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STRATEGIES FOR THE MODERNIZATION OF LOCOMOTIVE DEPOTS AND THE INTRODUCTION OF DIGITAL TECHNOLOGIES: OPTIMIZATION OF REPAIR PROCESSES BASED ON OPERATING DATA

Summary. *The article is dedicated to the analysis of modernization strategies for locomotive depots through the implementation of digital technologies as a key factor in enhancing the efficiency of railway transport. The aim of the research is to systematize approaches to the digitalization of maintenance processes and to substantiate their impact on the operational efficiency of depots. The study employs general scientific methods of cognition: analysis, synthesis, comparison, generalization, systematization, and a structural-functional approach. The results of the research demonstrate that the implementation of maintenance management systems (CMMS) and ERP ensures automation of technical condition control for locomotives, reduces repair cycle times by 18-30%, and minimizes operational errors by 25-40%. It is proven that the use of artificial intelligence algorithms for optimizing spare parts inventory management can reduce logistics costs by 12-25% through accurate forecasting of depot needs and preventing excess stocking. The study shows that the* *standardization of maintenance procedures according to international UIC and EN norms improves the quality of technical service, ensures reproducibility of processes, and facilitates the integration of the national railway network into the European transport space. It has been established that the digitalization of depots transforms labor organization, enhances the transparency of processes, improves inter-service interaction, and ensures the accuracy of operational planning. The practical value of the research lies in the potential application of generalized modernization strategies to increase the reliability of the locomotive fleet and the efficiency of railway infrastructure operation in the context of the digital transformation of the transport sector.*

Key words: *depot modernization, digitalization, CMMS, artificial intelligence, repair standardization, railway transport.*

Introduction. In modern conditions of global digitalization of transport infrastructure, locomotive depots face the need for a fundamental transformation of operational processes. According to the International Union of Railways, the inefficiency of maintenance and repair of rolling stock results in losses of more than 15 billion euros annually worldwide due to unplanned downtimes, excessive spare parts costs, and insufficient reliability of locomotives. In the context of increasing competition from road and air transport, as well as the need to meet sustainability requirements, the railway sector requires a radical rethinking of approaches to the operation and maintenance of technical means.

Locomotive depots, as key production units of railway infrastructure, are responsible for the technical readiness of traction rolling stock, which directly affects the regularity of train movements, the safety of transportation, and the economic efficiency of railway operations. However, traditional methods of organizing repair processes, based on paper documentation, the empirical experience of staff, and a reactive approach to maintenance, no longer meet the demands of the modern digital economy. The European Commission, in its transport development strategy, emphasizes the need for the digitalization of the railway sector as a prerequisite for creating an integrated, efficient, and sustainable transport space.

In this context, the implementation of digital technologies in the work of locomotive depots acquires strategic significance, as it lies at the intersection of technological innovations, operational efficiency, and the competitiveness of the railway industry. Research on modernization strategies of depots through the lens of digitalization is extremely relevant, as it allows for the systematization of approaches to transforming repair processes, justifying the economic feasibility of investments in digital systems, and forming practical recommendations for managers of production units in railway transport.

Literature Review. The issues of modernization of railway infrastructure and the implementation of digital technologies in depot production processes are well covered in foreign scientific literature and partially researched by domestic specialists.

Among foreign researchers, significant contributions have been made by Kumar [5], who analyzes the transformation of railway maintenance through the lens of Industry 4.0 and demonstrates that the integration of digital technologies is a critical factor in enhancing the operational efficiency of depots. The study by Patel and Singh [8] highlights the practical aspects of implementing CMMS systems in railway units and their impact on reducing rolling stock downtime. An important contribution is made by Bergquist and Söderholm [1], who systematized approaches to digital lifecycle management of railway assets and substantiated the economic effectiveness of data-driven preventive maintenance.

Rodríguez-Fernández and colleagues [9] conducted a comprehensive study on the application of machine learning algorithms for predicting spare parts needs, which has direct practical significance for optimizing depot logistics. The research by Li and Chen [6] focuses on analyzing the impact of digitalization on labor productivity of depot personnel and the formation of new competencies in a digital environment. Fontul and co-authors [4] consider digital technologies as a tool for ensuring compliance with European standards in railway transport maintenance.

Domestic researchers also pay attention to this issue. Butko [2] analyzes the prospects for implementing intelligent management systems in Ukraine's railway transport and justifies the need for systematic modernization of production units. Myamlin and Horobchenko [7] investigate the technical aspects of locomotive diagnostics and the possibilities of integrating digital monitoring systems into repair processes. The practically oriented research by Turpak and Vasylieva [10] examines the organizational aspects of digitalization in railway enterprises and the challenges that arise during the transformation of traditional production structures.

The International Union of Railways in its technical documents [11; 12] formulates requirements for the standardization of repair processes and emphasizes the role of digitalization in ensuring compatibility and efficiency in international rail transport. The European Union Agency for Railways [3] establishes regulatory frameworks for the implementation of digital technologies in the context of ensuring safety and reliability in railway operations.

Despite extensive research on digital transformation in railway infrastructure, there is still a lack of systematic studies that comprehensively integrate modernization strategies for locomotive depots with specific digital technologies while simultaneously addressing their operational impacts and economic efficiency. Existing publications tend to focus on isolated aspects - either technical implementation, organizational change, or economic outcomes- providing a holistic framework that connects these dimensions.

Furthermore, the literature rarely examines how different digital solutions (CMMS, AI-driven logistics, standardization tools) interact synergistically within a single depot environment. This gap is particularly pronounced in the context of integrating national railway systems into international transport networks.

Therefore, the present research employs various methods of scientific cognition to analyze, aggregate, and systematize information in light of these interconnected challenges.

Problem Statement. The aim of the article is to systematize key strategies for the modernization of locomotive depots through the implementation of digital technologies and to substantiate their impact on the operational efficiency of railway transport. To achieve this goal, the research addresses the following tasks:

- to characterize modern digital systems for managing repairs and their functional capabilities in the context of locomotive depots;
- to analyze the application of artificial intelligence algorithms for optimizing the logistics of spare parts;
- to determine the impact of standardizing repair procedures on the quality of maintenance and integration into the international transport space;
- to consider the organizational transformations in depots caused by the implementation of digital technologies.

Materials and Methods. The research employed general scientific methods of analysis, synthesis, comparison, generalization, and systematization. The methodology was based on a structural-functional approach to analyzing the processes of modernizing locomotive depots in the context of digital transformation. International standards for railway maintenance, including UIC and EN, as well as practical cases from leading European and global railway operators, were analyzed. Special attention was paid to studying the effectiveness of implementing CMMS and ERP digital systems, artificial intelligence algorithms for inventory management, and analyzing organizational changes in the production processes of depots. The research relies on technical documentation, statistical data from railway enterprises, and the results of empirical studies published in peer-reviewed scientific journals.

Research Results

1. *Digital Repair Management Systems as the Basis for Modernizing Depots*

The modern transformation of locomotive depots is impossible without the implementation of comprehensive digital systems for managing technical maintenance and repairs. CMMS and ERP systems represent integrated platforms that automate the entire range of production processes in the depot: from planning repairs and monitoring the technical condition of locomotives to managing personnel and financial resources.

As noted by Kumar [5] and Patel and Singh [8], the implementation of CMMS systems in railway depots ensures a shift from reactive to preventive maintenance based on the analysis of real data about the condition of equipment, rather than fixed schedules. This allows for the optimization of repair intervals, avoidance of premature interventions, and focusing resources on critical nodes that truly require attention. According to research, this approach reduces the duration of repair cycles by 18-30% compared to traditional planning methods.

A critical advantage of digital systems is the automation of document management and the creation of a unified information space within the depot. Traditionally, repair processes are accompanied by significant volumes of paperwork, leading to information loss, data duplication, and complicating timely decision-making. Digital systems ensure complete transparency of processes through electronic work permits, automatic tracking of work completion, recording of materials used, and real-time reporting.

Research by Bergquist and Söderholm [1] emphasizes the importance of integrating CMMS with locomotive diagnostic systems. Modern traction vehicles are equipped with numerous sensors that generate large volumes of telemetry data about the operational parameters of engines, braking systems, running gear, and electrical equipment. Integrating this data into CMMS allows for the detection of anomalies at early stages, predicting equipment failures, and automatically generating repair requests before critical malfunctions occur.

An important aspect of digitization is minimizing the human factor in repair processes. Experts estimate that 25% to 40% of operational errors in depots are related to inaccuracies in documentation, insufficient coordination among teams, and mistakes in fault identification.

Table 1

CMMS/ERP implementation in a depot: modules, data, and operational effects

Digital module	What it automates	Inputs (data)	Result (from literature)	Example KPI
Asset registry (e-passport)	Full life-cycle history for locomotives/components	Serial numbers, repairs, replacements	Transparency; fewer losses/duplicates	% units with complete digital history
Condition monitoring + CMMS	Early anomaly detection + automatic work request	Telemetry + diagnostics	Shift to preventive maintenance	Warning lead time; false alarms, %
Planning & scheduling	Repair calendar, bay loading, prioritization	Capacity, constraints, plan	Repair cycle reduced by 18-30%	Avg downtime (days); cycle time (days)
E-permits & e-checklists	Paperless work orders, acceptance, evidence	Tech maps, QC checklists	Fewer human-factor errors (25-40% are documentation/coordination)	Rework rate, %; nonconformities /100 jobs
Dashboards & accountability	Real-time KPI tracking and bottleneck alerts	CMMS/ERP logs, warehouse & HR	Faster data-driven decisions	Schedule adherence, %; cost per repair

Digital systems standardize work procedures, provide step-by-step instructions for personnel, and automatically verify the completeness of all necessary operations, which significantly improves the quality of repairs and reduces the likelihood of locomotives returning to the depot with similar problems.

2. Optimization of Spare Parts Logistics through Artificial Intelligence

Inventory management of spare parts is one of the most complex logistic challenges in the operation of locomotive depots. Locomotives consist of thousands of components of varying levels of criticality, which have different lifetimes, costs, and delivery speeds from manufacturers. Traditional inventory management approaches based on past statistics and expert assessments lead to two opposite problems: excessive stocking of slow-moving items and shortages of critical components at the moment of need.

As demonstrated by the research of Rodríguez-Fernández and colleagues [9], using machine learning algorithms to forecast spare parts needs allows for a significant reduction in logistics costs while simultaneously increasing the availability of necessary components. The algorithms analyze historical data on equipment failures, consider the operational intensity of specific locomotives, seasonal factors, diagnostic results, and repair plans, forming dynamic forecasts for short, medium, and long-term needs.

Optimizing inventory through artificial intelligence reduces storage costs by 12-25% due to a more accurate balance between the need to ensure continuity of repair processes and minimizing frozen capital in stocks. Particularly significant effects are achieved for expensive components with low failure rates, such as traction motors, generators, or electronic control units, where even a small reduction in safety stocks leads to substantial savings.

The research of Li and Chen [6] emphasizes that AI systems not only forecast needs but also optimize procurement strategies. The algorithms take into account storage costs, delivery times from various suppliers, order grouping possibilities to reduce transportation costs, and price dynamics in the market. This allows for the creation of optimal procurement schedules that minimize total costs across the entire supply chain of spare parts.

An important aspect is the integration of inventory management systems with CMMS and maintenance planning systems. When the system automatically generates a work order for repairs, it simultaneously reserves the necessary spare parts, checks their availability in stock, and, if needed, initiates an urgent procurement process. This ensures the continuity of repair processes and prevents downtime due to waiting for components.

The practical implementation of AI systems in the depot also includes supplier analytics modules that assess the reliability of partners based on criteria such as timeliness of deliveries, quality of components, and adherence to contractual obligations. This data is used to create supplier rankings and make informed decisions regarding the diversification or concentration of procurements.

3. Standardization of repair procedures in accordance with international norms

The integration of national railway systems into the European transport space requires the harmonization of technical standards and maintenance procedures according to the requirements of the International Union of Railways (UIC) and European norms (EN). The standardization of repair procedures is not merely a formal requirement but represents a systematic approach to improving the quality, reproducibility, and safety of locomotive maintenance.

UIC documentation, particularly UIC leaflets 505 and 623, sets detailed requirements for the maintenance of traction rolling stock, including inspection frequency, diagnostic methods, permissible deviations of parameters, and testing procedures after repairs. The implementation of these standards in depot operations ensures a uniform level of service quality regardless of the geographical location of the unit and allows locomotives to move freely between countries without the need for additional certifications.

As noted by Fontul and co-authors [4], the standardization of procedures is based on the principle of documenting all operations. Each repair procedure must be accompanied by a detailed technological map that outlines the sequence of operations, required tools, control parameters, and acceptance criteria. This ensures consistent quality of work performed by different teams and personnel with varying levels of qualifications.

The digitization of depots significantly facilitates the implementation of standardized procedures. Electronic systems can contain a complete database of technological maps with multimedia content: diagrams, video instructions, interactive drawings. Employees can access the current version of the documentation directly at their workplace via tablets or terminals, eliminating the use of outdated instructions and ensuring compliance with all standard requirements.

Standardization also applies to the quality control system for repairs. International norms require multi-level verification of completed work, including self-monitoring by the performer, oversight by the supervisor, and acceptance control. Digital systems automate this process through electronic checklists, photo documentation of critical components, and automatic locking of the locomotive's release from repair until all necessary inspections are completed.

Myamlin and Horobchenko [7] emphasize that the standardization of diagnostic procedures is particularly critical for ensuring safety. European standards establish clear methodologies for non-destructive testing of critical components such as wheel pairs, wagon frames, and coupling devices. The use of standardized equipment and procedures ensures the detection of defects at early stages and prevents catastrophic failures during operation.

4. Organizational transformation of the depot in the context of digitization

The implementation of digital technologies leads to fundamental changes in the organization of work at locomotive depots, affecting the structure of divisions, distribution of functions, communication systems, and personnel competency requirements. Digital transformation is not limited to technological upgrades; it requires a rethinking of the entire production culture and management philosophy.

Butko [2] notes that the traditional organizational structure of the depot, which has historically formed around specialized workshops and crews, is transforming into a more flexible and integrated model. Digitization eliminates information barriers between divisions: the planning and production department, the current repair shop, the warehouse, and the technical control service operate within a unified information space that ensures coordination of actions and prompt responses to production situations.

A key change is the shift to data-driven management. Depot managers gain access to analytical dashboards that display key performance indicators in real-time: the workload of repair positions, average locomotive downtime, material costs, crew productivity, and schedule adherence. This enables decision-making based on objective data rather than intuition or outdated reports that arrive late.

Digitization radically changes the nature of communication within the depot. Instead of paper work orders and verbal instructions, electronic task systems are implemented, which automatically distribute tasks among crews based on their qualifications, current workload, and task priority. Mobile applications allow workers to receive tasks, report on their completion, request technical support, and document identified problems directly from the work site.

Table 2

Standardization (UIC/EN): how digital tools support documented procedures and multi-level QC

Standard requirement	What must be standardized	Digital tool inside depot	Outcome
UIC leaflets 505/623	Intervals, tests, allowable deviations	Digital tech maps + automated limit checks	Uniform quality; easier interoperability
Procedure documentation	Sequence, tools, parameters, acceptance criteria	Single database + version control + tablets	No outdated instructions; repeatable quality
Multi-level QC	Self-check → supervisor → acceptance	E-checklists + photo evidence + release lock	Lower rework; fewer repeat failures
EN NDT methods	NDT procedure and reporting for critical parts	Standard digital forms + traceability	Earlier defect detection; higher safety

Research by Li and Chen [6] demonstrates that digitization enhances the transparency of production processes and individual accountability of employees.

The system records all personnel actions: who, when, and what operations were performed, how much time was spent, and what materials were used. This creates an objective basis for evaluating productivity, forming a motivation system, and identifying areas that require additional training or organizational improvements.

The transformation also touches on the competency system of the personnel. A modern depot requires specialists who combine traditional technical knowledge of locomotives with digital literacy: the ability to work with electronic systems, interpret diagnostic data, and use digital tools to solve technical problems. Turpak and Vasilieva [10] emphasize the necessity of a systematic approach to staff training when implementing digital technologies, which includes not only technical training but also the formation of a new mindset focused on continuous improvement and readiness for change.

Failure history + usage	→	*Diagnostics signals*	→	*ML forecast module*	→	*Inventory policy (reorder points)*	→	*Procurement & suppliers*
Integration with CMMS work orders: reserve parts automatically; if shortage → urgent procurement request								
Economic effect: 12-25% lower storage costs + fewer repair delays due to missing components (especially for expensive, low-failure items).								

Fig. 1. Closed-loop digital maintenance cycle (CMMS/ERP + diagnostics + QC + KPI feedback)

An important organizational aspect is the formation of an information technology service directly within the depot structure. Unlike the traditional model, where IT support was provided centrally at the railway company level, a modern high-tech depot requires its own specialists for supporting digital systems, analyzing data, and developing local solutions for process optimization. This ensures the timeliness of technical support and the ability to adapt systems to the specific needs of a particular unit.

Discussion of Results. The conducted research demonstrates that the modernization of locomotive depots through the implementation of digital technologies represents a comprehensive transformation that encompasses technological, organizational, and managerial aspects of production activities. The obtained results align with the conclusions of leading researchers in this field and confirm the hypothesis about the critical role of digitization in enhancing the efficiency of railway transport.

The implementation of CMMS and ERP systems not only provides automation of individual processes but also creates an integrated digital environment in the depot, where all elements of the production chain interact synchronously and transparently. Compared to the studies by Kumar [5] and Patel and Singh [8], our findings further emphasize the importance of integrating digital systems with the existing technical infrastructure of the depot and the necessity of phased implementation to minimize the risks of operational disruptions during the transition period.

Conclusions. The modernization of locomotive depots through the implementation of digital technologies represents a systemic transformation that encompasses the automation of production processes, optimization of logistics, standardization of procedures, and organizational changes. The implementation of CMMS and ERP systems ensures the automation of monitoring the technical condition of locomotives, reducing the duration of repair cycles by 18-30% and minimizing operational errors by 25-40%, which confirms the critical role of digital systems in enhancing the operational efficiency of the depot.

The application of artificial intelligence algorithms for managing spare parts inventory allows for a reduction in logistics costs by 12-25% through accurate forecasting of needs and preventing excess inventory while simultaneously ensuring the readiness of critical components. This demonstrates the economic feasibility of investments in AI technologies and their potential for optimizing the entire supply chain.

Practical implications for railway operators: Railway managers should adopt a phased implementation approach, beginning with CMMS deployment to establish a digital foundation, followed by AI-driven logistics optimization and progressive standardization alignment. Investment priorities should focus on systems with the highest immediate ROI - particularly condition monitoring and preventive maintenance modules that reduce unplanned downtime. Operators must simultaneously invest in workforce development, creating training programs that build digital competencies alongside traditional technical skills.

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