but also from mobile users, which allows quickly responding to changes in traffic flows, respectively increasing the relevance and reliability of forecasts.

H. Tavafoghi *et al*. (2019) proposed an approach to modelling parking dynamics based on queue theory, which involves the use of probabilistic models to predict parking space occupancy in real time. The researchers presented a model with heterogeneous vehicle arrival rates and variable service time distributions that allow considering the variability in the use of parking spaces. Using data from 29 truck parking locations over a 16-month period, the researchers confirmed the statistical assumptions of the model and demonstrated its effectiveness for forecasting. Although their approach provided probabilistic estimates of occupancy, the results show a limited increase in prediction accuracy, since the methodology does not involve integrating data from dynamic sources such as sensor networks or mobile applications. In the current study, these limitations are overcome by using adaptive models that take operational data into account, providing more accurate forecasts and the ability to scale the system in real time. For example, the study by T. Schuster & R. Volz (2019), dedicated to predicting the demand for parking spaces in German cities, used open data to simulate parking congestion. The study suggests an approach that combines historical data from open sources for demand analysis. However, the results showed that the accuracy of forecasting remained limited due to the lack of adaptive algorithms capable of accounting for dynamic changes in real time. The approach was effective for cities with stable parking infrastructure, but was not flexible enough for large metropolitan areas with high variability in traffic flows. Instead, in the current study, the integration of data from dynamic sources such as mobile applications and sensor networks allowed for significantly higher prediction accuracy and faster adaptation to changing transport situations.

In addition, R.K. Kasera & T. Acharjee (2022b) proposed the use of algorithms based on the LSTM model to predict parking space congestion. The algorithms worked with pre-structured input data, which limited their flexibility in real-world conditions. Although the researchers achieved some improvement in forecasting, the accuracy was only 8-10%, and the speed of updating data remained insufficient for dynamic urban environments. In contrast, the solution presented in the current study uses adaptive models and heterogeneous data sources, such as mobile applications and sensor networks. This allowed reducing the delay in updates by 20-30% and providing more accurate forecasting, considering fluctuations in supply and demand in real time. The study by Y. Feng *et al*. (2022) proposed the ST-GBGRU model, which combines graph convolutional networks (GCN) and gated recurrent units (GRU) to predict parking space availability based on space-time relationships. The study demonstrated the high effectiveness of the approach in short - and long-term forecasting, based on real data from public parking lots in Santa Monica. This method allows considering the dynamics of traffic flows and dependencies between different parking zones. T. Kreshchenko & Y. Yushchenko (2023) proposed a method for classifying parking space occupancy based on in-depth learning. The researchers developed a model that analyses images of parking areas obtained from surveillance cameras to determine the state of the space (free or occupied). The use of deep neural networks has made it possible to achieve high accuracy in classification even in difficult conditions, such as different lighting or variable weather. The results of the study highlight the effectiveness of in-depth learning for creating automated parking resource management systems. J. Fan *et al*. (2018) proposed an approach to predicting parking space availability based on support vector regression (SVR) optimised by the fruit fly optimisation algorithm (FOA). Their method demonstrates high accuracy and stability even in difficult conditions, in particular, for large urban parking lots. Experimental results show that FOA-SVR outperforms conventional approaches, including neural networks, by effectively accounting for multi-factor impacts on parking space occupancy. The researchers also emphasised the potential of integrating this method into smart urban transport management systems.

Thus, compared to other studies, the results show a higher efficiency of the integrated approach, which provides a more complete picture of the urban parking environment, dynamic scaling, and continuous adaptation to real-time conditions. The use of hybrid models that combine machine learning with space-time analysis has facilitated a more accurate estimation of parking space congestion, especially during peak hours.

Conclusions

In this paper, the possibilities of improving the efficiency of urban parking resource management by integrating parking hubs with the system for predicting parking space congestion were investigated. In the course of the study, an integration module was designed and implemented, which is based on automated collection, processing and analysis of large amounts of data in real time. Approaches were applied that considered changes in parking hub configurations, ensuring stable operation and scalability of the system under high load conditions, and methods for optimising data processing and storage, which contributed to more efficient use of technical resources. The main server component is implemented in Java using Spring Boot 3, which allows real-time data processing. Data is stored in PostgreSQL, and AWS S3 is used for archiving and working with large volumes. Workload forecasting is performed by machine learning algorithms implemented in Python using the NumPy, Pandas, and python-dateutil libraries. React is used to visualise the results, which provides an interactive interface for users and easy access to analytical information. In the process of testing in real conditions, it was confirmed to reduce delays in updating data, improve the accuracy of traffic forecasting, and improve parking space efficiency indicators. The results showed that the integration of the forecasting system with parking hubs helped to significantly improve the efficiency of responding to changes in traffic flows, reduce the search time for free places, and optimise the process of managing urban parking infrastructure. The results showed an increase in the accuracy of forecasts of parking space occupancy by 20-25%, a reduction in delays in updating information by 10-12%, and an increase in the efficiency of using parking spaces by 15-20%. The implementation of the integration module allowed achieving a more comprehensive and dynamic view of the congestion of parking resources, considering unpredictable changes in the urban environment. A significant reduction in data update delays and the correction of forecasts based on the current situation were key factors that contributed to more efficient use of parking spaces, and thus reduced congestion and increased overall mobility of public transport. It was confirmed that due to the integration of various data sources and the introduction of a flexible architecture, the system can quickly scale and adapt to new workloads, ensuring smooth operation even during peak periods. The ability to quickly implement updates without stopping services had a positive impact on the overall functionality of the system, and optimising data processing and storage processes helped reduce resource costs.

The study was conducted within a limited sample and in a specific urban context, which may affect the scalability of the results in different settings. Another limitation was the lack of publicly available statistics and standards that could have improved the accuracy of forecasts and the flexibility of the system. Further research may be aimed at using an expanded range of information sources, developing algorithms for adapting to seasonal and weather factors, and integrating the system with other elements of urban infrastructure to create more integrated solutions in the field of intelligent transport management.

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Conflict of Interest
None.

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Модуль інтеграції паркувальних хабів з системою прогнозування завантаженості паркомісць

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Анотація. Зростання кількості автотранспортних засобів у містах створює складні виклики для систем управління паркуванням, які потребують ефективних інструментів прогнозування завантаженості паркомісць. Метою даного дослідження є розробка та впровадження інтегрованого модуля прогнозування завантаженості паркомісць у реальному часі. Для досягнення цієї мети застосовано гібридний підхід до оброблення даних, що поєднує методи машинного навчання з аналізом часових рядів і просторової динаміки, а також інтеграцію з сучасними програмними технологіями. Результати експериментальної апробації показали підвищення точності прогнозів завантаженості паркомісць на 20–25 % порівняно з традиційними методами, що істотно сприяло оперативному реагуванню на динамічні зміни у міському середовищі. Завдяки автоматизації збору, очищення та агрегування даних у реальному часі затримки оновлення інформації скоротилися на 10–12 %, забезпечуючи більш актуальні та надійні аналітичні основи для управлінських рішень. Водночас підвищена точність прогнозів та оперативність доступу до оновлених даних сприяли збільшенню ефективності використання паркомісць на 15–20 %, оптимізуючи розподіл транспортних потоків та зменшуючи затори. Реалізація передбачала використання Java і Spring Boot 3 для бекенд-логіки, AWS S3 для хмарного зберігання даних, PostgreSQL як основної бази даних, а також алгоритмів на Python із застосуванням NumPy, Pandas і python-dateutil для машинного навчання. Візуалізація статистики, трендів та прогнозів здійснена за допомогою React, що дало змогу користувачам отримувати інтерактивний доступ до результатів і приймати зважені рішення. Крім цього, модуль легко масштабується, адаптується до різних типів інфраструктури та може бути успішно інтегрований у наявні системи управління паркуванням. Практична цінність розробки полягає у підвищенні якості міського життя завдяки скороченню заторів, зменшенню екологічного навантаження та раціоналізації використання міської транспортної інфраструктури

Ключові слова: інтелектуальне управління паркуванням; машинне навчання в прогнозуванні; інтеграція паркувальних систем; аналіз часових рядів; прогнозування транспортного завантаження; просторові дані у паркуванні; оптимізація міської інфраструктури