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PROSPECTS FOR CREATING DIGITAL TWINS OF FREIGHT CARS

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Summary

Introduction *The global industry and transport are rapidly moving into the era of digitalisation, which is radically changing approaches to the production, operation and maintenance of railway transport. Ukraine, as part of the global market, is also actively implementing innovative solutions. Rail transport is the circulatory system of the Ukrainian economy and logistics, combining strategic, economic and social functions.* ***Relevance.*** *A digital twin is a virtual copy of a physical object, process or service that is constantly updated with data from the real world. In the case of a freight car, its digital twin may include detailed information about its technical condition, operating history, current location, load, and other important parameters.* ***The purpose of the study.*** *The purpose of this research is to study in depth the prospects for the creation and implementation of digital twins of freight cars in the railway transport industry of Ukraine. The relevance of the study is due to the need to increase the efficiency of rolling stock operation, optimise maintenance processes and predict possible malfunctions.* ***Results.*** *An approach to design based on a digital twin has been introduced, which will provide an end-to-end design workflow in a single information space regardless of the software systems used to calculate the components and systems of freight cars, and a block diagram of the operation of a digital twin of a freight car has been constructed.* ***Conclusions.*** *Modelling various operating scenarios on virtual copies allows optimising maintenance and repair modes. Scientifically based algorithms integrated into digital twins contribute to the early detection of potential malfunctions. Applied conclusions indicate the possibility of a significant reduction in maintenance and repair costs. The introduction of digital twins allows for optimised planning of repair work and reduced downtime for wagons.*

Key words: *transport, railway transport, wagons, digital twins, computer technology, artificial intelligence, transport technology.*

ПЕРСПЕКТИВИ СТВОРЕННЯ ЦИФРОВИХ ДВІЙНИКІВ ВАНТАЖНИХ ВАГОНІВ

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Анотація

Вступ. *Світова промисловість і транспорт стрімко переходять в еру цифровізації, що кардинально змінює підходи до виробництва, експлуатації та обслуговування залізничного транспорту. Україна, як частина глобального ринку, також активно впроваджує інноваційні рішення. Залізничний транспорт є кровоносною системою української економіки та логістики, поєднуючи стратегічні, економічні та соціальні функції.* ***Актуальність.*** *Цифровий двійник являє собою віртуальну копію фізичного об'єкта, процесу або послуги, яка постійно оновлюється даними з реального світу. Щодо вантажного вагона його цифровий двійник може включати детальну інформацію про його технічний стан, історію експлуатації, поточне місцезнаходження, навантаження та інші важливі параметри.* ***Мета.*** *Метою цього наукового дослідження є глибоке вивчення перспектив створення та впровадження цифрових двійників вантажних вагонів у галузі залізничного транспорту України. Актуальність дослідження зумовлена необхідністю підвищення ефективності експлуатації рухомого складу, оптимізації процесів технічного обслуговування та прогнозування можливих несправностей.* ***Результати.*** *Впроваджено підхід до проєктування на основі цифрового двійника, який забезпечить наскрізний робочий процес проєктування в єдиному інформаційному просторі незалежно від програмних систем, які використовуються для розрахунків вузлів та систем вантажних вагонів, також побудована блок-схема роботи цифрового двійника вантажного вагона.* ***Висновки.*** *Моделювання різних сценаріїв експлуатації на віртуальних копіях дозволяє оптимізувати режими обслуговування та ремонту. Науково обґрунтовані алгоритми, інтегровані в цифрові двійники, сприяють ранньому виявленню потенційних несправностей. Прикладні висновки свідчать про можливість значного скорочення витрат на технічне обслуговування та ремонт. Впровадження цифрових двійників дозволяє оптимізувати планування ремонтних робіт та зменшити час простою вагонів..*

Ключові слова: *транспорт, залізничні перевезення, вагони, цифрові двійники, комп'ютерні технології., штучний інтелект, транспортні технології.*

Introduction. Global industry and transport are rapidly moving into the era of digitalization, which is radically changing approaches to the production, operation, and maintenance of railway transport [1]. Ukraine, as part of the global market, is also actively implementing innovative solutions. Railway transport is the circulatory system of the Ukrainian economy and logistics, combining strategic, economic and social functions. The rapid development of information technologies has truly revolutionized approaches to the management of industrial enterprises, in particular in the field of railcar construction. Therefore, scientific research and development of digital technologies - the introduction of digital twins of railcars for load modeling and structural optimization are very relevant, taking into account strategic goal No. 8 of stimulating research and development in conditions of limited material resources, enabling the implementation of innovative projects in priority industries [2].

Topicality. A digital twin is a virtual copy of a physical object, process, or service that is constantly updated with real-world data. In the case of a freight car, its digital twin can include detailed information about its technical condition, operating history, current location, load, and other important parameters. Creating such digital representations opens up many opportunities for optimizing fleet management.

In addition, the digital twin can be used to optimize loading and unloading processes. Having accurate information about the load capacity and condition of each wagon, it is possible to plan the placement of goods more effectively, avoiding overloading and inefficient use of space. This leads to reduced cargo handling times and increased throughput of the railway infrastructure.

Thus, conducting research and practical work to determine the prospects for creating digital twins of freight cars is not only relevant, but also a strategically important task for the development of railway transport. The introduction of this innovative technology will help increase the competitiveness of the industry, reduce operating costs, improve transportation safety and ensure more efficient use of transport infrastructure. Further research and practical implementation of these technologies will open a new era in rail fleet management.

Analysis of information sources on the topic under study. The scientific study [3] considers the concept of composite digital twins on the Digital Twin as a Service platform. The authors explore the architecture and possibilities of creating flexible and adaptive digital twins by combining various components and services. The paper discusses the advantages of such an approach for modeling complex systems and processes. The concept of composite digital twins contributes to the creation of more effective and versatile tools for analyzing and optimizing complex engineering systems. The article is an important contribution to the development of digital twin technologies.

In [4], the authors analyze the key characteristics and functionalities of modern platforms for creating and managing digital twins. The paper also discusses the challenges and potential directions of development of this technology. The article is a valuable overview for understanding the current state and future development of digital twin platforms. The study contributes to a better understanding of the capabilities and limitations of existing solutions.

The authors of the publication [5] explore the advantages of using a distributed architecture to create more adaptive and specialized digital twins. The paper discusses

approaches to the integration and interaction of various distributed components of digital twins. The concept of distributed digital twins is promising for modeling complex and geographically distributed systems. The article is an important contribution to the development of flexible and scalable solutions based on digital twins.

The paper [6] describes the process of "grounding" digital twins. The author explores the need to verify and validate digital twin data with real data to ensure their accuracy and reliability. The paper is likely to discuss methodologies for comparing virtual models with physical objects and environments. The paper emphasizes the importance of integrating real data to increase the trust and effectiveness of digital twins, especially in urban research. The research contributes to the development of digital model validation methodologies.

The paper [7] explores the application of agent-based artificial intelligence to digital twins. The authors explore the possibilities of providing digital twins with autonomous agent properties for more intelligent behavior and decision-making. The paper is likely to present concepts and architectures for integrating agent-based AI with digital twins, as well as the potential benefits of such an approach. This research is an important step in the development of more complex and autonomous digital twins. The paper demonstrates the prospects for integrating AI to improve the functionality of digital twins.

A chapter in the book "Digital Twins" by Springer [8] published in 2025 is devoted to the challenges associated with the development and implementation of digital twins. The authors are likely to analyze various problems that arise at different stages of the digital twin life cycle, including data collection and processing, modeling, integration and security. The paper may address technical, organizational and economic aspects of these challenges. This chapter is important for understanding the obstacles to the widespread implementation of digital twins. The study contributes to the identification of key issues for further research and development.

The analysis of literary sources revealed a noticeable lack of research devoted directly to determining the prospects for creating digital twins of freight cars. Existing works mainly consider general aspects of the digital transformation of transport or individual technological solutions without reference to the specifics of the freight car fleet. The potential economic, operational and safety benefits of implementing such twins have not been sufficiently studied. There is also a lack of in-depth analysis of technical requirements, integration problems with existing systems and possible risks. Therefore, the issue of determining the prospects for creating digital twins of freight cars requires more detailed and targeted scientific research. This opens up significant opportunities for future scientific exploration in this important field.

Research methods**.** The research is based on a comprehensive analysis, including a systems approach to understanding the railcar as a complex interacting system. Modeling and simulation theory is used to develop virtual copies capable of reproducing the behavior of real objects. Big data collection and analysis methods are used to process information from sensors and other sources, which is the basis for building accurate models. Machine learning and artificial intelligence are used to predict the technical condition, optimize maintenance and manage resources. The Internet of Things provides real-time data collection necessary for continuous updating of digital twins. Decision theory is used to develop support tools based on information obtained from digital twins.

Object and subject of research**.** The object of the study is a comprehensive system that encompasses technologies, processes, and data related to the creation, deployment, and use of digital twins of freight cars at different stages of their life cycle.

The subject of the study is the set of potential benefits, risks, technological and organizational prerequisites, as well as economic and social consequences associated with the implementation of digital twins for freight cars.

Purpose and objectives of the study. The purpose of this scientific research is to deeply study the prospects of creating and implementing digital twins of freight cars in the railway transport sector of Ukraine. The relevance of the research is due to the need to increase the efficiency of rolling stock operation, optimize maintenance processes and predict possible malfunctions. The creation of digital twins opens up new opportunities for modeling the behavior of cars in different operating conditions, analyzing their technical condition in real time and making informed management decisions.

To achieve this goal, it is necessary to solve a number of key problems. The primary task is to analyze existing technologies and approaches to creating digital twins in the transport industry, in particular, in the field of railway transportation. The next step will be to determine the key parameters and characteristics of freight cars that need to be reflected in the digital twin to ensure its functionality and informativeness. It is important to explore the possibilities of integrating digital twins with existing railway transport management and monitoring systems.

Presentation of the main material. The emergence of the concept of digital twins is associated with the works of Prof. associated with the works of Prof. M. Grieves. The idea of creating a virtual space in which information is exchanged with the real world was proposed by M. Grieves in 2002 as part of a presentation at the University of Michigan for industry representatives [9]. This concept, designated as "ideal PLM" (Product Lifecycle Management).

Within the freight car industry, the greatest effect can be achieved by building a digital twin of the entire freight car fleet, which will be a set of digital twins of individual freight cars operated on the railway network. The development of a digital twin of the freight car fleet will allow for the creation of a digital wagon resource management system.

The general algorithm of operation of a digital twin of a freight car at all stages of the life cycle, in general, the actions of twins can be divided into two types: training and control (Fig. 1). This was developed for a freight car, taking into account the experience [10].

Distributed machine learning can be used for training (step 1). The local training models are then sent to the twin level for aggregation in the blockchain miner (steps 2 and 3). Model updates from the blockchain are sent to the local systems, where the local models are updated accordingly (steps 4 and 5).

This iterative learning process can occur either synchronously or asynchronously. In asynchronous mode, a device sends its local model only when connected to the miner, while in synchronous mode, devices must send their local models to the miner for global aggregation at a predetermined point in time.

Therefore, we must choose the aggregation method according to the connection conditions. On the other hand, there are some scenarios, such as unmanned locomotives, where devices can generate up to 4000 GB of data per day, and this must be taken into

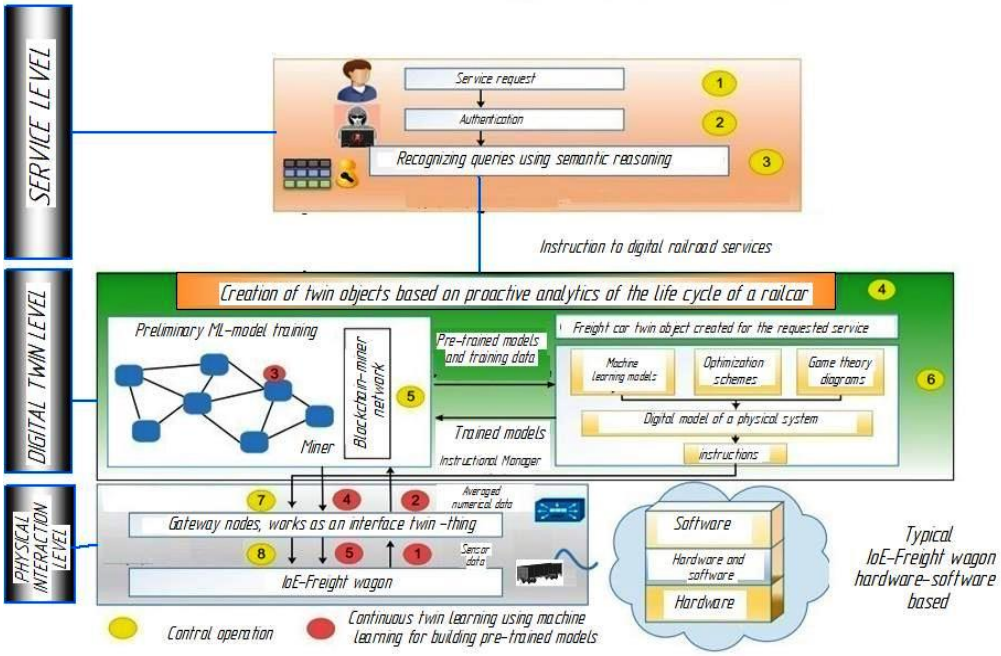

Fig. 1. Algorithm of operation of the digital twin of a freight wagon

account during training. Although centralized machine learning can be used for such scenarios, its disadvantage is that it requires more communication resources to transfer data from end devices to the central server. A solution to this problem can be federated learning, which allows the global model to be constantly updated to improve its efficiency.

In [9], a "five-dimension digital twin model" is presented, in which the problem is considered from a slightly different angle, the model is described by the formula:

MDT = (PE, VM, Ss, DD, CN), (1)

where PE - physical objects, VM - virtual models, Ss - services, DD - digital twin data, CN - interaction protocols.

Based on the considered model of the digital twin and the described algorithm of the digital twin operation, taking into account the defects obtained in operation considered in the work [11], a new approach to the concepts of the digital twin of a freight car at all stages of the life cycle has been created.

– Product development (**DT-1**);

– Production (**DT-2**);

– Operation (**DT-3**).

Digital twin in development (DT-1). At this stage, the key competitive advantages of a high-tech product are laid, for which a system of digital models of the product and, if necessary, technological processes will be created, interconnected and balanced on a single platform in a multi-level matrix. Tracking structural changes in the design AT the design stage This technique involves determining trends in changes in the properties of the design and its inclusion in calculation models. It is mandatory to conduct patent research on requirements, target indicators and resource constraints.

At this stage, the use of digital twin technology allows for rapid large-scale changes to the design of a product, its subsystems and components, as well as rapid verification of these changes through virtual testing and analysis of the impact of changes in the performance of some subsystems and components on others. This allows for reduced volume of field tests and their number to the minimum permissible and necessary, which in turn reduces the time to market for a competitive product and reduces the cost of development.

Digital twin in production (DT-2). It is responsible for accounting for "technological heredity" and is a system consisting of **DT-1** and information in the form of results of virtual tests and computer modeling of technological processes for manufacturing a product.

Digital twin in operation (DT-3). It is a system consisting of a digital twin of the first stage (**DT-1**), if necessary, a second stage (**DT-2**) and information coming from the operated product. DT-3, in particular, contains information for managing the maintenance and repair of a high-tech product. Here it is worth highlighting the model for diagnosing the state of structures separately in the blocks of digital models. This technique involves calibrating the digital twin to the readings of monitoring systems. Condition diagnostics consists in monitoring the inconsistency of measurement data with the results of the digital twin model (which indicates the occurrence of significant defects). Refined modeling will allow you to localize the places of occurrence of problems in the load-bearing or supporting system. And the model for predicting the residual resource (corrosion, strength)

(Fig. 2).shows, as an example, a digital twin at the development stage of the most popular freight cars for transporting goods.

At this stage, a product requirements management module has been developed, a significant amount of high-precision mathematical modeling of freight car elements has been performed (as an example, (Fig. 3).shows a digital twin of a gondola car at the development stage), a dynamic model of a gondola car has been created, and a software package has been developed to predict the technical condition and development of defects from corrosion and other operating factors. Preparations are underway for the second stage of engineering tests in real operating conditions to verify the applied approaches and developed mathematical models of freight cars.

One of the important tasks of the digital twin is to create end-to-end connections between requirements and technical solutions that need to be adopted as soon as possible to minimize the number of design errors, especially at those stages of development when the car is being manufactured and tested.

The implementation of a digital twin design approach will provide an end-to-end design workflow in a single information space, regardless of the software systems used to calculate freight car components and systems. This, in turn, will provide a powerful synergistic effect during the interaction of different design departments and increase the efficiency of the processes of creating and operating freight cars (Fig. 4).

Conclusions. Scientific research confirms the significant potential of digital twins in increasing the efficiency of rail transport. Analysis of data obtained from digital twins opens up new possibilities for predicting the technical condition of wagons.

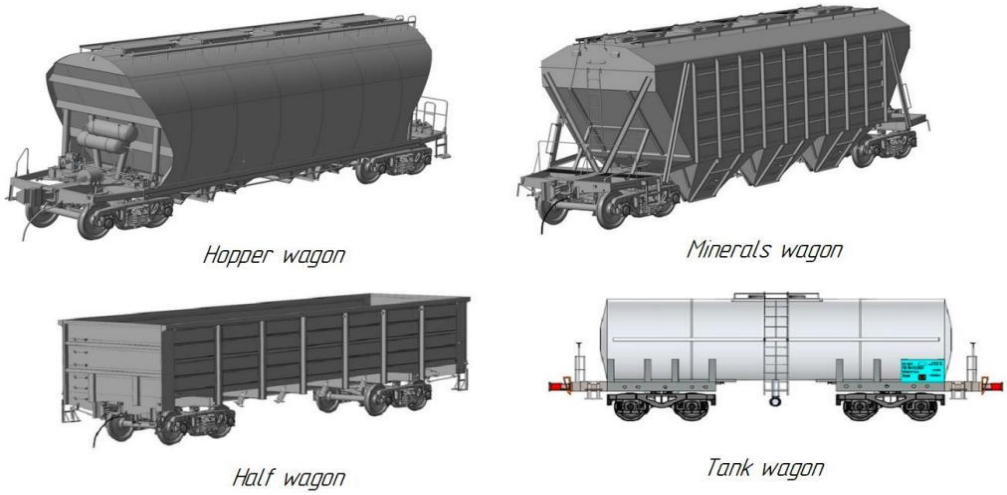

Fig. 2. Digital twins of freight cars under development

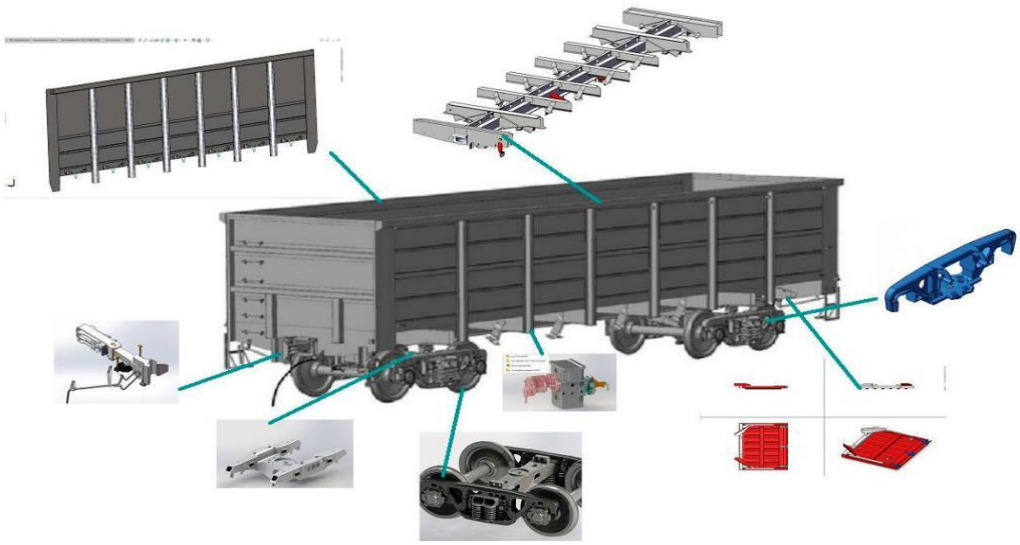

Fig. 3. Digital twin of gondola cars under development

Simulation of various operating scenarios on virtual copies allows for optimization of maintenance and repair modes. Scientifically based algorithms integrated into digital twins contribute to early detection of potential malfunctions. The use of machine learning methods on digital twin data improves the accuracy of predicting failures of components and assemblies. Studies show that digital twins provide a deep understanding of the dynamics of freight wagon behavior during movement.

The practical use of virtual models contributes to increasing the safety of rail transport operations. Digital twins provide valuable information for making informed management decisions regarding the fleet of wagons. The use of digital twins facilitates monitoring the condition of freight wagons in real time.

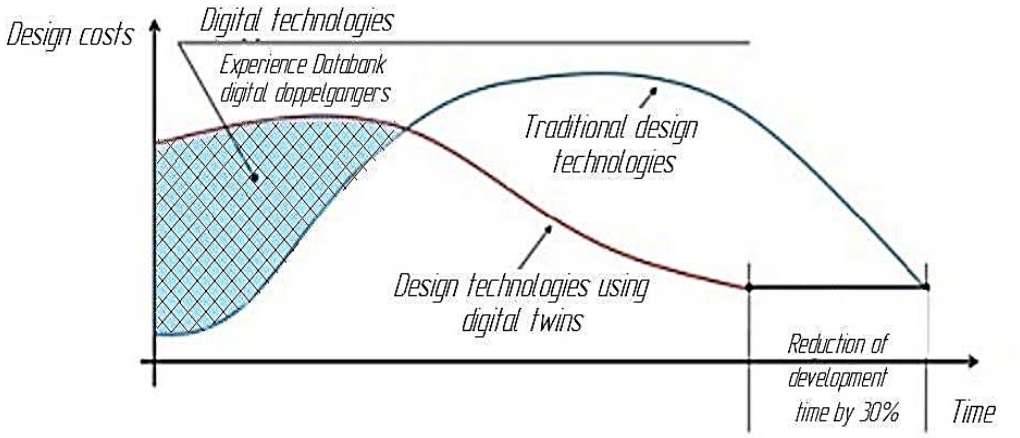

Fig. 4. Transformation of the development system using the concepts of the digital twin of the cargo wagon

The applied value of digital twins lies in the possibility of modeling the impact of various loads on the design of wagons. The introduction of this technology contributes to increasing the throughput of railways by reducing delays. Digital twins can be used to train personnel in the maintenance and operation of wagons. The practical application of virtual copies facilitates the process of certification and testing of new models of freight wagons. The economic effect of the introduction of digital twins is manifested in increasing the service life of wagons.

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