ABSTRACT

of the dissertation for the degree of Doctor of Philosophy (PhD) in the field of study 8D071 – "Engineering and Engineering Sciences," under the educational program 8D07102 – "Transport, Transport Equipment and Technologies"

BAIGOZHINA PERIZAT UVALIYEVNA

DEVELOPMENT OF A METHOD TO INCREASE THE EFFICIENCY OF FREIGHT WAGONS OPERATION BASED ON FORECASTING THEIR SERVICEABILITY

Relevance of the dissertation. This dissertation was prepared within the framework of the Concept for the Development of the Transport and Logistics Potential of the Republic of Kazakhstan until 2030, and in alignment with the objectives of the Concept for the Development of Railway Transport of the Republic of Kazakhstan until 2029. It is submitted for the degree of Doctor of Philosophy (PhD) in the field of study 8D071 – "Engineering," under the doctoral program 8D07102 – "Transport, Transport Equipment, and Technologies".

Railway transport plays a vital role in freight operations within the Republic of Kazakhstan. As freight volumes grow and the load on the rolling stock increases, it becomes increasingly important to assess the technical condition of freight wagons in a timely manner, to make well-founded decisions regarding their continued operation, and to ensure the rational use of available rolling stock resources.

During operation, defects in freight wagons are primarily identified at technical maintenance points. Decisions on whether to continue using a wagon or to send it for repairs are based on the results of technical inspections and the requirements of current regulatory documents. However, existing approaches do not always allow for a comprehensive assessment that accounts for both the actual technical condition of individual components and the economic rationale behind the decisions made.

Furthermore, ensuring that technical maintenance points are adequately stocked with necessary spare parts is a critical issue. An uneven distribution of inventory across stations can lead to surpluses at some locations and shortages at others, resulting in longer wait times for repairs and additional operational costs.

The existing methods of monitoring the technical condition of freight wagons, along with the current regulatory framework, ensure compliance with operational safety requirements. However, the processes for making informed decisions regarding the continued operation of wagons based on their technical condition, as well as the redistribution of spare parts among technical maintenance points, require further improvement. Therefore, there is a pressing need to develop a decision-making algorithm for the continued operation of freight wagons, along with a methodology for redistributing spare parts among technical maintenance points.

The research hypothesis posits that the operational efficiency of freight wagons can be enhanced by improving decision-making processes regarding their continued

use based on assessments of their technical condition and by optimizing the redistribution of spare parts among technical maintenance points.

The objective of this research is to increase the operational efficiency of freight wagons by developing a decision-making algorithm for their continued use (based on technical condition assessments) and by improving the management of spare parts at technical maintenance points.

To achieve this objective, the following tasks have been addressed:

- the current state of freight wagons in the Republic of Kazakhstan has been analyzed;
- a critical analysis of the system for the operation, quality control, and maintenance of freight wagons has been conducted;
- the research site has been selected and justified, and statistical data regarding the operational performance of freight wagons have been analyzed;
- the optimality criterion for selecting operational strategies for freight wagons has been established;
- the probabilistic-deterministic mathematical model for optimizing the operation and maintenance of freight wagons has been developed;
- the distribution of warehouse inventories has been optimized, using the Karaganda Railway Division as a case study;
- the research findings have been implemented, and their effectiveness has been evaluated.

This work examines two interrelated areas: decision-making regarding the continued operation of freight wagons and the reallocation of spare parts among maintenance facilities. Both areas are unified by the common objective of enhancing the operational efficiency of the freight wagon fleet through well-founded operational decision-making and the rational use of spare parts.

Research methods. The dissertation employs methods of statistical analysis, observation, mathematical modeling, multi-criteria assessment, and economic analysis.

The scientific novelty of the research lies in the following:

- the analysis of statistical data regarding malfunctions of freight wagons within the Karaganda Railway Division has made it possible to determine the probability of failure for key wagon components;
- the optimality criterion for assessing the effectiveness of decisions regarding the operation of freight wagons has been substantiated;
- the probabilistic-deterministic model for the operation and maintenance of freight wagons has been developed, providing an algorithm for decision-making concerning the continued use of these wagons;
- the deterministic relationship between economic indicators and operational costs has been established for the first time, contingent upon the functional condition of the wagons;
- relationships have been derived that determine the optimal distribution of required spare parts across stations within the Karaganda Railway Division;

– the mathematical model for the optimal distribution of required spare parts among a group of stations within the Karaganda Railway Division has been developed for the first time;

– the method of calculating the cumulative probability of failure for specific groups of wagon components has been proposed for the first time.

Scientific propositions submitted for defense are as follows:

- the decision-making algorithm for the continued operation of freight wagons, based on an assessment of the technical condition of key components and parts, taking into account both technical and economic criteria;

- the mathematical model and methodology for reallocating spare parts among maintenance facilities, accounting for the requirements of individual stations and the maintenance of minimum (safety) stock levels;

– - simulation results for various spare-part reallocation scenarios, detailing changes in storage and transportation costs, wagon downtime, and spare-part utilization;

- the assessment of the economic efficiency of the proposed solutions.

The author presents the following for defense:

1. The decision-making algorithm for the continued operation of freight wagons, based on an assessment of the technical condition of their key components and parts.
2. The approach to selecting an operational strategy for freight wagons, based on comparing the technical condition of components with the economic viability of the chosen course of action.
3. The methodology for assessing the technical condition of key freight wagon components to inform decisions regarding continued operation, repair, or decommissioning.
4. The methodology for reallocating spare parts among maintenance facilities, based on station requirements and the maintenance of minimum (safety) stock levels.
5. The software module that implements the decision-making algorithm for the continued operation of freight wagons.
6. The evaluation of the efficiency of the developed solutions, including reductions in inventory-related costs and wagon downtime.

The object of study encompasses the processes involved in the operation and maintenance of freight wagons, as well as the provision of spare parts to maintenance facilities.

The subject of study encompasses methods and algorithms for making decisions regarding the continued operation of freight wagons based on an assessment of their technical condition, as well as processes for optimizing and reallocating spare parts among maintenance facilities.

The practical significance of this work lies in the applicability of the developed solutions to the organization of freight wagon operation and maintenance. The research includes:

– developing a decision-making algorithm for the continued operation of freight wagons, based on an assessment of the technical condition of key components and parts;

– developing a software module that implements this decision-making algorithm;

– developing a methodology for reallocating spare parts among maintenance facilities, accounting for the requirements of individual stations and minimum required stock levels.

The results of this dissertation work have been provided for practical use to the VChD-13 (Freight Wagon Depot 13) of the Karaganda Railway Division and have been integrated into the curriculum for the course “Operational Use. Methods and Models” for first-year master’s students enrolled in the educational program 7M07104 – “Transport, Transport Engineering and Technologies”.

Reliability of the dissertation results. This is ensured by the correct formulation of the research objectives, the use of statistical data on the operation of freight wagons within the Karaganda Railway Division, and the application of statistical analysis methods, mathematical modeling, and comparative evaluation of the options under consideration. The developed decision-making algorithm for the continued operation of freight wagons, along with the methodology for the redistribution of spare parts, has been verified through both theoretical calculations and practical examples. The results obtained are consistent with current regulatory requirements and the operational conditions of railway transport. The key findings of the dissertation have been published in scientific journals and presented at academic and practical conferences.

All the sections of the dissertation are structured in a methodical sequence and are logically interconnected. They follow a coherent progression that reflects the stages of addressing the defined research objectives. The scientific and practical results obtained align with the overall goal and specific tasks of the research.

Summary of the dissertation

The first chapter provides the analysis of the current state of the freight wagon fleet in the Republic of Kazakhstan and examines the existing approaches to the operation, maintenance, repair, and technical condition monitoring of freight wagons. A critical analysis of the current system of operation and maintenance is presented that identifies the primary challenges and limitations of the existing practices. Based on this analysis, the goal and objectives of the research are formulated.

The second chapter provides the characterization of the Karaganda Railway Division. A statistical analysis of freight wagon malfunctions was conducted to identify the most frequent failures of the key components and parts based on the classification system "Major Malfunctions of Freight wagons" (KZHA 2005 04) as applied to the Karaganda Division.

The third chapter develops the decision-making algorithm for the continued operation of freight wagons based on an assessment of the technical condition of their primary components and parts. The parameters to be monitored for wheelsets,

axle-box assemblies, car bodies, braking equipment, and other elements were identified and systematized. Depending on technical and economic criteria, one of several courses of action can be selected: continuing operation without repairs, sending the car for repairs, replacing specific components or parts, or decommissioning the car. The cumulative probability of failure for the car, viewed as a single integrated system, is taken into account, allowing for a well-founded determination of the need for technical intervention at the stage when a car is uncoupled.

The fourth chapter presents the mathematical model and the methodology for reallocating spare parts among technical maintenance points, accounting for existing inventory, station requirements, and established minimum stock levels. Criteria for evaluating reallocation options are examined, including storage and transportation costs, car downtime, and the utilization of spare parts.

The fifth chapter covers the practical validation of the developed solutions. It examines the operation of a software module that implements the decision-making algorithm for freight wagon operation and simulates various spare-parts reallocation scenarios tailored to the conditions of the Karaganda Division. The results indicate an average reduction of 25.34% in inventory maintenance costs and an 11.25% decrease in car downtime. The economic assessment of the proposed solutions shows an estimated annual economic benefit of 4,278,300 tenge, and the payback period is 1.05 years.

Personal contribution of the author. The author personally collected, processed, and analyzed statistical data regarding malfunctions of freight wagons within the Karaganda Railway Division. In collaboration with the scientific supervisors, the author participated in developing a decision-making algorithm for the continued operation of freight wagons, as well as a methodology for reallocating spare parts among technical maintenance points. Furthermore, in conjunction with the scientific supervisor, the author conducted modeling of the scenarios under consideration, analyzed the resulting data, developed a software module, and assessed the economic efficiency of the proposed solutions.

Publication and validation of the research. The key findings of the dissertation were published in two articles indexed in the Web of Science and Scopus databases, two articles recommended by the Committee for Quality Assurance in Science and Higher Education of the Ministry of Science and Higher Education of the Republic of Kazakhstan, and two papers presented at international scientific and practical conferences. One certificate of state registration of copyright was obtained.

The article "Algorithm for Making the Optimal Decision for Further Operation of Freight wagons," published in the journal Communications: Scientific Letters of the University of Žilina, which is indexed in the Web of Science and Scopus databases under the category "Mechanical Engineering in Transport" (Q4 quartile, 47th percentile; 2025, Vol. 27, No. 4; DOI: 10.26552/com.C.2025.049), examines the methodology for determining the future operational status of freight wagons. The study compiles and processes statistical data on the failure of key freight wagon components, establishes an optimality criterion based on profit maximization, and

develops an algorithm to guide decisions regarding whether to continue operating, repair, or decommission a railcar.

The article "Reducing Storage Costs and Downtime in Railways Through Spare Parts Redistribution and MCDA-Based Optimization," published in the journal Applied Sciences, which is also indexed in the Web of Science and Scopus databases (Q2 quartile, 81st percentile; 2025, No. 24, Article 12957; DOI: 10.3390/app152412957), proposes an approach to improving the efficiency of spare parts management at railway stations. The research compares a traditional inventory storage system with various redistribution scenarios across stations and develops a mathematical model based on Multi-Criteria Decision Analysis (MCDA) that accounts for the costs associated with storing, transporting, and redistributing spare parts.

The article “Justification of the method for extending the service life of freight wagons,” published in the journal University Proceedings (2024, No. 4 (97), Section 3: “Construction. Transport”; DOI: 10.52209/1609-1825_2024_4_226), analyzes the issues related to ensuring the safety and operational efficiency of railway rolling stock and examines indicators of its technical condition and failure probability.

The article “Justification of the need to forecast the condition of railcars based on technical and functional diagnostics,” published in the journal University Proceedings (2025, No. 1 (98), Section: “Construction. Transport”; DOI: 10.52209/1609-1825_2025_1_273), discusses modern technical diagnostic tools for freight wagons, including systems for monitoring wheelsets, braking equipment, and running gear.

Structure and scope of the dissertation. The dissertation is presented in typewritten form and includes a list of notations and abbreviations, an introduction, five chapters, and a conclusion. It contains 74 figures, 52 tables, a bibliography of 174 sources, and 6 appendices.

The dissertation presents new, scientifically grounded results aimed at addressing a significant practical challenge: enhancing the operational efficiency of freight wagons. This is achieved by developing a decision-making algorithm for their continued operation and a methodology for the redistribution of spare parts among technical maintenance facilities.

The study yielded the following key results:

– the current condition of the freight wagon fleet of the Republic of Kazakhstan was assessed, and existing methods for wagon maintenance, diagnostics, and condition monitoring were critically reviewed. This analysis identified the main problems and provided a basis for defining the research aim and objectives.

– a statistical analysis of freight wagon defects was conducted in the Karaganda Railway Division (which served as the study area). A database of the most common failures of major wagon assemblies and components was compiled using the Main Freight Wagon Defects classification system (KZHA 2005 04).

– the condition parameters of the major freight wagon assemblies that inform the choice of a strategy for continued operation were identified.

– an optimality criterion for selecting a course of action for freight wagons was established and justified.

– a probabilistic-deterministic mathematical model was developed, serving as the basis for an algorithm to select the appropriate option for the further operation of freight wagons, taking into account their technical condition and economic indicators.

– the two-stage risk assessment methodology was tested in practice using freight wagon No. 75014324 as a case study. The results demonstrated its high technical effectiveness. Repairs reduced the overall probability of wagon failure from 94.16% to 27.34%, thereby ensuring that the wagon's reliability was restored and that it could be operated safely.

– the mathematical model and a methodology for redistributing spare parts among maintenance points were developed, accounting for station-specific requirements, existing inventory levels, and the necessity of maintaining a minimum reserve stock.

– spare parts reallocation options were optimized for the Karaganda Railway Division. The results showed that applying the methodology can reduce inventory holding costs by an average of 25.34% and wagon downtime by an average of 11.25%, while achieving an average spare parts utilization rate of approximately 72% after reallocation.

– a software module implementing the decision-making algorithm for freight wagons was developed and verified using worked examples.

– the economic effectiveness of the proposed solutions was evaluated. The estimated annual economic benefit was KZT 4,278,300. With a one-time investment of KZT 4,500,000, the estimated payback period was 1.05 years.

– the algorithm, software module, and spare parts reallocation methodology can be used to plan freight wagon operations and maintenance.

– future research will focus on further developing the scientific and methodological approach to improving the operational efficiency of freight wagons.